

Marine and continental water contributions to a hypersaline basin using diatom ecology, sedimentology and stable isotopes: an example in the Late Miocene of the Mediterranean (Hellin Basin, southern Spain)

S. Servant-Vildary^a, J. M. Rouchy^b, C. Pierre^d and A. Foucault^c

^{a,b,c}Museum National d'Histoire Naturelle (^aO.R.S.T.O.M., C.N.R.S. UA 1209), Laboratoire de Géologie, 43 rue Buffon, 75005 Paris, France

^dC.N.R.S. UA 388, Université P. et M. Curie, Département de Géologie dynamique, 4 Place Jussieu, 75252 Paris Cedex 05, France

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ABSTRACT

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A multidisciplinary approach including diatom ecology, petrography and stable isotopes of carbonates and sulfates is applied to reconstruct the conditions of evaporitic deposition in the Hellin Basin. The Hellin Basin is one of many similar restricted basins that evolved in this region just after the emplacement of the Betic thrust complex. These studies show that continental conditions prevailed in a restricted shallow basin during the evaporitic deposition. Episodic marine flooding, however, is indicated by diatom assemblages of diatomite layers intercalated in thick continental gypsum deposits which represent the last stage of concentration, controlled by arid climate.

Isotope data indicate a continental origin of the sulfate ions, which were probably supplied to the basin by continental waters enriched in sulfates from the weathered Triassic evaporites. So, during this time, the basin evolved into a continental drainage system with hypersaline magnesian conditions (dolomite dominant). Aqueous sulfate from Triassic sources is affected by bacterial sulfate reduction, but was further reoxydized as sulfate in oxydized fresh water. The importance of sulfate bacterial reduction indicates abundant organic matter and high organic productivity; it indicates anoxic condition in the bottom sediment and possible episodes of water stagnation.

This total sedimentologic and diagenetic picture, together with excellent paleoenvironmental (diatom) control reflects the complexity of the basin filling within the intramontane basins of the Betic Chain.

Introduction

Basically, two major conditions control the environmental changes which lead to hypersaline conditions: (1) the restriction of the basin from the open sea reduces the marine water inputs; (2) the aridity of climate causes the severe deficit in the hydrological balance. The dissolved salts can be brought either by marine waters or by continental waters containing the weathering products of

outcropping rocks, sometimes older evaporites. In fossil evaporites, the relationships between marine and continental contribution is often difficult to establish, because: (1) lack of accuracy in paleogeographical reconstruction; (2) biological remains are scarce, absent or ubiquitous; (3) geochemical records may be modified by diagenesis. Therefore, a multidisciplinary approach using diatom ecology, sedimentology and stable isotopes may be useful to resolve the problem. This was

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applied to the reconstruction of environmental changes in the Hellin basin which is a perimediterranean hypersaline basin of Late Miocene age.

The basin of Hellin is one of the intramontane basins located in the external part of the Betic chains in Southern Spain (Fig.1). Their sedimentary fill generally includes marls, diatomites and gypsum with local sulfur concentrations. The sediments were considered as deposited under lacustrine conditions with hypersaline episodes which gave the gypsum beds outcropping near the village of Las Minas. A more detailed study of these gypsum deposits revealed the presence of marine diatoms in thin intercalations of diatomites thus leading to a revision of paleoenvironmental data and a reinterpretation of the basin fill.

The approach appears to be very useful to reconstruct the history of the water composition in such a paralic domain, generally materialized by ubiquitous sedimentological and biological characters.

Geological setting

In the external part of the Betic chains, compressive tectonics produced the building of

Betic nappes and drastic paleogeographic changes during the Cenozoic (Durand-Delga and Fontboté, 1980). After these movements, a complex system of unconformable intramontane basins were formed in the Prebetic subautochthonous domain, in front of the Subbetic thrust. The Hellin basin is one of these small Betic basins whose morphology appears to be controlled by the Jura style pattern of the underlying strata folding (Foucault et al., 1987).

In the Hellin basin successive events produced the transition from open marine conditions that prevailed up to the Middle Tortonian to the lacustrine conditions in the Late Tortonian (Figs.1 and 2).

The last open-marine sediments are of Middle Tortonian age, they cover the nappes and the subautochthonous folded foreland and extended from the Calasparra basin to the north over the Hellin area. These sediments are characterized by algal limestones and foraminiferal-marls called "Marine Sequence" by Calvo et al. (1978); recently diatomites from Cobatillas have been found in the upper part of this marine sequence by Foucault et al. (1987) and studied by Monjanel (1987).

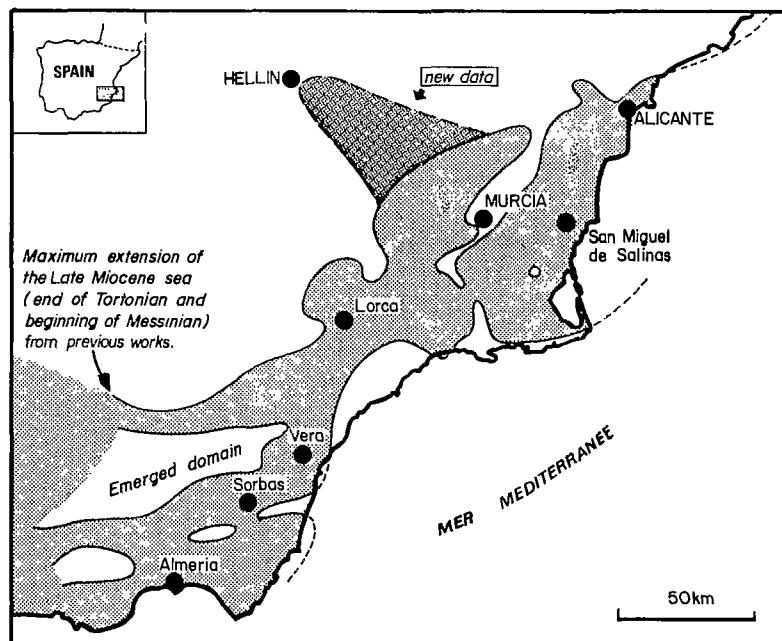


Fig.1. Location of the study area and paleogeography during the Late Miocene.

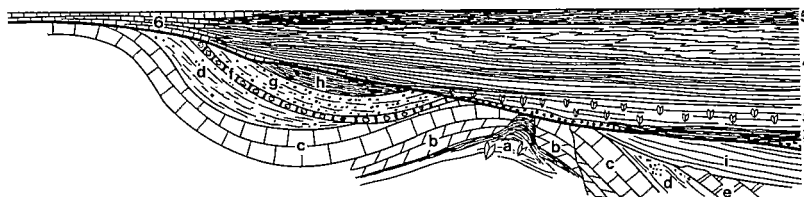


Fig. 2. Schematic structural relations between lacustrine and marine deposits and their substratum during the Late Miocene in the Hellin basin (not at scale).

Pre-tectonic series: *a* = Keuper evaporites. *b* = Lias–Dogger dolomites. *c* = Dogger–Malm limestones. *d* = Utrillas Member, sands and marls. *e* = Late Cretaceous Miliolites limestones.

Cobatillas series: *f* = Miocene red algae limestones. *g* = Miocene marls. *h* = Late Middle Miocene marine diatomites.

Calasparra series: *i* = Late Miocene marine marls.

Hellin Formations: 1 = Conglomerates and sandstones: Cenajo Formation. 2 = Calcareous marls: Casanueva Formation. 3 = Gypsum and marls: Las Minas Formation. 4 = Limestones and marls: Tesorico Formation. 5 = Lacustrine diatomites: Rambla Sorda Formation. 6 = Bedded limestones: Carasquilla Formation.

At the end of the late–middle Tortonian, a structural event separated the Hellin basin from the Calasparra one and reduced communication with the open sea. Thick gypsum/carbonate deposits with thin diatomitic intercalations, called the Las Minas de Hellin Formation, then took place.

A new paleogeographic reorganization inferred from a 40-m thick slumped interval leads to the change into stable freshwater conditions represented by massive diatomites which laterally grade to layered continental limestones (Servant-Vildary, 1986).

Several Triassic salt-domes intrude the sedimentary column around the Hellin basin. Near Cenajo the vertical setting of the Miocene sediments against the diapiric wall indicates that the uplift of these Triassic evaporites continued recently.

Sedimentology of the Las Minas Formation

The Las Minas Formation is about 80 m thick. It is mainly composed of alternating meter to decimeter-thick gypsum beds and marls. Only the 30 m middle part of the Formation were studied, because they contain some diatomitic layers. A native sulfur ore-body is present within the evaporitic interval.

Gypsum

The beds of gypsum whose thickness can reach several meters include various lithofacies which

result from syndepositional or early diagenetic origin as well as of secondary origin from replacement of carbonates.

The syndepositional gypsum is represented by aggregates of centimeter-to decimeter-sized crystals nearly perpendicular to the bedding planes (selenite facies) and by finely laminated gypsum resulting from free crystallization on the basin floor or within the brines body. These mechanisms indicate episodic calcium sulfate saturation in the water body. Early diagenetic gypsum is composed of lenticular crystals which grew displacively in the dolomitic mudstone and appears often dissolved in the outcrops. Another syndepositional facies is represented by layers of gypsarenites with graded bedding and oblique layering.

The secondary gypsum includes various lithofacies replacing former carbonate sediments. Gypsum laminites are formed by replacement of mm-thick-laminated carbonates. Under the microscope, the laminations of the host-carbonate appear preserved as relicts into a mosaic of large gypsum crystals whose limits cut sharply the former structure. Fibrous gypsum (satin-spar) occurs as laminae, parallel to the initial layering or as veins. Another facies is represented by irregular areas of microcrystalline gypsum which invade the dolomitic mudstone around dissolved sulfur nodules. The development of these secondary gypsum is often associated with deformations, sometimes folding of the host sediments, probably diagenetically induced. Genesis of both types of

replacement gypsum is probably related to the late oxydation of native sulfur which produced sulfuric acid and dissolved the carbonates and crystallized authigenic sulfate.

Carbonates

The carbonates are characterized by the abundance of dolomite; calcite and aragonite are observed in the lower part of the formation. A few limestone layers however appear to be the result of calcite replacement after gypsum, a process related to bacterial sulfate-reduction that also leads to the formation of native sulfur deposits. Such processes indicate the episodic development of anoxic conditions in the organic-rich bottom sediments, and possibly stagnation in the water body itself.

Some centimeter to decimeter-thick layers of white powdery sediment with surficial crystalline efflorescences are composed of complex magnesium sulfate that are probably the result of the surficial weathering of former magnesium minerals. These components argue for the permanence of magnesium-rich waters in the basin.

Stable isotopes of gypsum and carbonates

Stable isotope analysis have been performed on the gypsum and carbonate fractions (dolomite) of the diatomite intercalations. The aim of this geochemical study was primarily to verify whether or not significant amounts of marine water was supplied to the basin during deposition of the Las Minas de Hellin Formation.

Isotope composition of gypsum

The oxygen and sulfur isotope compositions of gypsum directly reflect that of the aqueous sulfate in the solutions where gypsum precipitated. The $\delta^{18}\text{O}$ and $\delta^{34}\text{S}$ values of sulfate of marine waters are quite constant since the early Tertiary (Claypool et al., 1980). These values were different in the Mesozoic seas, especially during the Permo-Triassic period when massive deposition of evaporites and of sulfides changed the global sulfur mass-balance (Claypool et al., 1980). This explains why $\delta^{18}\text{O}$ and ^{34}S values of marine evaporites are commonly

considered as good stratigraphic markers. Furthermore, oxygen and sulfur isotope compositions of sulfate are also useful environmental tracers because they may discriminate between the marine and non-marine origin of sulfate evaporites.

In the Hellin Basin, the $\delta^{18}\text{O}$ (+1.0 to +25.9) and $\delta^{34}\text{S}$ (-9.5 to +19.3) values of gypsum are obviously out of the range of the δ -values measured for marine Tertiary gypsum (average $\delta^{18}\text{O} = +15 \pm 2$; $\delta^{34}\text{S} = +22 \pm 2$). These results exclude a possible influence of sea water sulfate in the aqueous sulfate reservoir of the basin.

The highest δ values ($+25.2 < \delta^{18}\text{O} < +25.9$; $+13.4 < \delta^{34}\text{S} < +19.3$) are measured in the lower part of the sequence. The $\delta^{34}\text{S}$ values strongly suggest that the sulfate ions of the solutions where gypsum precipitated had a probable Triassic origin (Fig.4). The precipitation of gypsum involves complex set of processes: (1) dissolution of outcropping old gypsum deposits by continental waters; (2) partial sulfate reduction of the sulfate solutions collected in the basin; (3) evaporation and crystallisation.

The lowest δ values ($+1.0 < \delta^{18}\text{O} < +1.2$; $-9.4 < \delta^{34}\text{S} < -9.2$) are measured in the uppermost layers of secondary laminated gypsum. These values are typical of sulfate produced by oxidation of reduced sulfur in continental waters. This gypsum thus represents the weathering product of the native sulfur, previously formed by bacterial reduction.

Isotope composition of carbonates

Dolomite, having a nearly stoichiometric composition is the carbonate fraction of the diatomitic layers, where 14 samples have been selected for stable isotope analysis.

The wide range of $\delta^{18}\text{O}$ values from +1.50 to +7.63 argues for important variations of the $\delta^{18}\text{O}$ values of the waters where these dolomites crystallized.

These isotopic variations may be explained by variable levels of evaporation of either a mixture of marine and continental waters, or of only continental waters. Comparison of these data with isotope composition of sedimentary dolomites of various location formed in either marine, mixed or continental environments (Fig.5) shows that at this

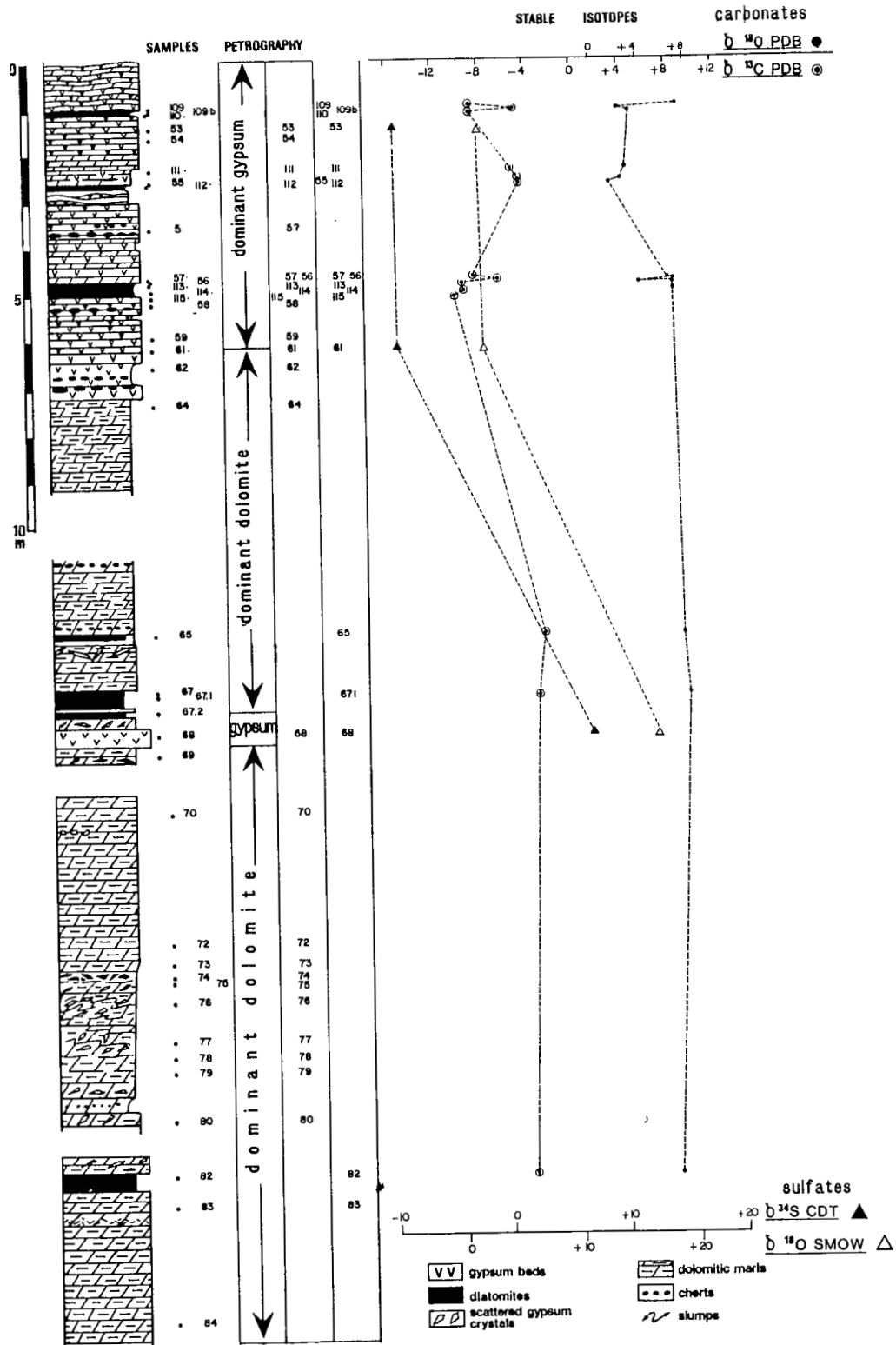


Fig.3. Las Minas Formation: lithostratigraphy, petrography and stable isotopes.

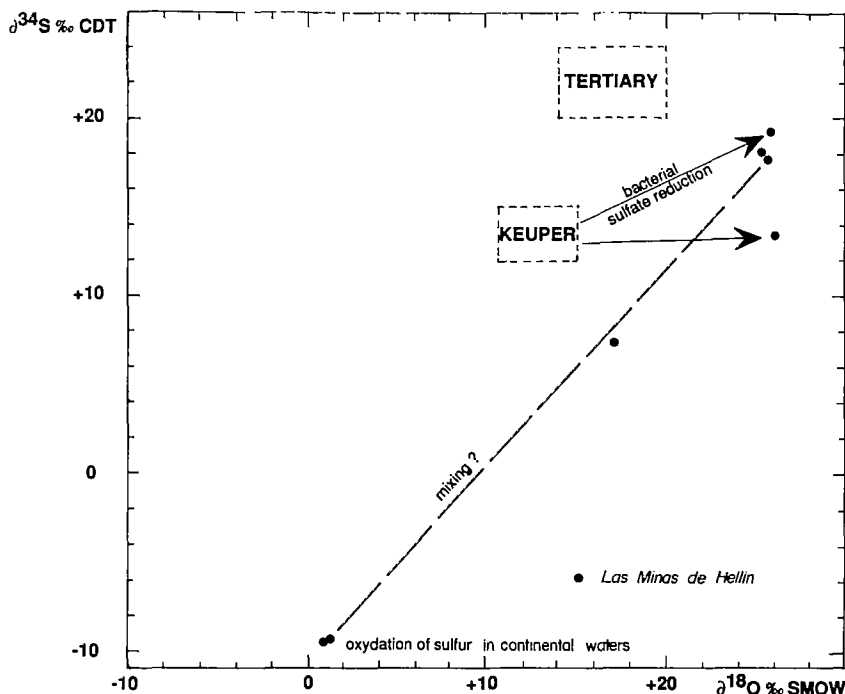


Fig. 4. Oxygen and sulfur isotope composition of gypsum from the Hellin basin. The average ranges of δ -values of marine evaporites of Tertiary and Keuper ages are reported for comparison. Black points indicate values measured in the Hellin basin.

stage of investigation it remains impossible to give by $\delta^{18}\text{O}$ content any discrimination between marine and non-marine evaporitic carbonates. A reasonable conclusion is that the water depth in the basin was shallow, which resulted in large and rapid $\delta^{18}\text{O}$ (i.e. mainly salinity) fluctuations.

The low $\delta^{13}\text{C}$ values (-10.29 to -2.47) of the dolomites are characteristic of restricted environments where high organic productivity combined with stagnation of waters produce ^{13}C -depleted CO_2 by bacterial metabolism of organic matter either by using dissolved oxygen or during sulfate reduction. Both processes have probably acted in the Hellin basin depending on whether waters were oxygenated or anoxic. The attendant increase of water alkalinity thus favored dolomite crystallization.

The diatom flora

Ecology

This part of the study gives information on the aquatic environment which episodically inter-

rupted gypsum deposition, and tries to identify the origin of the waters. Short duration and episodic water stagnations are recorded by the development of fine diatomitic levels (see Fig.3) which contain abundant diatom remains under free or aggregate form. The populations of these deposits are mostly mono or paucispecific (Fig.29, 31). Some aggregates are composed of well-preserved frustules (*Berkeleya*, Fig.31), (*Nitzschia*, Fig.37) and some of very eroded frustules (*Brachysira*, Fig.29). Most of them are consolidated by the microfilaments of marine, planktonic Chrysophytes (Fig.31, 35, 36).

Taxonomic identifications were done on 12 samples. Precise counts were not possible because the aggregates are so resistant that they were not separable, even by strong mechanical and chemical attack. Semi-quantitative estimations are thus used, assigning numbers 1–5 for very scarce, scarce, frequent, abundant and very abundant species. The species are divided into 3 ecological groups, referred by water salinity and using Ehrlich's classification (1975) with special references to water origin, marine or continental (Table 1).

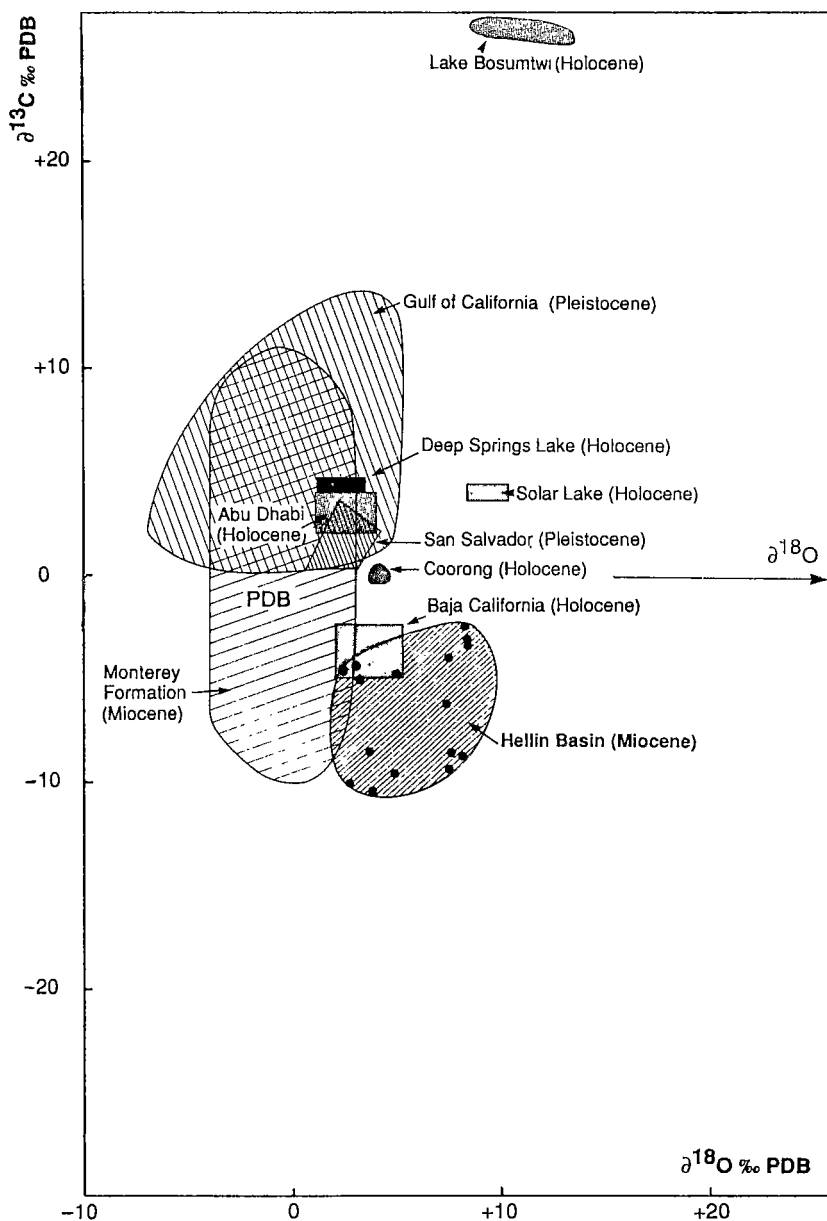


Fig.5. Oxygen and carbon isotope composition of dolomite from the Hellin basin. Comparison with isotope data on sedimentary dolomites of various locations. *Deep Springs Lake*: Clayton et al. (1968); *Abu Dhabi*: McKenzie (1981); *San Salvador*: Supko (1977); *Baja California*: Pierre et al. (1984); *Solar Lake*: Aharon et al. (1977); *Lake Bosumtwi*: Talbot and Kelts (1986); *Monterey Formation*: Hennessy and Knauth (1985); *Coorong*: Degens (1967).

(1) *Marine, poly and α-mesohalobous*

The polyhalobous (30–35 gl^{-1}) and α -mesohalobous species (10–30 gl^{-1}) are used for determining marine or diluted marine water inputs:

Actinocyclus ellipticus Grunow, *Actinoptychus senarius* (Ehrenberg) Ehrenberg, *Biddulphia tuomeyi* (Bailey) Roper (Figs.7, 8),

Campylodiscus innominatus Ross et Abdin, *Chaetoceros* cf. *holsaticus* Schütt (Fig.38), *C. radicans* Schütt, Choanoflagellates (Acanthoecaceae), (Fig.32), *Coscinodiscus* sp., *C. oscurus* Schmidt, *C. marginatus* Ehrenberg, *C. oculus-iridis* Ehrenberg, *Denticulopsis hustedtii* (Simonsen et Kanaya) Simonsen (Figs.13, 14), *Dimerogramma minor* (Gregory) Ralfs, *Diploneis bombus* Ehrenberg, *D. lineata* (Donkin) Cleve, *D. mediterranea* (Grunow) Cleve, *D. sejuncta* (A. Schmidt) Jorgensen (Fig.23),

TABLE 1

Semi-quantitative abundance and number of species of different ecological diatom groups

Sample ¹	All diatoms ³				Poly.α Mesoh. ¹				Holoeryth. ⁵		Olig. ⁵	
	B+P		B	P	B+P		B		B		B	
	N ²	A ^{3a}	A ^{3b}	A ^{3b}	A ^{4a}	N ^{4b}	A ^{4c}	N ^{4d}	A ^{5a}	N ^{5b}	A ^{6a}	N ^{6b}
109b	11	26	14	11	19	8	11	5	7	3	0	0
110	15	27	21	6	12	6	14	3	14	8	1	1
111	3	3	3	0	2	2	2	2	1	1	0	0
112	15	30	26	4	16	7	12	5	14	8	0	0
57	6	8	7	1	3	2	2	1	5	4	0	0
113	20	35	28	7	17	9	15	7	18	11	0	0
114	15	33	24	9	19	9	11	6	14	6	0	0
115	9	16	10	6	13	6	7	4	3	3	0	0
65	24	44	31	13	22	13	4	4	22	11	0	0
67.1	33	76	65	11	40	10	19	6	40	21	3	2
67.2	6	14	14	0	1	1	1	1	13	5	0	0
82	21	47	37	10	14	7	2	2	28	13	5	1

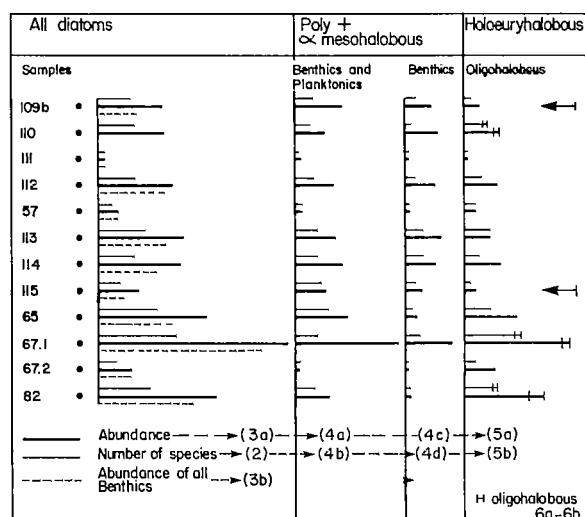
¹Samples.²Number of species.³Abundance: 3a = Semi-quantitative evaluation of total abundance of frustules in every sample, obtained by summing: Very abundant (5), abundant (4), frequent (3), scarce (2), very scarce (1); 3b = abundance of benthics; 3c = abundance of planktonics.⁴Polyhalobous-α mesohalobous "Marine"; 4a = abundance; 4b = number of species; 4c = abundance of benthics; 4d = number of benthic species.⁵Holoerythahalobous: 5a = abundance; 5b = number of species.⁶Oligahalobous "Freshwater"; 6a = Abundance; 6b = number of species.

Fig. 6. Distribution of the different ecological groups of diatoms in the upper part of the Las Minas Formation. Abundance and number of species of all diatoms (column 2); of all poly-α-mesohalobous (column 3); of benthic poly-α-mesohalobous (column 4); of all holoerythahalobous + oligohalobous (column 5).

Entomoneis cf. paludosa (W. Smith) Reimer, *Epithemia* sp., *Grammatophora oceanica* Ehrenberg (Fig.17), *Hemidiscus cuneiformis* Wallich, *Mastogloia cf. depressa* Hustedt (Figs.46–48), *Navicula palpebralis* de Brebisson, *Navicula directa* (W. Smith) Ralfs, *Nitzschia fossilis* (Frenguelli) Kanaya, *Nitzschia cf. porteri* Frenguelli, *Paralia sulcata* (Ehrenberg) Cleve (Fig.12), *Thalassionema nitzschioides* Hustedt (Fig.9), *Triceratium balearicum* Cleve et Grunow (Figs.10, 11), *Triceratium laetum* Pantocsek.

(2) Holoerythahalobous species

The holoerythahalobous species are able to adapt to a wide range of salinity from 0.5 to 200 g l⁻¹. These species cannot be used either as indicators of salinity nor as indicators of marine inputs, except the group composed of species which are commonly observed in marine habitats: *Berkeleya scopulorum* (de Brebisson) Cox (Fig.18, 19, 20, 21, 31), *Cocconeis scutellum* Ehrenberg (Fig.27), *Pleurosigma* sp., *Surirella gemma* (Ehrenberg) Kützing, *Surirella striatula* Turpin, *Synedra formosa* Hantzsch. The second group contains species which may develop in marine and/or continental

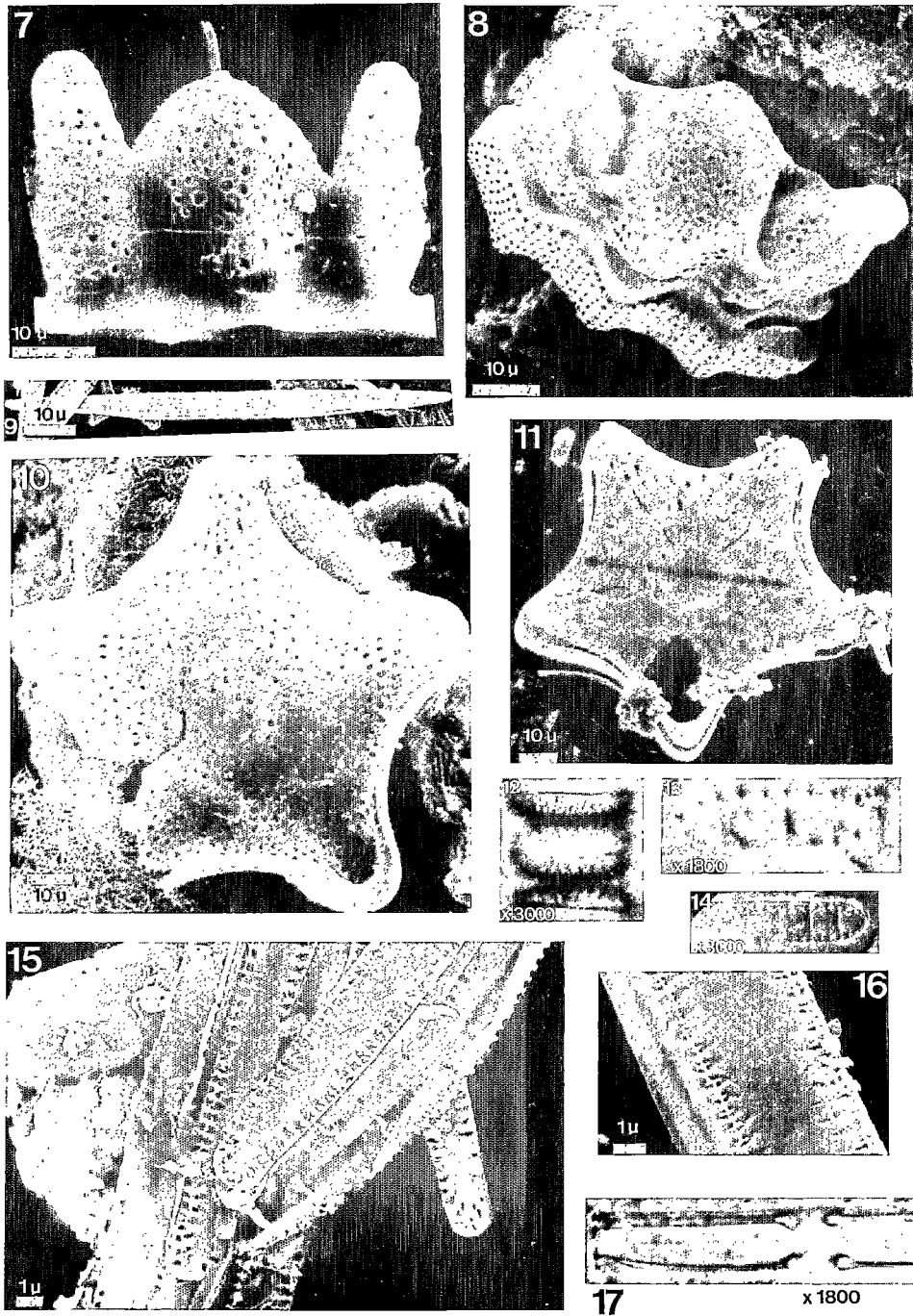


Fig.7, 8. *Biddulphia tuomeyi*.

Fig.9. *Thalassionema nitzschioides*.

Fig.10, 11. *Triceratium balearicum*.

Fig.12. *Paralia sulcata*.

Fig.13, 14. *Denticulopsis hustedii*.

Fig.15, 16. *Thalassionema nitzschioides*.

Fig.17. *Grammatophora oceanica*.

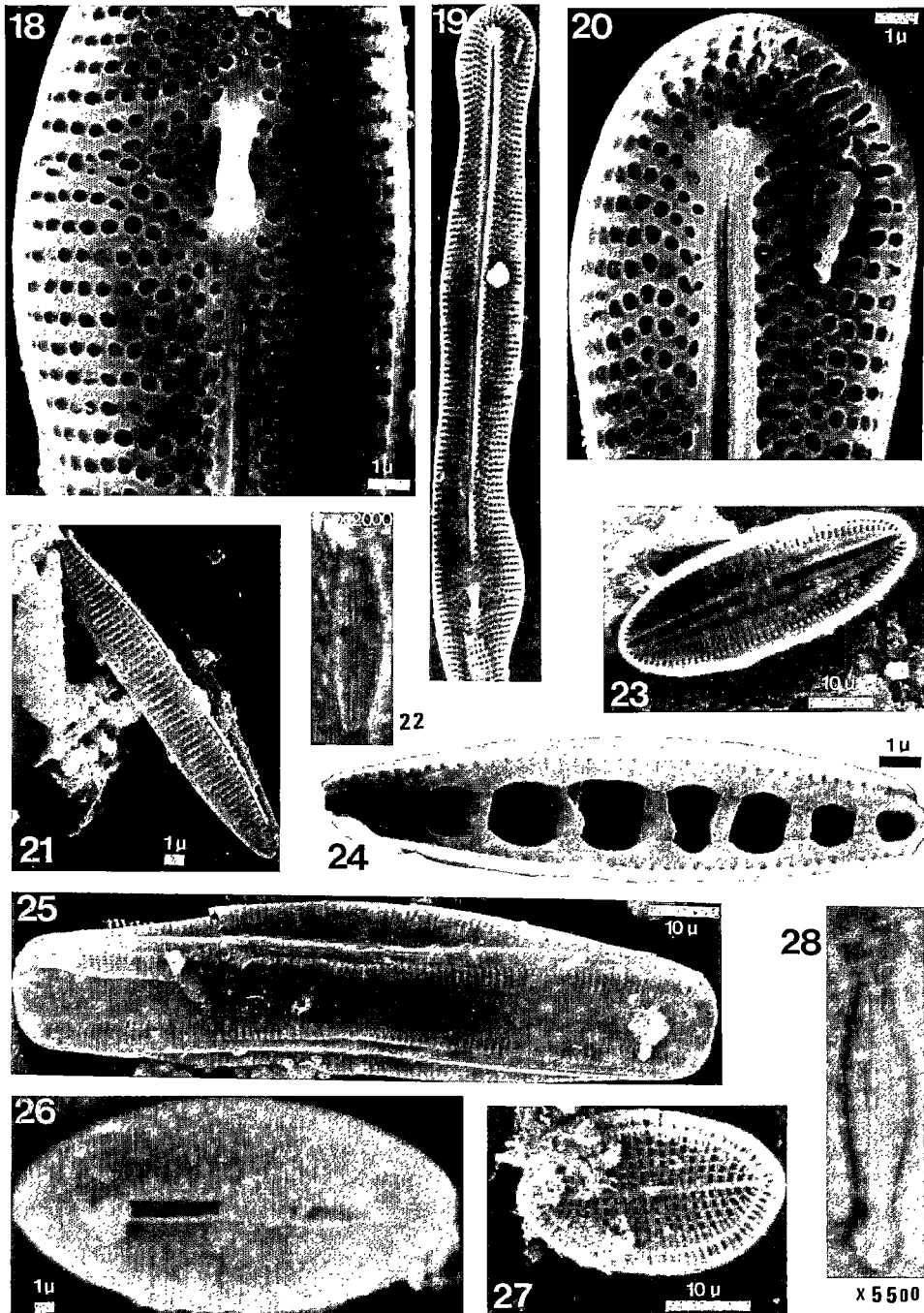


Fig.18–20. *Berkeleya scopulorum*.
 Fig.21. *Nitzschia* cf. *quadrangula*.
 Fig.22. *Navicula mutica intermedia*.
 Fig.23. *Diploneis sejuncta*.
 Fig.24. *Denticula thermalis*.
 Fig.25. *Amphora angusta*.
 Fig.26. *Dimitiada saccula*.
 Fig.27. *Cocconeis scutellum*.
 Fig.28. *Anomoeoneis* cf. *vitrea*.

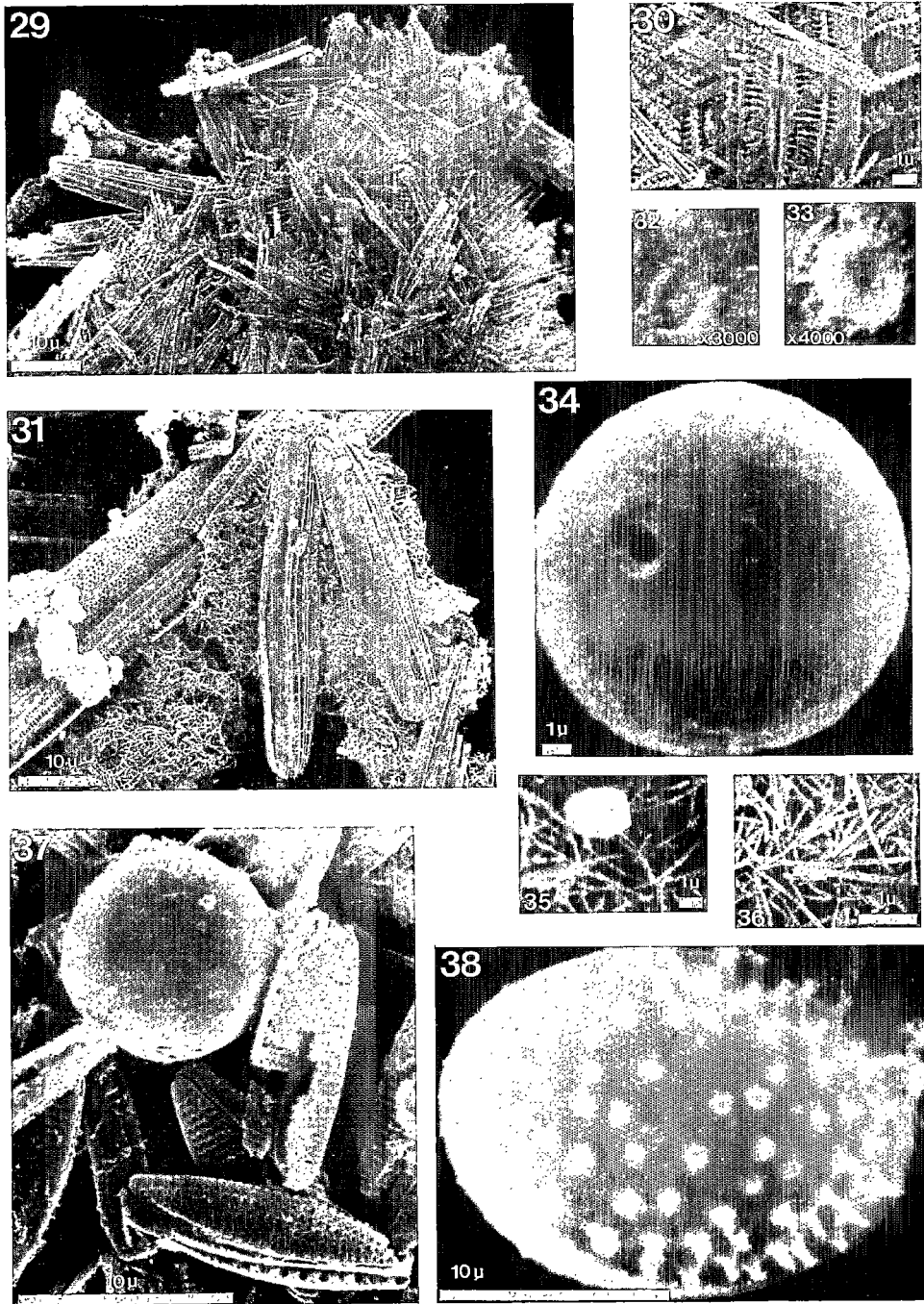


Fig.29. Aggregates of *Brachysira aponina*.

Fig.30. Detail of an eroded *B. aponina*.

Fig.31. Aggregates of *Brachysira aponina*, *Berkeleya scopulorum* and filaments of Chrysophyta.

Fig.32. Cell and collar of Chrysophyta, Class Craspedomonadophyceae, Family Acanthoecaceae, all marine.

Fig.33, 34. Cysts of Chrysophyta, Class Archaeomonadaceae, all marine.

Fig.35, 36. Chrysophyta, unknown cell and aggregates of silica fibers of lorica of Acanthoecaceae.

Fig.37. Aggregates of Archaeomonadaceae cysts and *Nitzschia quadrangulata*.

Fig.38. *Chaetoceros holsaticus*.

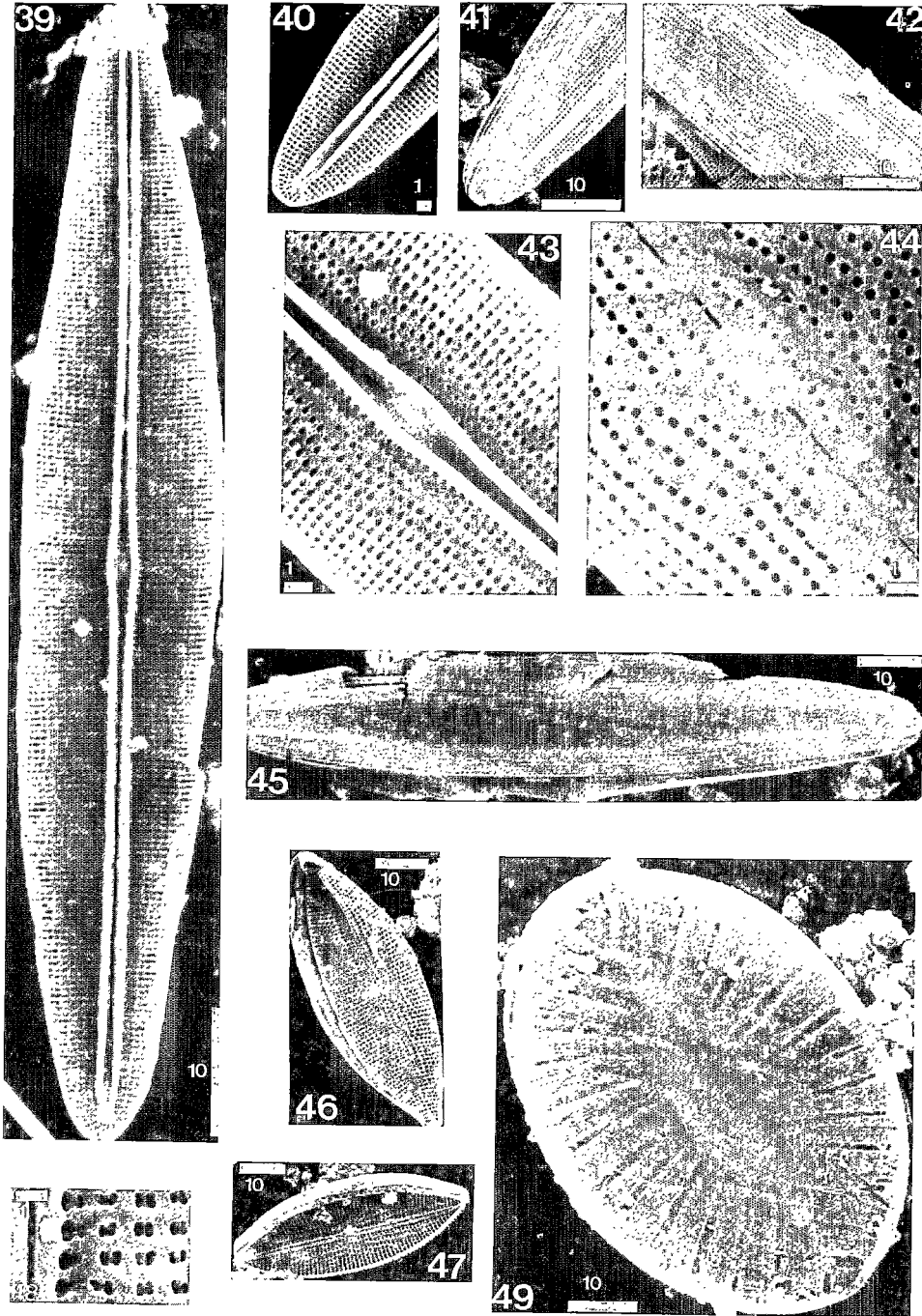


Fig.39-45. *Frustulia interposita*.
Fig.46-48. *Mastoglia cf. depressa*.
Fig.49. *Surirella ovata* var.?

water. These species cannot give precise information on salinity but most of them are located in diatomitic levels closely related to gypsum deposits without any sedimentary discontinuity. Let us assume, therefore, that diatoms were living in a concentrated environment. This assumption is reinforced by the fact that some of them are very common in hypersaline waters: *Frustulia interposita* (Fig.39 to 45) considered as living in low mineral content was found by J. John in 70 g l⁻¹ salinity (personal communication). Noël (1982, 1984) found *Surirella fastuosa* in 73 g l⁻¹, *Surirella striatula* between 64 to 102 g l⁻¹, *Navicula cincta* in 64 g l⁻¹ and *Brachysira aponina* in 132 g l⁻¹, whereas Servant-Vildary (in press) found this species in 13 to 45 g l⁻¹.

Amphora angusta Gregory (Fig.25), *Amphora veneta* Kützing, *Brachysira aponina* (Kützing) Round and Mann (Figs.29–31), *Cymbella pusilla* Grunow, *Dimitiada saccula* Hajos (Fig.26), *Cocconeis placentula lineata* (Ehrenberg) Cleve, *Diploneis smithii* (de Brebisson) Cleve, *Denticula thermalis* Kützing (Fig.24), *Frustulia interposita* (Lewis) Cleve (Figs.39, 45), *Mastogloia elliptica* (Agardh) Cleve, *Mastogloia smithii* Thwaites, *Navicula cincta* (Ehrenberg) Ralfs, *Navicula mutica intermedia* Hustedt (Fig.22), *Nitzschia cf. quadrangula* (Kützing) Lange-Bertalot (Fig.37), *Nitzschia hungarica* Grunow, *Nitzschia recta* Hantzsch, *Nitzschia sigma* (Kützing) W. Smith, *Nitzschia granulata* Grunow, *Nitzschia punctata* (W. Smith) Grunow, *Rhopalodia gibberula* (Ehrenberg) O. Muller, *Rhopalodia musculus* (Kützing) O. Muller, *Surirella fastuosa* (Ehrenberg) Kützing, *Surirella ovata* Kützing (Fig.49).

(3) The freshwater group

This is composed by only two species which seem to be true freshwater and by a third small one, frequent in sample 82, temporarily assigned to *Anomoeoneis vitrea* (Kobayasi and Yoshida, 1984), although it presents too rostrated extremities.

Anomoeoneis cf. vitrea (Fig.28), *Fragilaria* sp., *Rhopalodia gibba* (Ehrenberg) O. Muller.

Paleoenvironmental reconstructions

Although precise indications about paleosalinities cannot be furnished because of the wide range of adaptation for 29 of the 62 species, the diatom flora indicates unstable conditions fluctuating between true marine and diluted or concentrated waters. After stating the observation that there was an admixture of at least two ecologically different

floras, it is now necessary to diagnose which of the floras must be regarded as autochthonous since the knowledge of the land–sea boundaries during the past is our main problem. In view of an apparent mixture of “marine” and “saline” species in the diatomitic intervals, let us reconsider the paleogeographical setting of this area.

In the sediments, biocoenosis and thanathocoenosis determinations for mixed floras, cannot be reasonably resolved using living and dead frustules as in modern environments. Simonsen (1969) demonstrated, in an example taken in the Amazon river, that if the number of all the species to a given class of salinity is only taken into account, we can reach false conclusions. “The only method to distinguish between allochthonous and autochthonous components is to separate and use only the benthic forms” which are not so easily transported as the planktonic ones.

Habitats (Fig.6, left, Table 1: columns 3a, 3b, 3c).

Benthic species (3b) are more abundant than planktonic ones (3c) for each sample; thus indicating that most of the samples were deposited in very shallow water.

Water origin

— When the *abundance* of marine species (4a) is compared with the abundance of marine and/or non marine species (5a) + the freshwater species (6a), all being benthic or epiphytic, it appears that the marine diatoms slightly dominate in samples 109b, 111, 112, 114, 115 and if we compare the abundance of only the benthic marine species (4c) with group 5a + 6a, the first one dominates only in samples 109b, 111 and 115 (samples 112 and 114 are now not included). *Finally only the samples 109b and 115 and 111 can be considered as containing autochthonous marine flora.*

— When the *number of species* of the marine group (4b) is compared to 5b + 6b, it appears that samples 109b, 111, 115, 65 may be considered as essentially deposited in marine conditions; but if we consider only the benthic species (4d), *only samples 109b, 115 and 111 may be considered as representing marine inputs.*

These results demonstrate that, in this case,

abundance and number of benthic species give the same results and may be used as markers for possible non reworked diatoms.

— In the other samples, ubiquitous diatoms are dominant and we can suppose that they indicate a shallow isolated basin subjected to rapid changes of salinity of a water whose origin can be marine or continental.

The diatom assemblages observed in this study, indicate a shallow basin connected to the open sea during episodic stages with short steady marine conditions (samples 109b, 111 and 115), then rapidly subjected to evaporation and concentration in a domain, which prior to this study, was as wholly continental (Fig.1).

Chronology

Chronological markers are scarce, perhaps due to ecological exclusion. The rare presence of *Denticulopsis hustedtii* (sample 82), *Actinocyclus ellipticus* (samples 65, 110, 109), *Hemidiscus cuneiformis* (sample 65), *Nitzschia porteri* (sample 115), *Nitzschia fossilis* (sample 65) and perhaps of *N. praereinholdii* (only one specimen in sample 67.2) and the absence of *Nitzschia miocenica*, suggest that the base of the studied interval belongs to the Unitary Association 3 corresponding to the *Nitzschia porteri* zone, sub-zone A of Barron (1985) and Burckle (1972); the middle and the top belongs to Unitary association 2, *Nitzschia porteri* zone, sub-zone B, dated around 6.5 Ma in Monjanel (1987). The age of the studied interval could be included between 7.5 and 6.5 Ma. The marls (Tesorico Formation) overlying the Las Minas de Hellin Formation are related to the Mammal zone MN 13 of upper Turolian (Bellon et al., 1981).

We also note the presence of a brackish continental fossil diatom *Dimitiada saccula*, found by Hajos (1974) in the Sarmatian deposits of Hungary.

Conclusions

The previous geological studies (Calvo et al., 1978) had proven that the gypsum was included in a continental series: stable isotope analysis confirm its continental origin. However, the diatom flora

composed of rather diversified "marine" flora indicates that sporadic connections with the open sea might have taken place, at least during episodes of diatomite deposition.

The field examination revealed that the intra-Tortonian tectonic event led to the break-up of a prior marine setting leaving the Hellin basin as isolated and subjected to predominantly continental conditions. Nevertheless, the composition of the diatom flora shows undoubtedly that typical marine conditions were episodically reestablished in the basin.

The isotopic composition of carbonates suggests deposition in a continental, shallow water basin subjected to rapid concentration of solutions during dolomite crystallization, evolving toward gypsum deposition.

The isotopic composition of the gypsum excludes a marine origin for most of the sulfate ions, which were supplied to the basin by continental waters enriched in sulfates by the weathering of Triassic evaporites. Similar processes have been identified in the Granada basin, an other Late Miocene depression of the Betic domain (Rouchy and Pierre, 1979).

The aqueous sulfate was subjected to the effects of bacterial reduction producing native sulfur as a byproduct of the reaction. This reduced sulfur might be reoxydized as sulfate in oxidizing fresh water. The bacterial reduction of sulfate occurring at a large scale in the basin, was favored by the abundance of organic matter and by episodic development of anoxic conditions. This process caused increasing water alkalinities, which combined with high Mg^{2+} concentration apparently promoted dolomite formation.

The Hellin basin was thus a restricted paralic area occasionally flooded by marine incursions. During arid evaporitic periods, this area evolved with a continental drainage basin under highly saline and magnesian conditions. Additionally, episodic anoxic conditions in the bottom sediments and possibly stagnant waters developed.

Finally, input of marine waters into the predominantly continental basin show that the area was located not far from the limits of the open sea that was considered until now about 100 km southwards. Such a situation prevailed up to a new

paleogeographical event that produced the complete isolation of the basin and the installation of stable fresh water conditions documented by the Rambla Sorda Diatomite Formation which overlies the Las Minas de Hellin Formation.

This study emphasizes the complexity of the hydrological parameters in an hypersaline basin. Although marine waters episodically entered the basin, they were not the source for the sulfate of the brines; the dissolved salts were carried by continental waters which dissolved older evaporitic deposits.

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