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The Ninyerola Gypsum unit: an example of cyclic, lacustrine sedimentation (Middle Miocene, E Spain)

La unidad Yesos de Ninyerola: un ejemplo de sedimentación cíclica lacustre (Mioceno Medio, E España)

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Abstract

The Ninyerola Gypsum unit is a Middle Miocene lacustrine deposit, close to 200 m in thickness, which crops out mainly along an anticline structure trending NNE-SSW near the city of Valencia. This anticline structure is comprised of Keuper (Upper Triassic) diapiric materials in the core and a Miocene succession on its flanks. The Ninyerola Gypsum unit appears at the base of this succession and is overlain by alluvial deposits. The latter deposits grade upwards to terrigenous, coastal marine sediments presumably of Tortonian age.

The anticline flanks of the Miocene succession differ markedly not only in terms of their depositional and diagenetic facies but also in thickness and cyclicity. These differences suggest that synsedimentary deformation of the Triassic basement exerted control on Miocene sedimentation. On the eastern flank, where the succession is thicker (>230 m) and well exposed, we distinguished the following stratigraphic intervals from base to top: nodular gypsum (a), bioturbated gypsum (b), alternation of laminated gypsum and carbonate (c), a calcareous interval (d), red lutites and bioturbated gypsum (e), and a clastic alluvial alternation (f); this assemblage unconformably underlies a clastic, coastal marine interval (g). The Ninyerola Gypsum unit constitutes the lacustrine sediments −intervals (a) to (e)− of the succession. In this unit, numerous carbonate-gypsum cycles are recorded in intervals (a) to (c), whose average thickness approaches 6 m.

The lacustrine stages of this succession were interpreted as the result of the gradual development of a saline lake of the sulphate-carbonate type overlying the Triassic materials, which extruded during the Lower Miocene. Interal (c) represents the maximum extension, depth and subsidence of this saline lake. This deep lake stage (c) was preceded by a shallow lake stage (b), which initially experienced anhydritic sabkha conditions (a). Stage (c) was followed by a diluted lake stage (d) and a final evaporitic lake stage (e). Subsequently, an input of alluvial clastic materials (f) and marine transgression (g) brought an end to the evaporative conditions in the area.

Gypsum is secondary –derived from the hydration of its anhydrite precursor– in interval (a) and is primary in the remaining gypsum intervals. The isotope compositions of the different gypsum facies indicate they arose from Triassic sulphates through a process of chemical recycling.

Keywords: evaporites, gypsum, lake model, cyclicity, sedimentation, Miocene, Spain

Resumen

La unidad Yesos de Ninyerola es un depósito lacustre del Mioceno Medio, de potencia cercana a los 200 m, que aflora principalmente a lo largo de una estructura anticlinal de orientación NNE-SSW cerca de la ciudad de València. Esta estructura está formada por materiales diapirizados del Keuper (Triásico Superior) en el núcleo y por una sucesión miocena en los flancos. En la base de esta sucesión se desarrolla la citada unidad Yesos de Ninyerola, la cual se encuentra recubierta por depósitos aluviales que gradan verticalmente a sedimentos terrígenos marinos. Estos últimos tienen una probable edad Tortoniense.

Existen diferencias significativas en la sucesión miocena de ambos flancos del anticlinal, no sólo en las facies deposicionales y diagenéticas, sino también en las potencias y en la ciclicidad, todo lo cual sugiere que la deformación sinsedimentaria del basamento triásico controló la sedimentación miocena. En el flanco este del anticlinal, donde la sucesión miocena es más potente (>230 m) y se presentan las mejores condiciones de afloramiento, podemos distinguir los siguientes intervalos, de base a techo: yeso nodular (a), yeso bioturbado (b), alternancia de yesos y carbonatos laminados (c), intervalo calcáreo (d), lutitas rojas y yeso bioturbado (e), y alternancia detrítica de ambiente alluvial (f); el anterior conjunto viene recubierto discordantemente por un intervalo detrítico marino de ambiente costero (g). La unidad Yesos de Ninyerola comprende el conjunto lacustre integrado por los intervalos (a) a (e). Se observan numerosos ciclos de carbonato-yeso en los intervalos lacustres (a), (b) y (c), con una potencia promedio de ciclo próxima a los 6 m.

Los estadios lacustres de esta sucesión del flanco este del anticlinal se interpretan como el resultado de la implantación progresiva de un lago salino del tipo carbonatado-sulfatado sobre los materiales triásicos, que ya habían extruido durante el Mioceno inferior. La máxima expansión, profundidad y subsidencia de este lago salino se alcanzó durante la sedimentación del intervalo (c). Este estadio más profundo (c) fue precedido de un lago somero (b) que estuvo afectado en su inicio por episodios de sabkha anhidrítica (a). Posteriormente, dicho estadio profundo salino fue seguido por un estadio de dilución (d) y un estadio final de lago somero de nuevo evaporítico (e). Finalmente, un aporte de materiales clásticos aluviales (f) y una transgresión marina (g) acabaron con las condiciones lacustres y evaporíticas en el área de estudio.

El yeso es secundario (procedente de la hidratación de anhidrita precursora) en el intervalo (a), y primario en los restantes intervalos yesíferos. Las composiciones isotópicas de las diferentes facies de yeso indican una procedencia triásica del sulfato mediante un proceso de reciclaje químico.

Palabras clave: evaporitas, yeso, modelo lacustre, ciclicidad, sedimentación, Mioceno, España

1. Introduction

Evaporite formations of a lacustrine origin are common in many Tertiary basins of Spain. These formations are important for a number of reasons including their direct implications in geotechnical problems, the industrial uses of their minerals and rocks, the paleoclimatic interpretations derived from their marked cyclicity, and the new sedimentological models they suggest.

Such formations are, however, scarce in eastern Spain. An exception is the Ninyerola Gypsum unit, a small unit showing low salinity conditions located about 15 km to the SW of the city of Valencia. This unit consists of a thick succession of carbonate and gypsum facies arranged in a cyclic pattern. The unit is also interesting because its large gypsum nodules have been used in the past as high quality alabaster for sculptures. In effect, some of these pieces form a significant part of Valencia's historical heritage (Cebrián, 2000; García de Miguel *et al.*, 2001).

This paper describes a general survey performed on the Ninyerola Gypsum unit from a stratigraphic, petrologic and sedimentologic perspective. Despite its preliminary nature, we hope that some of the aspects dealt with will contribute to a better understanding of the environments and processes characterizing the Tertiary lacustrine record of Spain.

2. Geological setting

The Ninyerola Gypsum unit occurs in the western zone of the Coastal Depression of Valencia (Fig. 1), which was filled by Tertiary and Quaternary sediments. In this zone, non-marine Miocene materials extend across a wide band oriented E to W, which occupies the central part of the 1:50,000 Geological Map 721, of Cheste (IGME, 1980). These deposits, mainly lacustrine carbonates and alluvial siliciclastics, commonly overlie Triassic facies. The latter are comprised of Keuper clays and evaporites and, to a lesser extent, Muschelkalk carbonates (Ortí, 1974). These Triassic facies were largely disturbed by diapirism during the Lower Miocene and subsequently exposed and eroded in numerous outcrops (IGME, 1980).

The non-marine Miocene materials locally exhibit evaporitic characteristics, as may be observed in the SW corner of the Cheste Geological Map. In this zone, the Ninyerola Gypsum unit crops out between the villages of Montserrat to the W and Picassent to the E (Fig. 1). The unit was designated 'Formación de Niñerola' by the authors of this geological map (IGME, 1980), who dated it as Lower Miocene and measured a thickness of 300 m. These authors also emphasized the gypsiferous and calcareous composition of this formation at the base and top, respectively, as well as the bituminous character of

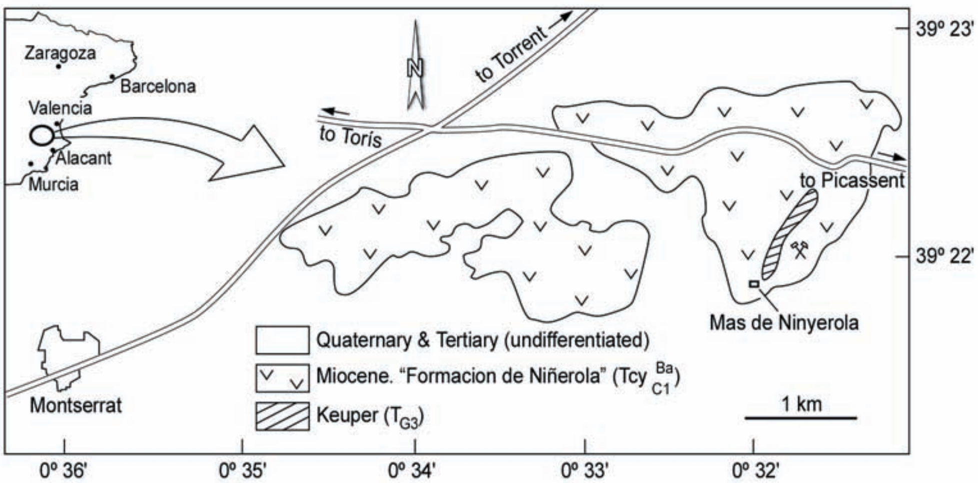

Fig. 1- Location map of the Ninyerola Gypsum unit. The represented area is the SE corner of the Geological Map 721 on a scale of 1:50.000, Cheste.

Fig. 1- Mapa de situación de la unidad Yesos de Ninyerola. El área representada corresponde al ángulo SE de la Hoja Geológica a escala 1:50.000, Cheste (nº 721).

the gypsum and presence of lacustrine limestones with abundant marly intercalations.

More recently, Anadón and Alcalá (2004) considered the materials forming the Ninyerola Gypsum unit as the oldest Neogene sediments filling the Coastal Depression of Valencia. According to these authors, these sediments consist of 150 m of lacustrine gypsum, marls and limestones, bearing some conglomerate intercalations, which are discordantly overlain by calcareous sandstones containing a marine fauna initially dated as Miocene by Brinkmann (1931). However, based on an unpublished report by Roca, Agustí and Anadón describing the presence in the Ninyerola succession of a micromammal fauna of Middle Miocene age (MN6 zone), Anadón and Alcalá (2004) suggested that the lacustrine system of the Ninyerola succession was deposited in the Middle Aragonian, during phase II of the paleogeographical evolution of the Neogene basins in the Iberian Chain, as defined by Calvo *et al*. (1993).

The overlying marine sediments (calcareous sandstones and lutites with intercalations of bioclastic limestones) of the eastern zone of the Coastal Depression of Valencia have been dated as Tortonian (Usera, 1974). In the present paper, this age is also assumed for the marine sediments that discordantly overlie the Ninyerola succession.

In the area where they crop out, the Miocene materials of the Ninyerola Gypsum unit are severely deformed, exhibiting numerous folds and fractures hindering their precise stratigraphic analysis. The unit is best observed to the N of the 'El Mas de Ninyerola', an area with an anticline structure oriented NNE-SSW (Fig. 2). The Keuper materials of the anticline core have suffered erosion, whereas the Miocene materials forming the two flanks exhibit sharp relief. This structure, here denoted the 'Ninyerola anticline', is asymmetric, its eastern flank being more tilted (>45º) than the western one (<45º). The basal gypsum layers of the Miocene succession in contact with the Keuper core have been actively exploited in quarries.

3. Evaporite facies

The evaporitic facies of the Ninyerola Gypsum unit are mainly composed of sulphates and carbonates. No evidence of the existence of chlorides was found. Minerals were determined by X ray diffraction (XRD) in 26 samples and petrographic study was performed on 32 large-sized thin sections (5.5 cm x 5.4 cm). Sulphate minerals are limited to gypsum and small amounts of anhydrite (XRD), although some celestite was also observed in the petrographic examinations. Calcite was the only carbonate mineral identified both by XRD and under the microscope.

In this paper, we use the terms 'lamina' (<1 cm), 'thin bed' (1 to 10 cm), and 'thick (or massive) bed' (<10 cm) for bedding thicknesses. Two main groups of sulphate facies can be distinguished according to the primary or secondary nature of the gypsum:

Bedded nodular, and meganodular gypsum (secondary gypsum). Nodules in this facies show size variation from a few millimetres to >1 m. Nodules with a diameter greater than 50 cm are hereafter referred to as 'meganodules'. Both nodules and meganodules form dense mosaics with sutured boundaries. Locally, meganodules have a fluid-like appearance and, in some beds, they are elongated vertically. The genetic interpretation of this facies appears below (in the section Sulphate diagenesis).

Massive bioturbated gypsum (primary gypsum). This facies forms individual beds of low relief and variable thicknesses of up to 10 m. It is composed of fine-grained lenticular gypsum, grey to dark-brown in colour, which is very pure locally. Bioturbation galleries with a diameter of few millimetres (generally <1 cm) are often observed. In dark lutite layers locally associated with this facies, total organic carbon contents (T.O.C.) have been determined. Despite the bituminous appearance of these lutite layers, T.O.C. were always <0.5 % (A. Permanyer, oral com., 2005).

Similar facies of massive bioturbated gypsum have been described in many lacustrine evaporite formations of Tertiary age in Spain (Rodríguez-Aranda and Calvo, 1998; Ortí and Rosell, 2000; Ortí *et al.*, 2003). In all these cases, the facies were interpreted as having been deposited in shallow lakes of low salinity (with very low chloride contents), where invertebrates actively burrowed the gypsiferous sediments on the lake bottom.

Thin-bedded bioturbated gypsum (primary gypsum). In this facies, gypsum is also fine-grained, showing a microlenticular texture and brownish colour, and may be associated with carbonate. The thickness of the thin beds commonly ranges from a few centimetres to 10 cm (locally up to 25 cm). In general, bioturbation structures are not as obvious as in the massive bioturbated gypsum facies.

This facies is interpreted as deposited in a shallow to moderately deep lake setting, in which dilution episodes with carbonate precipitation alternated with more evaporative stages leading to gypsum precipitation. Here again, the chloride content in the brines is thought to be very low, allowing for burrowing activity on the lake bottom. A similar thin-bedded bioturbated gypsum facies was described in the Libros Gypsum unit (Ortí et. al, 2003), although this facies was not associated with carbonate layers.

Laminated gypsum (primary gypsum). This facies is composed of laminae and thin beds of fine-grained gypsum, which may intercalate some carbonate laminae. Gypsum textures oscillate from microlenticular to equant-subhedral and are always arranged in differentiated laminae. Microselenite textures (upward oriented, single to twinned crystals up to a few millimetres in length) locally exist.

This facies is interpreted as deposited in a shallow lake setting. The absence of burrowing organisms is probably the consequence of relatively high salinities in the brines, although evidence of halite precipitation was not found.

Laminated-to-massive carbonate. In this facies, the carbonate layers associated with gypsum are of variable thickness (bedding spans from laminated to thick bedded) and display wackestone and packstone textures. These textures contain variable amounts of micrite, which bears abundant remains of charophyte stems and gastropod shells. The local presence of discontinuous laminae of gypsum is also apparent.

This facies is interpreted as deposited in a shallow to moderately deep saline lake setting during dilution episodes, in which carbonate production was high.

4. The stratigraphic succession

The Ninyerola anticline area was geologically mapped on a scale of 1:5.000 (Fig. 2). Indicated in this map, are the different intervals distinguished in the stratigraphic succession of this area, i.e. intervals (a) to (g) (see below). Figure 3 provides a composite cross section (A – A'), roughly normal to the axis of the anticline structure, as well as an expanded view of the eastern part of this geological section. In addition, two stratigraphic profiles (Figs. 4 and 5) were measured on the flanks of the anticline. The locations of these profiles are very close to the sites of the geological section.

A number of features related to this anticline structure should be noted: (1) Miocene successions on each of its flanks differ significantly such that they are described separately below; (2) the succession on the eastern flank is thicker than that of the western one; and (3) on the eastern flank, alluvial clastic materials followed by coastal marine sediments overlay the lacustrine facies. Accordingly, we designated the most complete stratigraphic succession, i.e., that of the eastern flank comprising from base to top lacustrine, alluvial, and marine sediments, the 'Ninyerola succession' and restricted the use of the Ninyerola Gypsum unit to the lacustrine assemblage –intervals (a) to (e) –, which displays a maximum thickness of 195 m.

4.1. The Ninyerola succession

On this eastern flank, the basal beds of the Miocene succession are exposed almost vertically at the contact with Keuper materials, and the overlying beds are tilted between 50º and 70º. The total thickness of this succession is over 230 m, of which only the lower portion is shown in Figure 4. The following stratigraphic intervals can be distinguished, from base to top:

(a) *Nodular gypsum interval*. This interval, almost 30 m thick, has been extensively exploited in quarries. It is made up of bedded nodular and meganodular gypsum facies. Original bedding is relatively well preserved, al-

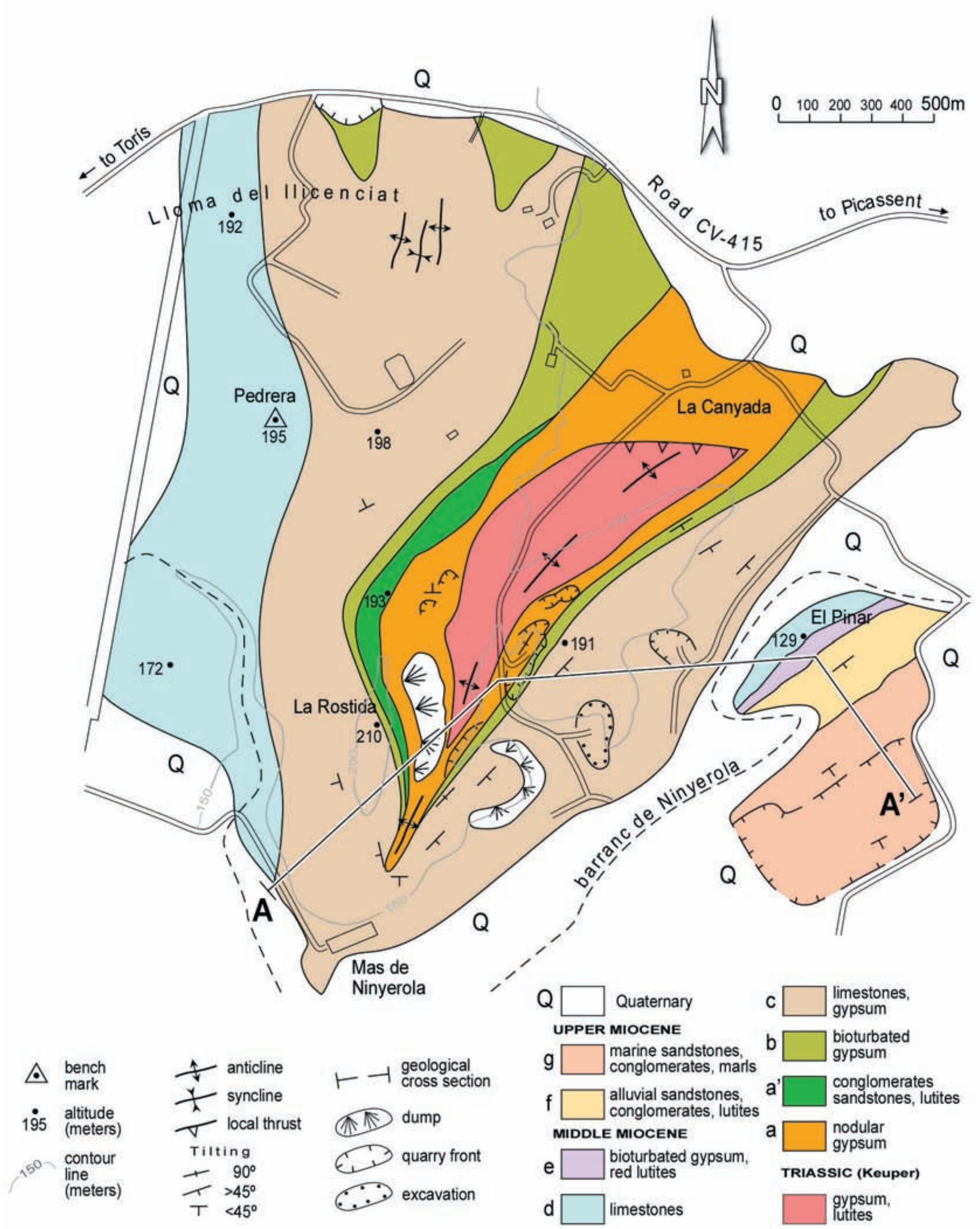

Fig. 2- Facies distribution shown by the Ninyerola Gypsum unit in the area of the Ninyerola anticline. Small faults and other features disturbing the anticline structure have been omitted.

Fig. 2- Distribución de facies de la unidad Yesos de Ninyerola en la zona del anticlinal del mismo nombre. Las pequeñas fallas y otros accidentes que afectan la estructura anticlinal han sido omitidos.

though somewhat disturbed by the presence of meganodules. Some beds of laminated carbonate appear intercalated with the gypsum beds. A thin level (10 cm thick) of chert is present locally (Fig. 4).

(b) *Bioturbated gypsum interval*. This interval of relatively massive bedding has a thickness of about 19 m. It is made up of dark massive bioturbated gypsum facies with associated layers of carbonate and dark lutites.

(c) *Alternation of carbonate and gypsum*. This is the thickest (up to 120 m) interval in the succession. Although it is more calcareous at the base, it rapidly grades upwards into a rhythmic alternation of laminated-to-massive limestone beds and thin bedded-to-massive gypsum beds. In the gypsum beds, predominant facies are thin-bedded bioturbated gypsum and massive bioturbated gypsum. Despite tectonic disturbances, the cyclic character of the interval is easily observed.

(d) *Calcareous interval*. This interval, up to 15 m thick, is poorly exposed. It is mainly composed of thin-bedded limestones with nodular to massive textures.

(e) *Red lutites and bioturbated gypsum interval*. This interval, which is also partly covered, is characterized by thick beds of massive bioturbated gypsum associated with red lutites (claystones). The thickness of this inter-

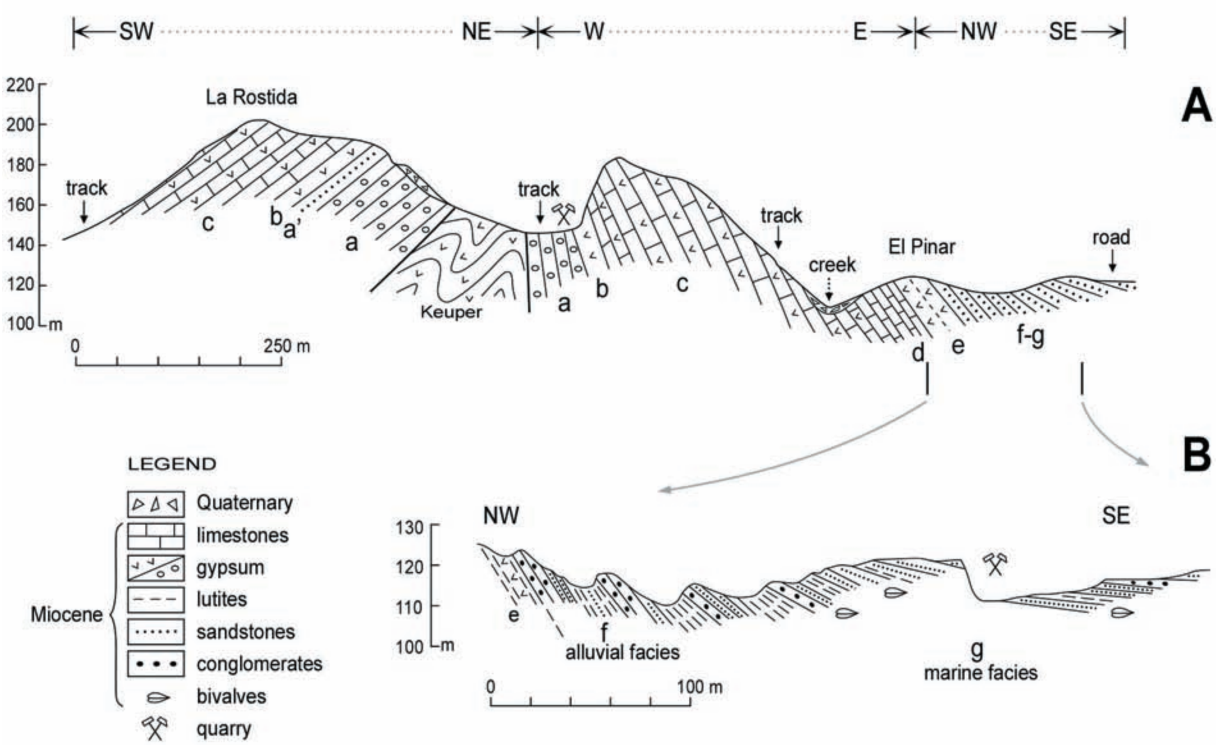

Fig. 3- Geological section of the Ninyerola anticline. The location of this section is indicated in Figure 2. The lower part of the figure shows an enlarged view of the eastern portion of the section.

Fig. 3- Corte geológico a través del anticlinal de Ninyerola. La posición del corte se indica en la Figura 2. En la parte inferior de la figura se muestra un detalle ampliado del extremo oriental del corte.

val is about 10 m. This interval and its two overlying intervals −(f) and (g)− can be observed in the El Pinar zone (Fig. 2).

(f) *Clastic alternation*. This interval, up to 25 m thick, exhibits four main alternations, which consist of basal conglomerates, middle sandstones, and top lutites. Ruditic clasts are mostly calcareous (mainly derived from the surrounding Cretaceous formations) and sub-angular to sub-rounded in texture. To a minor extent, ruditic clasts are siliceous and well-rounded. The size of the clasts is very coarse (up to 1 m) at the base of the lowermost conglomerate bed and decreases upwards in each bed. Idiomorphic quartz crystals typical of Keuper facies ('jacintos de Compostela') were observed in association with the clasts in the conglomerate beds; in general, these crystals are sub-rounded suggesting a polycyclic nature. Sandstone beds are mainly composed of quartz grains and display large-scale cross bedding. Tilting is 65º to 70º in the lowermost alternation, but gradually decreases to 30º in the uppermost one. The interval is mainly interpreted as an alluvial deposit. However, some clastic fragments of marine molluscs −reworked oyster shells− were observed in the uppermost (the fourth) conglomerate-sandstone alternation. This indicates marine influence towards the top of the interval, and makes it difficult to establish a precise boundary between this and the overlying marine interval (g). A lateral and a vertical gradation between these two intervals is possible.

(g) *Clastic marine interval*. Actively exploited in quarries, this interval is composed of calcareous conglomerates, quartzose and calcareous sandstones, and marls. Exposed thickness is about 15 m, but the top of the interval has been eroded in the studied profile. Sandstone beds display large-scale cross bedding. Both the conglomerate and the sandstone layers include reworked oyster fragments. Some marly layers up to 1 m thick, however, are very rich in large oyster shells oriented subvertically. Tilting in this interval grades progressively from about 30º at the base to <10º at the top.

4.2. The succession on the western flank

On this flank, tilting of the beds is <45º in general (commonly it is about 30º). The following stratigraphic intervals can be distinguished (Fig. 5):

(a) *Nodular gypsum interval*. This interval, some 30 m in thickness, differs largely from its counterpart on the eastern flank: carbonate and chert beds are absent; lutite intercalations are more abundant and lack dark tones; and the size of the gypsum meganodules is often smaller.

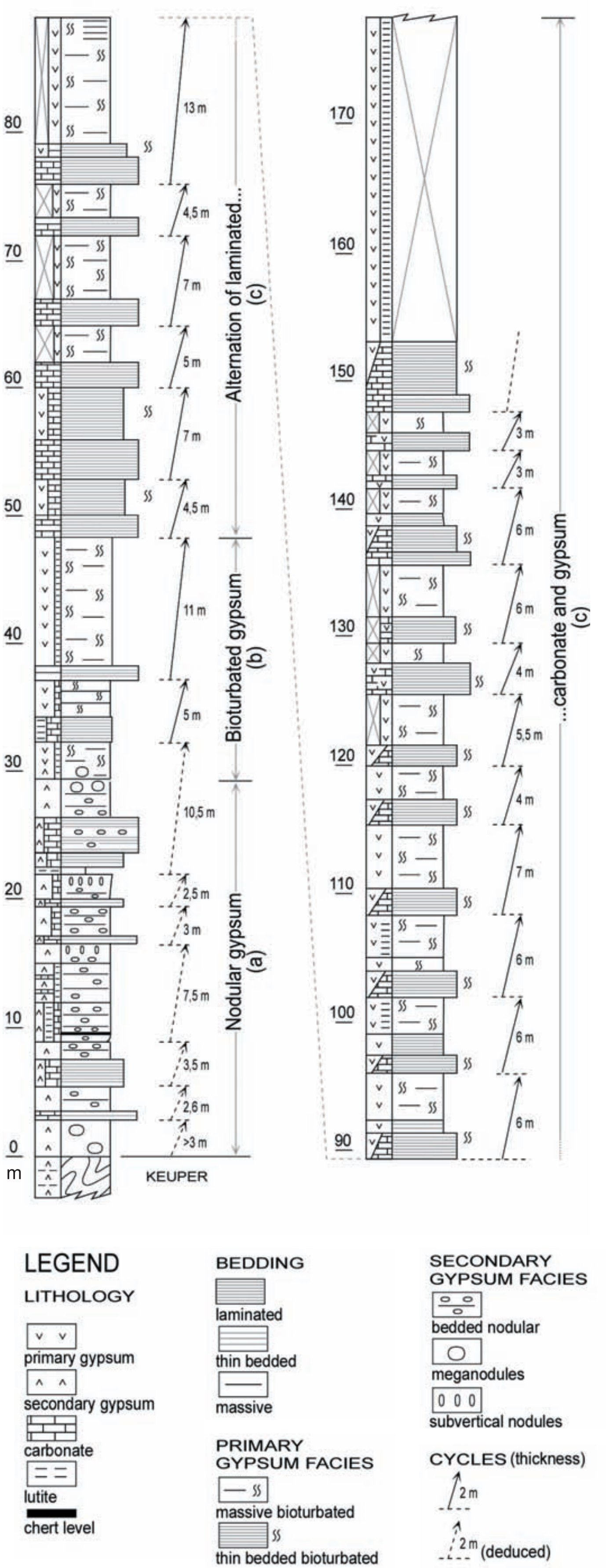

Fig. 4- Partial stratigraphic profile (intervals a, b and c) of the Ninyerola Gypsum unit on the eastern flank of the Ninyerola anticline. Carbonate-gypsum cycles are indicated.

Fig. 4- Columna estratigráfica parcial (intervalos a, b, y c) de los Yesos de Ninyerola en el flanco oriental del anticlinal de Ninyerola. Se indica los ciclos de carbonato-yeso.

(a’) *Clastic interval*. This interval, without an equivalent on the eastern flank, is about 15 m thick. It is composed of conglomerate, sandstone and grey lutite beds. Conglomerate clasts are calcareous and, to a lesser degree, siliceous. Conglomerate beds display paleochannel structures with erosive bases. Lutites are locally blue.

(b) *Bioturbated gypsum interval*. This interval, up to 17 m thick, is richer in grey lutite intercalations than its eastern counterpart, but poorer in gypsum beds. Moreover, it contains a number of thick carbonate beds, which locally include fragments of calcitized plant tubes. Towards the N, the interval thickens and develops into massive beds of bioturbated gypsum (Fig. 2).

(c) *Alternation of carbonate and gypsum*. This interval is similar to its eastern flank equivalent. Its thickness in the profile examined was about 35 m; its overall thickness in other zones of this flank are not likely to exceed 60 m. The interval is more clayey than on the eastern flank. A further appreciable difference is that, towards the base, it contains a level, 4-6 m thick, composed of laminated, primary gypsum. In the central portion of this level, however, transformation into nodular and meganodular secondary gypsum occurs.

(d) *Calcareous interval*. This interval cannot be observed in the profile studied and its analysis in other areas of the western flank is often difficult. It is composed of massive to nodulose limestones with a thickness (probably >50 m) greater than that recorded on the eastern flank.

5. Sulphate diagenesis

In the nodular gypsum interval (a), the core of nodules and meganodules is made up of fine-grained, white, secondary alabastrine gypsum. In the outer nodule zones, dark envelopes comprised of porphyroblastic crystals of secondary gypsum are common; inside these porphyroblasts, abundant relics of anhydrite were observed petrographically. Around these nodules and meganodules, a number of enterolithic veins composed of alabastrine secondary gypsum appeared. These veins are randomly arranged and embedded in a clay matrix. The presence of both porphyroblastic textures and anhydrite relics clearly points to anhydrite as the gypsum’s precursor.

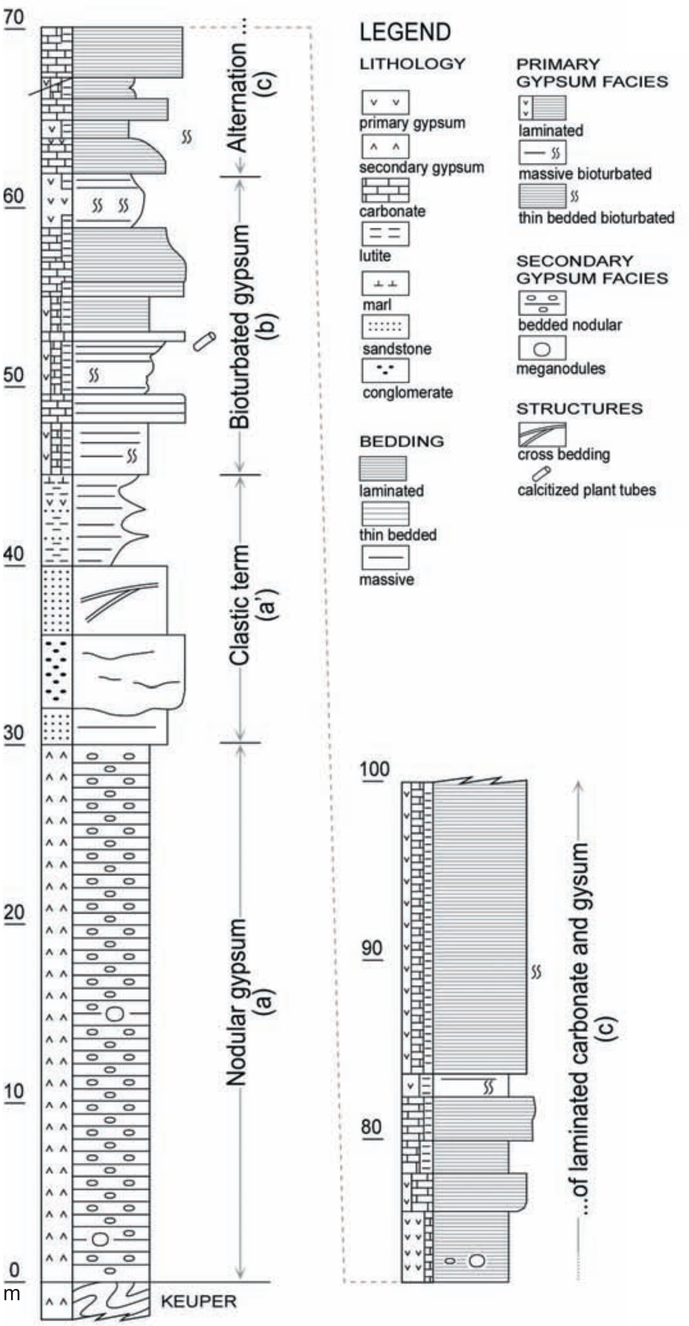

Fig. 5- Stratigraphic profile of the Ninyerola Gypsum unit on the western flank of the Ninyerola anticline. Carbonate-gypsum cycles in interval (c) are not indicated.

Fig. 5- Columna estratigráfica de los Yesos de Ninyerola en el flanco occidental del anticlinal de Ninyerola. No se señalan los diferentes ciclos de carbonato-yeso del intervalo (c).

Nodular gypsum interval (a) is described here as a stratigraphic unit (Figs. 2 to 5). However, due to the outcropping conditions, it is not easy to see whether the boundary between the top of this interval and the base of the overlying interval (b) is conformable or not. For the first possibility (conformable boundary), the growth of bedded nodular anhydrite in interval (a) could be interpreted as an early diagenetic product. Moreover, at the base of interval (b) some isolated meganodules, which clearly replace the bioturbated gypsum facies, are still present (Fig. 4). This suggests a transition between these two intervals. In the case of an unconformable boundary, the growth of nodular anhydrite could be interpreted as late diagenetic, occurring under burial conditions. In the absence of new observations or additional criteria, in this paper we consider the possibility of an early diagenetic origin (inner sabkha or playa-lake environment) for the anhydrite. During the final exhumation of the unit, this anhydrite was rehydrated into secondary gypsum, a process that has permitted the local use of the bedded nodular and meganodular facies as alabaster for sculptures.

6. Sulphate isotopy

The isotope composition ($\delta^{34}S$, $\delta^{18}O$) of gypsum samples (Table 1) from several facies, both primary and secondary, is similar to that of the Triassic sulphates (Fig. 6), although $\delta^{34}S$ values are slightly heavier than Triassic ones and $\delta^{18}O$ values are clearly heavier. These differences, however, can be explained by the heavy isotope enrichment that occurs during gypsum precipitation (1.65 ‰ for $\delta^{34}S$ and 3.5 ‰ for $\delta^{18}O$). Consistent with this, we propose a process of almost direct chemical recycling of Triassic sulphates to give rise to the Miocene sulphates of the Ninyerola Gypsum unit, reinforcing the hypothesis of a non-marine origin of the parent waters. Effectively, this mechanism has been established for many lacustrine evaporites of Tertiary age in the Iberian Peninsula (Utrilla *et al.*, 1992).

7. Evaporite cycles

The eastern flank of the Ninyerola anticline allows the detailed observation of the carbonate-gypsum cyclicity present in interval (c). Three main facies can be distinguished in this interval: laminated-to-massive carbonate, thin-bedded bioturbated gypsum, and massive bioturbated gypsum. The most common cycles resulting from the combination of these facies are shown in Figure 7. The simplest cycle, type I, is comprised of laminated-to-massive carbonate at the base and massive bioturbated gypsum at the top. Type II is also formed of laminated-to-massive carbonate at the base, which is followed by an alternation of thin-bedded bioturbated gypsum and laminated carbonate, ending with massive bioturbated gypsum. In type III, thin-bedded bioturbated gypsum overlies the former alternation and underlies the massive bioturbated gypsum forming the top. However, cycles as complete as type III, which show a perfect gradation from carbonate

Strati-graphic interval	Sample	Gypsum lithofacies	$\delta^{18}O_{SMOW}$ ‰	$\delta^{34}S_{CDT}$ ‰
Interval (a)	MÑ-1	Nodular gypsum (secondary)	18.82	15.0
	MÑ-4	Nodular gypsum (secondary)	19.13	15.7
	MÑ-7	Nodular gypsum (secondary); alabastrine nodules.	–	15.7
Interval (c)	MÑ-73	Thin-bedded bioturbated gypsum (primary)	16.33	16.3
	MÑ-25	Massive bioturbated gypsum (primary)	16.36	14.8
	MÑ-34	Massive bioturbated gypsum (primary)	18.11	15.8
	MÑ-38	Massive bioturbated gypsum (primary)	19.30	16.4

Table 1- Isotope compositions (‰) of gypsum samples from the Ninyerola Gypsum unit.

Tabla 1- Composición isotópica (en ‰) de muestras de yesos de la unidad Yesos de Ninyerola.

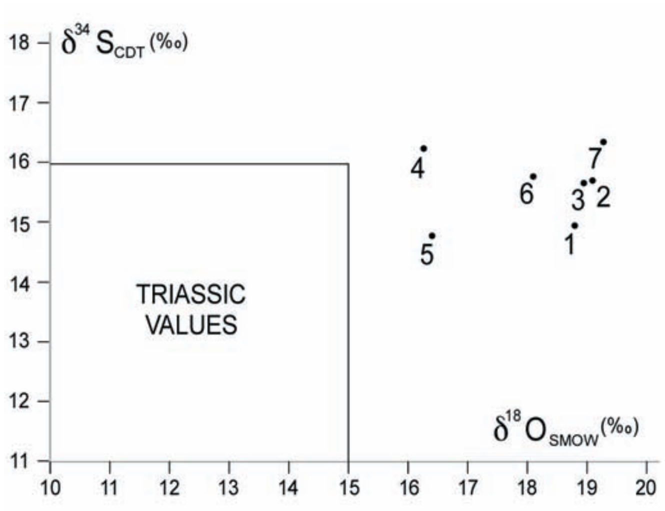

Fig. 6- Isotope compositions (‰) of gypsum samples from the Ninyerola Gypsum unit. Part of the areal distribution of the Triassic sulphates is represented.

Fig. 6- Composiciones isotópicas (en ‰) de muestras de yeso de la unidad Yesos de Ninyerola. Se representa también parte del área de distribución de los sulfatos triásicos.

to gypsum and from thin-bedded gypsum to massive bioturbated gypsum, are not so common in interval (c) (Fig. 4). All these types are interpreted as shallowing upwards cycles, with salinity increasing from the base to the top. Presumably, ion concentrations remained relatively low, as anhydrite and halite did not form.

Although it is somewhat difficult to observe these cycles in interval (a) because of the diagenetic transformations, their existence can be deduced from the carbonate beds rhythmically interbedded within the nodular gypsum beds (Fig. 4). In intervals (b) and (c), it is easier to detect these cycles. However, at the top of interval (c), outcrop conditions hinder precise observations. With this limitation in mind, up to 27 cycles were recorded in the assemblage of intervals (a), (b) and (c), with a total thickness close to 170 m. The thickness of the individual cycles ranges from 2.5 to 13 m, with an average value close to 6 m. In many of these cycles, the thickest facies is the massive bioturbated gypsum at the top.

Similar cycles, also with laminated carbonate at the base and massive bioturbated gypsum at the top, have been described in the Libros Gypsum unit (Anadón *et al.*, 1998; Ortí *et al.*, 2003). A cyclic succession of carbonate and sulphate has also been identified in the Lécera Formation (lowermost Lías, central Spain), although this succession occurs in a different depositional setting (Ortí and Salvany, 2004) and records a lower an upper group of salina-sabkha cycles of average thicknesses of 6 m and 8 m, respectively. Other cyclic evaporitic successions have been described by Krijgsman (1996) and Abdul Aziz *et al.* (2004) in the Miocene formations of the Iberian Peninsula; all of which have been attributed to a climatic origin (precession cycles of astronomic control).

In the Bicorp Basin (Valencia province), where Miocene sedimentation was controlled by the diapirism of Triassic evaporites, Anadón *et al.* (1998) illustrated the existence of various orders of sedimentary sequences, some bearing gypsum. The sequences of first and second order could have been controlled by diapir movements, whereas those of third, fourth and fifth order may be the result of climatic fluctuations.

8. Depositional model for the evaporites

8.1. Additional observations

Besides these observations, the following facts should also be considered for the sedimentological interpretation of the Ninyerola Gypsum unit:

(1) *The Miocene regional context*. The depositional history of this unit seems to differ somewhat from that of the remaining Miocene units of the Geological Map of Cheste. Presumably, the Ninyerola Gypsum unit was deposited in a small lake in which saline solutions −generated by the dissolution of Triassic evaporites− accumulated, giving rise to a saline lake of the carbonate-sulphate type.

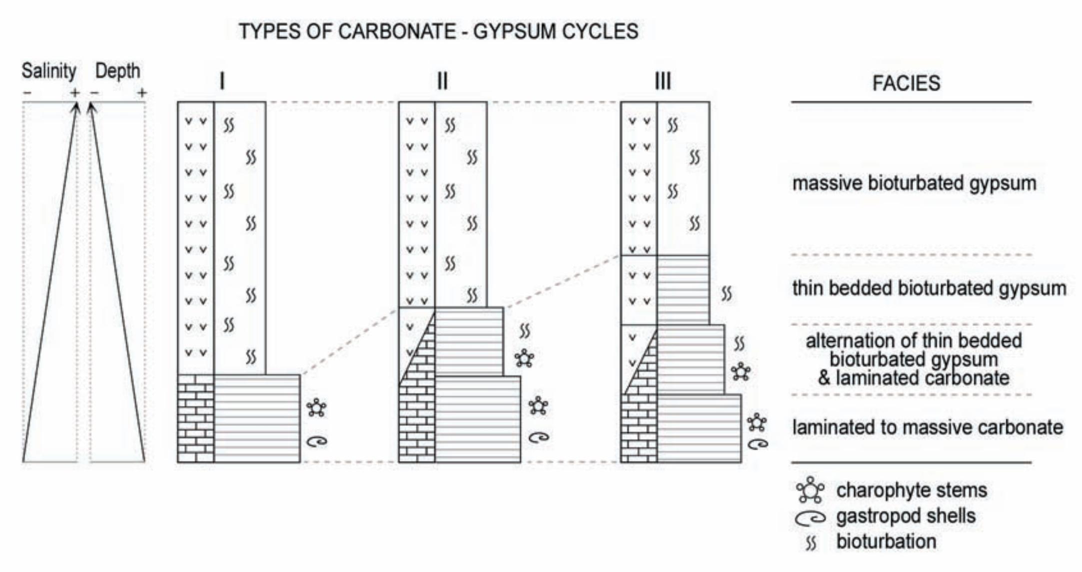

Fig. 7- Image showing the three types of carbonate-gypsum cycles present in interval (c) (see text for explanation).
Fig. 7- Detalle de tres tipos de ciclos de carbonato-yeso presentes en el intervalo (c) (ver explicación en el texto).

(2) *Evaporitic facies in other outcrops of the Ninyerola Gypsum unit*. Observations in other outcropping areas of the unit, in particular to the W of the Ninyerola anticline (Fig. 1), indicate the presence of the massive bioturbated gypsum facies. Nodular gypsum was not observed and, given the poor outcrop conditions, the alternation characterizing interval (c) was not surely identified (a poorly gypsiferous, laminated-to-massive carbonate facies is probably the equivalent to this alternation). This suggests that the massive bioturbated gypsum was the predominant facies at the margins of the saline lake.

(3) *Control of the Triassic basement*. The marked facies differences between the two flanks of the Ninyerola anticline suggest that, from the very beginning, an active structure in the Triassic substratum exerted control on Miocene sedimentation both in terms of lithology and subsidence rate. The nature of such a structure, however, remains unknown. Possible options would be a substratum fracture or an intumescence or differentiated relief (shoal) caused by initial reactivation of diapirism of the Triassic evaporites.

8.2. Lake model

The depositional setting of the Ninyerola Gypsum unit is interpreted as a saline lake in which there was contrast between a deeper zone with carbonates and sulphates (the area where the Ninyerola anticline currently crops out) and a wider marginal zone with massive bioturbated gypsum and lutites. As stated above, it is assumed that the asymmetry in the distribution and thickness of the sedimentary facies, including limited amounts of terrigenous deposits, was conditioned by the presence of an active structure in the Triassic basement. Presumably, this structure also conditioned the position and rise of the future anticline. On both sides of the structure, the evolution of the saline lake can be summarized as follows:

(1) *Shallow lake to sabkha stage − interval (a)*. From the start of evaporitic sedimentation, differentiation occurred in the depositional setting. An anhydritic sabkha formed on the western side of the basement structure, whereas a shallow lake developed on the eastern side. In the latter, an alternation of carbonate beds and primary gypsum beds was deposited subaqueously, with some of the gypsum being replaced by chert. The depositional gypsum facies on this eastern side remains unknown, but was probably thin-bedded bioturbated gypsum. The transformation of this gypsum into bedded nodular and meganodular anhydrite affected the sediment intermittently after fluctuations in the water level: during lacustrine episodes, gypsum precipitated; during exposure or sabkha episodes (underground position of the water table), anhydrite formed interstitially. On the western side, however, carbonate precipitation did not occur in the sabkha setting, in which the host sediment was of a clay or marl nature. It seems likely the evaporitic system attained maximum salinity during this stage, favouring anhydrite growth (on the western side) or rapid gypsum replacement by anhydrite (on the eastern side).

(2) *Shallow lake stage − intervals (b) and (a')*. This stage reflects the first expansion of the shallow saline lake, in which massive bioturbated gypsum precipitated subaqueously throughout the evaporitic system. However, sedimentation on both sides of the basement structure

varied drastically. On the western side, an alluvial episode took place at the beginning of this stage; apparently, the basement structure prevented such terrigenous input to the eastern side. Also on the western side, carbonate precipitation was higher and the deposited massive bioturbated gypsum largely varied in thickness from one place to another, becoming thicker in the north.

(3) *Deep lake stage − interval (c)*. Maximum expansion of the saline lake occurred during this stage. Both the depth and subsidence rate were higher on the eastern side, where cyclicity was also better developed. The predominance of thin-bedded bioturbated gypsum during this stage also suggests a lake level deeper than in the former stage. On the western side, however, the limited thickness suggests a lower subsidence rate.

(4) *Final lake stages − intervals (d) and (e)*. After the deposition of interval (c), again shallower water depths were established in the saline lake. First, a dilution stage leading to carbonate precipitation −interval (d)− appeared, which was followed by a last evaporative stage −interval (e). This last stage was probably restricted to the eastern side of the basement structure.

The abrupt change from this lacustrine record to alluvial sedimentation −interval (f)− and subsequently to Tortonian marine conditions −interval (g)− could have been provoked by tectonic activity in the area. However, the precise interpretation of the tilting gradation (Fig. 3) from the base of interval (f) to the outcropping top of interval (g) needs further study.

In the diapir-graben system of the Bicorp Basin (SW Valencia), an extensional stage of Tortonian age was identified by Roca *et al.* (1996) as the main factor controlling the final development of both the diapirism of Triassic materials and the associated deformation of the Miocene sediments in the graben. A similar development process seems likely for the Ninyerola succession studied here.

9. Concluding remarks

(1) The Ninyerola Gypsum unit, a lacustrine deposit of Middle Miocene age and about 200 m in thickness, crops out on both flanks of an anticline structure, whose core is comprised of Triassic diapiric evaporites. In this unit, there is a predominance of carbonate and sulphate facies, which formed in a saline lake of low ionic strength.

(2) The Ninyerola Gypsum unit can be subdivided into several stratigraphic intervals. These intervals, however, display marked differences on both flanks of the anticline, suggesting that some type of active structure present in the Triassic substratum controlled the sedimentation of the unit from the beginning. The most complete and thickest Miocene succession is found on the eastern flank.

(3) The basal interval of the unit −interval (a)− is made up of bedded nodular and meganodular facies of secondary gypsum. The precursor of these gypsum facies was anhydrite, which formed in the centre of the shallow lake during exposure (sabkha) episodes, and also in marginal sabkhas. Today, these nodules and meganodules are comprised of a fine-grained, alabastrine variety of secondary gypsum. These meganodules seemed to be the most appropriate facies for artistic purposes in the past.

(4) In the rest of the gypsiferous intervals –intervals (b) to (e)–, the different gypsum facies have been largely (although not exclusively) preserved as primary gypsum.

(5) The alternation of carbonate and gypsum beds −interval (c)− is the most representative facies of the saline lake. Both the thickness and the perfect cyclicity recorded in this alternation suggest that the maximum lake expansion, deepest environment, and highest subsidence rate were reached during the deep lake stage. In this alternation, at least 27 cycles of carbonate-gypsum have been recorded, with an average thickness close to 6 m. Presumably, these are climatic (astronomic) cycles.

(6) On the eastern flank of the anticline, the Ninyerola Gysum unit exhibits evaporative contributions until the sedimentation of its uppermost interval (e), which reflects shallow lake conditions. Subsequently, the unit was covered by the alluvial clastic sediments of interval (f). This interval graded upwards to the coastal marine clastic materials of interval (g), presumably of Tortonian age. These marine sediments display unconformable relationships with the underlying lacustrine unit.

(7) The isotope compositions ($\delta^{34}S$, $\delta^{18}O$) of gypsum samples from the Ninyerola Gypsum unit indicate they originated from Triassic sulphates through a chemical recycling mechanism.

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