# Nodular anhydrite growth controlled by pedogenic structures in evaporite lake formations

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**Abstract**

Several nodular gypsum beds exhibiting a remarkable vertical arrangement of individual nodules are present in the Miocene continental evaporite formations of the Calatayud Basin, northeastern Spain. The growth of the gypsum nodules, initially anhydrite, took place within magnesitic carbonate deposits which display incipient pedogenic features such as rhizoliths and clotted to peloidal textures. Simultaneous and after the pedogenic modification of the carbonate substratum, displacing nodules started to grow, their arrangement being closely conditioned by the development of vertical fissuring related to root penetration. The transformation of anhydrite to gypsum was probably realized early after little burial of the sulphate–carbonate deposits. The occurrence of vertically oriented gypsum nodules can be seen as a diagnostic feature for palustrine conditions developed in evaporitic lake settings, this peculiar morphology of the sulphate nodules having been strongly controlled by the internal structure of the palustrine palaeosols

*Keywords:* anhydrite; pedogenic; sulphate nodules; Miocene; Calatayud Basin

## 1. Introduction

Gypsum and anhydrite nodules form in a variety of marine and non-marine environments, either ancient or recent (Tucker, 1991). Research on their formation was stimulated after the discovery of present-day sulphate nodules accumulating in sabkhas of the Trucial Coast and along the Mediterranean coast of Egypt (Shearman, 1966; Kinsman, 1969; Butler, 1969; West et al., 1979). In settings where the evaporation is sufficiently intense, gypsum is early replaced by anhydrite (Bush, 1973; Shearman, 1983), although primary anhydrite has also been reported (Shearman, 1966, 1983; Bush, 1973). Likewise, rehydration of anhydrite to form gypsum nodules has been documented by Shearman (1966) and West et al. (1979). Common morphologies of nodular gypsum and anhydrite consist of isolated spheroidal or coalesced nodules resulting in entherolitic and chicken-wire structures. After considerable burial, the formation of secondary anhydrite nodules replacing crystalline gypsum may result in nodular morphologies similar to those formed in early diagenetic conditions (Loucks and Longman, 1982; Rouchy et al., 1994).

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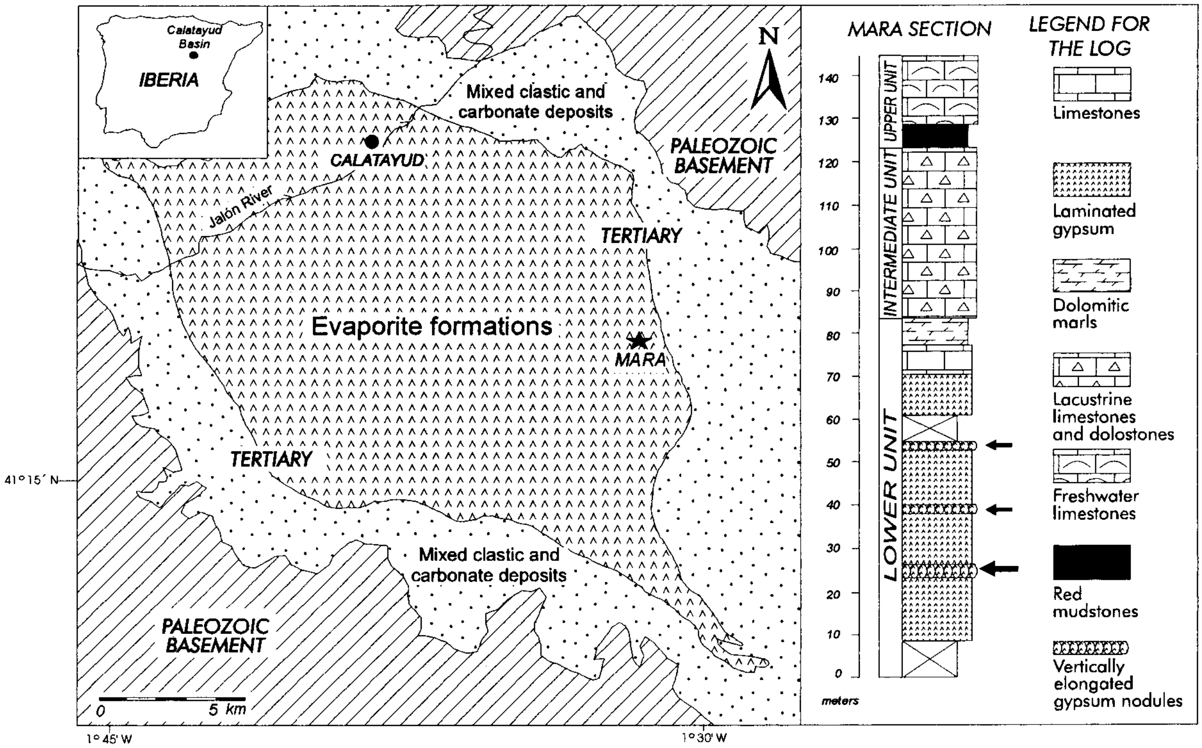


Fig. 1. Schematic map showing the palaeogeographical distribution of the evaporites and related continental sediments in the Miocene Lower Unit of the Calatayud Basin, northeastern Spain (Hoyos and López Martínez, 1985). The location of Mara section presented at the right of the figure is marked on the map. Arrows aside of the section indicate the stratigraphic position of the nodular beds studied; the thickest arrow marks the location of the outcrop seen in Fig. 2.

An unusual morphology of nodular gypsum has been found in Lower to Middle Miocene continental evaporite formations of the Calatayud Basin (northeastern Spain) (Fig. 1). In these formations, some beds exhibit a vertical arrangement of individual gypsum nodules which occur in sequences formed of magnesite, nodular and laminated gypsum beds. These beds have not been subject to significant burial (no more than 150 m), so that all diagenetic features shown by the sulphate deposits are interpreted to have been formed as a result of early diagenetic and=or later rehydration processes. The gypsum nodules display features indicative of transformation after primary anhydrite.

Vertically elongated nodules of calcium sulphate constitute a rather uncommon feature in evaporite formations. Purser (1985) illustrated sub-rounded anhydrite nodules displaying a vertical pattern in supratidal environments of the Arabian Gulf. Columnar features of alabastrine and mesocrystalline gypsum have been observed in southern Tunisia and the central Namib Desert related to the development of recent surficial and subsurficial gypsum crusts (Watson, 1985), and Miocene gypcretes from the Calama Basin, northern Chile (Hartley and May, 1998). Magee (1991) interpreted the formation of tubular-like gypsum growing displacingly within permeable deposits of the Late Quaternary Prungle Lakes (SE Australia) as being controlled by the fluctuation of groundwater interplaying with the development of bio-tubules, both factors working together for the mobilization of sulphate. Tucker (1978) described vertical features in gypsum crusts (gypcrete) from recent alluvial deposits of northern Iraq which are controlled by the polygonal pattern of cracks. Besides these occurrences, vertically elongated gypsum and=or anhydrite nodules have been recognized as a product of transformation from primary macrocrystalline (selenite) gypsum in both near-surface (Shearman, 1983; Rouchy et al., 1994) and burial conditions (Loucks and Longman, 1982; Rouchy et al., 1994).

In this paper we present a description and interpretation of these peculiar nodules, which are clearly different from other reported occurrences of elongated gypsum elsewhere.

## 2. Sedimentological context of the nodular gypsum occurrences

The Calatayud Basin is a Tertiary intramontane basin elongated NW–SE, parallel to the main structures of the Iberian Range. The basin was filled by Palaeogene and Neogene sediments reaching up to 1200 m in thickness and comprising three main stratigraphic units (Hoyos and López Martínez, 1985): the Lower and Intermediate Units, both containing evaporite sediments (Ortí et al., 1994), and the Upper Unit mainly composed of terrigenous and fresh-water carbonate deposits. The nodular gypsum occurrences described in this paper have been found in the Lower Unit in the vicinity of the village of Mara, approximately 15 km southeast of Calatayud. The section studied reaches up to 144 m in thickness (Fig. 1) and consists, from bottom to top, of a package of detrital and microselenite laminated gypsum with intercalated magnesitic marlstone (Lower Unit) which grades upward into partially calcitized (dedolomitized) dolostone beds which include abundant gypsum pseudomorphs (Intermediate Unit). The section is capped by red mudstones which are in turn covered by tufa and palustrine limestones (Upper Unit).

## 3. Sequential arrangement and description of the vertically oriented gypsum nodules

The nodular gypsum beds are present at three distinctive levels in the Lower Unit (Fig. 1). Each bed can be traced laterally for a few hundred metres. The nodules are present within a rather monotonous succession of laminated gypsum associated with a gypsiferous–magnesitic matrix. The three levels in which the nodular gypsum occurs are capped by beds

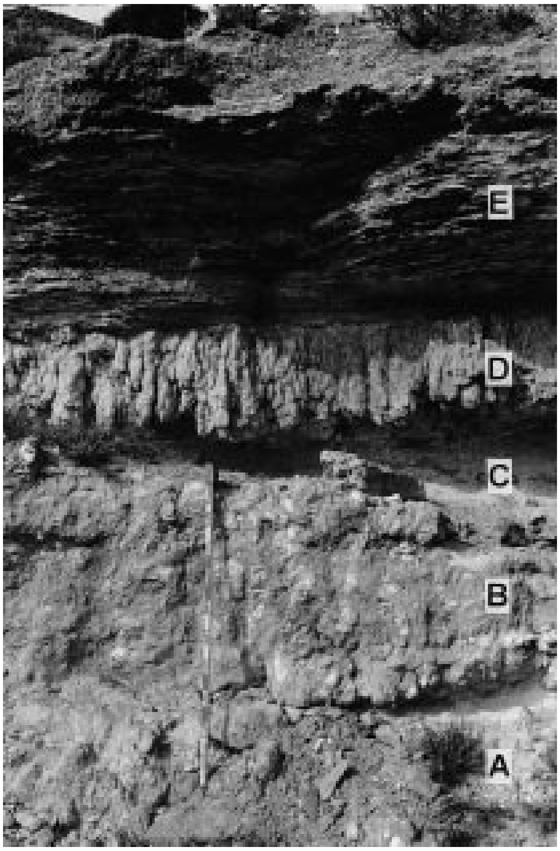

Fig. 2. Outcrop view of the deposits containing vertically oriented gypsum nodules. The sedimentary succession is in Fig. 3 (letters B and D denote beds with remarkable development of elongated nodules). Stick for scale D 1 m.

comprising laminated gypsum with thin clay intercalations. The outcrop selected for description comprises the following lithological beds (Figs. 2 and 3):

(A) Roughly laminated, whitish grey magnesite containing scattered gypsum nodules. The magnesite displays a peloidal to clotted texture cemented by poikilotopic gypsum. Clear peloids, 0.1 to 0.8 mm in size, are locally seen as detached from larger magnesite masses exhibiting desiccation and root traces (Fig. 4). Scattered yellowish gypsum nodules, 3 to 30 cm in diameter, show sub-spheroidal to vertically elongated shapes and are formed of a mosaic of mesocrystalline gypsum including scattered relics of anhydrite.

(B) White to grey massive gypsum containing irregularly distributed patches of magnesite and oc-

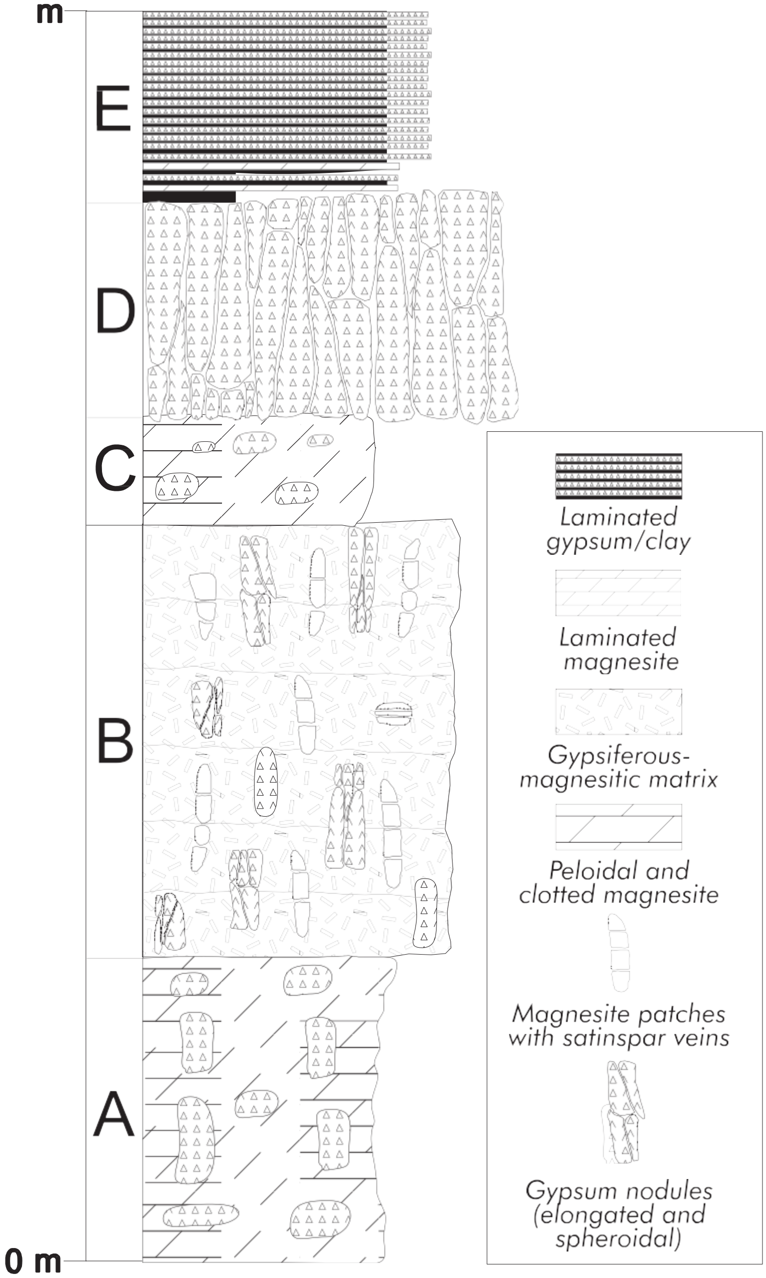


Fig. 3. Detailed log sketching the main lithological terms recognised from the outcrop shown in Fig. 2.

casional gypsum nodules (Fig. 3). The bottom of the bed is transitional from the underlying magnesite, whereas its top is sharply defined. Patches of dense and massive magnesite, 1–15 cm in size, display a preferential vertical orientation and an internal horizontal fissuring infilled by fibrous (satin-spar) gypsum (Fig. 5). The gypsum matrix consists of a mosaic of anhedral mesocrystalline gypsum containing abundant remains of magnesite displaying peloidal to clotted textures and relic anhydrite (laths

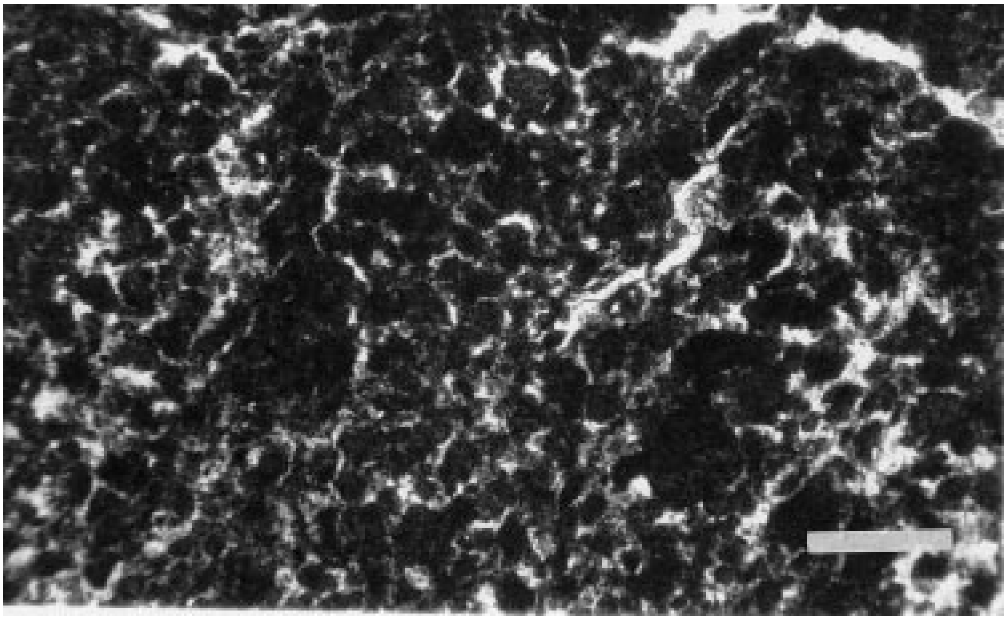

Fig. 4. Photomicrograph (plane polarised light) of the magnesite matrix displaying a peloidal to clotted texture as well as fissures owing to small plant roots and irregular desiccation cracks. Sample from level A. Scale bar D 0.3 mm.

arranged in felted fabrics, and orthorhombic crystals) which provide evidence that the gypsum formed after primary anhydrite. The fabric of the bed is quite similar to that of recent gypsiferous soils of the Ebro Basin, Spain (Herrero and Porta, 1987).

(C) Roughly laminated, whitish magnesite containing either isolated or coalesced gypsum nodules. These nodules, a few centimetres to 40 cm in size, show spheroidal to sub-spheroidal shapes and contain both orthorhombic crystals and relics of anhydrite laths. The magnesite consists of loosely packed peloids cemented by poikilotopic gypsum and contains a network of small-scale rhizotubules, especially towards the upper part of the bed.

(D) Vertically oriented gypsum nodules which are laterally arranged giving a remarkable columnar appearance (Fig. 2). The bottom of the bed is marked by differences in the downwards growth of the nodules, whereas the top of the nodules is gently smoothed which suggests erosion of the bedtop. In overview the nodules display more or less rounded features with no evidence of a polygonal pattern. Each column, reaching almost the entire bed thickness (about 0.50 m), is formed of several minor elongated nodules which are tightly packed in a way that resembles that of the classical chicken-wire structure; however, in our case, the length of the individual nodules is about three or four times the width. The gypsum nodules contain abundant relics of laths and orthorhombic crystals of anhydrite. Magnesite patches typically show fissures infilled by satin-spar gypsum. The patches appear as residual products after lateral, compressive growth of the gypsum nodules.

(E) Laminated gypsum beds (3–4 m thick) with green-grey clay intercalations including locally thin magnesite layers, and resting sharply upon the underlying nodular gypsum. The laminated gypsum consists of laterally coalesced micronodules formed after selenite and detrital gypsum.

## 4. Interpretation and significance of the vertically oriented nodular gypsum

The vertically oriented gypsum nodules from Mara village have not been subject to significant burial and they do not show any evidence for precursor macrocrystalline gypsum fabrics, which precludes a late diagenetic origin under burial condi-

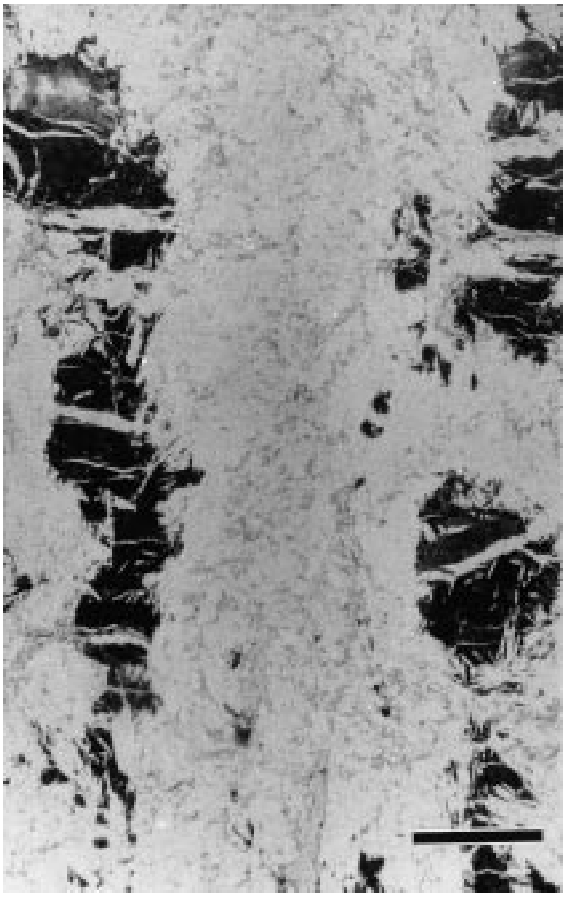

Fig. 5. Root hole infillings of dense, massive magnesite (in dark) showing characteristic horizontal to gently oblique fissures infilled by fibrous (satin-spar) gypsum precipitated after hydration from anhydrite. Lighter areas paralleling and=or protruding the magnesite patches correspond to intergrown gypsum nodules with abundant minute prismatic pseudomorphs of anhydrite in the lower right side of the photomicrograph (plane polarised light). Scale bar D 1 mm.

tions. On the contrary, all features lead to interpret them as formed syndepositionally (or early diagenetically) and they underwent some diagenetic modification close to the surface. Initial accumulation of calcium sulphate took place within roughly laminated magnesite strata which were deposited in periods of relative dilution. The deposition of magnesite in both coastal and inland evaporite lakes has been documented by Irion and Müller (1968), Pueyo Mur and Inglés Urpinell (1987), Warren (1990) and Renaut (1993). Magnesite occurrences are frequent in the Lower–Middle Miocene of the Calatayud Basin (Rosell and Ortí, 1992; Sánchez-Moral et al., 1993). The peloidal and clotted textures are considered to result from incipient pedogenic modification of the carbonate substratum (Braithwaite, 1975; Freytet and Plaziat, 1982), this process having been conditioned by episodical colonization of phreatophytic plants and desiccation of the substratum. Root penetration caused severe disruption of the carbonate resulting in a marked anisotropy of the sediment (stage 1, Fig. 6). After decay of the plants, the root holes were filled by magnesium carbonate which, different from the host-sediment, is typically massive although disrupted by horizontal fissuring related to desiccation (stage 2, Fig. 6), as commonly observed (Calvo et al., 1985; Retallack, 1990).

The gypsum beds suggest that the growth of the calcium sulphate nodules was strongly conditioned by the vertical fissuring of the carbonate substratum. Precipitation of the sulphate took place initially as small, displacing nodules of anhydrite which also replaced parts of the clotted–peloidal magnesite groundmass but affecting to a minor extent the root hole infillings (Fig. 5). The growth of these primary anhydrite nodules is interpreted as a result of intense pumping evaporation in periods of water-table fall related to more arid conditions (stage 3, Fig. 6).

The processes described (i.e. deposition of magnesite or other hydrated magnesium carbonate?), pedogenic modification, and growth of anhydrite nodules, could be repeated in alternating periods of wetter and drier conditions (stage 4, Fig. 6), so leading to the formation of composite profiles as aggradation progressed. The section studied (Fig. 3) records two separate episodes, represented by levels B and D, respectively, in which these processes took place. The main difference between the deposits deals with the higher development of the vertically oriented gypsum nodules which in level D are tightly packed, laterally forming most of the volume of the bed. This could be explained by a more drastic and probably longer period of subaerial exposure under arid climatic conditions of the lake deposits. In this setting, the mechanism of pumping evaporation should be highly effective in favouring capillary rise from the water-table and continued supply of saline moisture could account for the pervasive growth of sulphate nodules within the magnesite sediment (stage 5, Fig. 6). Thus, the uppermost bed formed of vertically oriented nodular gypsum (level D) is thought to represent a more advanced stage of accumulation of sulphate as compared with level B, although the pattern of formation of both deposits was quite similar.

An unsolved problem concerns the time at which the syndepositional or early diagenetic anhydrite nodules grown within the pedogenically modified carbonate were transformed into gypsum. Rehydration of anhydrite commonly occurs when evaporite series are exhumed and exposed to wet surficial conditions (Holliday, 1970) but also takes place in the evaporitic environment from contact with fresh continental ground waters (Tucker, 1991). In the study case we favour an early diagenetic transformation of the anhydrite to secondary gypsum. This assessment is based on the good preservation of the internal structure of the beds and the fact that the rehydrated sulphate products conforms well with some specific fabrics of the sediment. This is particularly clear in the horizontal fissures developed by desiccation of the magnesite that filled root holes (Fig. 5), these fissures being in turn infilled by fibrous (satin-spar) gypsum which is interpreted to derive from the excess volume of gypsum expected from the rehydration of anhydrite (Shearman et al., 1972).

## 5. Significance of the nodular gypsum occurrences from Mara

The remarkable vertical arrangement of the nodular gypsum in several beds of the section of Mara in the Calatayud Basin constitutes a striking feature that is clearly distinctive from the occurrences reported in the sedimentological literature and which are mentioned in the introduction (Tucker, 1978; Watson, 1985; Magee, 1991; Hartley and May, 1998). First of all, the initial sulphate accumulation was as anhydrite nodules. Secondly, the host-sediment in which the calcium sulphate precipitated, is a shallow lake

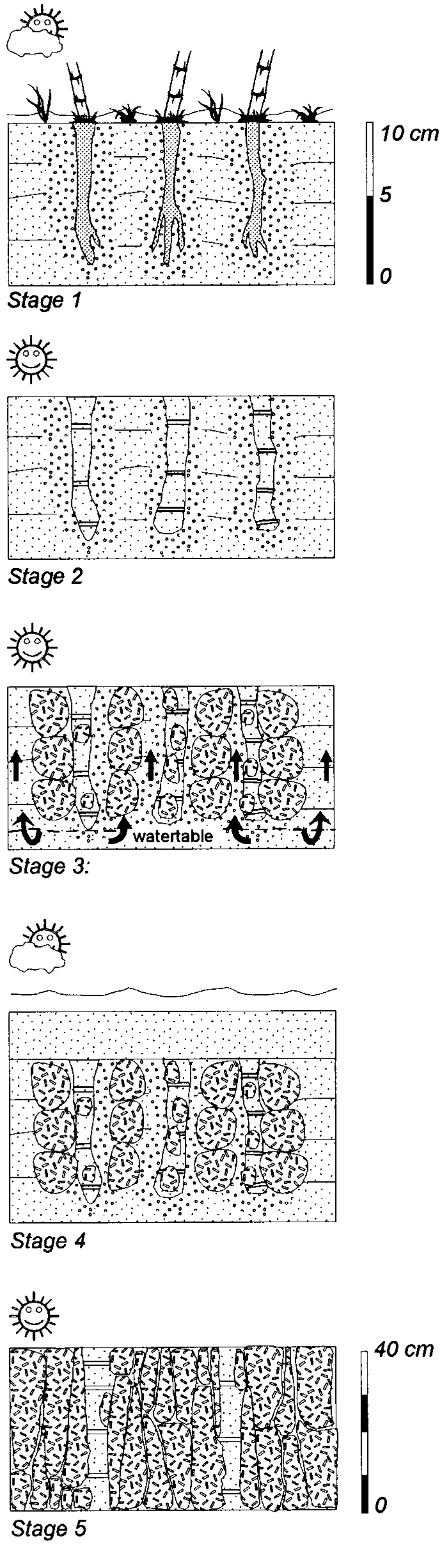


Fig. 6. Sketch showing a full cycle in the development of the vertically oriented sulphate nodules (see text for detailed explanation of the successive stages).

carbonate deposit extended towards the central part of the evaporite lake basin. Moreover, the recognition of rhizoliths and clotted to peloidal textures within the carbonate may be ascribed to incipient pedogenesis of the lake sediment, this picture being characteristic of what could be expected in palustrine carbonate environments (Freytet and Plaziat, 1982; Platt and Wright, 1992; Alonso-Zarza et al., 1992). Accordingly, our concluding remark is that the vertically oriented nodular gypsum described in this paper can be seen as a diagnostic feature for palustrine conditions developed in evaporitic lake settings, this peculiar morphology of the sulphate nodules having been strongly conditioned by the internal structure of the palustrine palaeosols.


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