

## Messinian stratigraphy of the Nijar Basin (S.E. Spain) and the origin of its gypsum-ghost limestones

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### Abstract

The Middle Messinian of the Nijar-Carboneras area (S.E. Spain) shows common rapid lateral transitions from thick-bedded massive gypsum to brecciated or massive limestone with voids and pseudomorphs after gypsum crystals. These 'gypsum-ghost limestones' are underlain by, and interbedded with, laminated marly sediments that contain a restricted marine microfauna attesting to oxygen-deficient conditions. Oolite-rich series of the basin margin, which include gypsiferous stromatolite and a few restricted marine fauna levels, probably constitute a lateral equivalent.

Upper Messinian fine-grained laminites of the central part of the basin contain brackish fossil assemblages and numerous tongues of coarse clastic material derived from the basin margins.

The gypsum-ghost limestones are interpreted to be essentially the product of two phases and types of diagenesis. Microbial sulfate-reduction during oxygen-deficient periods of the Middle Messinian first played a role in their formation. An important fresh-water diagenetic phase took place later, probably in the Late Messinian.

### Introduction

Unfossiliferous limestone containing pseudo-morphs after, and voids moulding, gypsum crystals, is common in the Messinian of Carboneras (Figs 1–3, Plates I–IV) (Van de Poel et al. 1984, Dronkert 1985). This 'gypsum-ghost limestone' was referred to as 'Calcare di Base-like rock' (Dronkert et al. 1979) because of its similarity in field-texture and stratigraphic position to the classical Messinian Calcare di Base of Sicily (Richter Bernburg 1973, Decima et al. 1988). This lithology also occurs in the 'caprock' of salt domes (Richter Bernburg op. cit., Pierre & Rouchy 1988).

The interest in this type of rock lies both in the position it takes in scenarios for the Messinian Sa-

linity Crisis (Hsü et al. 1977, Mueller & Hsü 1987), and in its reservoir potential for hydrocarbons and metal sulfides (Friedman 1980, Rouchy et al. 1985). Different mechanisms, however, have been proposed for its origin. The Sicilian Calcare di Base has been interpreted to be essentially either a primary carbonate deposit (Richter Bernburg 1973, Decima et al. 1988) or the product of microbial transformation of sulfate (Dessau et al. 1962, Neev & Emery 1967, Pierre & Rouchy, 1988). Fresh-water diagenesis of massive sulphates, proposed as origin for similar rocks from the Purbeck (uppermost Jurassic) of southern England by West (1973, 1975), is a mechanism, that has so far been little considered for the Messinian.

The objective of this paper is to give a detailed

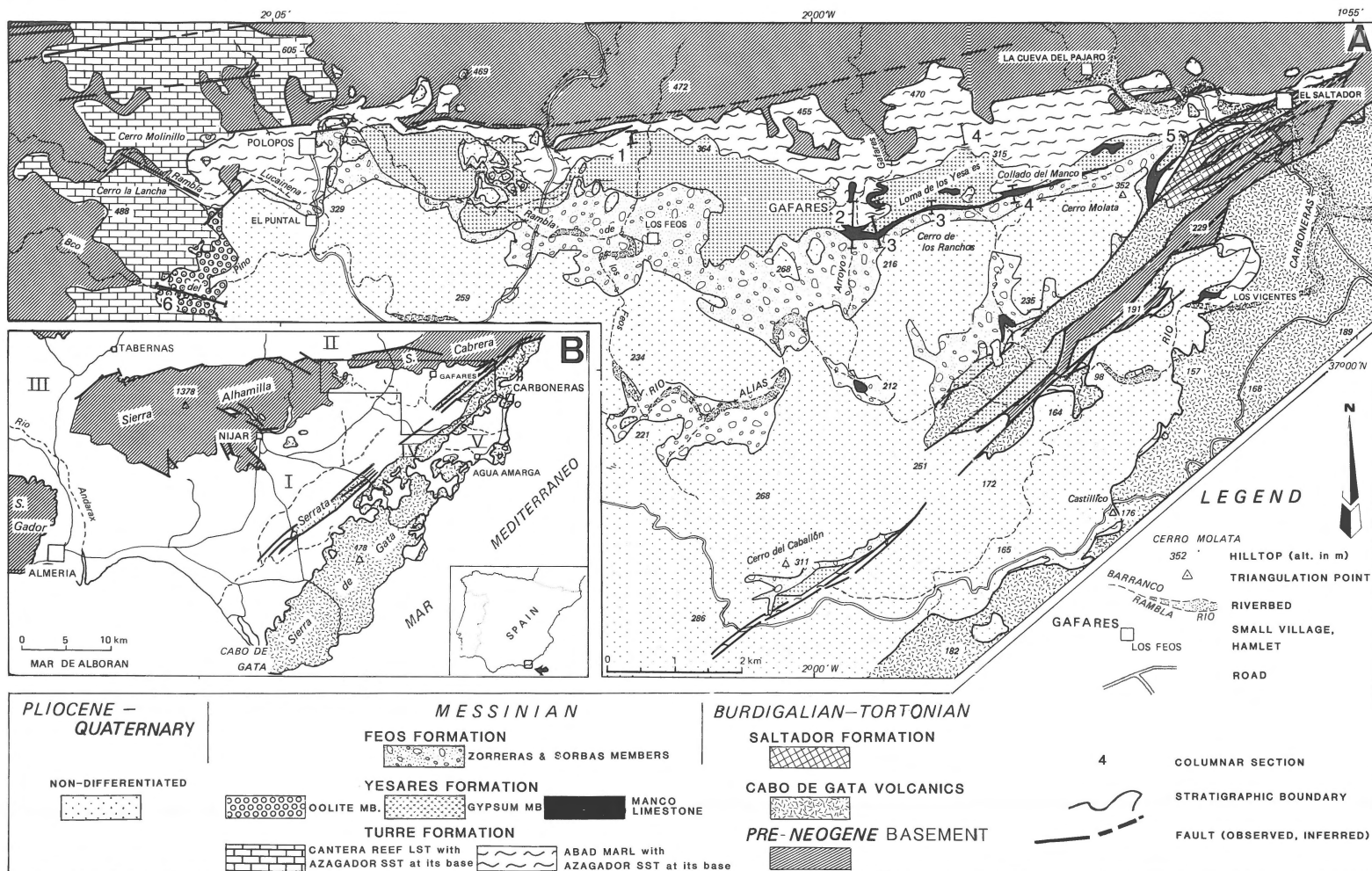


Fig. 1. Geological map of the northern part of the Nijar Basin (A), with distribution of gypsum-ghost limestones (in black), localities of sections discussed in text and regional setting (B) (I = Nijar Basin; II = Sorbas Basin; III = Tabernas Basin; IV = 'Castillico Ridge'; V = Agua Amarga Basin).

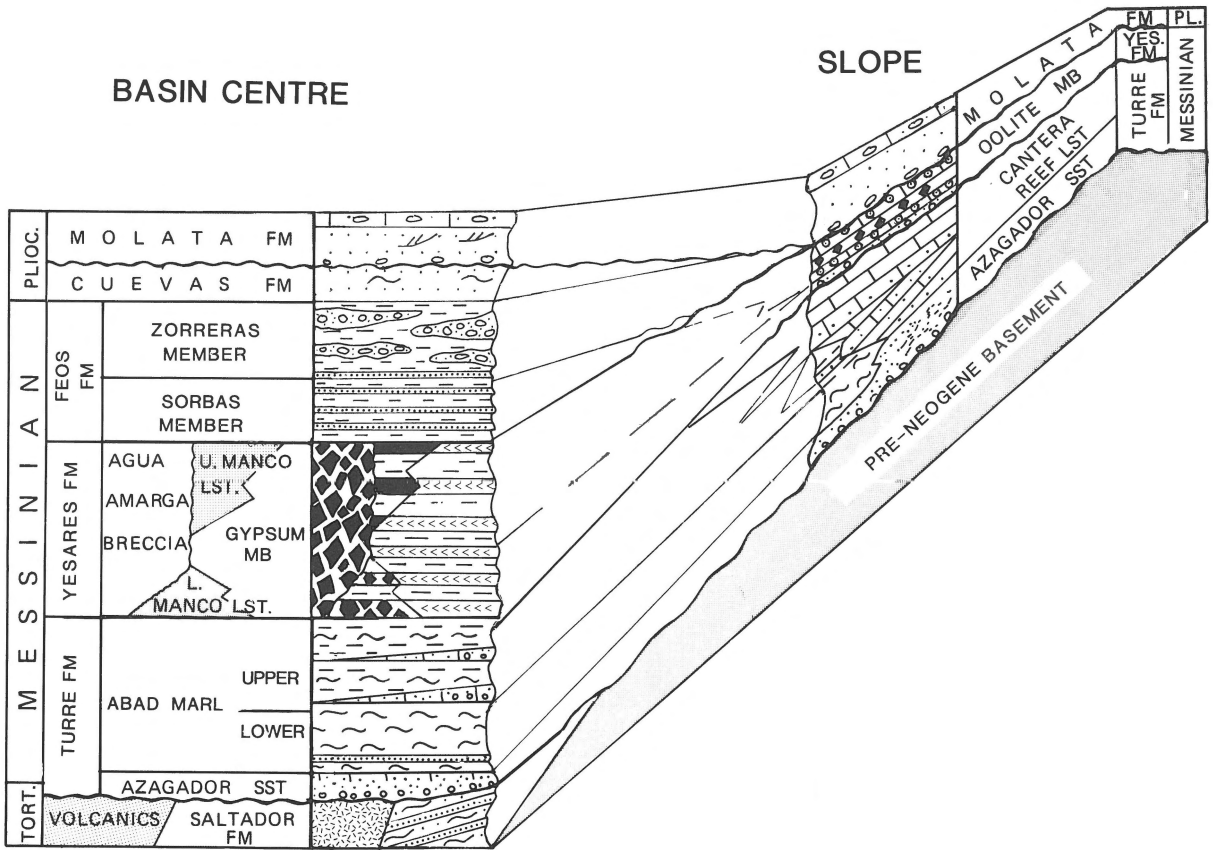


Fig. 2A. Lithostratigraphy of the Carboneras area (see Fig. 3A for legend).

Volk & Rondeel, 1964		Dronkert & Pagnier, 1977		This paper		AGE
VERA BASIN		SORBAS BASIN		NIJAR BASIN		
MAR-GIN	CENTRE	MAR-GIN	CENTRE	MAR-GIN	CENTRE	PLIOCENE
ESPIRITU SANTO FM	not studied	SORBAS MB	ZORRERAS MB	MOLATA FM		
CUEVAS FM				CUEVAS FM		
TURRE FM	CANteras MB	SORBAS MB	SORBAS MB	ZORRERAS MB	FEOS FM	
				YESARES MB		SORBAS MB
ABAD MB	TURRE FM	YESARES MB	YESARES MB	OOLITE MB	UPPER MANCO LST	
AZAGADOR MB				ABAD MB		GYPSUM MB
				CANTERA REEF LST	ABAD MB	UPPER MARL
				AZAGADOR SANDSTONE		LOWER

Fig. 2B. Stratigraphic correlations with nearby basins.

description of facies and stratigraphy of the ‘gypsum-ghost limestone’ and associated sediments from the Nijar Basin and to reconstruct the basin configuration and paleoenvironmental conditions that led to their formation.

### Geological setting

The Nijar Basin is a vast SW-NE elongated depression near Cabo de Gata (Fig. 1B). It is one of the Neogene-Quaternary basins of southern Spain, which formed by pull-apart of the Alpine basement of the Betic Cordilleras, and is situated in the ‘Eastern Betic Transcurrent Shear Zone’ of Montenat et al. (1987). The Nijar Basin is bounded to the north and west by intensely tectonized, and mostly metamorphic, pre-Neogene rocks of the Sierras Cabrera, Alhamilla and Gador, which are separated by

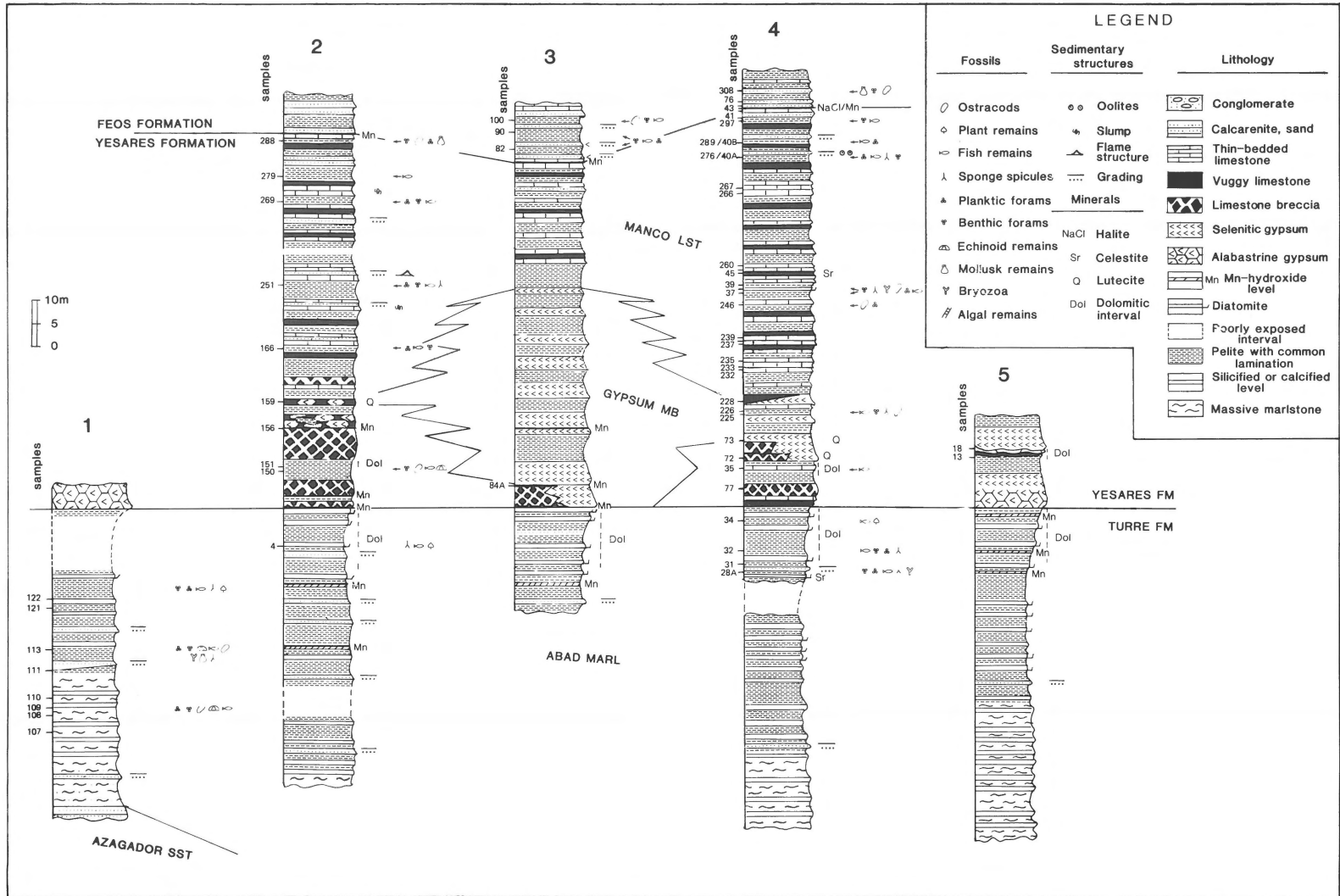


Fig. 3A. Lithologic sections of the Messinian Yesares Formation and associated deposits of the central part of the Nijar Basin (see Fig. 1 for locations). Multiple intervals of 'gypsum-ghost limestone' (in black) characterize the Manco Limestone.

lower areas connecting the basin to the Sorbas and Tabernas Basins in the north (Fig. 1B). The basin is bounded to the southeast by the Miocene volcanics of the Sierra de Gata (Fuster et al. 1965, Bellon et al. 1976). A northern continuation, the 'Castillico Ridge', forms a hilly range separating the Nijar Basin from the Basin of Agua Amarga (Van de Poel et al. 1984). The Castillico Ridge roughly parallels the NW-SE trending left-lateral Serrata-Carboneras Wrench Zone, which still shows some activity today (Bousquet & Philip 1976, Greene et al. 1977). To the southwest the Nijar Basin opens into the Alboran Sea of which it can be considered an uplifted part (Fig. 1B).

Most outcropping sediments of the Nijar Basin are marine Pliocene and continental Quaternary (Figs 1, 2) (Van de Poel et al. 1984). Older, Messinian material, is found in areas directly adjacent to the Sierras and in the Serrata Wrench Zone, which, near the village of El Saltador, also has tectonic slivers of marine Late Burdigalian to Tortonian sediment (Figs 1, 2A).

### Stratigraphy and facies description

Figure 2A gives the lithostratigraphic subdivision of the younger Neogene of the Nijar-Carboneras area. Messinian rocks were deposited in one major sedimentary cycle. The subdivision in a lower Turre Formation, a middle Yesares Formation, and an upper Feos Formation is primarily based on richness in marine fossils, (bio)chemical precipitates and terrigenous debris.

Figure 2B gives the relation of my lithostratigraphic scheme to earlier work on part of the Nijar Basin and the adjacent Vera and Sorbas Basins.

#### A. The Turre Formation

The Turre Formation is a complex of marine fossiliferous sediments that unconformably covers pre-Neogene basement along the northern and western basin margin and volcanic basement along its eastern margin (Figs 1 and 2A). Like Dronkert & Pagnier (1977) I recognize three members of the Turre Formation: the Azagador Sandstone at its base, grading upwards into the Abad Marl in more central parts of the basin and covered by the Cantera Reef Limestone along the basin margin (Figs 1, 2A, B).

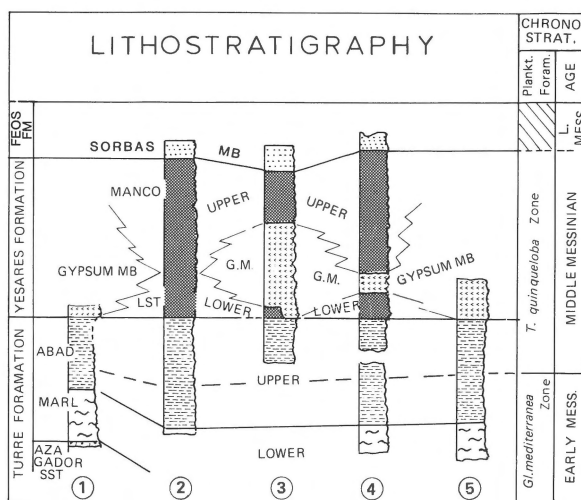


Fig. 3B. Lithostratigraphy, age and correlation of lithologic sections of Fig. 3A, showing thinning of Abad Marl in westernmost section (1) and rapid lateral transitions between Gypsum Member and Manco Limestone.

The Azagador Sandstone consists of brown to yellow, mixed siliciclastic-bioclastic sandstone with basal conglomerates of coarse fragments of the directly underlying pre-Neogene or volcanic basement (Rondeel 1965, Van de Poel et al. 1984). Its top is especially rich in diverse marine macrofossils (molluscs, echinoids, Bryozoa, *Heterostegina* sp., calcareous algae and, locally, corals).

The Abad Marl is characterized by the dominance in foraminifera-rich marl, which, near the top of this unit, alternates with numerous soft, white, ca. 50 cm thick diatomitic beds (Fig. 3A, Plates Ia and IIa, b). Calcified or silicified diatomitic levels interrupt the marlstone at regular intervals in the lower part of this unit, while bioclastic calcarenite layers are present both near its base and in its upper part. The informally distinguished Upper and Lower Abad Marl contrast in the field by a darker, yellowish, versus a lighter, greyish colour, respectively. At a fresh surface, the boundary coincides with an upwards change from bluish-grey, massive, bioturbated marlstone to laminated yellowish pelitic sediment (marl, lime-mud, calcisiltite). The yellowish colour of the Upper Abad Marl is caused by a relatively high content in fine-grained iron-hydroxides, whereas, at the same time, its sediments are rich in microscopically small gypsum crystals (cf. Fe and SO<sub>4</sub> curves of Fig. 4). An upward increase in manganese-hydroxide gives rise to a number of conspicuous, dark-brown levels of a few centimetres thick and the Abad Marl terminates in a dolomitic interval (Fig. 3A, Mn and Mg-curves of Fig. 4).

Near the base of the Upper Abad Marl, the first of a number of bioclastic layers occurs, that are typical for this interval (Fig. 3A, Plate IIb). Most of these beds rapidly wedge out and display normal grading, sometimes with parallel lamination and horizontal burrowing at the top. The richness in fragments of algae,

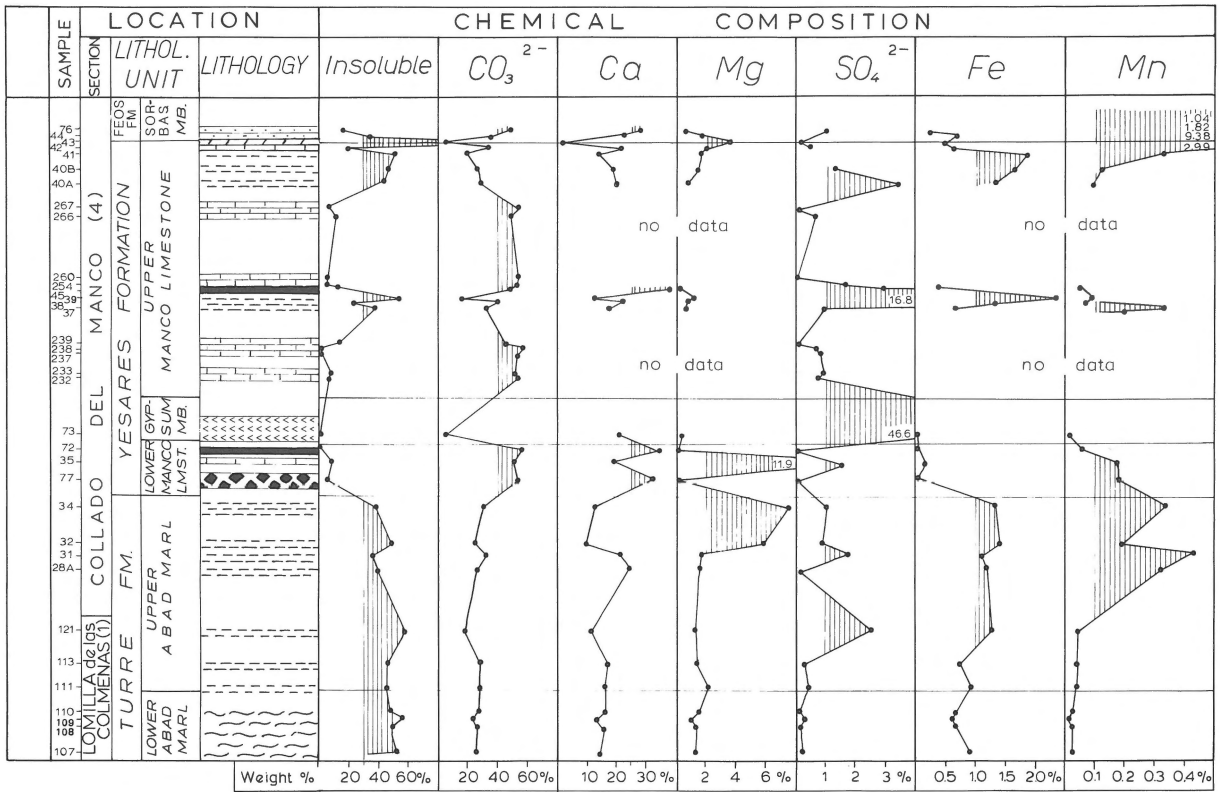


Fig. 4. Vertical distribution of major and some minor chemical constituents in the Lower-Middle Messinian of the central part of the Nijar Basin (see Fig. 3A for legend). Note: (1) similar composition of Upper Abad Marl and laminated pelites of the Yesares Formation; (2) pure calcium carbonate composition of vuggy limestones and limestone breccia of the Manco Member.

Bryozoa, molluscs, and larger Foraminifera attests to turbidity currents and debris flows originating from a carbonate shoal. Frequency and thickness of these layers increases in a westerly direction (Fig. 3A). Besides, fine-grained turbidites, rich in shallow-water benthic foraminifera (*Ammonia beccarii* LINNE, *Elphidium* sp., *Florilus boueanum* D'ORBIGNY, Miliolidae), ostracods and fragile bryozoan remains, are common in the Upper Abad Marl. Such sediments dominate in the westernmost Upper Abad exposure, at El Puntal. Both in the latter locality and in the easternmost section (Lost Vicentes, Fig. 1A), isolated slumped blocks of coral reef limestone have been found embedded in regularly laminated marl. The Abad Marl wedges out further to the west and north of El Puntal, where the Azagador Sandstone and Cantera Reef Limestone are directly superimposed (Figs 1, 2A, 9).

The Lower Abad Marl has a rich and diverse fossil content (Fig. 3A) and correlates with the lowermost part of the Messinian stratotype (Fig. 8). Foraminiferal assemblages of the Upper Abad Marl are commonly dominated by small forms (*Bulimina* sp., *Turborotalita quinqueloba* Natland). Remains of siliceous fossils (sponge spicules, diatoms), and of plants and fish (Plate IIc, d), increase in importance going upwards in the Abad section, to become virtually the only fossils present in the

dolomitic top (Fig. 3A). A consistent change in coiling direction of *Neogloboquadrina acostaensis* BLOW, marking the boundary between the local planktic foraminiferal *G. mediterranea* and *T. quinqueloba* Zones (Fig. 3B), takes place some tens of metres below the top of the Abad Marl and is also found within the Messinian Tripoli Formation of Sicily (Fig. 8).

*The Cantera Reef Limestone*, formed by massive reef limestone with associated bioclastic calcarenite and calcirudite, only occurs in the northwestern part of the studied area. In sections most proximal to the basin margin, the Reef Limestone rests directly on Azagador Sandstone (e.g. Cerro de la Lancha and Molinillo) while, more basinward, it progrades over the Abad Marl, as can be seen in the vicinity of Polopos (Figs 1, 2A, 5, 9). Sediments in the same stratigraphic setting near Nijar (Fig. 1B) have been described as the 'Reef Complex' by Dabrio et al. (1981). They discerned three facies that can also be recognized in our area (Fig. 5): 1) massive reef core with dominance of the coral *Porites* sp. (extensively exposed at the top of the hills along the higher streambed of the Rambla Lucainena); 2) reef fore-slope deposits with high-angle giant cross-bedding (well-exposed in the southern bank of the Barranco del Pino); c) light-

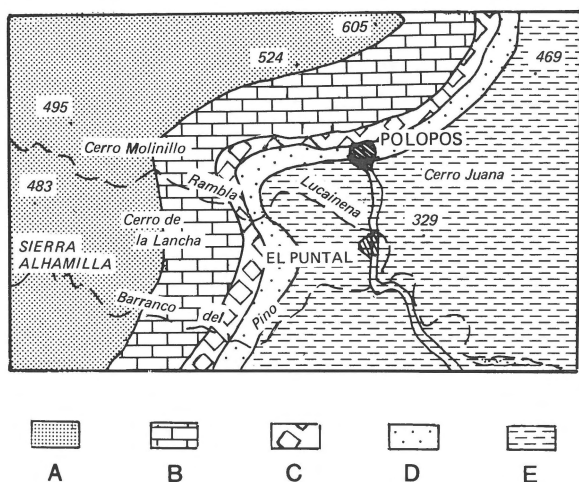


Fig. 5. Distribution of (youngest) Cantera Reef Limestone subfacies in the Polopos area (partially reconstructed). A = older formations; B = massive reef limestone; C = proximal fore-reef; D = distal, toe-of-slope facies; E = basinal Upper Abad Marl. Numbers refer to hilltop elevations in metres.

coloured, bedded calcarenite and calcirudite, representing the toe of a slope-facies (hills around Polopos).

Due to erosion, that already started in the late Messinian (Fig. 9C), the continuous transition from reef to basinal facies is not preserved. As yet, the Cantera Reef Limestone can be correlated with the Upper Abad Marl since: (a) the west to east distribution of reef to slope subfacies of the Cantera Reef Limestone

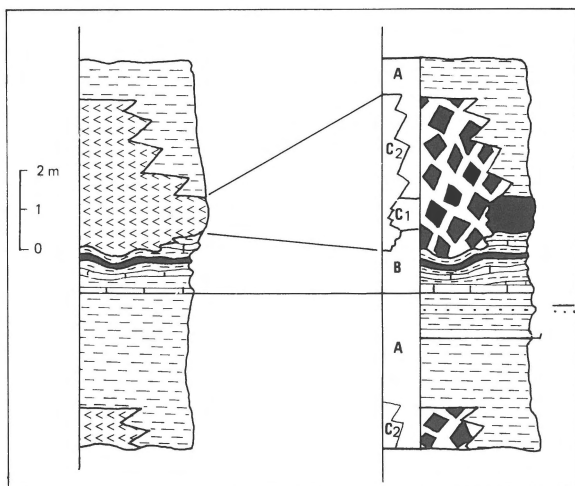


Fig. 7. Schematic sections to illustrate modal cycles in the Gypsum Member (left, slightly modified after Rouchy, 1981) and the Manco Limestone (right). Legend as in Fig. 3A. C1 and C2 refer to the two gypsum-ghost limestone types.

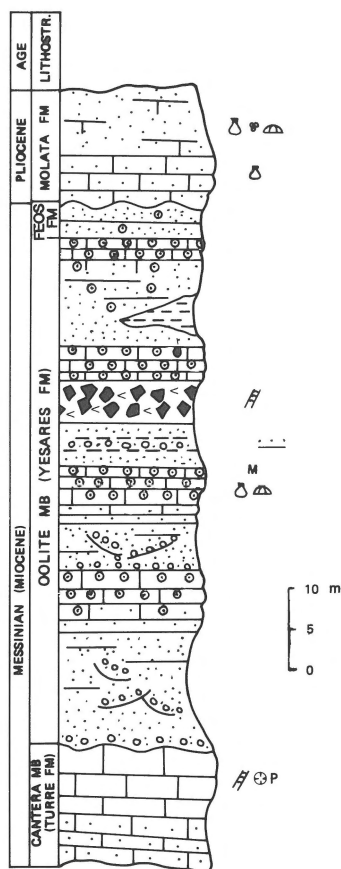


Fig. 6. Type section of the Oolite Member in the Barranco del Pino (location 6 of Fig. 1). P = *Porites* coral; M = *Microcodium*; For further legend, see Fig. 3A.

can be matched with an east-west increase importance of reef debris in the Abad Marl; (b) Cantera deposits prograde around Polopos over older Abad Marl, which also underlies Upper Abad Marl in more central parts of the basin; (c) the coral faunas of the Reef Limestone and of the Upper Abad Marl are both oligotypic; (d) in the adjacent Agua Amarga Basin, both Upper Abad Marl and Cantera Reef foreslope deposits are conformably overlain by a coarse breccia of limestone with evaporite-relics (Van de Poel et al. 1984).

*B. The Yesares Formation*

The Yesares Formation is characterized by thick-beds of evaporite or of breccia or massive limestone with 'ghosts' of gypsum (Figs 3A, 6, 7; Plates I, IIa, III). In the central part of the basin, the Yesares Formation covers the Abad Marl conformably and is intercalated with laminated pelitic sediments that are similar to the Upper Abad Marl (Figs 3A, 4). At the NW basin margin,

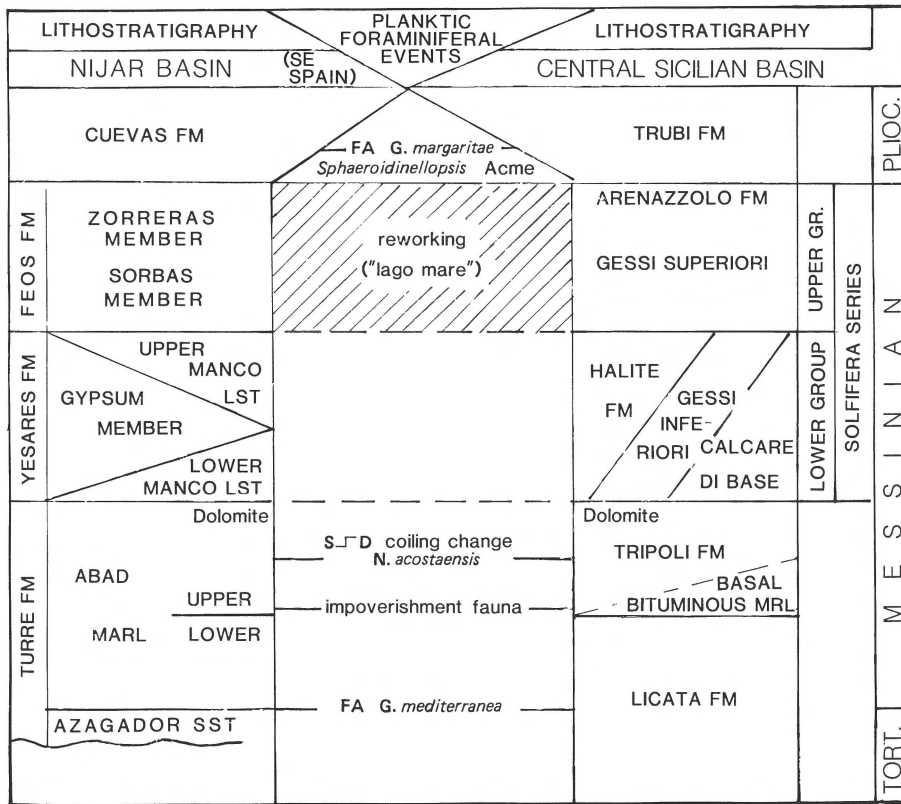


Fig. 8. Suggested litho-, and biostratigraphic correlation between the Messinian of the Nijar Basin and the Messinian of the stratotype area in Sicily (basal contacts of respective evaporite and 'lago mare' units may not be exactly synchronous). Sicilian stratigraphy data from: Decima & Wezel (1973), Colalongo et al. (1979); McKenzie et al. (1979) and personal observations. No vertical scale implied.

a series of oolitic limestones and intercalated gypsiferous algal breccia, covers the Cantera Reef Limestone with an erosional contact (Fig. 6). The massive Messinian gypsum-bearing strata of southeastern Spain were originally referred to as Yesares Member of the Turre Formation (Völk & Rondeel 1964) or as Yesares Member of the Caños Formation (Ruegg 1964, Dronkert & Pagnier 1977) (Fig. 2B). Here, a separate formational status is given to the series that bears thick beds of evaporite or of limestone with ghosts of gypsum crystals. Most of the constituent facies are represented in the Loma de los Yesares, the type-area designated by Völk & Rondeel (1964) for their Yesares Member (cf. section 3 of Figs 1 and 3). The formation is especially well exposed in sections 2 and 4 at the western and eastern ends of the type-area, respectively (Plate Ia, b, IIa).

The Yesares Formation is subdivided in three Members: the Oolite Member of the NW basin margin (Figs 1, 6), and the Gypsum Member and Manco Limestone of the central part of the basin (Figs 1-3).

*The Oolite Member* is a mixed clastic-evaporitic series with oolitic limestone as its most characteristic element (Fig. 6). It is only found onlapping Cantera Reef Limestone along the north-western basin margin (Figs 1, 2A, 9). The oolite-rich facies is

especially well developed about 1 kilometre SW of the hamlet El Puntal (Fig. 1). A section in the northern bank of the Barranco del Pino serves as type-section (section 6 of Figs 1 and 6). Here, the karstic top of the Cantera Reef Limestone is covered by a decimetres thick basal conglomerate, containing up to 6 cm large pebbles of the pre-Neogene basement. In the overlying 50 metres or so, terrigenous clastics alternate with carbonatic intervals, consisting of oolitic limestones that may display megacrossbedding, and a thick bed of grey-yellow limestone breccia. The breccia consists of stromatolite fragments of up to one decimetre, containing vugs that can have the form of gypsum crystals, and in which gypsum sometimes is preserved.

Some limestones of the Oolite Member contain abundant mollusc and echinoid remains. *Microcodium* is occasionally present at the top of the carbonatic intervals. The terrigenous-clastic intercalations are barren of fossils except for scattered reworked fragments. These clastic intervals largely consist of material derived from the pre-Neogene metamorphic basement as exposed on the nearby slopes of the Sierra Alhamilla. Brown-red to purplish colours are common in the graded and mega-cross-bedded fine conglomerates and sands and laminated silts.

Similar oolitic series have been described as 'Terminal Carbonate Complex' by Dabrio et al. (1981) from localities near

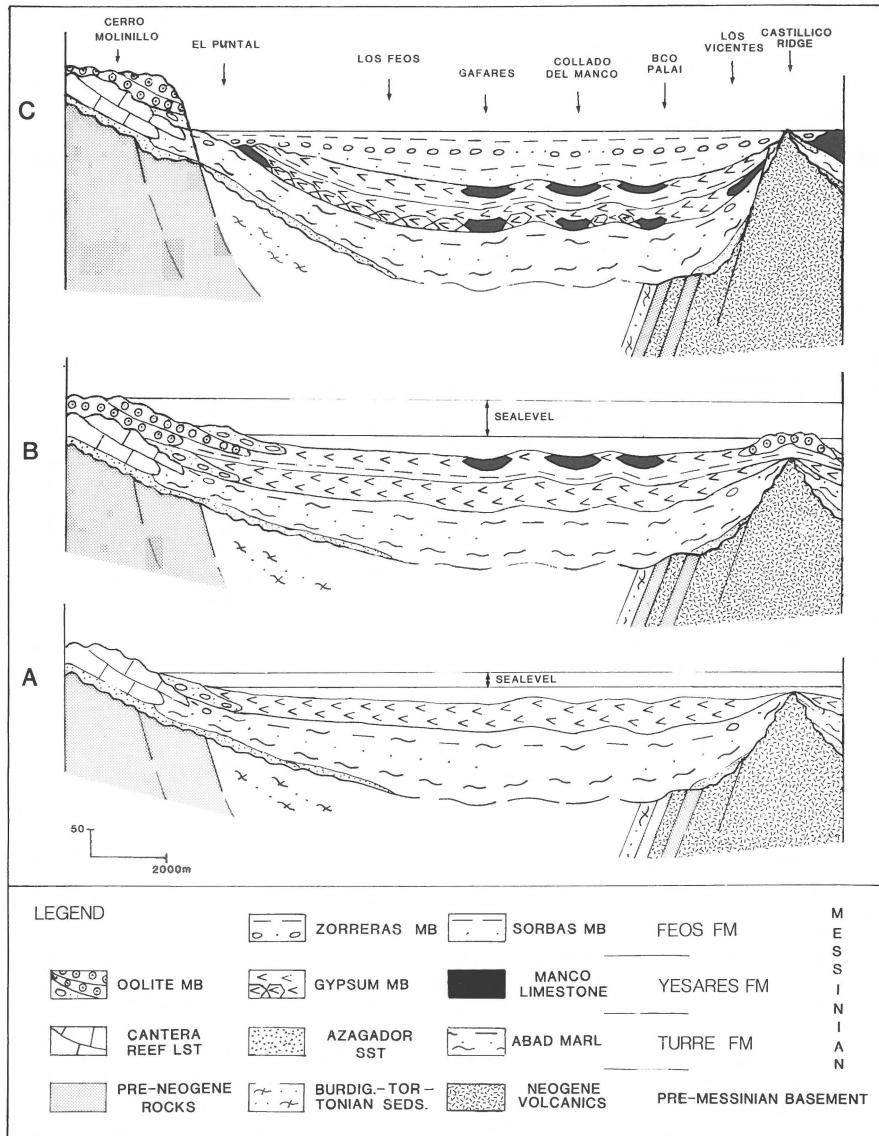


Fig. 9. Proposed model for the evolution of the Messinian depositional environment of the Nijar Basin with emphasis on the Manco Limestone. 'Stage A': Early middle Messinian low sea level results in deposition of thick-bedded gypsum (? and anhydrite) in the basin centre. 'Stage B': Late middle Messinian important sea level fluctuations lead to alternating evaporitic and oxygen-deficient, sulfate reducing, conditions in the basin centre, where thinner gypsum beds, gypsiferous limestones and laminated pelites are deposited. 'Stage C': Late Messinian brackish 'lago mare' in the very basin centre and subaerial exposure in its more external parts results in dissolution of gypsum crystals and alteration of thick-bedded sulphate rocks from the underlying Yesares Formation to limestone breccia and alabaster gypsum.

Nijar and by Esteban & Giner (1980) from magins of the adjacent Agua Amarga Basin (Fig. 1B). The transition from Oolite Member to basinal facies is not exposed (Figs 1, 9). As yet, the Oolite Member is considered the basin margin facies of the Yesares Formation, because of its stratigraphic position on top of the Turre Formation and its alternation of evaporitic, restricted marine and non-marine sediments (Fig. 2A; Esteban &

Giner 1980, Dabrio et al. 1981).

*The Gypsum Member* is characterized by thick beds of massive gypsum (Figs 3A, 7; Plates Ia, b, IIIa, b). In good exposures these can be seen to be separated by important intervals of fine-grained, laminated pelite (e.g. base of section 5, Plate IIIb). The middle part of section 3 is the type-section for the



(a)



(b)

Gypsum Member. It contains 8 gypsum layers with an upward decrease in bed-thickness. The Gypsum Member is here overlain by three cycles of Manco Limestone (Fig. 3A). In the SE flank of the Loma de los Yesares, 11 gypsum layers could be counted and no Manco Limestone is present (c.f. Plate Ib, left foreground). The gypsum beds generally consists of coarse-crystalline translucent 'selenite' (Plate IIIb). Crystal-size decreases upwards within each individual layer. The base of the Gypsum Member commonly comprises fine-crystalline, white 'alabastrine' gypsum with chickenwire structure (e.g. sections 1 and 5 of Fig. 3; Plate IIIa), which possibly contains relics of anhydrite (Dronkert 1985).

The Gypsum Member of the Nijar Basin differs from that of the adjacent Sorbas Basin (Dronkert 1985) by the more common development of alabastrine subfacies, levels of manganese hydroxide and ferrous silica concretions. Small aggregates of lutecite (length-slow chalcedony) have been found in gypsum beds of the Collado del Manco (section 4) and in rocks transitional from gypsum to limestone at Gafares (section 3; Fig. 3A). Marly interbeds may contain levels of thin-bedded laminated limestone and minor amounts of vuggy limestone towards their dolomitic top (Plate IIIb).

The Gypsum Member is largely unfossiliferous but in some of the interbedded laminated pelites a restricted marine foraminiferal microfauna (small-sized Buliminacea and planktics) has been found, as in the interbeds of the laterally equivalent Manco Limestone (Figs 3 and 7).

*The Manco Limestone* is characterized by thick beds of unfossiliferous, vuggy limestone or limestone breccia (Figs 3A, 7; Plates Ia, b, IIa, III d, f). Together, they are referred to as 'gypsum-ghost limestone', since sedimentary and mineralogical features attesting to the original presence of gypsum are common in both types of rock (e.g. Plates IIa, IIIc, d, f, IVb, c, d, f). They are most common at the base or top of the Yesares Formation, but account for virtually the whole interval in the dry riverbed at Gafares (section 2) and in the type section in the Collado del Manco (Plate I; section 4 of Figs 1 and 3) (Van de Poel et al. 1984). The gypsum-ghost limestones alternate with metre-scale, laminated intervals (Fig. 3, Plate III d-f). Rouchy (1981) described cyclic sedimentation in the Gypsum Member from our area. A similar cyclic arrangement of sediments can be

recognized within the Manco Member (Fig. 7). A medium to coarse-grained limestone breccia (*Facies C 2*) is the dominant lithology in the Lower Manco Limestone (Fig. 3; Plates I and IIa). Thick levels of thin-bedded, dolomitic, and medium-bedded, vuggy, limestone (*Facies B and C 1*) dominate the Upper Manco Limestone (Fig. 3; Plate III d-f).

*Facies A* (Plate III d), the softer, marly lithology of the Manco Limestone is, like the Upper Abad Marl, laminated, displaying various colours, of which yellowish tints are the most common, and is rich in dispersed microscopic gypsum crystals and iron and manganese hydroxides (Fig. 4). Oligotypical planktic foraminiferal assemblages consisting of small species (*T. quinqueloba*, *Neogloboquadrina* sp., *Globigerinita* sp.) occur and may be accompanied by small Buliminacea, and small Globorotaliidae (samples 166 C and 251 of section 2). Shallow-water microfossils (*Elphidium* sp., smooth ostracods, together with some miliolids and *Ammonia beccarii*) commonly are the dominant fauna constituents. Soft, white layers, rich in siliceous fossils (sponge spicules, diatoms) and bryozoan remains, occur in intervals 37-39 and 40A-B of section 4 (Fig. 3A).

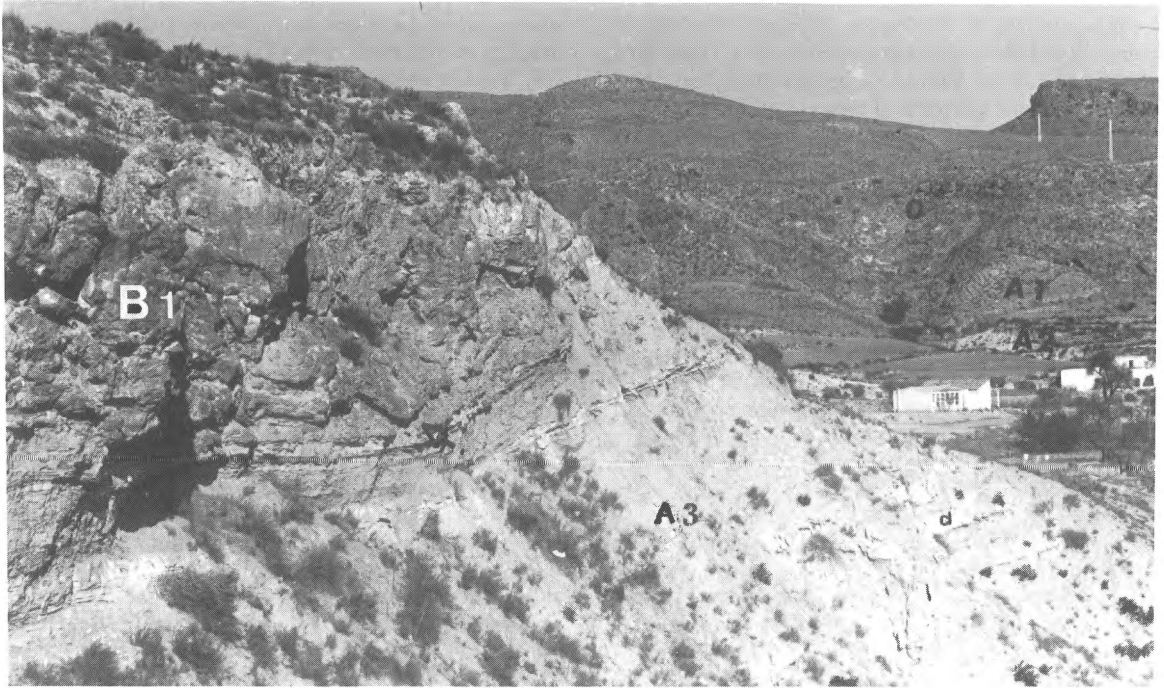
*Facies B* (Plates III d-f, IVa, b), consists of white, soft dolomitic marl, commonly containing numerous, hard, 4 to 10 cm thick, dolomitic limestone beds. In the Upper Manco Limestone, this facies continues uninterrupted for several metres (Plate III, e). Commonly developed lamination in the dolomitic limestone (Plate IVa), may be wavy caused by the growth of small gypsum crystals in a still soft sediment (Plate IVb) (Rouchy 1981). This rock-type is transitional to facies C 1. Rare siliceous fossils (sponge spiculae, silicified miliolids) are found.

*Facies C 1* (Plates III d, f, IV c-d) is a grey to yellowish, massive vuggy limestone or, less common, a fine-grained limestone breccia, which occurs in beds of some decimetres to one metre. In the massive type, numerous cavities occur, which commonly mould gypsum crystals (Plate IVc, d). They are generally less than 1 centimetre in size and, within a single layer, may show an upwards decrease in size. Often, they are partially or completely filled with sparry calcite forming pseudomorphs after gypsum. Rocks consisting entirely of pseudomorphed gypsum (Plate IVf) are rare. In the fine-grained limestone breccias (Fig. IVe), vugs are smaller and less common than in the massive limestone, and often of irregular form. A thin section from the base of the vuggy limestone layer of Plate IVc, demonstrates

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Plate I. Stratigraphy of gypsum-ghost limestones and associated sediments of the central part of the Nijar Basin.

a. Collado del Manco Section (4 of Figs 1 and 3), with type-section for the Manco Limestone. From lower left to upper right are exposed: (A) Upper Abad Marl with white diatomitic intercalations (d); (B1) Lower Manco Limestone: thick-bedded limestone breccia with white dolomitic intercalation; the upper two limestone breccia beds pass laterally, towards the top of the hill, into thick-bedded gypsum (B2: Gypsum Member); (B3) Upper Manco Limestone: alternation of grey, medium to thin-bedded, limestone levels with light-coloured, soft, pelitic intercalations, marked at its top by the strongly manganiferous level (m); (C) the Feos Formation; (D) Pliocene calcarenites (below) and limestone of the Cerro Molata;

b. Panoramic view of the Collado del Manco area, showing the rapid lateral transition from thick-bedded gypsum (section 5 in the left background) into gypsum-ghost limestone (the only characteristic lithology in section 4'). The hill in the left foreground again entirely consists of bedded gypsum (cf. Plate Ia and Figs 1, 3A, 3B). (a) = alabastrine gypsum along the local base of the Gypsum Member. Further legend as in a.



(a)



(b)



(c)



(d)

that the fine-grained breccias formed by collapse of vuggy limestones after the disappearance of the gypsum crystals (Plate IVd).

Some vuggy limestones contain abundant celestite, but geochemical analysis of these rocks mostly shows a pure calcitic composition with a Mg-content oscillating between 0.15 and 0.20% (Fig. 4; pers. comm. J.A. McKenzie 1983). At the top of section 4, a siliceous laminated limestone layer contains cube-shaped moulds and crystals of halite. The same level has strong manganese hydroxide enrichment (up to over 25%; Van de Poel & Klaver 1989). This Mn-hydroxide enrichment level (Fig. 3; Plate Ia, b) marks the top of the Yesares Formation over a large area in the central part of the basin (from the Cortijada de los Feos in the west, up to the northern flank of the Cerro Molata in the east and the Rio Alias in the south, Fig. 1). Strong enrichment in manganese hydroxide is also common in Facies B and C 1 of the Lower Manco Limestone at Gafares (Fig. 3A; Plate IVb, e). No fossils have been found in this facies.

*Facies C 2* (Plates Ia, IIa, IVe) is a thick-bedded, medium to coarse-grained limestone breccia, composed of unsorted angular to subrounded fragments, which commonly show a saccharoidal microtexture. Components attain decimetre-size and lutecite aggregates, or small cavities moulding them, occur. Mineralogical composition is otherwise the same as in Facies C 1. No fossils have been found in this facies.

*Additional facies.* All Manco Limestone rocks of section 2 (Arroyo Gafares) are relatively rich in fine siliciclastic detritus. Sedimentary structures as lateral thinning (Plate IIIId), distorted and graded bedding, with occasional flame structures and mud-clasts along the base and parallel or cross-laminations at the top of the beds are here common (Fig. 3A).

All Manco Limestone sections show an increase in fine terrigenous debris towards their top, where graded calcarenites, embedded in soft, white laminites with some small *Elphidium* sp. and *Cyprideis* sp., are found. This lithology heralds the overlying Feos Formation.

The Manco Limestone correlates with the Messinian 'Calcare di Base' of Sicily (Fig. 8) for the following reasons: 1) it overlies in stratigraphic continuity diatomaceous Upper Abad Marl, which is correlative with fossils and lithofacies of the Sicilian Tripoli Formation; 2) similarly to the Calcare di Base it forms a lateral equivalent of 'middle' Messinian evaporites and is overlain by gypsum arenites, followed by a series with the typical late Messinian 'lago mare' fauna. Moreover, the Manco Limestone displays the same primary facies types and has the presence of celestite in common with the Calcare di Base (Richter Bernburg 1973, Decima et al. 1988).

The Manco Limestone differs from the 'Calcare' in the rarity of

Table 1. Isotopic data for Lower Manco Limestones\*

Sample	Limestone lithology	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$
1	massive	- 5.12	- 6.31
2	wavy laminated	- 5.29	- 6.65
3	breccia	- 4.96	- 7.06
4**	massive	- 4.31	- 5.46

\* sample locality Arroyo Gafares (section 2).

\*\* base of Lower Manco Limestone.

halite voids and the absence of elemental sulfur and unambiguous algal remains. In addition, a uniformly negative oxygen isotope signal (Table 1), as well as common manganese hydroxide-enrichment and interbeds of laminated marl with marine microfossils seem characteristic of the Manco Limestone.

### C. The Feos Formation

In the central part of the basin, the Yesares Formation is conformably overlain by white, commonly laminated, fine-grained sediments with numerous coarser, clastic intercalations; the Feos Formation (Feos Member of Van de Poel et al. 1984) (Figs 1-3, 9; Plate Ia, b). It is subdivided in the Sorbas Member (below) and the Zorreras Member (above):

*Sorbas Member.* The lower part of the Feos Formation consists of laminated pelite with calcarenitic intervals containing ochreous, siliceous, thin laminated limestone beds (Fig. 3A). This interval is comparable in facies and stratigraphic position with the Sorbas Member of Ruegg (1964, in Dronkert & Pagnier 1977) from the Sorbas Basin (Fig. 2B). The characteristic interbedded calcarenites consist of carbonate intraclasts, fragments of laminated and vuggy Manco Limestone, oolites and fragments of stromatolitic limestone. Gypsum arenites are common near the base of this unit. Slump structures and graded bedding, sometimes with flutecasts at the base of the beds, attest to the importance of gravitative sedimentation (Roep & Van Harten 1979).

Some of the soft, white laminated marls contain a few small *Elphidium* sp. and *Cyprideis* sp.. The coarser beds contain scattered reworked fossils. In sample 208 of section 3, a rich 'lago mare' fauna (ostracods and small molluscs) was identified.

←  
Plate II. Stratigraphy and facies of Lower Manco Limestone and Upper Abad Marl at Gafares (section 2). Cm-scale for rock-samples.

- In the foreground: (B1) Lower Manco limestone: thick limestone breccia bed with (at arrow) coneshaped downward projection at base (calcified gypsum bush); (A3) Upper Abad Marl with numerous white diatomitic intercalations (d). In the background: (A2): Base of Lower Abad Marl; (A1) basal Azagador Sandstone of the Turre Formation and (0) pre-Neogene basement.
- Typical lithology of the Upper Abad Marl: laminated marl with thick biocalcarenic turbidite (t) and white diatomitic intercalations (d) (level 4).
- Large plant-fragment from laminated marl (level 122, section 1).
- Small fish-skeleton from diatomite (level 4, section 2).



(d)



(f)



(e)



(c)

**UPPER MANCO LIMESTONE**

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**LOWER MANCO LIMESTONE**

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**GYPSUM MEMBER**



(a)



(b)

*Zorreras Member.* The upper part of the Feos Formation is referred to as Zorreras Member, since it is equivalent in facies and stratigraphic position to the main part of the unit described under this name from the Sorbas Basin (Ruegg 1964, in Dronkert & Pagnier 1977; Fig. 2B). Three subfacies can be discerned:

1) Fluvial fan deposits, rich in pre-Neogene basement debris and fragments of Messinian reef and oolitic limestone, associated with thick, reddish, knobby levels of caliche soil formation and relatively thin, but widespread, white laminated intervals. This subfacies is abundant west of Gafares (Roep & Van Harten 1979; Dronkert et al. 1979) and has a strongly erosive base to the west and north of Los Feos, whereas it unconformably covers early Messinian Abad marls at El Puntal, near the western basin margin.

2) Green conglomerates, rich in well-rounded pebbles from the volcanic basement exposed to the east of the basin (Fig. 9C), alternating with white, laminated pelite. This subfacies is common in, and restricted to, the eastern part of the basin (sections around the Cerro Molata and Cerro del Caballon).

3) Light-coloured marly sediments with intervals of thin-bedded, laminated limestone and characteristic, white, carbonate intraclast conglomerates, that contain relatively few pre-Neogene or volcanic debris. This inter-fan subfacies is found between Gafares and the Cerro Molata.

Fine-grained sediments of the Feos Formation often contain ostracods (*Cyprideis*) and the foraminifers *Ammonia beccarii* and *Elphidium* sp.. In the uppermost levels, these are associated with the ostracod genera *Loxoconcha* and *Tyrrhenocythere* (det. D. van Harten), small lamellibranchs, gastropods and the oogonia of *Chara* sp.. This brackish to fresh biofacies is characteristic of the late Messinian 'lago mare' (e.g. Ruggieri & Sprovieri 1976, Colalongo et al. 1978). Its late Messinian age is confirmed by a local, conformable cover with marine silt of the Cuevas Formation (Figs 2A, B), containing a *Sphaeroidinellopsis-Globorotalia margaritae* planktic foraminiferal fauna of earliest Pliocene age (Fig. 8). The marls of the Feos Formation also contain marine planktic and benthic foraminifera reworked from the older Messinian.

## Discussion

### *Evolution of the depositional environment*

#### *Early Messinian*

The upward change within the Abad Marl from

massive bioturbated marlstone with a diversified microfauna to laminites with oligotypical fossil assemblages attests to the initiation of restricted marine conditions in the earlier part of the Messinian (Troelstra et al. 1980).

Several phenomena suggest that oxygen-deficiency was the main feature of this restricted marine environment: (1) laminations, which can only be preserved in waters with an oxygen content about one tenth of normal and (2) dwarfism and diversity reduction of foraminifera, with strong dominance of the Buliminacea in the benthic assemblages (e.g. Harman 1964); (3) abundant fine plant material, well-preserved large plant fragments and entire fish skeletons (Plate IIc, d); (4) authigenic microscopic gypsum crystals, common in organic-rich environments (Robert & Chambley 1974, Siesser & Rogers 1976, Briskin & Schreiber 1978).

The persistence of planktic foraminifera during upper Abad deposition precludes a dramatic rise in salinity because these organisms have limited maximum tolerance values (ca. 50‰: Reiss & Hottinger 1984). The dominant *Porites* in the Cantera Reef Limestone also indicates similar maximum salinity values (Kinsman 1964).

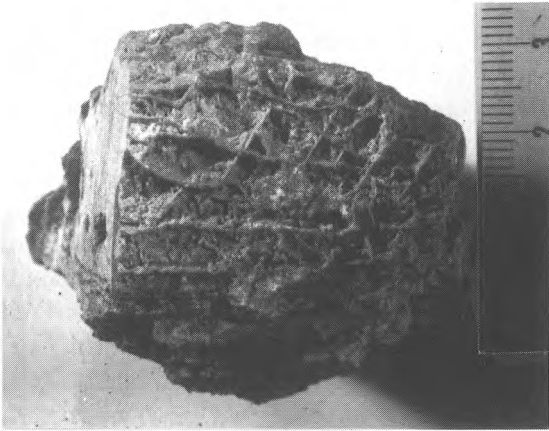
#### *Middle Messinian (Fig. 9A, B)*

Important hypersaline periods are recorded by the massive gypsum beds and the gypsum-ghost limestones of the Yesares Formation (Figs 3, 7, 9).

Interbedded marly sediments (Facies A of the Manco Limestone), with the same litho- and biofacies as the Upper Abad Marl (Figs 3A, 4), represent nearly normal saline, but oxygen-deficient interruptions. At times, open-marine conditions may have been approximated, because some planktic foraminiferal faunas include small globorotaliids. Levels with abundant echinoid and mollusc re-



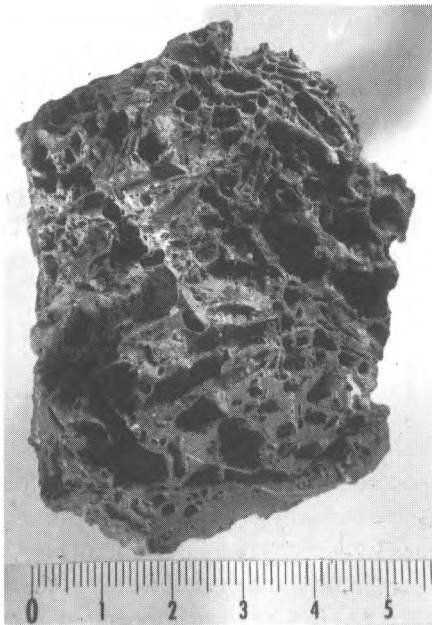
*Plate III.* Subfacies of Gypsum Member (below) and Upper Manco Limestone (above) (hammer for scale): a. Alabastrine gypsum with chickenwire structure (top of section 1); b. Thin-bedded alternations of pale dolomitic marl and limestone, overlain by selenitic gypsum with downward projecting cone (level 13–18, section 5); c. Calcitized gypsum bed with cones along lower contact (section 2, level 159); d, e, f. Typical subfacies of the Upper Manco Limestone (upper part of section 2). d. (from bottom to top): (A) Laminated marl with turbidite intercalations (below hammer); (B) thin-bedded to laminated dolomitic limestone; (C) medium-bedded vuggy limestone (above hammer); e. Several metres of thin-bedded laminated dolomitic limestone (facies B). Note slumping; f. 30 cm thick bed of vuggy limestone (facies C1) within thin-bedded dolomitic limestone (facies B).



(a)



(b)



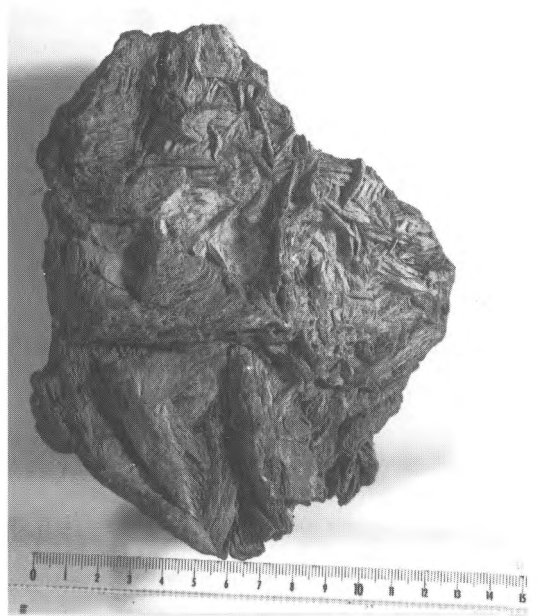
(c)



(d)



(e)



(f)

Table 2. Different diagenetic pathways to produce (low magnesium) calcite from an evaporitic sediment

Type	Name	Original material	Diagenetic agent	Final product
Early ('sedimentary')	A1 (Neev & Emery 1967, Friedman 1972)	'Basinal' gypsum	Sulfate-reducing bacteria + organic C	Calcite + H <sub>2</sub> S
	A2 (Decima et al. 1988)	'Marginal' aragonite	Meteoric water (+CO <sub>2</sub> )	Calcite + strontianite
Late ('alteration')	B1 Feely & Kulp 1957)	Massive gypsum & anhydrite	Sulfate-reducing bacteria + organic C	Calcite + S <sub>2</sub>
	B2 (West 1973)	Massive gypsum & anhydrite	Meteoric water + CO <sub>2</sub> (+ Sr <sup>2+</sup> )	Calcite + celestite

mains from the marginal oolitic limestone similarly record important marine incursions (Fig. 9B).

Periodic emergence and erosion of the marginal oolitic series, on the other hand, can probably be correlated with gypsum deposition in the basin centre (Esteban & Giner 1980, Dabrio et al. 1981). Emergence indicated by *Microcodium* at the brecciated top of oolitic intervals in the Barranco del Pino area (section 6) was the precursor to local fluvial-deltaic deposition recorded by thick siliclastic intercalations.

#### Late Messinian

The composition and sparseness of the fauna in the basal part of the Feos Formation indicate hypersaline or brackish conditions. Hypersalinity may well have been maintained through the reworking of Messinian evaporites (gypsum turbidites).

The composition of the clastic intercalations and the existence of hiatuses attest to repeated subaerial exposure and erosion in more external parts of the basin centre (Fig. 9C). The considerable fresh-water supply to the most central part of the basin, indicated by common brackish 'lago mare' faunas and intercalation of river-laid conglomerates along its margin reflect increasingly humid climatic conditions towards the end of the Feos deposition.

#### Origin of the gypsum-ghost limestones

The unfossiliferous nature, the narrow stratigraphic relation to massive gypsum beds, as much as the features they have in common with the latter which attest to the former presence of gypsum, all indicate that the gypsum-ghost limestones were originally deposited in a strongly evaporitic environment. The lateral transitions between these limestones and the gypsum can be explained by assuming either original 'sedimentary' facies transitions or later localized alteration of original gypsum beds. Since both, sedimentary facies transition and late alteration of gypsum, can have two different modes, four 'mechanisms' can hypothetically explain the common rapid lateral substitution of Messinian massive gypsum beds by gypsum ghost-limestone in the Carboneras area (Table 2). Their composition of low-magnesium calcite, which is not the normal CaCO<sub>3</sub> phase in an evaporitic environment (Friedman 1972, Decima et al. 1988), indicates that the original sediment underwent some type of diagenesis.

#### 'Sedimentary' formation

The data on the original sedimentary environment and on the respective distribution of limestone and gypsum are used to evaluate whether environmen-

←

Plate IV. Sedimentary structures and microfacies of the Manco Limestone (cm-scales for rock samples): a. Laminated dolomitic limestone (facies B) with cellular structure (level 235, section 4); b. Thin section of laminated limestone with small gypsum crystals (as voids up to 2 mm), which distort laminations into wavy forms. Blackness due to manganese hydroxide (transitional between facies B and C1, section 2, level 156); c. Heavily vugged limestone (facies C1) with fine-grained breccia in base (section 4, level 228); d. Thin section from bottom of sample of Plate IVc, showing brecciated vuggy limestone in the base. Largest diameter of vugs (light) is 7 mm; e. Limestone breccia (facies C2) with Mn-hydroxide coatings. (section 3, level 84A); f. Coalescent large pseudomorphs of calcite after gypsum (section 2, level 159).

tal conditions originally promoted an early formation of gypsum-ghost limestone and, if so, to attempt to discriminate between the two 'sedimentary' mechanisms (A1 and A2 of Table 2).

The respective distribution of Manco Limestone and Gypsum Member within the Yesares Formation is rather irregular (Figs 1, 9C). Facies distribution within the Yesares Formation and in the under- and overlying rock units suggests that, the Upper Manco Limestone, in particular, represents a relatively deeper sedimentary environment than the Gypsum: (1) it is concentrated in the eastern-central part of the basin, where the underlying Abad Marl reaches its greatest thickness and predominantly consists of fine-grained sediment (Figs 1–3, 9) and (2), it is overlain by a thick, predominantly fine-grained, Feos Formation, while the Gypsum Member in the western-central area is covered by a Feos series in which continental red-bed and fluviatile facies dominate (Fig. 9C). There are no erosional surfaces and no unambiguous shallow-water indicators in the Manco Limestone. Gypsum ghost limestones from its upper part are typically interbedded with marine marls and, locally, with turbidites and slumps (Arroyo Gafares).

The relative importance of reducing conditions during the formation of the original sediment of the vuggy limestone type (facies C1) becomes most apparent when its vertical facies relations are considered. Oxygen-deficiency is already indicated by the preservation of lamination, oligotypical microfaunas and an abundance of microscopically authigenic gypsum in the underlying Upper Abad Marl and in similar intercalated marls (facies A) of the Manco Limestone itself. The dolomitic intervals at the top of the Abad Marl and within the Manco Limestone (facies B), to which facies C1 is most closely associated (Figs 3A, 4, 7; Plate IIIId, f, IVb), probably reflect highly anoxic conditions, as early diagenetic formation of dolomite commonly is accompanied by bacterial sulphate reduction (Friedman 1966, Kelts & McKenzie 1982, Patterson & Kinsman 1982). McKenzie et al. (1979) and Bellanca & Neri (1986) provided stable isotope evidence of anoxic conditions during the formation of dolomitic intervals at the top of the Tripoli Formation and within the Calcare di Base from the Messinian of

Sicily. These formations are equivalent in facies and stratigraphic position to the top of the Abad Marl and Manco Limestone, respectively (Fig. 8).

The stratigraphic setting of the gypsum ghost limestones, in particular those from the Upper Manco Limestone, thus is highly suggestive of an original formation in a relatively deeper, anoxic part of the basin, a prerequisite for 'mechanism A1', and early bacterial sulfate reduction probably was a first instrument in producing limestone (Fig. 9B).

#### *Later alteration*

A Late bacterial transformation of gypsum (mechanism B1) is considered less likely to have produced the gypsum-ghost limestones of Carboneras, since they lack characteristic native sulphur and strontium depletion in  $\delta^{13}\text{C}$  (Table 1; Dessau et al. 1962, Decima et al. 1988, Pierre & Rouchy 1988).

A later fresh-water diagenetic and dissolution stage for the vuggy limestones (facies C1) is indicated by the common voids moulding gypsum crystals, the occurrence of fine-grained dissolution-collapse breccias and the presence of celestite. Fresh water alteration of massive sulfate rock is considered to have been the essential mechanism (B2 of Table 2) to produce the thick-bedded coarse limestone breccias (facies C2) of the Lower Manco Member. Massive replacement of gypsum by limestone is documented by coalescing pseudomorphs of calcite after gypsum (Plate IVf) and in cone-shaped projections, at the base of thick Manco limestone beds, that are identical to features at the base of gypsum beds (Plate IIa; IIIb, c). Accessory lutecite is a further strong indicator for 'vanished evaporites' (Munier Chalmas 1890, Folk & Pitman 1971).

The extent of coarse limestone breccia of the Manco Member is closely related to the nodular alabastrine gypsum subfacies of the Gypsum Member. Both are restricted to the base of the Yesares Formation and in a number of localities nodular alabastrine gypsum is found as intermediate in the rapid, lateral substitution of massive selenitic gypsum by thickly-bedded limestone breccia (e.g. eastern end of the Collado del Manco: Plate Ib). Alabastrine gypsum is commonly considered a product of fresh-water diagenesis of nodular anhydrite (e.g. Shearman 1966, Toulemont 1980).

The uniform, strongly negative oxygen-isotope values of limestones from the Lower Manco Member, lastly (Table 1), support a fresh-water diagenetic origin for the gypsum-ghost breccias.

Although paleontologic data do not exclude temporary brackish-water conditions in the basin centre during Yesares Formation deposition (Van de Poel, in prep.), a fresh-water diagenetic stage is most easily envisaged in the latest part of the Messinian, when there is ample evidence of abundant meteoric water in the centre of the basin and sub-aerial exposed Yesares beds in its somewhat more external parts (Fig. 9C). Major dissolution collapse of the entire Yesares Formation of the centre of the adjacent Agua Amarga Basin probably took place at this time (Van de Poel et al. 1984).

## Conclusion

The formation of the gypsum-ghost limestones of the Carboneras area was a multi-stage process. Most of the gypsum ghost limestones originally formed as gypsum in the central part of the basin. During periods of low oxygen, sulphate-reducing bacteria rapidly transformed thinner gypsum beds, as especially developed in the upper part of the Yesares Formation, into predominantly carbonatic sediment. In a later stage, substantial dissolution and alteration of gypsum took place when the porous rocks of the Yesares Formation served as fresh-water reservoirs.

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