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The deep record of the Messinian salinity crisis: Evidence of a non-desiccated Mediterranean Sea

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Abstract

This research is focused on a complete reexamination of the evaporite facies present in all the cores that cut through the topmost deposits of the Messinian salinity crisis lying below the floor of the Mediterranean Sea (DSDP Legs 13 and 42A, ODP Legs 107 and 161). This review suggests that the uppermost evaporite units in both western and eastern deep Mediterranean basins consist mainly of clastic (gypsrudite, gypsarenite and gypsiltite) and fully subaqueous deposits (laminar gypsum, selenite and cumulate halite) that are partially affected by burial anhydritization and tectonic-induced recrystallization. No unequivocal evidence of shallow water or even supratidal (sabkha) deposition is in evidence, suggesting that at the very last phase of the salinity crisis the Mediterranean Sea did not experience desiccation, but that deposition took place under permanent subaqueous conditions.

Keywords: ODP; DSDP; Messinian salinity crisis; Evaporites; Mediterranean Sea

1 Introduction

More than 40 years have passed since the discovery of the evaporite giants buried below the Mediterranean floor and the enunciation of the Messinian paradigm claiming for the deep desiccation of the Mediterranean (Hsü et al., 1973a,b). The formulation of the “deep basin shallow water basin” was based on three main points: i) the recognition of very deep water deposits before and after the evaporites suggesting the presence of a deep basin well before the onset of the salinity crisis; ii) the widespread erosional features along the margin of the Mediterranean that were supposed to be subaerially exposed during the deep desiccation iii) the recovery of evaporitic facies in the uppermost portion of the thick Messinian evaporite unit that have been interpreted as supratidal deposits accumulated in a sabkha environment.

The study of the Messinian salinity crisis in the Mediterranean has moved a considerable step forward in the last decade. The debate on the origin and evolution of the crisis is still an hot topic (see Rouchy and Caruso, 2006 and Roveri et al., 2014a, for a summary of the controversy), but a reliable stratigraphic framework largely shared by the scientific community is now available as a basis for discussion (CIESM, 2008; Roveri et al., 2014a) and the onshore relationships between shallow and relatively deep evaporite facies have been largely clarified (Manzi et al., 2007, Roveri et al., 2008).

The most important problem in understanding the salinity crisis is that the largest volume of the giant evaporite deposit lies unexamined beneath the floor of the Mediterranean. This large portion of the sedimentary products of the salinity crisis was sampled only for several meters by a few cores drilled in the '70s and '90s. The decision to limit drilling and not to penetrate the evaporites more than a few meters was taken to avoid a possible hydrocarbon blowout in the Mediterranean, an event that would have possibly been even more catastrophic than that observed in 2010 in the Gulf of Mexico.

Until a new drilling campaign will be launched to sample those deposits, utilizing new technologies, that were not available in the past, the result is that any discussion about depositional environments (shallow vs. deep evaporite facies) is still open to considerable speculation.

Although there is only sparse sampling of the very thick successions that lay below the floor of the Mediterranean, these short cores are pivotal for the understanding of the crisis evolution. On the other hand, no modern evaporite facies analysis have been performed on most of the few meters of evaporites recovered from ODP-DSDP wells, the only descriptions being those compiled during the recovery or shortly thereafter. Important exception is the work of Hardie and Lowenstein

(2004), who questioned the original facies interpretation given by the scholars of the original deep desiccation model (Hsü et al., 1973a,b), suggesting that most interpreted shallow-water facies features described beneath the floor of the Mediterranean may be the result of deep-water deposition. Unfortunately this process of re-examination was restricted only to the DSDP drillcores of Legs 13 (1970) and 42A (1975). The same hypothesis was put forward by Roveri et al. (2001), Manzi et al. (2005) and Roveri and Manzi (2006), based on the facies analysis carried out on the resedimented evaporites of the Northern Apennines foredeep, and by Lofi et al. (2005), based on the new seismic data of deep Mediterranean settings.

With the aim of providing a new data set for this discussion, we performed a complete re-examination of the petrography and sedimentology of the evaporite facies of all the cores that are available to the scientific community (Fig. 1): not only from DSDP Legs 13 and 42A, but also from ODP Legs 107 (1990), 161 (1999). These are the very same set of cores that were considered to provide the evidence of the desiccation of the Mediterranean Sea during the Messinian.

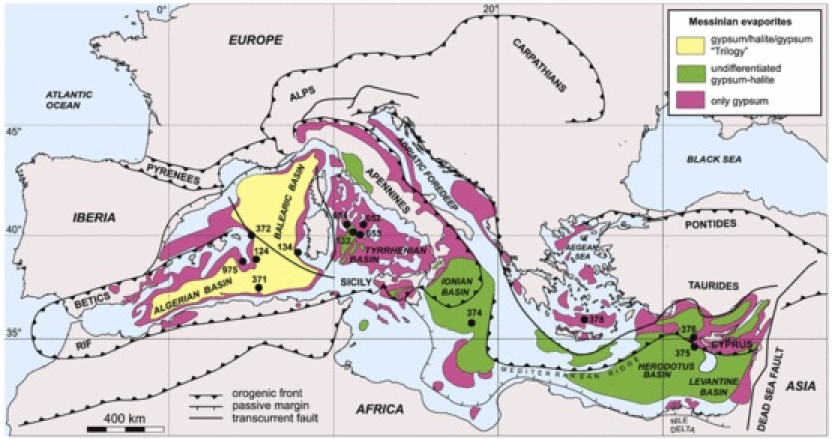

Fig. 1 Messinian evaporite lithological associations in the Mediterranean. ODP and DSDP drilling sites are also shown (black dots).

2 The Messinian salinity crisis: a facies problem

The Messinian salinity crisis is one of the most complex geological events that happened on our planet. The degree of complexity of this event that turned the Mediterranean into a giant salina producing a biological-catastrophy for most marine species is well represented by the many different alternative hypotheses that have been proposed to unravel its origin and evolution. The consequence has been a scientific controversy that lasted since the discovery of the evaporite sequences buried below the Mediterranean floor (see Rouchy and Caruso, 2006).

One potentially comprehensive approach for the understanding this crisis is to unravel the intricate evaporite facies array that was deposited in the different Mediterranean areas (Fig. 1).

Although we are aware that no modern analogues are available to compare all the Messinian facies architecture, at a first glance the evaporite products are surprisingly similar to what one would expect just by simple evaporation of seawater. Evaporite deposits range from carbonate (the first to precipitate from seawater) to gypsum ($CaSO_4 \cdot 2H_2O$), halite (NaCl), kainite ($MgSO_4 \cdot KCl \cdot 3H_2O$) and finally bishofite ($MgCl_2 \cdot 6H_2O$; the last to precipitate), a rather rare very soluble salt that has an extremely low potential of preservation in the rock record and yet is present in the Messinian succession in Sicily.

Yet a simple facies comparison with modern evaporites forming in the Mediterranean, both natural (sabkhas and associated salinas in North Africa) and artificial (commercial solar works), reveals many profound differences, suggesting that still other mechanisms may have influenced precipitation and sediment preservation, to some degree, in the past. One of these processes is probably the vast input of freshwater into the basin during gypsum deposition, as revealed by the Sr isotope geochemistry (Flecker and Ellam 2006; Lugli et al., 2010; Roveri et al., 2014b) and fluid inclusion data (Natalicchio et al., 2014). Another important factor may be the organic matter associated with the sediments, as accumulations of cyanobacteria and archea are included in most of the evaporite products, especially gypsum (Panieri et al., 2010) and argillaceous sediments (Dela Pierre et al., 2014). These important aspects still need to be fully explored.

Even more different and unexpected is the facies association and architecture of these deposits that are arranged in a fashion that exclude the reasonable, but in a way simplistic, view that different evaporite mineral facies should tend to form lateral equivalent deposits ("Walther's Law"), one adjacent to the other, as in a modern solar works. This disparity exists because the deposition of gypsum is strongly influenced by anoxia, bacterial activity and, in turn, by brine depth (De Lange and Krijgsman, 2010; Lugli et al., 2010; Dela Pierre et al., 2012) and deposition and attendant preservation was probably limited to relatively shallow settings (less than 200 m). The lateral equivalent of gypsum in deep basinal settings is not necessarily halite but, as indicated by cyclostratigraphy, the shale and carbonate deposits also formed in the first salinity phase (Manzi et al. 2007, 2011, 2013). Adding to the complexity of evaporite interpretation, some of the biological remains are contradictory, as we see that both marine and brackish fossils are documented in the same sequences (see for example Carnevale et al., 2008).

The architectural facies approach is based on a few concepts that were applied to the Messinian crisis for the first time:

a) the concept of an "evaporite event" (Hardie, 1984), indicating that dm-scale layers of halite and m-scale gypsum layers represent a complete evaporite cycle that may be independent from the previous and the following layer;

b) the diverse cyclicity of the evaporite bodies that range from precession (~~21~~ 21 kyrs; Krijgsman et al., 1999) to very high frequency (annual to pluriannual in gypsum and halite; Manzi et al., 2012);

c) the widespread and thick clastic evaporite facies are not very common in the rock record elsewhere, but are essential for the understanding of the sedimentary evolution here (Manzi et al., 2005; Lugli et al., 2013);

d) the strong possibility that some of the evaporite deposits were formed by brine mixing (Raup, 1970) and not only by simple evaporation, as brine saturation was possibly reached by downslope flows of hypersaline, dense waters, in a process similar to present-day "dense shelf water cascading" (Roveri et al., 2014c).

According to the above criteria and waiting for the possibility of a more complete drilling program through the entire sequence in the deep Mediterranean settings, the most complete stratigraphic frameworks for the salinity crisis taking into account all the observed sedimentary facies is the three-steps model proposed by CIESM (2008) and recently refined by Roveri et al. (2008, 2014a) and Manzi et al. (2013):

1) the first stage of deposition (5.97~~-~~–5.6 Ma; Manzi et al., 2013) is dominated by massive bottom-grown selenite (Primary Lower Gypsum; Lugli et al., 2010) in semi-isolated sub-basins, whereas only organic-rich shale and dolomitic limestone accumulated in deeper and/or more open settings (Manzi et al., 2007).

2) the second stage is the salinity crisis acme (5.6~~-~~–5.55 Ma) with the deposition of carbonates (Manzi et al., 2011) and halite and K-bearing salts (Lugli et al., 1999) during a phase of erosion and tectonic activity producing clastic deposits (Resedimented Lower Gypsum; Manzi et al., 2005; Roveri et al., 2008) from erosion and resedimentation of previous deposits; huge primary halite bodies (not reworked) were mainly deposited in the deeper basinal settings. This is the only stage where it was possible to demonstrate that local desiccation was achieved in some peripheral salt basins in Sicily (Lugli et al., 1999), probably as a result of the complete filling of intermediate basins (400 to 600 m depth) due to tremendous depositional rate of halite (Manzi et al., 2012).

3) the third stage (5.55~~-~~–5.33 Ma) is mainly characterized by $CaSO_4$ evaporites (Upper Gypsum) in shallow settings that alternated with hypohaline sediments (Lago Mare deposits; Manzi et al., 2009).

3 Materials and methods

We examined all the sections of the cores drilled through the Messinian evaporites in the Mediterranean by scientific cruises: DSDP Legs 13 (drilled in 1970) and 42A (1975), ODP Legs 107 (1990), 160 (1998), 161 (1999); see Fig. 1 for location of the drilling sites. These cores are stored at MARUM~~—~~—Zentrum für Marine Umweltwissenschaften, Universität Bremen (Germany).

All the cores were cut with a diamond saw to document the sedimentary features. Part of the segments were trimmed to obtain large standard thin and thick sections (4.5x6 cm and up to 100 µm in thickness for halite) for the examination under the optical polarizing microscope in transmitted light.

4 Evaporite facies in the drill cores

The ODP and DSDP cruise recovered evaporites that were formerly grouped into the Upper Evaporite (Hsü et al., 1973a) or Upper Unit of Lofi et al. (2005) on the basis of seismic stratigraphy. According to our Sr-isotope stratigraphic reinterpretation of the Mediterranean Messinian evaporites (Roveri et al., 2014b), the drillings reached mostly sediments belonging to stages 3 (Upper Gypsum) and 2 (Resedimented Lower Gypsum and halite) of the salinity crisis (see previous chapter). Only at site 378a the drilled sequence is from stage 1 (Primary Lower Gypsum).

The evaporite sediments consist of gypsum, anhydrite and halite rocks that show evidence of primary, clastic and secondary facies modified by diagenesis and tectonics.

4.1 In situ primary evaporites

These rocks originated by subaqueous chemical precipitation from concentrated brines.

4.1.1 Selenite gypsum

Massive selenite (facies EF3, Lugli et al., 2010) consists of bottom-grown vertically aligned swallow-tail gypsum crystals up to about 10 cm tall. A local limited transition to layers of banded selenite (facies EF4, Lugli et al., 2010) is also visible (site 375) showing thin layers consisting of vertical crystals about 1 cm-thick with corroded terminations draped by sand-size gypsum grains (gypsarenite). The massive selenite has been drilled only at sites 375 SW of Cyprus and 378a in the Aegean Sea (Fig. 1). At site 378a the massive selenite form an apparently continuous 40 m-thick interval, but at site 375 it is present as blocks included in a clastic unit consisting of gypsrudite and gypsarenite.

4.1.2 Laminar gypsum with or without nodular selenite

The laminar gypsum is a millimeter-scale rhythmic succession of gypsum laminae. There are two main types: the equigranular, which is inversely graded (Figs. 2C and 3C), and the acicular gypsum, which is directly graded (Figs. 2D and 3D). The gypsum laminae consist of inversely graded (i.e., with crystal size increasing toward the top of each lamina) cumulates of fine-grained equigranular crystals separated by very thin veneers of organic matter (less than 1 mm). The inverse gradation resemble that described in the Sicilian evaporites (Ogniben, 1957; Schreiber et al., 1976; Manzi et al., 2012). Small-scale cross-lamination is occasionally present (Figs. 2 E and 3L).

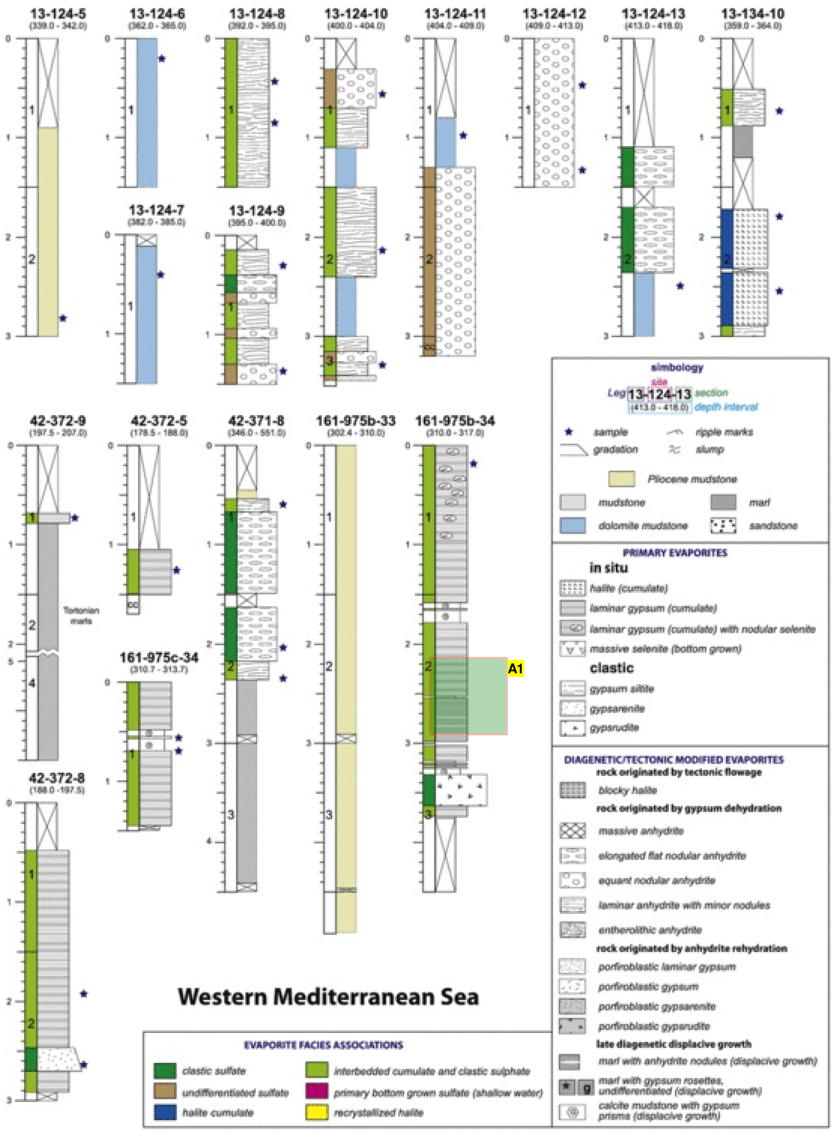

Fig. 2 A) Core slab of halite rock from Site 134 showing sandy silt (light greay at the top) and fine-grained halite cube cumulate (light greay at the bottom). The clastic layer is composed of corroded cubic halite, planktonic forams, quartz, feldspar and glauconite grains. The white nodules consist of felted displacive anhydrite. This sample is 10 cm below the core section cut by a crack originally interpreted as a desiccation feature by Hsü et al. (1973a and b) and displays the same facies association (see also Fig. 4). A thin section of the core is shown in Figs. 3A and 4G and F.

B) Core slab of halite rock made up of clear blocky and elongated crystals. This rock appears to have recrystallized during tectonic flow (see Fig. 3B for a thin section of a similar rock). Relict of the original layering is the dark banding appearing on the top of the sample and consisting of scattered argillaceous material. Site 376.

C) Core slab of a laminar rock consisting of fine-grained graded granular gypsum with a clastic gypsum intercalation (at center of picture). A thin section of a similar cumulite rock is shown in Fig. 3C. Site 654.

D) Core slab of a undulate coarse gypsum laminite consisting of mm-size granular crystals (light gray beds) draped by fine-grained gypsum cumulate (dark laminae). A thin section of a similar cumulite rock is shown in Fig. 3E. Site 975.

E) Core slab of a deformed undulate coarse gypsum laminite consisting of mm-size granular crystals (light gray beds) draped by fine-grained gypsum cumulate (dark laminae). Site 653.

F) Core slab of an anhydrite rock consisting of large elongated nodules possibly partially modified by pressure solution, but showing some pseudomorphs after swallow tail selenite crystals. Arrow is pointing to the re-entrant angle of a swallow tail crystal. Site 124.

G) Core slab of graded gypsarenite–gypsrudite rock consisting of corroded selenite fragments. A thin section of this rock is shown in Fig. 3I. Site 654.

H) Core slab of a cross bedded clastic gypsum rock consisting of reworked granular cumulate gypsum. A thin section of this rock is shown in Fig. 3L. Site 654.

Annotations:

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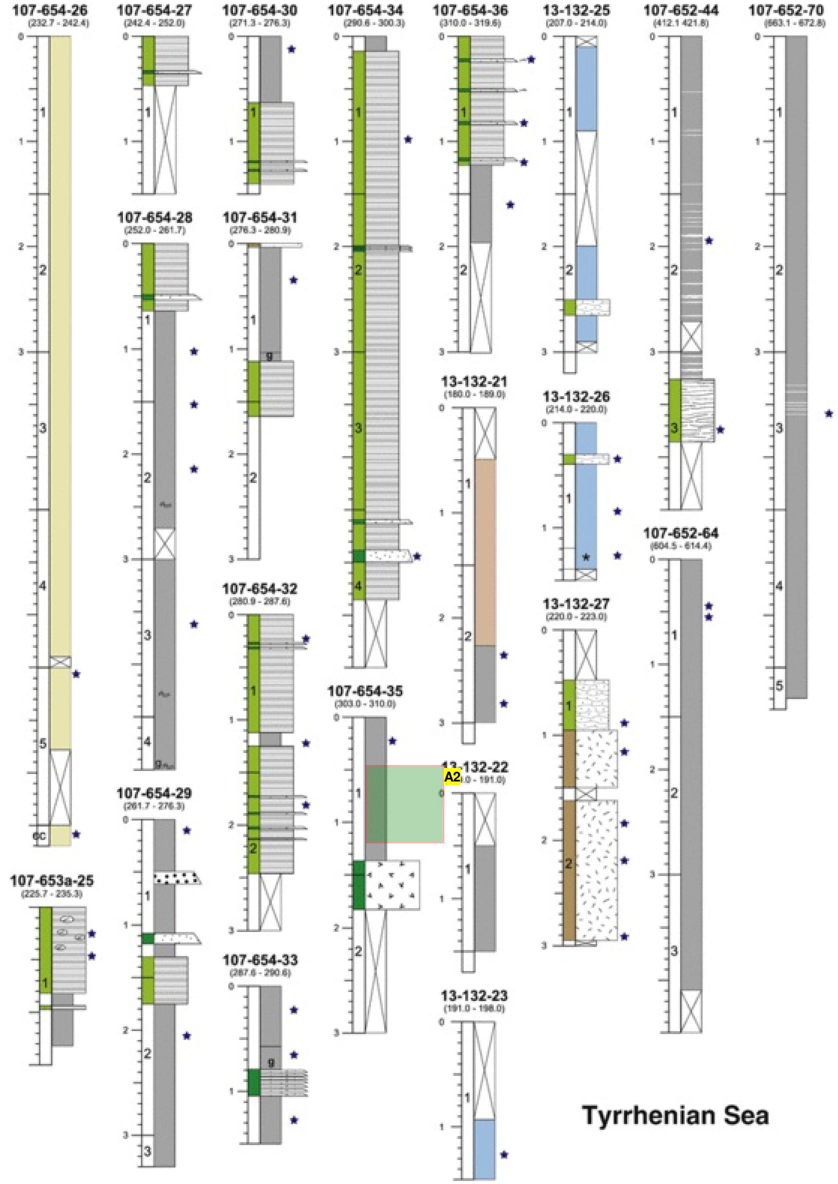

Fig. 3 A) Thin section photomicrograph of a cumulite rock consisting of fine-grained cubic halite crystals. The crystals show trails of primary fluid inclusions and may have formed at the brine–air interface or in the water column and sunk to the bottom of the basin. Plane polarized, transmitted light. Site 134.

B) Thin section photomicrograph of a blocky halite rock showing evidence of recrystallization by grain boundary migration. The large crystals contain a few cubic fluid inclusions, possible relict of primary fluid inclusions trails or secondary in origin, whereas most of the visible fluid inclusions are secondary and grouped at intra-crystalline positions as irregular vermicular structures. Plane polarized, transmitted light. Site 374.

C) Thin section photomicrograph of a laminite rock consisting of cumulate graded granular gypsum crystals. These laminae probably represent annual cyclicity Crossed polars, transmitted light. Site 372.

D) Thin section photomicrograph of a laminite rock consisting of cumulate graded prismatic gypsum crystals. These laminae probably represent annual cyclicity Crossed polars, transmitted light. Site 654.

E) Thin section photomicrograph of a undulate laminated rock consisting of partially reworked cumulate graded granular gypsum crystals. The finer upper laminae are draping the undulate upper boundary of the coarser laminae. The laminae probably represent annual cyclicity. Crossed polars, transmitted light. Site 975.

F) Thin section photomicrograph of laminated rock containing small vertical bottom-grown selenite crystals (light gray at right). The selenite crystals are onlapped, draped and drowned by the cumulate crystals which settled from the water column. The selenite boundaries are also corroded suggesting that the crystal was probably standing free above the brine–sediment interface during the winter dilution which is marked by the very fine grained dark laminae containing organic matter and fine-grained carbonate. Crossed polars, transmitted light. Site 654.

G) Thin section photomicrograph of an anhydrite laminite rock consisting of felted crystals. The original rock was probably a laminated gypsum cumulite very similar to Fig. 3C. Crossed polars, transmitted light. Site 975.

The graded equigranular gypsum facies may display undulate laminae and deformation. The undulations are related to the presence of bottom-grown coarser granular crystals, up to a few cm across, that are draped by the subsequent fine-grained gypsum laminae (Fig. 2D). The deformation appears to be the consequence of early diagenetic overgrowth of the selenite nodules (Fig. 2E).

The graded and laminated rock may contain locally small vertical bottom-grown selenite crystals onlapped, draped and drowned by the cumulate crystals (Fig. 3F).

Some samples show minor displacive growth of gypsum prisms into carbonate mud associated with laminar gypsum (Fig. 3H).

4.1.3 Laminar halite

The laminar halite has been recognized exclusively at site 374 and consists of thin-bedded accumulations of fine-grained halite cube crystals (up to 0.3 mm across) showing primary fluid inclusions along growth bands (Fig. 3A). The cubic halite cumulate layers are 5 to 10 cm-thick and are separated by tiny (less than 0.1 mm) sheets of argillaceous mud and white coalescent displacive nodules of fine-grained acicular (felted) anhydrite (Fig. 4E and G). The mud appears to drape and rim some of the halite crystals downward. In these areas the halite crystals show slightly corroded and rounded corners suggesting that the mud penetrated downward along narrow dissolution pits developed at intercrystalline positions (Fig. 4F). Polyhalite needles less than 0.1 mm in size are scattered throughout the rock and commonly radiate out from the areas where mud is concentrated. A few cross-bedded clastic layers a few cm-thick are intercalated in the cumulate halite (Fig. 4d and E). The clastic layers are normally graded and contain grains composed of partly corroded and slightly rounded cubic halite crystals, planktonic foraminifera tests and fragments, quartz, feldspar and glauconite (Fig. 4F). The clastic grains are also partly displaced by white nodules of felted anhydrite up to a few mm in size (Fig. 4D and G). This clastic facies contains a single crack, up to 2 mm-wide, filled by clear, fluid inclusion-free halite, which is described in detail in the discussion chapter (Fig. 4D).

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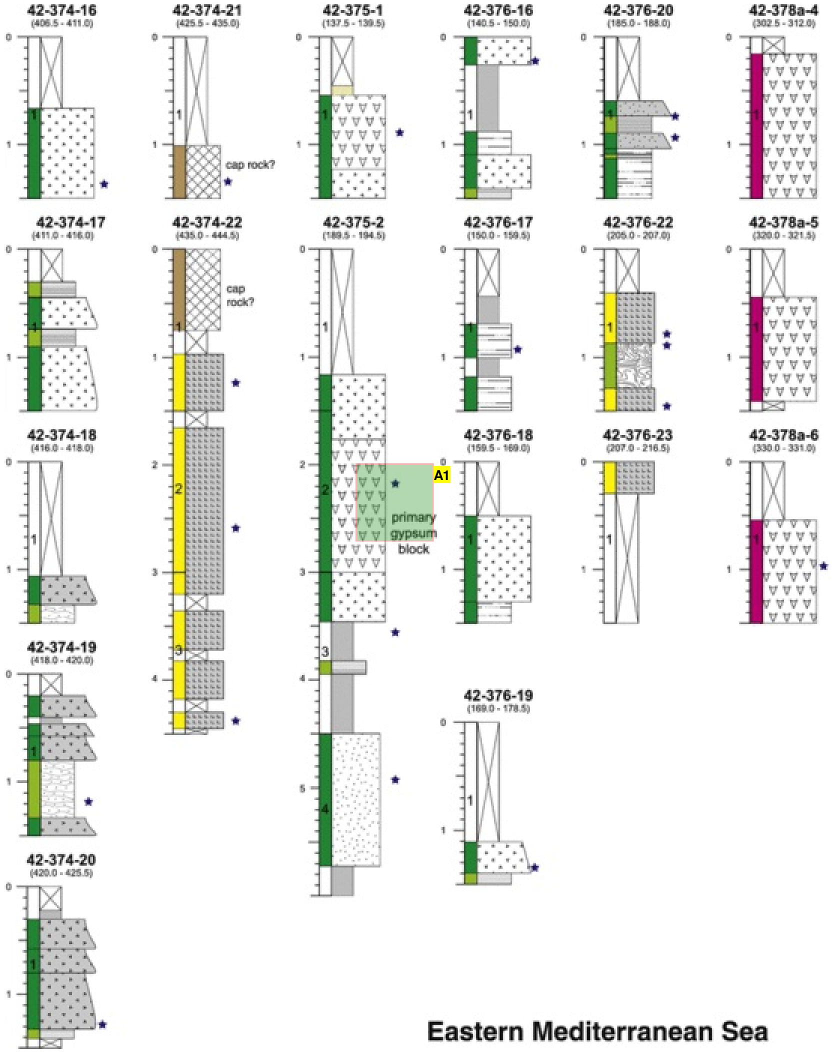

Fig. 4 Halite sedimentology and petrography from site 134. A) Halite core section 10 from Site 134 as re-photographed in 1984. B) The crack cutting through a clastic layer as depicted in Hsü et al., 1973b. C) The same core section of the previous picture as shown in a reverse orientation in Hsü et al., 1973a. D) A new cut surface of the same core from the opposite slab shows that the crack is actually extends above and below the clastic layer into the subaqueous cumulate halite rock and is thus more consistent with a post depositional fracture filled with clear halite. E) Core slab of halite cumulite and halite sandy siltstone described in ~~Fig~~Fig. 2A. F) Thin section photomicrograph of a portion of Fig. E showing the graded halite sandy siltstone (top) and the fine halite cube cumulite (bottom); the lower center part contain very thn veneers of mud (black) draping slightly corroded halite cubes; the mud also penetrates down for a couple of millimeters forming small dissolution pits located at intercrystalline position of corroded halite cubes; transmitted, plane light. G) The same thin section of Fig. F shown at crossed polars; halite is black and the felted anhydrite nodules appears as bright spots; bright tiny polyhalite needles are also common.

Annotations:

A1. this is fig 7

4.2 Clastic evaporites

4.2.1 Gypsrudite, gypsarenite and gypsiltite

Clastic rocks composed of sulfate fragments are widespread in the cores. They consist of gypsrudite (facies R1, R2 sensu Manzi et al., 2005), gypsarenite (facies R3, R4, R5, R6, Manzi et al., 2005) and gypsiltite (facies R7, Manzi et al., 2005), components. The coarser sediments are composed of corroded fragments of twinned crystals indicating erosion and redeposition of primary massive and banded selenite. The sedimentary features include graded laminae of gypsum granules and carbonate clasts and commonly exhibit cross-lamination (Figs. 2G and H and 3I, L and M).

4.3 Diagenetic/tectonic modified evaporites

Some of the evaporite facies show the evidence of complex post-depositional modifications related to burial diagenesis and tectonic deformation.

4.3.1 Halite rocks exhibiting deformation and recrystallization

4.3.1.1 Blocky halite This facies consists of large halite crystals up to a few mm across that are blocky or elongated along the main layering (Fig. 2B). The crystals are clear and show only rare primary fluid inclusions banding. Most of the visible fluid inclusions are and grouped at intra-crystalline positions as secondary irregular vermicular structures (Fig. 3B). These characteristics indicate recrystallization by halite deformation, as migrating grain boundaries consume the fluid-inclusion-rich parts of the crystals transferring the brine into the grain boundaries and providing conditions for pressure solution creep (Schléder and Urai, 2005)

4.3.2 Anhydrite rocks formed from gypsum dehydration

4.3.2.1 Massive anhydrite Massive anhydrite consists of fine-grained whitish rocks composed of fine-grained acicular and interlocking anhydrite crystals and may contain large anhydrite porphyrotopes.

4.3.2.2 Elongated flat nodular anhydrite Anhydrite rock containing flat elongated nodules may form massive or graded beds. The anhydrite fragments are aligned with their long axes parallel to bedding and in some cases show a distinctive swallow-tail shapes suggesting pseudomorphs after selenite, as demonstrated by the presence of the re-entrant angle of the former twin morphology (Fig. 2F).

Petrographically the clasts consist of polycrystalline intersecting lath-shaped anhydrite and the original shape of the clastic sulfate fragments is commonly outlined by argillaceous or fine-grained carbonate material.

4.3.2.3 Equant nodular anhydrite This type of rock is composed of equant anhydrite nodules, made up of fine-grained acicular crystals, that grew displacively and are separated by thin veneers of organic-rich mud.

4.3.2.4 Laminar anhydrite with minor nodules Laminar anhydrite consists of thin laminae, up to a few mm-thick, composed of felted (Fig. 3G) and lath-shaped anhydrite separated by argillaceous laminae containing organic matter. No pseudomorphs are visible within the sulfate laminae.

4.3.2.5 Entherolithic anhydrite Entherolitic structures consist entirely of fine-grained acicular anhydrite and affect deformed undulate laminar anhydrite rocks with the maximum deformation at the margin of large displacive nodules. The entherolitic structures appear to have formed by the coalescence of anhydrite nodules grown into layers of laminated sulfate facies and deforming them to various extents.

4.3.3 Gypsum rocks originated from anhydrite hydration

4.3.3.1 Porphyroblastic laminar gypsum This facies consists of large cloudy-ameboid and xenotopic gypsum (as described in Lugli, 2001; after Ciarapica et al., 1985) containing small relicts of anhydrite crystals and parallel laminae of argillaceous material. These characteristics suggest an origin by hydration of fine-grained acicular and lath anhydrite laminites.

4.3.3.2 Porphyroblastic gypsum This porphyroblastic gypsum is made up of cloudy-ameboid and xenotopic gypsum containing anhydrite relicts. These rock probably originated by gypsification of massive anhydrite.

4.3.3.3 Porphyroblastic gypsrudite and gypsarenite This facies consists of cloudy-ameboid and xenotopic gypsum containing small relicts of anhydrite. The rock is crossed by a network of curved argillaceous laminae cross-cutting each other. these characteristics indicate an origin by hydration of former nodular anhydrite in turn formed by burial of gypsrudite and gypsarenite rocks.

4.3.4 Mudstone with displacive sulfate nodules and crystals

4.3.4.1 Marl with anhydrite nodules This facies is represented by scattered displacive nodules of fine-grained acicular anhydrite that grew within mudstones.

4.3.4.2 Marl with gypsum rosettes and calcite mudstone with gypsum prisms This facies is characterized by displacive rosettes composed of interlocking gypsum lenses and hexagonal gypsum prisms grown within marls and calcitic mudstones, respectively.

5 Discussion and interpretation of the evaporite facies

Previous studies of Messinian evaporites during the ODP-DSDP cruises pointed out the presence of shallow water to supra-tidal evaporitic deposits that became pivotal evidence for the definition of the “*deep basin shallow water*” model implying the deep desiccation of the Mediterranean (Hsü et al., 1973a,b).

Our analyses of the “deep” Messinian evaporites suggest that some evaporite facies may have a different interpretation than originally given (see Table 1 for interpretations comparison). In the next sections we briefly discuss our review of the original evaporitic facies interpretations.

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Table 1

Primary evaporites					
In situ – *rock originated by subaqueous chemical precipitation*					
This study		Location		Previous studies	
Sedimentary facies	Parent rock	Depositional process	LEG-site/core	Sedimentary facies	Depositional environment
Massive selenite (EF3)*	–	Subaqueous bottom grown (depth < 200 m)	378a/4-5-6	Coarse selenite	Garrison et al. (1975)
L – laminar gypsum (with minor nodular selenite)	–	Subaqueous cumulate (any water depth)	372/5-8-9	Laminated to nodular gypsum	sabkha, evaporite flat, hypersaline lagoon Garrison et al. (1975)
				Flat to wavy laminated	diagenetic altered deep water evaporite Hardie and Lowenstein (2004)
			374/17	Laminated gypsum and nodular to wavy-bedded gypsum	sabkha, evaporite flat, hypersaline lagoon Garrison et al. (1975)
				flat to wavy laminated	diagenetic altered deep water evaporite Hardie and Lowenstein (2004)
			375/2	Laminated clastic gypsum	shallow subaqueous (Garrison et al., 1975)
			376/16-19-20	Laminated clastic gypsum	shallow subaqueous Garrison et al. (1975)
				Flat to wavy laminated	diagenetic altered deep water evaporite Hardie and Lowenstein (2004)
			653a/25	Regular laminated “balatino”	clastic and interstitial precipitation Pierre and Rouchy (1990)
			654/27-28-29-30-31-32-34-36	Regular laminated	clastic and interstitial precipitation Pierre and Rouchy (1990)
				“Balatino” to alabastrino (nodules)	shallow-water to supratidal Borsetti et al. (1990)
			975b/34	laminated gypsum	cumulate, below wave base Marsaglia and Tribble (1999)
			975c/34	Laminated gypsum	cumulate, below wave base Marsaglia and Tribble (1999)
LN – laminar gypsum with nodular selenite	–	Subaqueous cumulate with early diagenetic selenite (any water depth)	653a/25	Regular laminated “balatino” with primary selenit	shallow-water and diagenetic overgrowth Pierre and Rouchy (1990)
			975b/34	Pinch-and-swell gypsum	cumulate, below wave base with gypsum overgrowth Marsaglia and Tribble (1999)
H – laminar halite	–	Subaqueous cumulate (any water depth)	134/10	Hopper and banded halite alternated with aeolian dust	brine pool and sabkha desiccation (Hsü et al., 1973)
				Granular aggregate of well sorted cubic crystals	subaqueous cumulate (any water depth) Hardie and Lowenstein (2004)

* lithofacies sensu Lugli et al., 2003

Primary evaporites					
Clastic (R)—*rock originated by evaporite erosion, transport and resedimentation by subaqueous gravity flows*					
This study		Location		Previous studies	
Sedimentary facies	Parent rock	Depositional process	LEG-site/core	Sedimentary facies	Depositional environment
gypsrudite (R1, gypsrudite; R2, pebbly gypsarenite)**	–	Subaqueous clastic from bottom-grown selenite (any water depth)	374/16-17	Coarse-grained gypsum	Displacive, subaqueous–subaerial Garrison et al. (1975)
gypsarenite (R3, coarse gypsarenite; R4, plane laminated gypsarenite; R5, megarippled gypsarenite; R6, fine gypsarenite, silt and shale)**	–	Subaqueous clastic from bottom-grown selenite (any water depth)	372/8	Not described	
			375/2	Clastic gypsum	Shallow subaqueous to subaerial Garrison et al. (1975)
			654/27-28-29-30-31-32-33-34-36	Regular laminated	Clastic, interstitial precipitation Pierre and Rouchy (1990)
				Clastic	Shallow lagoon Borsetti et al. (1990)
				Paraconglomerate	Subaqueous debris flow Hardie and Lowenstein (2004)
			375/1-2	Clastic gypsum	Shallow subaqueous to subaerial Garrison et al. (1975)
			376/16-18-19	Clastic gypsum	Shallow subaqueous to subaerial Garrison et al. (1975)
			654/35	Clastic	Shallow lagoon with debris flow Borsetti et al. (1990)
			975b/34	Not described	
Gypsiltite (R7, silt shale and limestone)**	–	Subaqueous clastic from cumulate gypsum or bottom grown selenite (any water depth)	376/16-17-18-20	Gypsiltite	Shallow subaqueous to subaerial Garrison et al. (1975)
**–lithofacies sensu Manzi et al. (2005)					

Diagenetic/tectonic modified evaporites					
This study		Location		Previous studies	
Sedimentary facies	Parent rock	Depositional process	LEG-site/core	Sedimentary facies	Depositional environment
Halite *rock originated by tectonic flowage recrystallization*					
BH—blocky halite	Undifferentiated halite	Undetermined	374/22	Laminar, chevron, displacive	Sabkha and evaporite flat Garrison et al. (1975)
			376/22-23	Banded halite, translucent halite	Sabkha, evaporite flat and recrystallization Garrison et al. (1975)
Anhydrite *rock originated by gypsum dehydration*					
A1—massive	Massive selenite or matrixfree gypsrudite–gypsarenite	Subaqueous bottom grown (depth <200 m) or Subaqueous clastic from bottom-grown selenite (any water depth)	124/10	Nodular and chicken-wire	Sabkha Friedman (1973)
				Nodular, mosaic and “chicken-wire”	Burial diagenesis and other processes Hardie and Lowenstein (2004)

			374/21-22	Laminar, nodular (bedded mosaic) and chicken-wire	Sabkha Garrison et al. (1975)
				Nodular, mosaic and “chicken-wire”	Burial diagenesis and other processes Hardie and Lowenstein (2004)
A2—equant nodular	Matrix-poor massive or banded selenite or gypsrudite—gypsarenite	Subaqueous bottom grown (depth < 200 m) or subaqueous clastic from bottom-grown selenite (any water depth)	24/9-10-11-12;	Nodular and chicken-wire	Sabkha Friedman (1973)
				Nodular, mosaic and “chicken-wire”	Burial diagenesis and other processes Hardie and Lowenstein (2004)
A3—elongated flat nodular	Gypsrudite	Subaqueous clastic from bottom-grown selenite (any water depth)	124/9-13	Nodular and chicken-wire	Sabkha Friedman (1973)
				Nodular, mosaic and “chicken-wire”	Burial diagenesis and other processes Hardie and Lowenstein (2004)
			371/8	Nodular with nodular mosaic to bedded mosaic and chicken-wire	Sabkha Garrison et al. (1975)
A4—laminar with minor nodules	Laminar gypsum	Subaqueous cumulate or clastic gypsum (any water depth) partly deformed by diagenesis	124/8-9-10	Algal laminated with nodules	Sabkha Friedman (1973)
				Flat to wavy laminated	Diagenetic altered deep water evaporite (Hardie and Lowenstein,2004)
			134/10	Algal laminated with nodules	Sabkha Friedman (1973)
				Flat to wavy laminated	Diagenetic altered deep water evaporite Hardie and Lowenstein (2004)
			371/8	Algal laminated with bedded mosaic structures	Sabkha Garrison et al. (1975)
				Flat to wavy laminated	Diagenetic altered deep water evaporite Hardie and Lowenstein (2004)
			652/44	Clastic	Turbidites and diagenetic Borsetti et al. (1990)
A5—entherolithic	Laminar gypsum	Subaqueous cumulate or clastic gypsum (any water depth) deformed by diagenesis	376/22	Entherolitic nodular anhydrite	Sabkha Garrison et al. (1975)
Diagenetic/tectonic modified evaporites					
This study		Location		Previous studies	
Sedimentary facies	Parent rock	Depositional process	LEG-site/core	Sedimentary facies	Depositional environment
Porphyroblastic gypsum (PG)—*rock originated by anhydrite hydration*					
PG1—porphyroblastic laminar gypsum	Laminar anhydrite after laminar gypsum	Subaqueous cumulate or clastic gypsum (any water depth)	132/25-26-27	Re-crystalized gypsum after flatpebble conglomerate	Tidal flat during desiccation Friedman (1973)
				Flat to wavy laminated	Diagenetic altered deep water evaporite Hardie and Lowenstein (2004)
			374/18-19	Laminated gypsum with coarse recrystalization mosaic	Sabkha to burial diagenesis Garrison et al. (1975)
PG2—porphyroblastic gypsum	Undifferentiated selenite	Undetermined	132/27	Nodular gypsum after anhydrite	Sabkha Friedman (1973)
PG3—porphyroblastic	Anhydrite arenite aftergypsarenite	Subaqueous clastic from bottom-grown selenite (any water depth)	374/18-	Coarse recrystalization mosaic	Sabkha to burial diagenesis Garrison et al.

gypsarenite			19-20		(1975)
Mudstone with displacive sulfate (DS) *rocks originated by displacive growth within mudstone*					
DS1 – marl with anhydrite nodules	Displacive anhydrite or gypsum	Marl with no evaporite (any water depth)	652/44-70	Clastic	Turbidites and diagenetic Borsetti et al. (1990)
DS2 – marl with gypsum rosettes, undifferentiated	Displacive gypsum	Marl with no evaporite (any water depth)	132/26	Gypsum porfirotopes	Sabkha Friedman (1973)
			654/31	Primary selenite	Shallow-water Pierre and Rouchy (1990)
DS3 – calcite mudstone with gypsum prisms	Displacive gypsum	Mudstone with no evaporite (any water depth)	975b/34	Gypsiferous chalk	Shallow water lacustrine, in situ diagenetic growth Marsaglia and Tribble (1999)
			75c/34	Gypsiferous chalk	Shallow water lacustrine, in situ diagenetic growth Marsaglia and Tribble (1999)

5.1 Halite

Based on the original interpretation (Table 1), the halite deposits were described as chevron, laminar and displacive (Hsü et al., 1973a,b; Garrison et al., 1978) and were sedimented in brine-pools or sabkhas. A shallow water origin for these halite deposits was also proposed for sites 374 and 376 (Garrison et al., 1978), based on the presence of chevron crystals (Kuehn and Hsü, 1973).

Hardie and Lowenstein (2004) provided a different interpretation suggesting that the halite rocks were actually cumulate deposits formed in subaqueous conditions at any water depth.

Our observations suggest that most of the halite rocks recovered by the drilled cores show evidence of recrystallization by halite deformation and flow that partially obliterated the original texture preventing or misdirecting the reconstruction of the depositional environment. The only unequivocal primary features come from DSDP site 134 and indicate deposition of fine-grained cumulate halite. From this site comes one of the sedimentary features that became famous after the enunciation of the "*deep basin shallow water*" model (Hsü et al., 1973b): a "desiccation crack" cutting through a sandy silt layer interbedded with unaffected laminated halite (Fig. 4). The interpretation was confirmed in another paper (Hsü et al., 1973a; their Fig. 5) although the same core sample was pictured in the opposite orientation (upside down). In our opinion the orientation shown in Hsü et al. (1973b) may be the correct one because the sand–silt layer appears to be a normal graded bed possibly deposited by a unidirectional gravity flow capped by cubic cumulate halite crystals settled at the bottom from the surface or the brine column (Fig. 4).

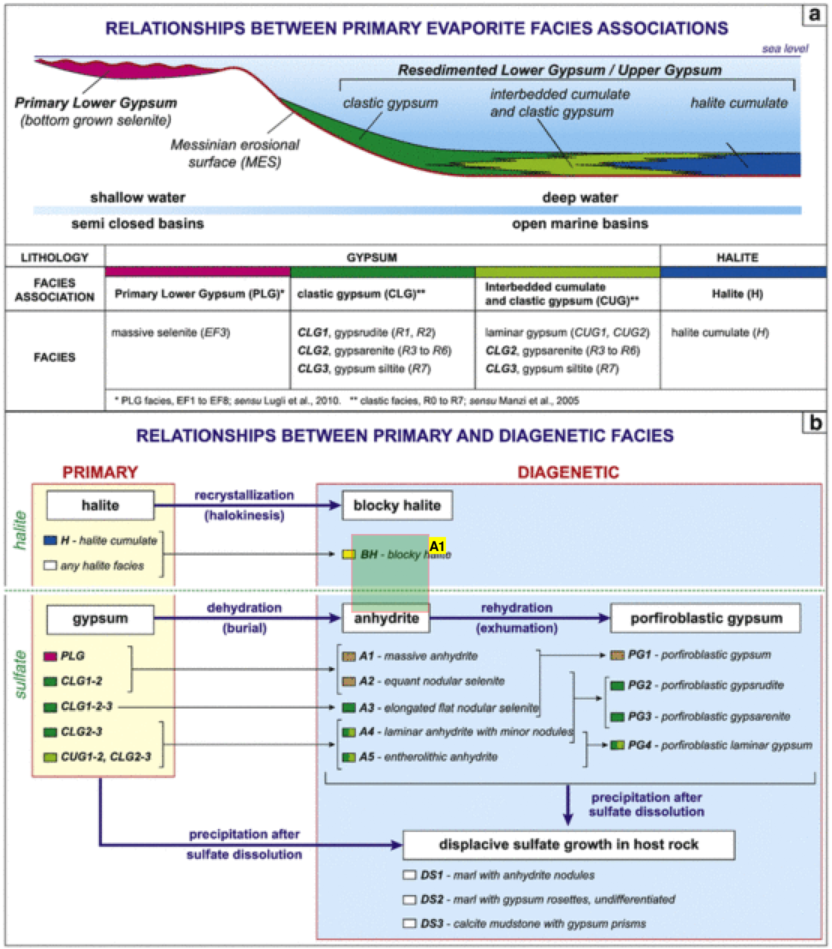

Fig. 5 Facies association for the cores that crossed evaporite sediments in the ODP and DSDP legs in the Western Mediterranean Sea.

Annotations:

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The presence of the primary cubic cumulate points to subaqueous deposition in a relatively deep water environment; differently to what is observed in shallow water settings, where chevron halite is the most common sedimentary feature for the Messinian sections, especially for those layers that are affected by exposure features such as meteoric dissolution pipes and large contraction polygons in the Sicilian mines of Realmonte (Lugli, 1999; Lugli et al., 1999) and Racalmuto. The white anhydrite nodules displace the cube cumulate and the clastic layer and thus, appear to have grown in situ. Such type of growth is not exclusive of supratidal environments (as originally proposed by Hsü et al., 1973b), but may occur also in subaqueous deposits during late diagenesis (Shearman, 1985). Furthermore, the clastic layer cut by the crack that contains a large number of planktonic foraminiferal tests appears to have been deposited under subaqueous conditions instead of representing an aeolian deposit (Hsü et al., 1973b). This is because the halite cubes are only slightly corroded and rounded and the carbonate-siliciclastic fraction is relatively coarse and poorly sorted (silt–sand grain size; Fig. 4F). Moreover no exposure features have been recognized in the core section at any scale. The only dissolution features are characteristic of subaqueous environments and are very limited to the tiny mud veneers that represent annual winter and/pluriannual dilution by refreshment of the brine column that may have occurred at the winter of annual and pluriannual cycles (Fig. 4F).

Our observations on a new cut of the original core demonstrate that the crack extends further in the cumulitic halite layer above and below the sandy bed (see also Roveri et al., 2014c) and does not start from an horizon showing exposure features, such as dissolution pipes (Fig. 4D). All these features suggest that the crack can be more properly interpreted as a late post-depositional fracture probably because of its different mechanical proprieties with respect to the sand and does not represent evidence of subaerial exposure.

5.2 Gypsum

5.2.1 Laminar gypsum

The large part of the gypsum deposits recovered from the depth has been described as laminar gypsum with or without nodules. The laminar gypsum was interpreted as a sabkha deposit (see Table 1; Garrison et al., 1978; Borsetti et al., 1990), whereas the presence of nodules was related to cumulate below wave-base (Marsaglia and Tribble, 1999), shallow- (Garrison et al., 1978; Borsetti et al., 1990) to deep-subaqueous (Hardie and Lowenstein, 2004) and clastic deposits (Pierre and Rouchy, 1990).

We do not have a clear explanation for the formation of equigranular v~~ersu~~s. needle-gypsum laminate (cumulate) and direct v~~ersu~~s. inversely grading more generally seen in these deposits. The sedimentation of such facies appears to be the result of accumulation of crystals settled from the brine air interface or from the brine column (in agreement with Marsaglia and Tribble, 1999; Hardie and Lowenstein, 2004) and the different cumulate facies may be the complex result of salinity, temperature and organic matter content. Each lamina appears to be a discrete seasonal episode occurring throughout the basin in a relatively deep environment. As for the example of Sicily, statistics can be successfully applied to the study of these annual deposits, revealing the influence of climatic forcings which are active today, such as ENSO oscillation, soli-lunar cycles, etc. (Manzi et al., 2012).

Our observations led to the identification of a facies association formed by alternation of primary cumulate and clastic gypsum layers. The clastic portion is provided by reworking of cumulate sediments that were resedimented downslope by low-density gravity flows, as suggested by normal grading and unidirectional ripples. This facies association has been previously described only in the deeper depocenters of Sicily (Manzi et al., 2011; 2012) and Cyprus (Robertson et al., 1995; Manzi et al., in press).

The very early diagenetic overgrowth of the crystals settled at the bottom also created the undulate and nodular facies; however, the growth of these new overgrowth crystals was rapidly drowned by the continuous rain of other settling crystals (Fig. 3E and F). In our opinion the sulfate nodules that are present in these deposits are diagenetic features and do not indicate supratidal environment. Moreover, cumulate gypsum deposits were not described in modern and ancient sabkha cycles.

5.2.2 Massive selenite

The only massive selenite beds at site 378A ~~was~~ were interpreted as shallow subaqueous by Garrison et al. (1978). They show a strontium isotope signature usually present in the field of the Primary Lower Gypsum (Roveri et al., 2014b). In particular, the described crystal facies and the presence of microbial inclusions (Panieri et al., 2010) are indicative of selenite facies EF3 and EF4 (Lugli et al., 2010). Such selenite sedimentation, seen elsewhere, was restricted to permanent marginal silled, shallow water (less that 200 m deep) subaqueous environments periodically affected by brine dilution which partially dissolved the crystal terminations but with no evidence of desiccation, as no dissolution pits are present. Generally large scale mass-wasting during the second stage of the salinity crisis were responsible or the displacement of selenite blocks downslope and their association to clastic selenite at site 375, as described for Sicily (Roveri et al., 2008; Lugli et al., 2010), Cyprus (Manzi et al., in press) and onshore Israel (Lugli et al., 2013).

5.2.3 Clastic gypsum

The presence of clastic gypsum was considered indicative of shallow subaqueous to subaerial deposition (Garrison et al., 1978), shallow lagoon with debris flow (Borsetti et al., 1990), and subaqueous debris flow (Hardie and Lowenstein, 2004).

We recognized a large variety of clastic gypsum deposits ranging from gypsrudites to gypsiltites, some of them modified by burial diagenesis (Figs. 2F, G and H; 3I~~,~~-L and M). They formed from the dismantlement of previous cumulate or bottom grown selenite deposits and subsequent resedimentation by gravity flows in a subaqueous environment (as suggested by Borsetti et al., 1990). Nevertheless, the absence of shallow to subaerial depositional features such as wave ripples, paleosoil or karstification point to deposition in relatively deep environments (Hardie and Lowenstein, 2004; Manzi et al., 2005; Roveri et al., 2008).

5.3 Anhydrite

Nodular and “chicken-wire” anhydrite/gypsum deposits were interpreted as sabkha deposits (Friedman, 1973; Garrison et al., 1978) or as burial diagenetic features (Hardie and Lowenstein, 2004). Flat to undulate laminated anhydrite/gypsum rocks were variously described as sabkha sediments (Friedman, 1973; Garrison et al., 1978) or turbidite and diagenetic deposits (Borsetti et al., 1990) and diagenetic altered deep-water evaporites (Hardie and Lowenstein, 2004).

The studied sediments extend down to a maximum depth of 673 m below the seabed (site 652) in areas with a relatively high heat flow and are thus partially within the stability field of anhydrite that forms at the expenses of gypsum by burial diagenesis. Anhydrite rocks are present in the cores portions buried more than 350 m below the seabed (site 371; see Fig. 5), but some anhydrite rocks have been also rehydrated back to gypsum (see next section).

In agreement with what proposed by Hardie and Lowenstein (2004), all the anhydrite deposits show no evidence of primary sabkha deposits and may be interpreted as related to diagenetic changes induced by lithostatic burial. The lithology of the original gypsum deposits, cannot be always determined, but could have been primary selenite, gypsrudite or laminar gypsum. The amount of matrix (carbonate or shale) and the sedimentary structures seems to control the shape and size of the anhydrite nodules that grew at the expenses of the original gypsum rock.

5.3.1 Massive and equant nodular anhydrite

The original deposits from which the massive or equant nodular anhydrite formed was probably a massive selenite with very little matrix; gypsum, both primary (massive and banded selenite) or clastic (gypsrudite and gypsarenite) may have been the original protoliths.

5.3.2 Elongated flat nodular anhydrite

The deposits from which this facies originated was probably a gypsrudite (clastic reworking) with a relatively abundant matrix content. This hypothesis is also supported by the bed gradation commonly associated with these deposits.

5.3.3 Laminar and entherolithic anhydrite

This facies formed from laminar gypsum that could have been either cumulate or clastic in origin. Despite the mesoscale undulate lamination, no clear evidence of algal structures have been recognized under the microsope; thus, in our opinion, the undulate to entherolithic appearances may be related to progressively stronger diagenetic deformations rather than any primary structure.

5.4 Gypsum after anhydrite

All the porphroblastic gypsum facies include anhydrite relicts or are characterized by hydration textures. These features indicate re-hydration of burial-diagenetic anhydrite. As stated for the anhydrite facies, no sabkha features have been recognized. For the definition of the original gypsum rock from which these facies originated see description of corresponding anhydrite facies.

5.5 Mudstone with sulfate

As illustrated in Table 1, isolated gypsum crystals within mudstones were interpreted as shallow water primary selenite (Pierre and Rouchy, 1990), sabkha porphyrotopes (Friedman, 1973), turbidite and diagenetic deposits (Borsetti et al., 1990), in situ diagenetic growth (Marsaglia and Tribble, 1999). Our observations suggest that the crystals and nodules are the result of early to late diagenetic displacive growth within a soft mud, in agreement to what proposed by Marsaglia and Tribble (1999).

6 Implications for the salinity crisis

The result of our review and the facies associations for all the drillcores are shown in Figs. 5, 6 and 7. These new facies associations suggest different perspective for the salinity crisis compared to the previous interpretations (see also Table 1). We have already discussed some of the features that were considered to support a deep desiccation of the Mediterranean such as “subaerial canyons”, “fluvial deposits”, “shallow water fossils” and “subaerial carbonate dissolution”. They have also a different explanation, not exclusively related to desiccation (see Roveri et al., 2014a,b,c). The paradigmatic *deep basin shallow water model* (Hsü et al., 1973a) that envisaged the total desiccation of the Mediterranean Sea is built upon the fundamental pillar that the recognition of features present in supratidal deposits, interpreted to have deposited in a coastal sabkha environment, also are in the deepest portion of the basin. According to the previous suggestions of Hardie and Lowenstein (2004), who first challenged the shallow water-desiccation hypothesis, a thorough re-examination of the DSDP and ODP cores drilled in the deep Messinian evaporites reveals that:

i) no unequivocal evidence of the presence of shallow-water or even supratidal environment can be inferred;

ii) the largest part of the evaporites consists of cumulate or clastic deposits;

iii) the coarse clastic evaporites cannot provide clear paleobathymetric constraints, but can be exclusively associated with subaqueous environments.

(See Fig. 8.)

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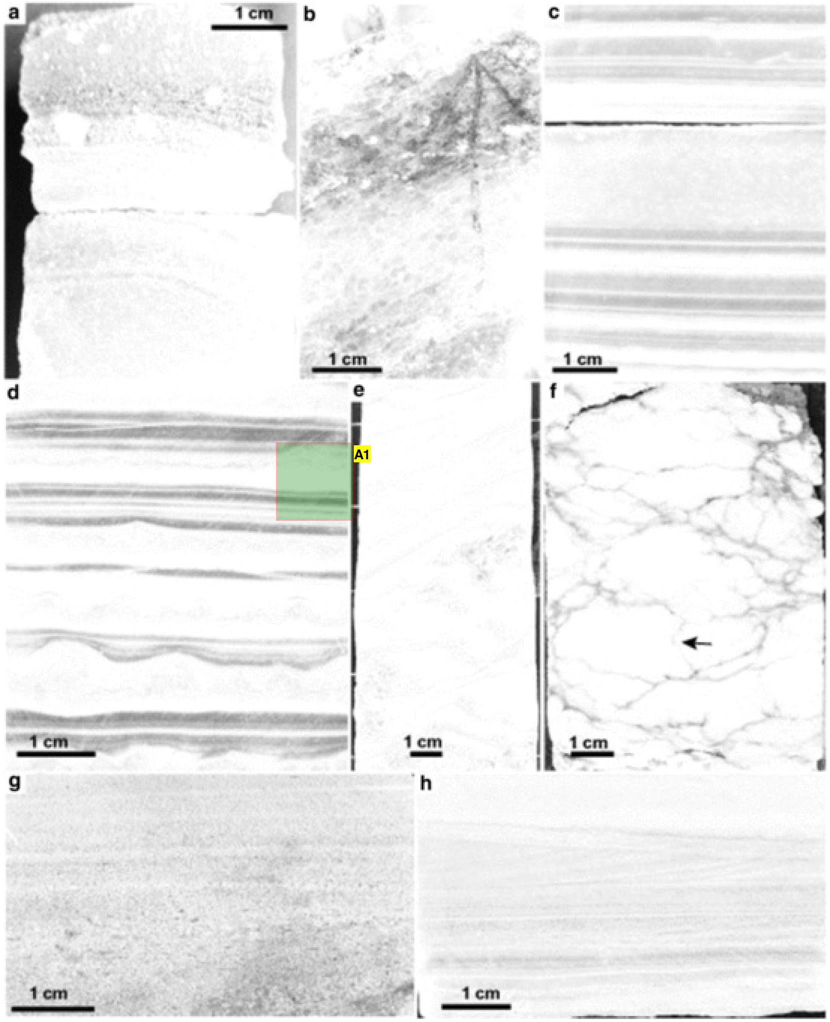

Fig. 6 Facies association for the cores that crossed evaporite sediments in the ODP and DSDP legs in the Tyrrhenian Sea.

Annotations:

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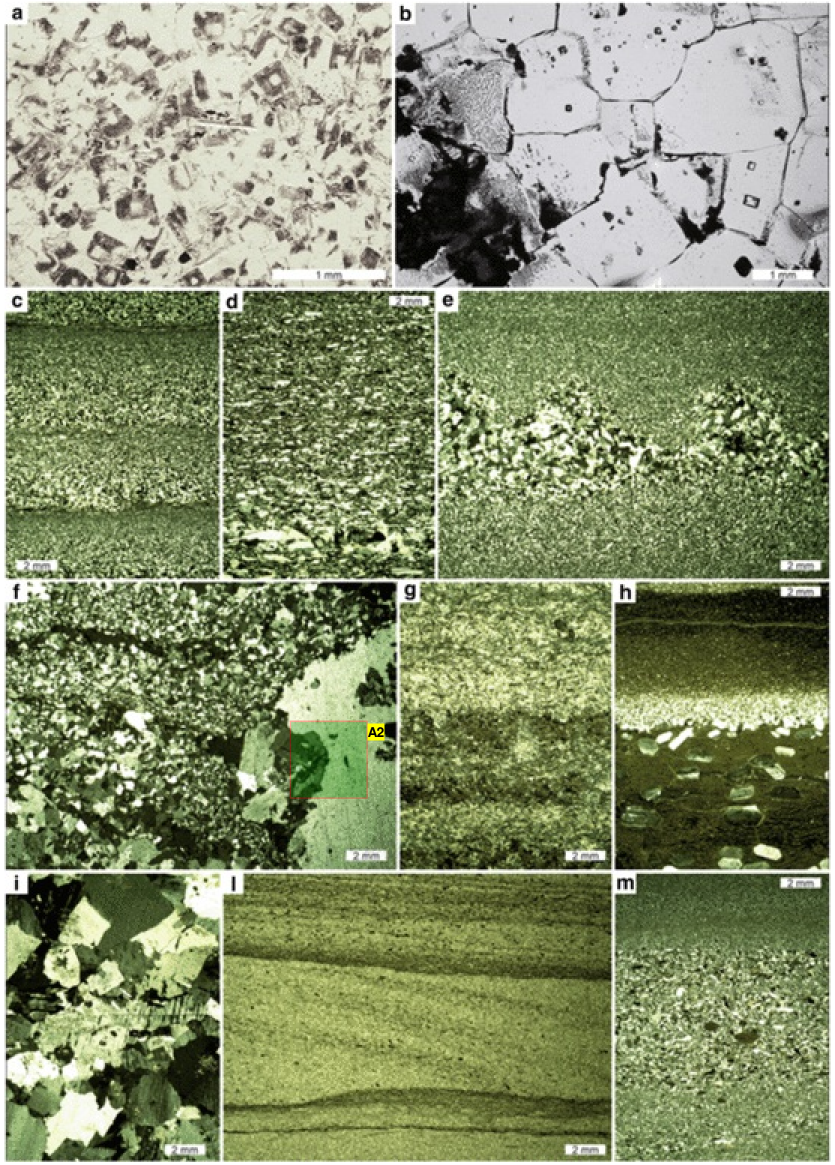

Fig. 7 Facies association for the cores that crossed evaporite sediments in the ODP and DSDP legs in the Eastern Mediterranean Sea.

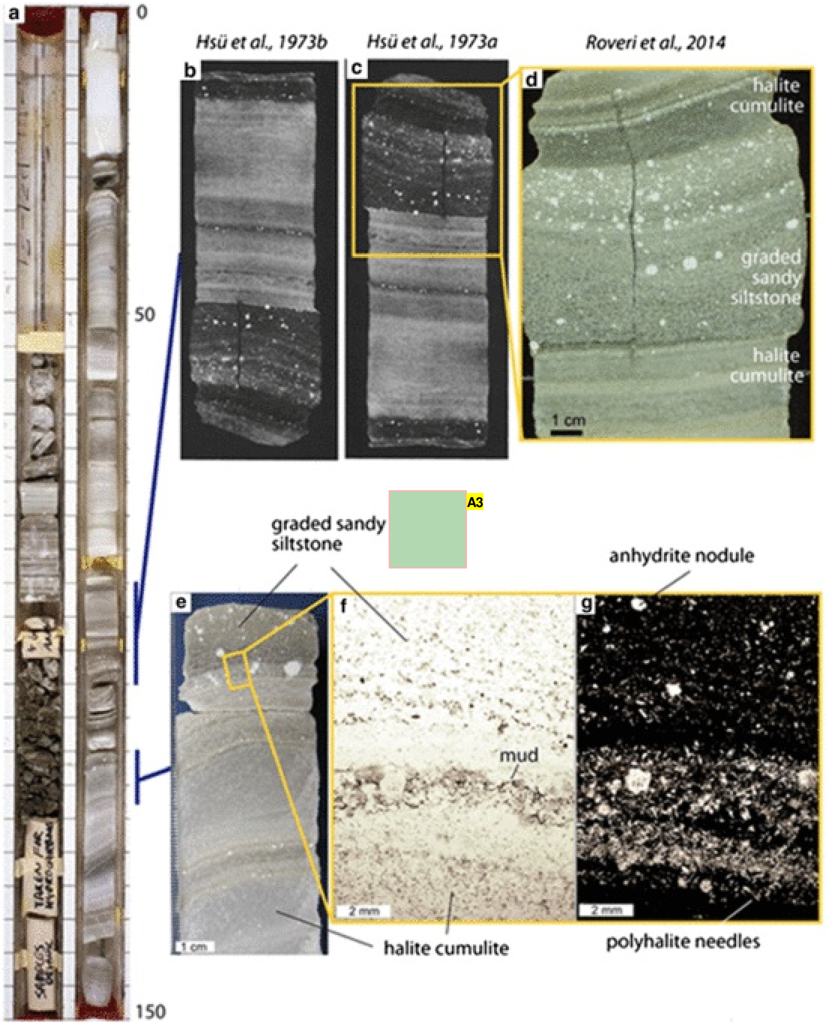

Fig. 8 a) Relationship between primary evaporites facies associations. b) relationships between primary and diagenetic facies.

The evaporites share many similarities with the onshore deposits accumulated in the deeper basins of the peri-Mediterranean areas that have been included in the Resedimented Lower Gypsum unit (Roveri et al., 2008). Clastic evaporites similar to those recovered during the ODP-DSDP cores have been recognized in several geological settings, e.g.. Apennines (Parea and Ricci Lucchi, 1972; Manzi et al., 2005), Sicily (Manzi et al., 2011), Spain (Fortuin and Krijgsman, 2003; Martinez del Olmo, 1996; Omodeo Salè et al., 2012), Greece (Kontopoulos et al., 1997; Karakitios et al., 2013) and Cyprus (Manzi et al., in press). These sediments have been interpreted as gravity flow deposits derived from the dismantlement of the primary gypsum deposits of the 1st stage of the salinity crisis. Primary cumulate gypsum and halite are also intercalated within clastic deposits in Sicily (Manzi et al., 2012) and Cyprus (Robertson, 1995; Manzi et al., in press).

Clastic evaporite deposits have been recently discovered in the onshore heads of the canyons excavated along the Levant margin (Israel; Lugli et al., 2013). These deposits lie unconformably atop an erosional surface that could be correlated to the base of the Lower Evaporite unit in the Eastern Mediterranean.

Although the large part of the cored deposits discussed here represents only the uppermost portion of the seismic Upper Evaporites unit and our observations ~~can not~~cannot be extrapolated for the entire Messinian suite, our findings suggest that the deposition of the late deep evaporites occurred in a persistent water body. This permanent basin was dominated by resedimentation of evaporite previously accumulated in shallow settings and by the formation of cumulate primary evaporites from supersaturated brine likely formed at the water surface or a density boundary (pycnocline) and have moved downslope by gravity, as suggested by Manzi et al. (2012).

7 Conclusions

Although the ODP-DSDP core record is fragmentary and limited to the topmost part of the Messinian evaporite sequences, a modern sedimentologic and petrographic study of all the available cores has been the only possible source of direct data on the sedimentary products of the salinity crisis lying at depth below the floor of the Mediterranean Sea. This has been possible even though some of the rocks have been modified by a complex array of diagenetic processes.

This study provided us with some significant clues:

a) understanding of the read-through factors useful for the interpretation of some of the diagenetic overprints, that have modified the original evaporite facies;

b) recognition of the significance of the widespread clastic and cumulate evaporites facies similar to the laminar gypsum in Sicily (Manzi et al., 2012);

c) rule out the presence of sabkha environment and of desiccation features, including the famous “desiccation crack” (Hsü et al., 1973a,b).

The major portion of the evaporites collected by ODP and DSDP cruises are clastic or cumulate deposits that cannot provide clear bathymetric indications but do help us to exclude shallow-water and supratidal depositional environments and a total basinal desiccation. Conversely, our data suggest that the deeper portion of the Mediterranean Sea was characterized by a permanent water body during the last phase of evaporite deposition.

8 Uncited reference

Karakitsios et al., 2013

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Highlights

- We reexamined the Messinian evaporites below the floor of the Mediterranean Sea.
- We recognized mainly clastic and fully subaqueous evaporite deposits.
- No unequivocal evidence of shallow water or supratidal deposition is in evidence.
- Evaporite deposition took place under permanent subaqueous conditions.
- During the last phase of the salinity crisis the Mediterranean was not desiccated.

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Answer: Roveril M. and Manzi V., The Messinian salinity crisis: looking for a new paradygm? *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **238**, 2006, 386-398.

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Answer: Dela Pierre F., Clari P., Bernardi E., Natalicchio M., Costa E., Cavagna S., Lozar F., Lugli S., Manzi V., Roveri M., Violanti D., Messinian carbonate-rich beds of the Tertiaty Piedmont Basin (NW Italy): Microbially-mediated products straddling the onset of the salinity crisis, *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **344-345**, 2012, 78–93.

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