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Algal crusts, autochthonous and clastic gypsum in a cannibalistic evaporite basin: a case history from the Messinian of Northern Apennines

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ABSTRACT

The Messinian Vena del Gesso Basin in the Northern Apennines is filled by very thick (up to 35 m) beds of coarse crystalline gypsum (selenite) associated with thinner carbonate and shaly (euxinic) intercalations. The conventional Usiglio model of salt fractionation does not apply to this evaporitic sequence for the following reasons: carbonate which underlies gypsum is not evaporitic but algal in origin; most gypsum did not precipitate from surface brines but at and below a sediment-water interface occupied by algal mats; a significant portion (10–80%) of gypsum beds is composed of redeposited selenite which was removed from the margins and transported toward the centre of the basin by slope-controlled currents and gravity flows (debris flows).

We call this process cannibalistic because of its intraformational character (connected with evaporative fall of water level) and volumetric importance.

A recurrent vertical pattern of six main facies (euxinic to gypsum fanglomerates) is interpreted as a bathymetric, regressive cycle controlled by both sedimentological and tectonic-eustatic factors. The inferred environmental setting is a residual turbidite trough (Marnoso-arenacea) evolving abruptly toward lagoonal conditions and filled up to sea level by evaporitic and mechanical (mostly fluvial) processes. Repeated inundations of restricted-marine water started the depositional cycle thirteen or fourteen times.

INTRODUCTION

The Messinian (Upper Miocene) evaporite formations of the Mediterranean area are characterized by massive beds (up to 35 m thick) of coarsely crystalline gypsum (selenite). No close analogues of these bodies are found in the recent record: selenite occurs as isolated crystals, clusters and rosettes growing within organic, detrital and carbonate sediments of intertidal and supratidal zones. Messinian selenite has been studied from the mineralogical and petrographical viewpoint since last century (for references see the monograph by Ogniben, 1957). Only recently were detailed observations made on its megascopic appearance and sedimentary structures, and its primary origin proposed by comparison with modern occurrences (Hardie & Eugster, 1971; Nesteroff, 1973; Richter-Bernburg, 1973; Schreiber, 1973; Schreiber & Kinsman, 1975; Sturani, 1974, personal communication). Systematic patterns of facies variations in selenite beds and associated sediments have so far received less attention; some depositional cycles were described only in thinbedded selenite units (Schreiber *et al.*, 1976; Heiman & Mascle, 1974).

The purpose of this paper is to illustrate and discuss some new data from the Vena del Gesso Basin of Northern Apennines (Emilia-Romagna region); the main items are the following: (1) the regular recurrence of a well defined vertical sequence of facies within the selenite beds; (2) the growth of selenite in association with algal mats; (3) the importance of intraformational reworking and redeposition of selenite (evaporitic cannibalism).

GEOLOGIC SETTING

The Vena del Gesso is a gypsum body 150–170 m thick outcropping as a continuous ridge along the Apennines strike for a distance of 30 km, from the Sillaro Valley to the west to the Marzeno Valley to the east (Fig. 1). The inferred original extent is approximately 100 km (Fig. 2). Most of the Vena del Gesso (which is the local expression of the Gessoso-solfifera Formation of the Apennines and Sicily) was dismembered by gravity tectonics (see area of allochthonous units in Fig. 2) or buried by thick Plio-Pleistocene sediments of the Po Valley. The linear outcrop of the Vena del Gesso is part of a thick homocline gently dipping toward the Po alluvial plain (NE). The basin was bounded by tectonic highs which can still be recognized in the subsurface (to the northeast) and in outcrop (to the east).

Other evaporitic basins of apenninic Periadriatic area, with different thickness and types of facies, are not shown in Fig. 2. Some of them had been sinking and filling by turbidites since Early-middle Miocene, others were set up during the Messinian in areas of previous stability and slow hemipelagic sedimentation. For more information, see Ricci Lucchi, 1975).

STRATIGRAPHY

The stratigraphic succession encompassing the evaporite formation (Gessoso-solfifera Formation) is the following from top to bottom:

3—	marine blue-grey clays	Pliocene
	unconformity	------
2—	(c) post-evaporitic clastics	
	(b) gypsum, carbonates, and shales (Gessoso-solfifera)	Messinian
	(a) pre-evaporitic euxinic shales	
1—	(b) slope mudstones	---
	(Marnoso-arenacea)	
	(a) channelized deep-sea fan sandstones	Tortonian

The slope mudstones form the top of a progradational, off-lapping turbidite suite (Ricci Lucchi, 1975): they consist of silty marls and clayey marls (30–40% $CaCO_3$)

Fig. 1. Central part of the Vena del Gesso Ridge (view from south east). A, B, C: location of the sections of Fig. 3. Open triangles indicate the base of the evaporites.

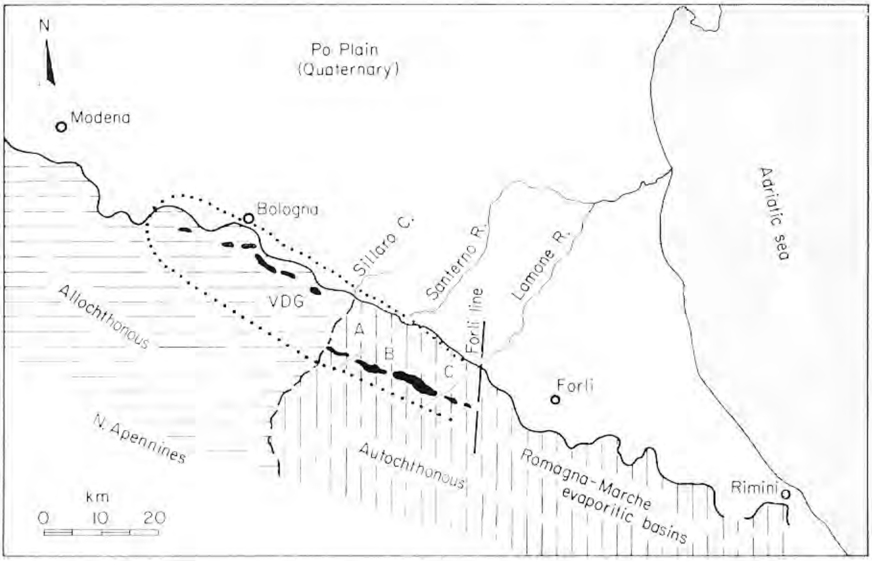

Fig. 2. Vena del Gesso outcrops (black) and inferred original extent of the basin (VDG) delimited by dotted lines. Forli line: structural high separating VDG from Romagna-Marche evaporite basins to the southeast.

with thin intercalations of very fine sandstones which gradually disappear upwards. Deposition in open marine waters of depth in the order of some hundreds of metres is inferred from the fauna where planktic forms (foraminifers, coccoliths, pteropods) prevail on benthic forms (foraminifers, gastropods, pelecypods).

The upper transition to euxinic shales is lithologically gradual but palaeontologically quite abrupt (overall impoverishment of the fauna, disappearance of pteropods, strong reduction in the number of planktic foraminifers, restriction of benthos to a few specialized forms, preservation of organic matter, fish, insect and plant remains). These modifications, common to the entire Periadriatic area, have been attributed to restricted water circulation and density stratification related to increasing salinity (Parea & Ricci Lucchi, 1972) or as independent from evaporitic conditions (Sturani and Sampo', 1974).

The base of the Gessoso-solfifera is represented by a carbonate level (Calcare di base) whose origin was assumed to be an inorganic evaporitic precipitate until very recently (Ogniben, 1957; Parea & Ricci Lucchi, 1972; Richter-Bernburg, 1973; Hsü, 1973). Sturani (1973) first discovered (in equivalent units of the Piedmont Basin) stromatolitic, tepee and desiccation structures. We subsequently re-examined outcrops and specimens from other areas of Periadriatic Apennines (Romagna, Marche) and found a substantial confirmation of the non-evaporitic origin of Calcare di base (see next section). This means that it should be placed at the top of the pre-evaporitic sequence rather than at the base of the evaporite formation. A further implication is that a remarkable shallowing occurred during or after the deposition of euxinic shales; it is not reflected by apparent facies transition but by sudden palaeontological changes (data under study) and by slumps involving also the 'basal' limestone (Ricci Lucchi, 1973; and Fig. 3). The possibility that such a depth change was produced by a sudden evaporative drop of sea level, inducing failure on exposed slopes, was suggested by Sturani (1975) in the light of the 'desiccation model' proposed by Hsü, Cita & Ryan (1973). As soluble salts were not precipitated, a reflux of residual brines to the ocean or to other parts of the Mediterranean is implied: this poses palaeogeographic problems which still await a solution. We also point out the Calcare di base is not a lithostratigraphic unit but a facies occurring repeatedly within the evaporitic formation (see next section).

Overlying evaporites consist of thick gypsum beds usually separated by euxinic shales and locally, algal carbonates; a cyclical pattern of sedimentation is clearly developed in the whole formation and will be described below. We recognized, on a reconnaissance basis, strikingly similar characteristics of bedding, facies and cyclicity in the stratigraphically equivalent Gessi Inferiori (Lower Gypsum) Formation of Sicily, described by Decima & Wezel, 1971, 1973.

Post-evaporitic Messinian sediments of the Vena del Gesso area are a condensed equivalent (about 10 m thick) of the clastic Colombacci Formation of the Periadriatic Foredeep and of clastic-evaporitic Gessi Superiori (Upper Gypsum) and Arenazzolo formations of Sicily which may reach a thickness in excess of 400 m. They consist of grey marls enclosing acicular gypsum crystals, varicoloured clays, and cross-bedded coarse sandstones and conglomerates of probable continental (fluvio-lacustrine) deposition.

THE DEPOSITIONAL CYCLE

Depositional cycles varying in thickness and number of component members were recognized and measured in two major sections (Fig. 3) and sparse outcrops of Gessoso-solfifera. The modal cycle (Fig. 4), which is also the most complete, will be described in detail, then the main variations, the number and correlation of cycles will be briefly dealt with.

Each major gypsum bed is preceded and followed by a shaly or shaly-carbonate parting; this couplet represents a first-order, evaporitic-clastic or evaporitic-euxinic cycle. Ogniben (1957), following Sander (1936), called it a m-rhythm (m means metre scale). As the shaly bed indicates the return to depositional conditions preceding the onset of evaporite precipitation, it seems logical to assume it as the lower member of the cycle.

The picture of a binary cycle or rhythm is greatly simplified: there are, as a rule, more than two rock types or facies forming complex sedimentation units. Though keeping the shale-gypsum couplet as a first approximation descriptive term, we split the cycle into six members or facies following each other in the same constant order. Four of these facies have been established within what is usually called a single gypsum bed. We use here the term facies for a distinct, relatively homogeneous lithological interval consisting of an individual bed, a group of beds or an internal subdivision of a bed. Facies will be referred to also as members, particularly when alluding to their thickness.

The order of description is from the base upwards.

Facies 1—Bituminous shale (see base of Figs 10, 12)

Description. Finely (paper-thin) laminated silty clays and silts with rare laminae of

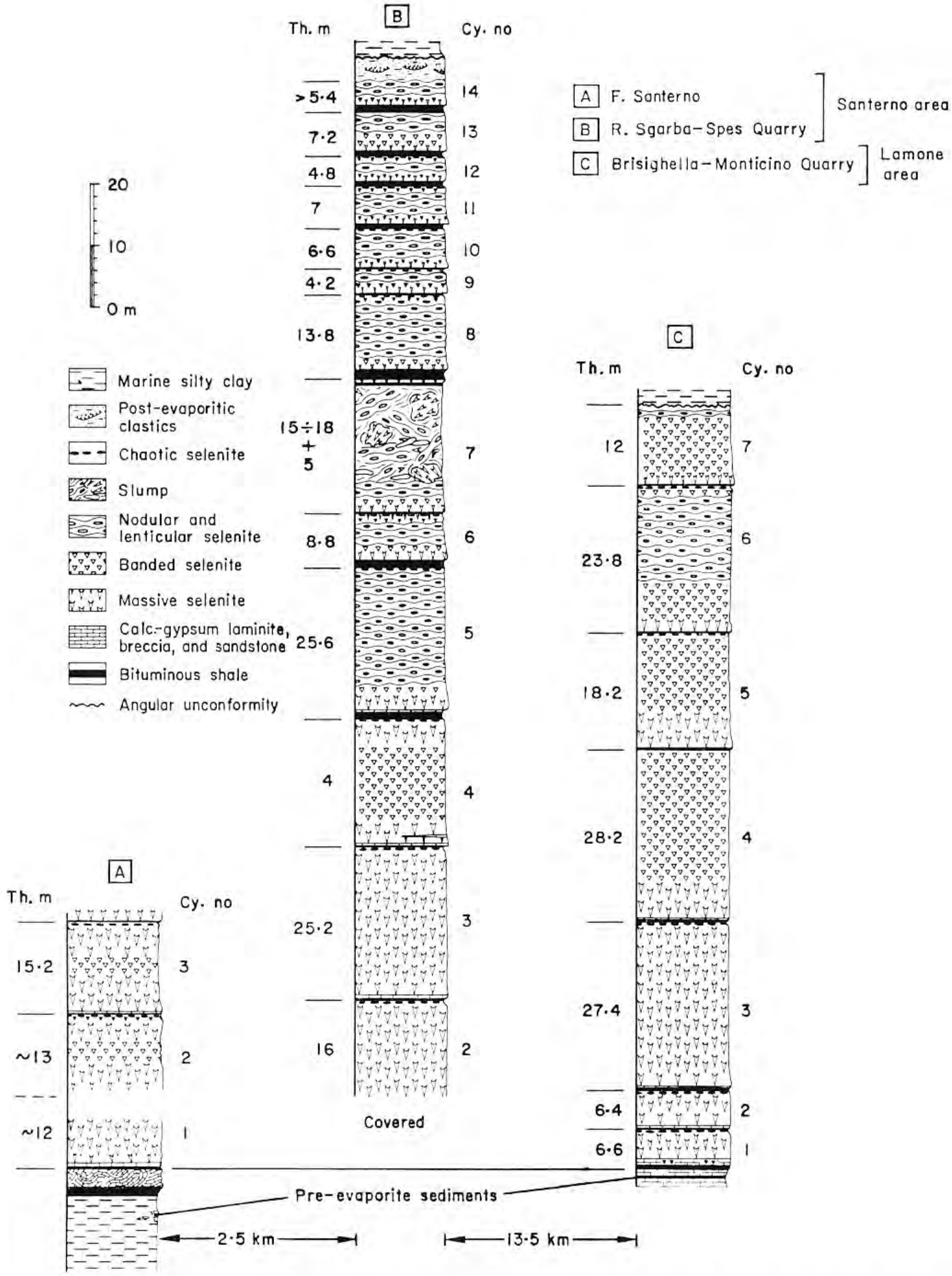

Fig. 3. Recurrence of depositional cycles in Gessoso-solfifera formation of Vena del Gesso Basin. The basal cycle is covered but recognizable in B.

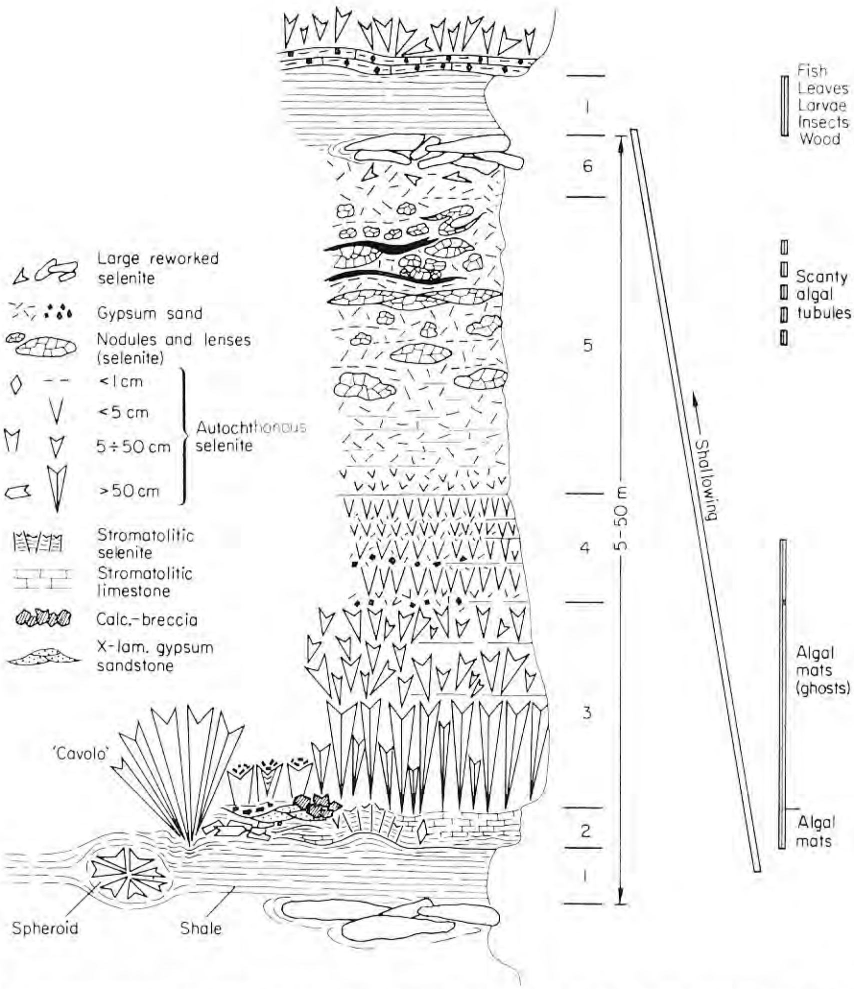

Fig. 4. The ideal cycle composed of six facies: diagram showing peculiar features and regular sequence of facies.

very fine sand; they have a dark-blue colour (yellow on weathered surfaces) and a high content of vegetal debris, bituminous matter, authigenic pyrite, calcite and gypsum. The two last minerals are found in scattered euhedral crystals whose maximum size (0·25 and 1·0 mm, respectively) greatly exceeds that of enclosing clastic particles, whereby they are regarded as chemical, diagenetic components. The carbonate amounts to 25–30% (computed as $CaCO_3$); both calcian and stoichiometric dolomite are present (ratio to calcite about 1 : 6). Fossiliferous content: euryhaline fishes (*Pachylebias*, etc.), insects, leaves and twigs, oligotypical benthic forams (*Ammonia, Elphidium, Bolivina*, etc.), rare planktic forams (small Globigerinae). The almost complete absence* of megabenthos and bioturbation is remarkable.

* Selli (personal communication, 1975) found oysters (*Pycnodonta cochlear*, which is present today below a depth of 50 m) and other marine molluscs in one of these shaly beds (1–2 m thick).

The thin laminae are even, plane or slightly wavy, and look like lacustrine varvae; isolated sets (1–3 cm thick) of wave or current ripple-cross laminae are sporadically intercalated. Other features are: plastic deformations reflecting load structures of overlying gypsum, and scattered diagenetic spheroids up to 1–2 m in diameter composed of radially arranged selenite twins.

The bituminous shales form distinct beds up to 2 m thick and of great lateral continuity.

Interpretation. Slow settling of fine-grained terrigenous particles and organic remains on a muddy bottom of undetermined depth. The lamination is probably the result of small seasonal variations of the terrigenous input. The preservation of laminae and organic matter indicates the existence of anoxic conditions; water exchanges with the open sea were strongly reduced but not totally suppressed as shown by the fauna. We can deduce that, on average, the rate of oxygen consumption was higher than the rate of supply. Low-energy waves sporadically impinging on the bottom suggest a shallow depth, but their evidence is not undisputable.

Facies 2—Calc-gypsum algal laminate (stromatolite), breccia, and sandstone (Figs 5–9)

The most significant feature of this facies is the presence of algal stromatolites. They were preserved either in place or as reworked fragments, and cemented by carbonate and/or gypsum. A number of sub-facies can thus be distinguished.

Stromatolitic limestone (Fig. 5)

Description. Limestone beds 5–20 cm thick (a maximum thickness of 50 cm was recorded in the 'basal limestone' of lowermost cycle) vertically grading into shales (varying ratio of carbonate and silty-clayey laminae) or passing abruptly (indented contact) to gypsum of facies 3. Thin (1 mm or less), plane to wavy, locally crenulated laminae with organic structures are sporadically intercalated by thicker clastic laminae. The first type of laminae is characterized by a network of shoestring or spaghetti-like micritic bodies (Fig. 5b) mostly lying on laminar surfaces and looking like pellets in transverse sections. These cylindrical bodies have a diameter of 0·06–0·1 mm (average 0·08) and a maximum length of about 1 cm. Most of them appear structureless in thin section and more or less dark-stained by organic matter and iron sulphide; in some cases it is possible to distinguish an external coating from an inner part. Interstitial spaces are occupied by micrite and sparite in variable proportions, sometimes with anhedral gypsum in the centre. Both framework and cement are composed of calcite with the exception of the basal limestone of lowermost cycle, where protodolomite occurs in a 1 : 1 ratio to calcite (R. Sartori, personal communication).

Clastic laminae consist either of isolated tubular fragments in micrite matrix or of tabular fragments of indurated laminae and lamina-sets still surrounded by micrite and lying flat or edgewise (flat-pebble conglomerates with maximum thickness of a few centimetres and grain size of 1 cm).

Interpretation. Previous descriptions based on thin sections overlooked the three-dimensional aspect of this facies (Ogniben, 1957, 1963; Rabbi, 1964; Rabbi & Ricci Lucchi, 1968): the pelletal or grumuleuse texture was regarded as the product of flocculation of carbonate-clay particles with subsequent rounding by gentle agitation. A possible faecal origin was discussed and rejected by Ogniben (1963); we may add to

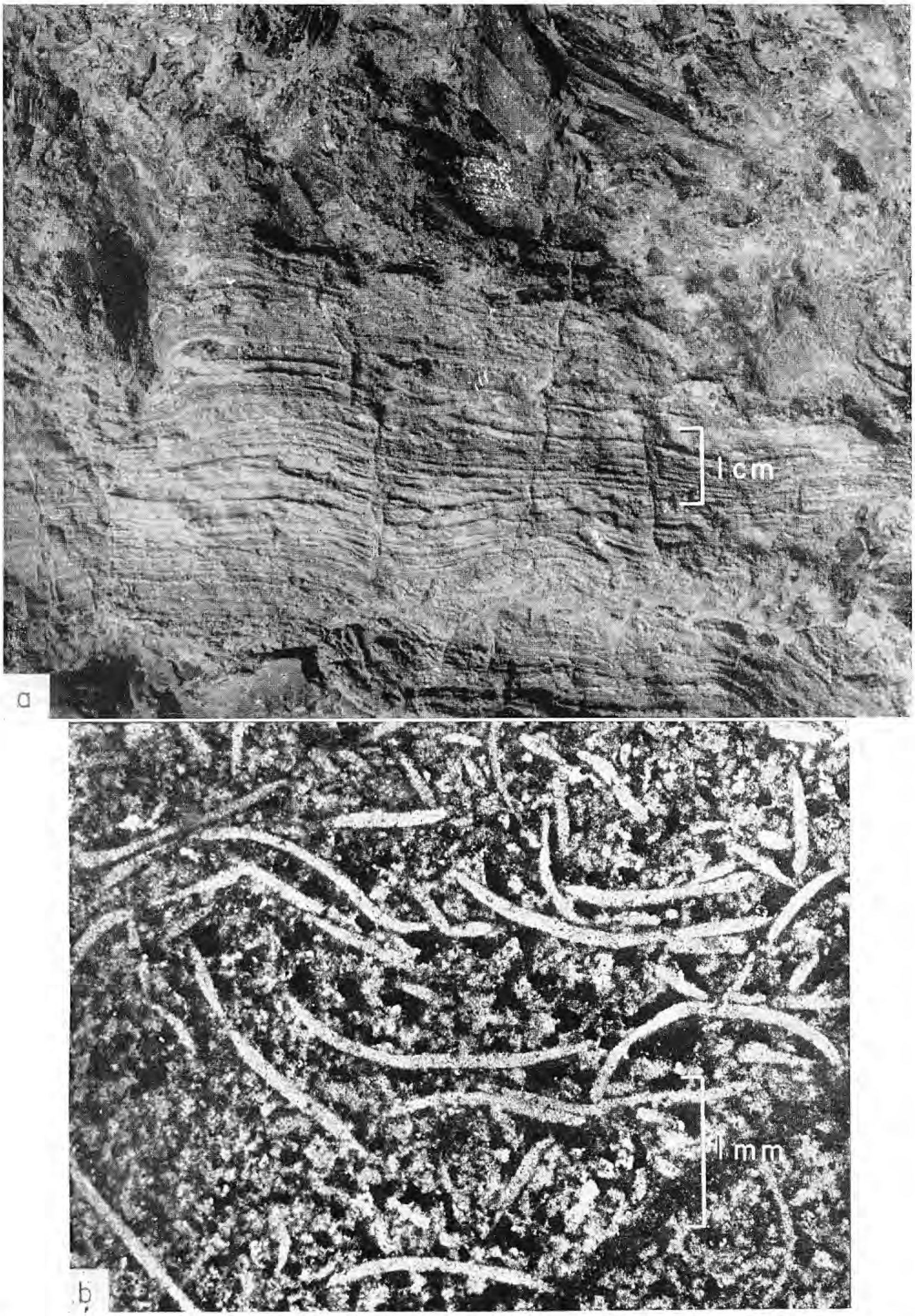

Fig. 5. Facies 2. (a) Stromatolitic limestone passing abruptly into selenite gypsum of facies 3. Outcrop view, Monticino quarry, Brisighella. (b) Shoestring-like micritic coatings of algal filaments. Thin section cut parallel to bedding.

his arguments that supposed burrowers like *Artemia gracilis* (a crustacean tolerating hypersaline conditions) produce pellets much shorter (1 mm max.) than our shoestrings. On the other hand, their striking morphologic similarity with recent algal crusts (compare Fig. 6a, b) supports their interpretation as coated algal filaments. The limited episodes of mechanical reworking may be related to subaerial exposure, but the lack of desiccation structures, birdseyes, etc. in most laminae induced us to believe that algal mats grew in subtidal and partly intertidal conditions (see Gebelein & Hoffman, 1973, for recent analogues). Absence of predators favours the subtidal extension of algal mats (Garrett, 1970), and this condition did occur in the Messinian as pointed out by Hardie & Eugster (1971) and Schreiber *et al.* (1976).

L. Hardie (personal communication, 1976) disagrees with the subaqueous interpretation. He points out that the calcified algae in the Everglades and Bahamas occur in fresh water marshes; these algae (*Scytonema* sp.) do not survive in subtidal environments nor do they calcify in seawater or very brackish water. J. Smoot (personal communication, 1976) adds that absence of birdseyes and crinkles in the mats may also be due to the coarse filamentous nature of the mats, the lack of abundant fine-grained detritus and the possibility of it being kept continuously wet. We agree that a freshwater algal marsh setting should be seriously considered, provided that the Messinian algae are exactly comparable to recent ones.

The stromatolitic limestone of the basal cycle has an almost basinwide distribution, whereas its lateral continuity is reduced in the other cycles where transition to gypsified mats are more frequently observed.

Stromatolitic selenite (Figs 6, 7)

Description. Lenticular beds 5–30 cm thick composed of upstanding selenite crystals of length equal to bed thickness. The selenite encloses micritic algal laminae whose filament coatings can be seen with a hand-lens. The beds may be internally layered by dissolution surfaces and clastic calc-gypsum laminae interrupting the algal laminae and the selenite crystals. The algal laminae are also truncated laterally by dissolution or erosion furrows filled by pocket of calc-gypsum detritus. Adjacent selenite crystals show compromise boundaries, often stylolitic; clear syntaxial rims grew where interstices were available. Deformation of the interstitial fill seems to indicate that overgrowth was displacive and occurred after corrosion or erosion of the already gypsum-cemented algal framework. Occasional mechanical breakdown is shown, for example, by inclined and partly ripped-up crystals (Fig. 7b); the spatial association of stromatolitic selenite with clastic laminae is well illustrated by Fig. 7a.

Isolated or clustered selenite crystals within carbonate stromatolites mark the transitional relations of calcite-cemented and gypsum-cemented algal laminites (Fig. 7c).

Interpretation. This facies represents gypsified algal mats. The coatings of algal filaments are in fact identical to those preserved in the carbonate levels. The gypsum poikilitically invaded the algal framework during or immediately after its accumulation as indicated by the intraformational reworking which affected the already indurated crust. A subtidal to intertidal precipitation of selenite was postulated by Hardie & Eugster (1971) and Schreiber *et al.* (1976). A supratidal growth would be suggested by known recent occurrences of selenite (Masson, 1955; Kerr & Thomson, 1963; Shearman, 1966; Kinsman, 1966, 1969; Butler, 1969; Kendall & Skipwith 1969; etc.) and particularly by its association with algal crusts (Horodyski & Vonder

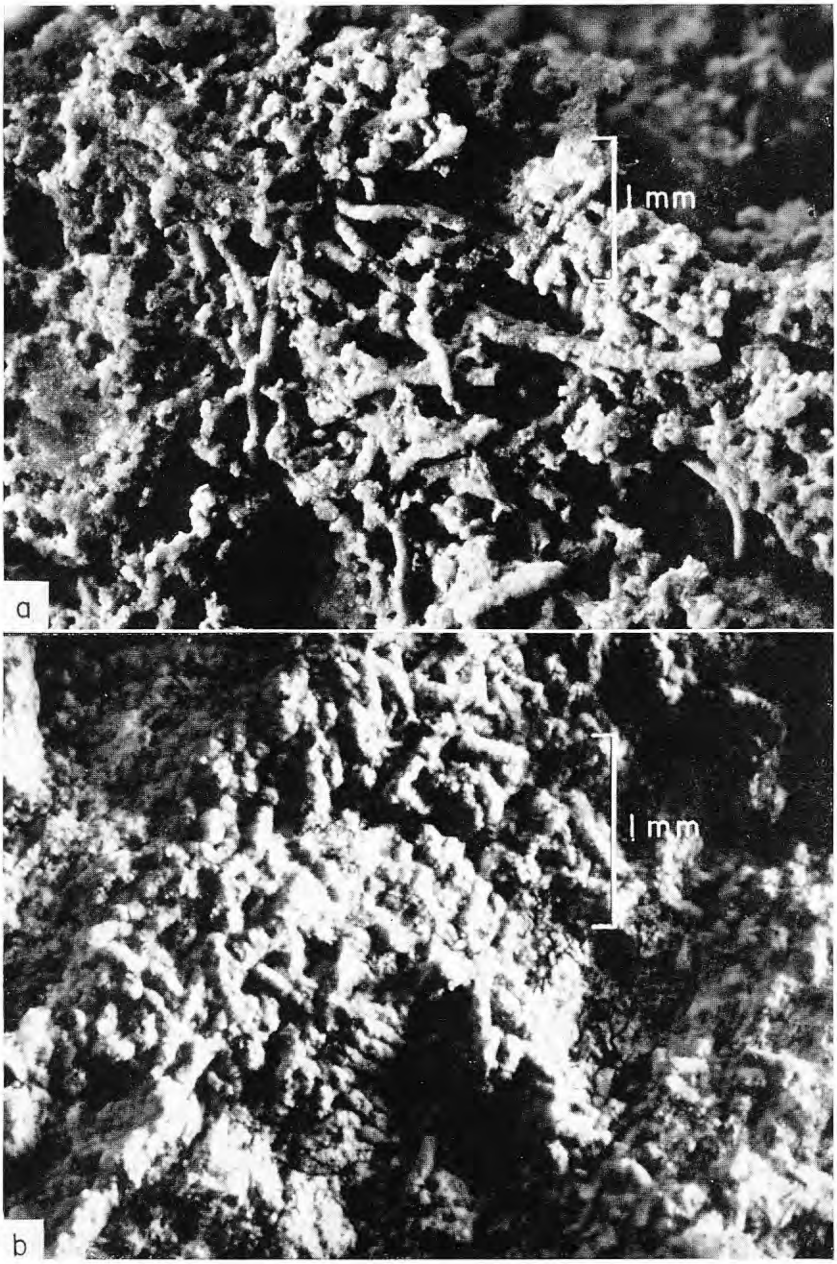

Fig. 6. Facies 2: stromatolitic selenite. (a) Framework of micritic algal tubules visible after leaching of gypsum. F. Santerno, Borgo Tossignano. (b) Same texture in a recent inter to supratidal algal crust. Everglades, Florida (sample kindly provided by R. Sartori).

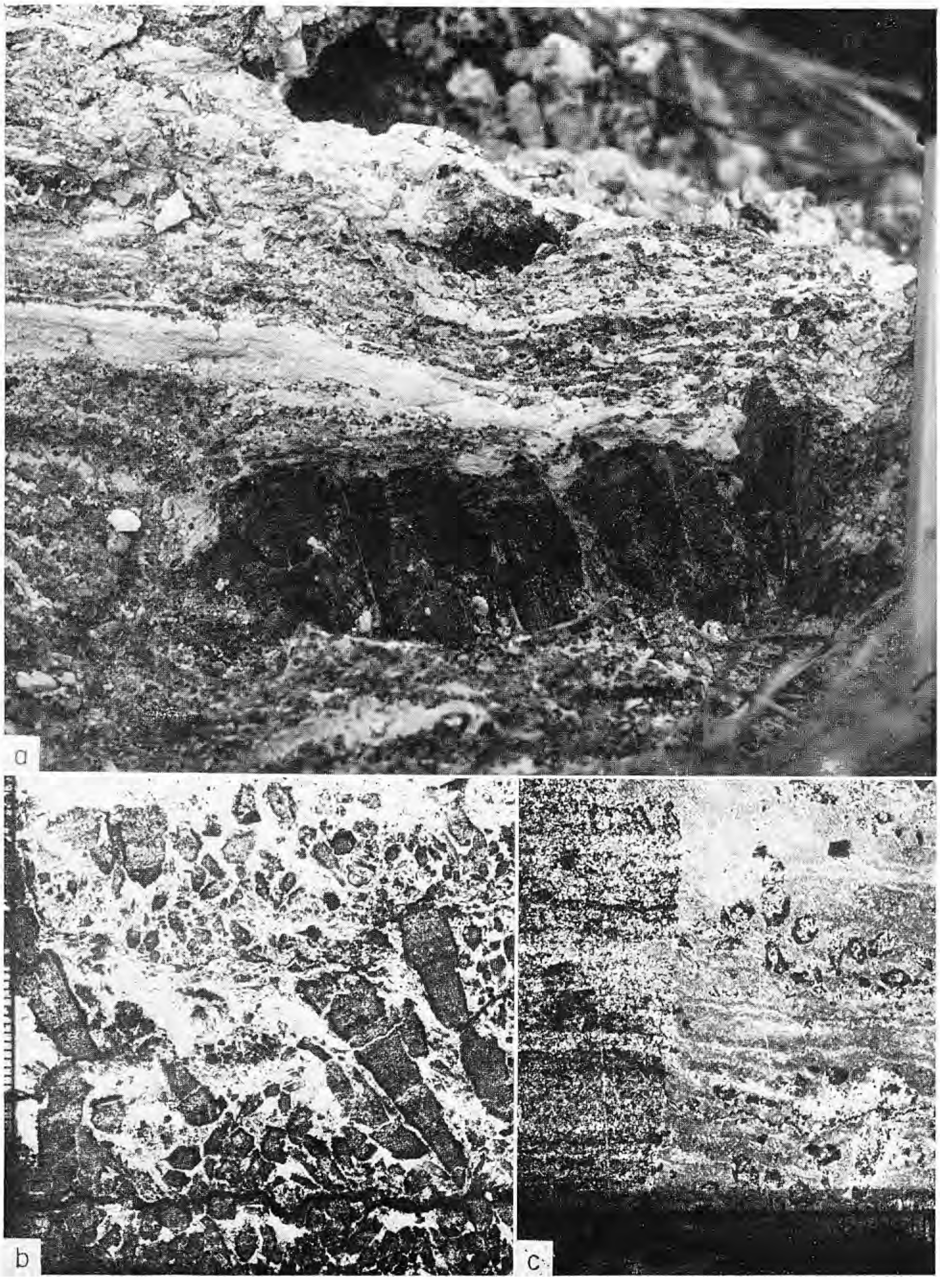

Fig. 7. Facies 2: stromatolitic selenite. (a) Dark selenite 'palisade' showing faint algal laminae, enclosed by clastic laminae. Pencil for scale, F. Santerno, Borgo Tossignano. (b) Mechanical reworking of stromatolitic gypsum: inclined and slightly removed selenite crystals with marked clear (black) syntaxial rim; white matrix is carbonate. Polished slab. (c) Sharp lateral transition between gypsum-cemented and calcite-cemented algal laminites. A single selenite crystal (left side) poikilitically cements the mat. Polished slab.

Haar, 1975; Hardie, personal communication, 1976; Smoot, personal communication, 1976). We favour at the moment a subaqueous precipitation on the basis of the almost continuous, undisturbed crystal growth (which is more evident in next facies 3, massive selenite).

The algal-free rims of selenite crystals reveal a distinct growth stage of displacive character which occurred after definitive but probably shallow burial (see also DSDP cores from the Balearic Basin: Ryan *et al.*, 1973, Fig. 16, Chapter 6). The temporal relation between carbonate and gypsum cementation of algal framework cannot be clearly defined; available data do not suggest either mutual replacements or simultaneous growth (absence of competing crystal boundaries), but this problem has petrographical and geochemical implications which have not been considered in this work. We think that precipitation of selenite was first localized, then expanded its domain with increasing salinity. The spaces left by the first gypsum crystals were possibly occupied by micrite and coarser carbonate material, before the massive precipitation of sulphate occurred.

Calcareous breccia

Description. The occurrence of this facies is much more limited areally than the previous ones. Two varieties can be recognized: (a) fractured beds of stromatolitic carbonate with no or little displacement of fragments (welded by sparite or gypsum); similar deposits were described by Schreiber & Friedman, 1976; (b) irregular lenses, decimetre to a metre thick, of disordered breccia (Fig. 8) composed of centimetre-size, angular, irregularly shaped clasts of stromatolitic limestone. The clasts are self-supporting, interstices being filled by a micritic matrix (including loose algal filament coatings) or, more rarely, by crystalline gypsum. No sedimentary structures were observed.

Interpretation. We saw type (a) brecciation clearly related with load deformation imparted by overlying clusters of growing gypsum crystals (see facies 3 below); type (b) may derive from strong local turbulence, slumping or, more probably, solution collapse of interbedded carbonate and gypsum. The fragments do not look like desiccation polygons but very irregular bodies; they are not admixed with foreign material or worn. The filament coatings in the matrix suggest a penecontemporaneous origin of the breccia possibly connected with salinity fluctuations of the initial evaporative stage.

Laminated calc-gypsum sandstone (Fig. 10)

Description. Beds, 30–60 cm thick of fine to very coarse sandstone composed of gypsum and carbonate grains with minor amounts of quartz, feldspar, mica and vegetal fragments; the coarser sandstone is poorly sorted and contains a clayey-carbonate-gypsiferous matrix. The gypsum grains are cleavage flakes or irregular fragments of selenite crystals with low degree of roundness. The beds, which have a good lateral continuity, are entirely laminated with prevalence of plane-parallel, wavy and low-angle laminae; ripple cross-lamination is sporadically present with small, mostly isolated and symmetrical ripple forms (Boersma, 1970; Newton, 1968) and truncated wave ripple laminae (Campbell, 1966). Small scour-and-fills with granule and pebble-size gypsum were noted. No evidence of graded bedding or turbidite like those occurring in other Periadriatic basins was found (Parea & Ricci Lucchi, 1972; Ricci Lucchi, 1973).

Fig. 8. Facies 2: limestone breccia of type (b); algal tubules visible within fragments; the cement is gypsum. Bar is 1 mm. 'Calcare di base', F. Santerno, Borgo Tossignano.

Interpretation. These deposits are clearly the products of tractive flows of both upper and lower flow regime. They are attributed to current and wave activity sweeping the algal crusts and redistributing the intraformational detritus in the sublittoral to supralittoral zone. No major bodies were formed in this way.

Flat-lying selenite crystals (Fig. 9)

Description. Patches of interconnected or loose selenite crystals lying with their long axes in the plane of bedding. The crystals have a prismatic-pseudohexagonal habit but contain a turbid core with a needle-like swallow-tail shape and clayey, organic and algal inclusions. The surrounding clear overgrowth has a greater volume than the core.

This facies does not form well defined beds but a sort of pavement or crust some centimetres thick which loses its identity downwards where crystals rarify and are embedded within bituminous shale. Stellate aggregates or random orientations are visible here, whereas a certain degree of alignment and intercalations of gypsum sand appear in the upper part.

Interpretation. Two possibilities are suggested: (1) the crystals grew horizontally, which is quite unusual for selenite and seems contradicted by the arrangement of the

Fig. 9. Facies 2: flat-lying selenite crystals; stellate aggregates of or randomly oriented prismatic twins directly above bituminous shales of facies 1. Photographed from below; bar is 1 mm; SPES quarry, near Borgo Tossignano.

Fig. 10. Facies 2: laminated calc-gypsum sandstone. Wavy lamination with some faint cross-laminae; some half millimetre-thick laminae of bituminous shales are visible at the very base of the sample. SPES quarry.

inclusions; scattered algal tubules, however, cross the growth lamellae; (2) crystals first grew vertically on soft mud, then fell apart when reaching a certain weight or because of slight mechanical disturbance; the wider than usual overgrowths should have formed when the crystals already lay flat and loose. A late diagenetic origin is excluded by the algae and the clear overgrowths which testify the same growth stages of other selenite varieties. We suppose that sparse crystals of this type began to grow on the quiet muddy bottom of the euxinic facies; their number progressively increased with increasing salinity, while a slight agitation oriented them and removed some mud and algal mats.

Facies 3—Massive selenite (Figs 11–13)

Description. This facies, described as 'coarse twinned selenite' by Hardie & Eugster (1971), provides the greatest volumes of gypsum (see Fig. 3). It forms parts or members of complex gypsum beds with a thickness ranging from 80 cm to more than 30 m. Typical swallow-tail twins show their maximum development here (length: 10–100 cm) with a fining-upward trend through the member (Fig. 12); they have a more or less pronounced orientation known as Mottura rule (elongation normal to bedding, tails pointing upwards, Fig. 12). At the base of the member (which is also the base of the bed), the twins are often arranged in conical clusters (baptized as cavoli by Richter-Bernburg, 1973) with apices pointing downwards and protruding into underlying laminated deposits which are bent and broken (Fig. 12). When exposed, these basal surfaces show knobs known as mammelloni in the Italian literature (Ogniben, 1957; see Parea & Ricci Lucchi, 1972, Fig. 15). In other cases, the crystals have a more uniform vertical fabric and the base of the bed is flat.

The selenite mosaic is tightly interlocked with serrated and sutured contacts underlined by carbonate-clayey films (Fig. 13); it results from two stages of growth. The first stage formed an open framework of turbid twins which enclosed carbonate, clay and organic impurities along with algal tubules; the second stage enlarged the crystals by adding displacive clear overgrowths which squeezed and concentrated the remaining interstitial material. The turbid core of selenite twins shows a chevron pattern of lamellae (Fig. 11) marked by different concentrations of algal tubules on upper crystal faces (where also pockets of detrital gypsum may be trapped).

Repetition of the upward crystal-size grading may result in a faint bedding toward the top of the member.

Interpretation. The origin of the thick-bedded selenite is inferred to be essentially the same of previously described stromatolitic gypsum. In this case a more massive and apparently continuous poikilitic growth occurred in algal mats; this suggests to us a slightly deeper, subaqueous environment (however, we do not disregard the possibility of a supratidal setting as suggested by Hardie & Smoot, personal communication, 1976). The V-shaped pattern of algal laminae might be attributed to: upward pressure of growing crystals against an overlying mat; projection of upper crystal faces from the mat (providing irregular substratum for algal growth (this is the hypothesis we prefer); entombment of reworked algal tubules in hollow skeletal crystals (Kinsman, personal communication, 1976).

In any case, selenite grew concurrently with algal mats, and therefore contemporaneously with deposition as stated by Hardie & Eugster (1971, p. 212) on other line of evidence (see also Nesteroff, 1973, p. 115; Richter-Bernburg, 1973, p. 133;

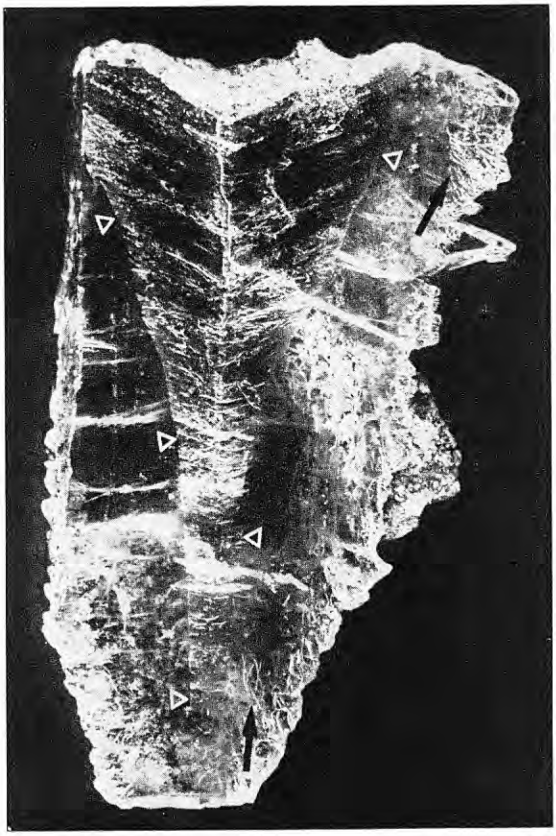

Fig. 11. Facies 3: massive selenite. Isolated upright twin showing a turbid core (delimited by open triangles) with chevron lining (concentrated algal tubules) marking growth stages and a clear overgrowth squeezing interstitial material including fragments of algal tubules (arrows). Notice the upward increasing apical angle of the ghost crystal.

Sturani, 1974, communication at meeting of Italian Working Group on the Messinian; Schreiber *et al.*, in press).

It is not clear whether selenite should be classified as an early diagenetic product or an original sediment-forming material; its qualification as primary would apply to the latter case only. It has, however, another meaning, i.e. directly precipitated from solution, not having a precursor. Massive selenite fits also this meaning, and the hypothesis of its derivation from anhydrite, proposed by Ogniben (1957) and accepted by one of us until recently (Parea & Ricci Lucchi, 1972), must be abandoned. This does not imply that all selenite is primary: secondary selenite was found in veins and diagenetic structures of the same beds (see facies 5) and within laminated gypsum of other areas (Rabbi & Ricci Lucchi, 1969; Sturani, 1973).

The terms primary and secondary are not unequivocally defined, whereby at the moment we prefer syndepositional and postdepositional. A more precise nomenclature should be established by referring distinctly to time of deposition, sedimentary interface and sequential order of mineral phases.

Fig. 12. Facies 3: massive selenite. Notice fining-upward trend of selenite crystals (relatively squat swallow-tail) and load deformation of underlying fine-grained, laminated calc-gypsum (facies 2); bituminous shales crop out at the base (bottom right). ANIC quarry, Borgo Rivola.

The enormous amounts of sulphate ions involved in the almost continuous growth of large selenite crystals suggest a continuous influx of brines from a marine reservoir, other sources being inadequate in the Messinian-Apennine setting (see discussion in Schuiling, 1973). Proper ion concentrations, rate of supply, rate of evaporation, etc. should be investigated on geochemical grounds. After interruption of growth, possibly accompanied by partial dissolution, the bottom was repopulated by a new layer of crystals (see repeated grading, Figs 3, 14). The increasing frequency of this phenomenon marks the upward transition to facies 4.

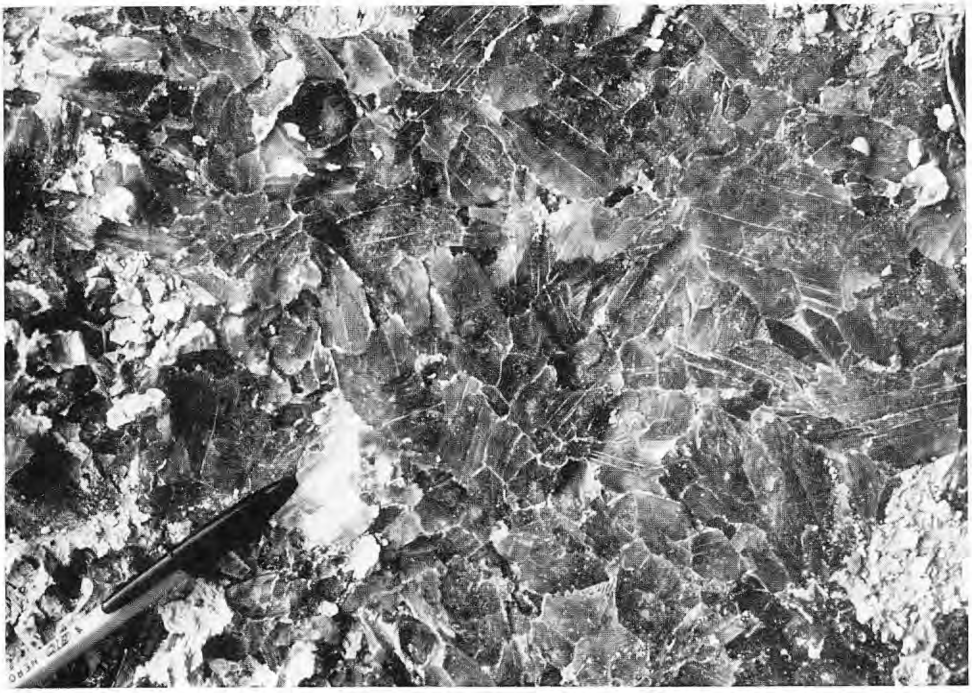

Fig. 13. Facies 3: massive selenite. Sutured stylolitic contacts in selenite mosaic. Outcrop view parallel to bedding; F. Santerno, Borgo Tossignano.

Facies 4—Banded selenite (Figs 14, 15)

Description. This facies was referred to as bedded selenite by Hardie & Eugster (1971) from Sicily (see their Fig. 4) and consists of subparallel bands,* 1–20 cm thick, vertically repeated over a maximum thickness of 10 m with an upward thinning trend. The bands look like palisades: upstanding selenite twins form their upper (and thicker) part (or subunit) and determine a more or less rough top surface, the lower part is composed of mechanically deposited crystals a few mm or less in size (Fig. 15). A reverse grading is thus developed in each band. It is quite distinct from that described by Ogniben (1957) in thinner laminae of fine crystalline gypsum. Clayey-carbonate pelite is found either as matrix between gypsum grains and as distinct partings, pockets and drapes between the bands; dissolution or pressure solution surfaces may replace the pelite partings or concur with them in giving a sharper contrast to the banding.

The banding may look even and continuous in small outcrops but ondulations and low-angle truncations of groups of bands are visible on a larger scale (Fig. 14).

Interpretation. Two facts must be pointed out, the mode of growth of the selenite is the same as in facies 3 (including the association with the algae), and the growth was repeatedly interrupted by dissolution and/or mechanical reworking thus giving a

* We avoided here the use of bed or layer (reserving them for sedimentation units delimitable in the field by major lithological changes, in this case the aggregate sequence of selenite facies) and lamina (because of the thickness).

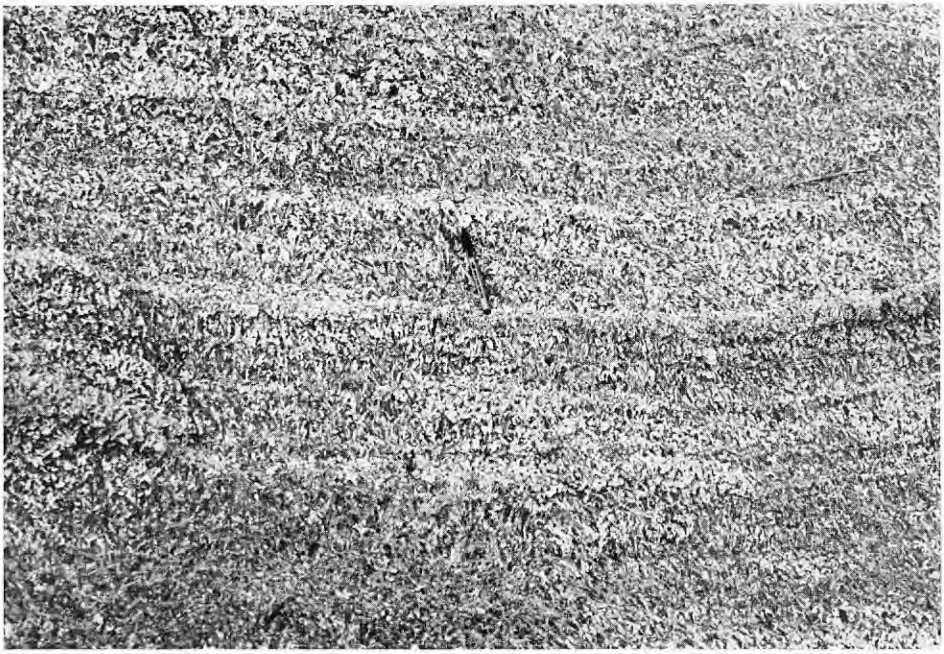

Fig. 14. Facies 4: banded selenite. Autochthonous selenite crystals with clayey-carbonate matrix (lighter). F. Santerno, Borgo Tossignano.

sequence of minor cycles. According to B. C. Schreiber (personal communication, 1976), penetrative dissolution affected the clastic gypsum (lower subunit) during phases of refreshment; it was followed by renewed crystal overgrowth during the subsequent reconcentration.

The general decrease in size of autochthonous selenite through facies 3 and 4 suggests a continuous evolution of the brines toward increasing concentration which favoured a more abundant nucleation of crystals. More frequent dilution of brines, in comparison with facies 3, does not exclude that the general trend was toward increasing concentration as shown by decreasing crystal size (= more abundant nucleation).

A shallowing was the most probable cause of the greater variability of both chemical and mechanical conditions with respect to facies 3. It may have resulted not only from evaporative depression of sea level, but also from sedimentary buildup (if we assume that it exceeded the subsidence).

The clayey-micritic material has several possible origins: concentration *in situ* of insoluble residues contained in dissolved gypsum; winnowing of offshore mud; terrigenous influx. This problem is connected with the definition of the main mechanism responsible for reworking of gypsum: either storm waves (see Hardie & Eugster, 1971) or fluvial currents may be proposed, but sufficiently diagnostic features are lacking. We shall return to this subject while discussing facies 5.

Facies 5—Nodular and lenticular selenite (Figs 16, 17)

Description. This facies may be lacking or, conversely, represent up to 80% of gypsum beds with a maximum thickness of 14 m. It consists of wavy bands (> 1 cm)

Fig. 15. Close-up of a single band of Fig. 14: showing a graditional contact between mechanically deposited (below) and autochthonous selenite crystals. The top of the underlying band displays a sharper contact between autochthonous and reworked selenite.

and laminae ($<$1 cm) of mm-size selenite crystals enclosing nodules and lenses of lighter and coarser selenite. In the lower part of the member, mostly gypsum bands of the type described in facies 4 with scattered simple nodules occur. Nodules and lenses become more frequent and aggregated upwards (sometimes simulating flaser bedding: see Fig. 16) with an attendant increase of clastic gypsum laminae which contain broken and whole prismatic crystals lying parallel or obliquely to the bedding. The gypsum sand is coarse, poorly sorted and associated with carbonate and clayey pelite up to 50% in volume. Rounded and corroded selenite grains can be recognized. Interlayered with the thicker clastic laminae are thin, monocrystalline (one crystal thick) laminae of acicular gypsum crystals (maximum length: few millimetres, diameter of cross-section $<$1 mm) which lie with their long axes randomly oriented on the depositional surface.

Lenses and stringers of terrigenous silt, silty sandstone and carbonate pelite appear in the upper part of the member, they also enclose nodules of selenite.

The nodules and lenses are composed of coarse selenite crystals of various sizes, shapes and fabrics; they generally coarsen toward the centre of the body where a cavity is often present. This variety of selenite is algal-free and clear: scattered anhydrite crystals and faint cloudy ghosts (reminiscent of felted aggregates) can be seen in thin section.

Interpretation. The main points requiring an explanation are the following: increased proportion of clastic gypsum with respect to accretionary, autochthonous

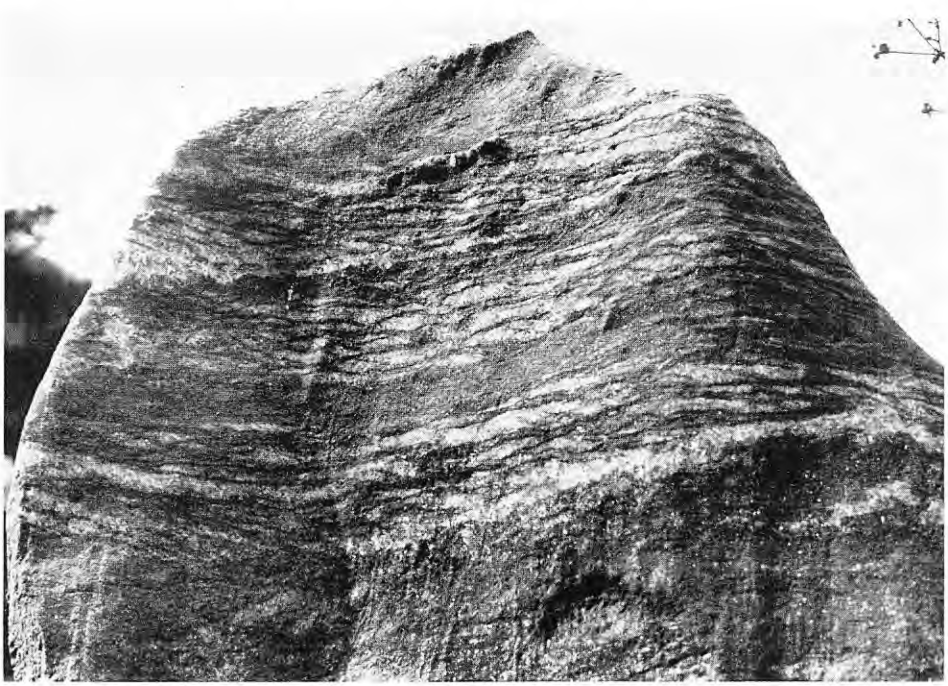

Fig. 16. Facies 5: nodular and lenticular selenite. Levels with aligned, anastomosing lenses simulating flaser bedding; lighter parts are composed of secondary selenite. C. Varnello quarry, Brisighella.

gypsum; interbedding of terrigenous clastics; meaning of gypsum needles; nodular, lenticular and flaser bedding.

As a general explanation of all these facts, we propose the progradation of fluvial bodies, mostly fed by previous evaporitic deposits, into a desiccating basin. We favour stream flood action to sea-generated turbulence as the main transporting mechanism for the following reasons: the poor sorting and the high matrix content of the clastic gypsum (suggesting mass transport, i.e. downslope displacement and absence of winnowing); the presence of land-derived materials; the great thickness changes of this facies; the vertical grading into coarser and more obvious debris flow deposits (facies 6); the probability of widely exposed areas of selenite occurring along the basin margins during a retreat of the sea caused by evaporative lowering, high rate of sedimentation, or both processes. We do not exclude wave action from playing a role in the clastic progradation; some lenses and flasers of selenite (Fig. 16) might actually represent ripple forms modified by diagenesis rather than purely diagenetic structures.

The gypsum needles are regarded as products of direct precipitation from the surface of very shallow supratidal ponds (for a modern analogue, see Shearman, 1970, pp. 211–212).

As for the nodules and lenses, their geometry, the inclusion in deposits of different composition and origin, and the displacive growth testified by the deformation of surrounding sediment are convincing evidence of diagenetic origin (with the possible exception of some primary flaser bedding, as said above). The closest recent analogues are the nodular and chickenwire structures of anhydrite in coastal sabkhas (Shearman, 1966; Kinsman, 1966, 1969): some selenite crystals would suggest a replacement of

Fig. 17. Close-up of nodules in facies 5: displacive growth is shown by deformation of surrounding material (clastic gypsum with terrigenous impurities); the nodules are composed of secondary selenite.

anhydrite (which is quite unusual, as hydration of anhydrite generally produces microcrystalline or alabastrino gypsum: see Holliday, 1970), but the internal fabric of most nodules supports a void-filling process. The following sequence of events was likely to occur: displacive growth of anhydrite nodules, dissolution of anhydrite leaving molds, precipitation and centripetal growth of selenite. This variety of selenite should be therefore considered as late diagenetic or epigenetic. We do not state here that our nodules are certainly of supratidal origin, nor that all anhydrite nodules are supratidal: however, if our interpretation of the depositional fabrics of this facies as well as of the other facies is correct, we are dealing with a regressive cycle, and the nodules are found in the upper part of this cycle, exactly where they should be expected to occur if they originated close to or above sea level.

Facies 6—Chaotic selenite (Figs 18, 19)

This facies constitutes not only the uppermost member of the cycle, but also independent beds (see next section).

Description. Coarse-grained, 30–100 cm thick deposits of disordered, large selenite crystals in a clayey or clayey-carbonate matrix. Blocks of aggregated gypsum crystals, large clay chips and wood fragments (often gypsified) occur in minor amounts. The lower contact with facies 5 is gradational, the top surface is sharp but irregular. A coarsening-upward trend usually characterizes the member (Fig. 19). The selenite clasts are slightly abraded large, elongate crystals lying parallel or gently inclined to the bedding. A particularly fortunate, wide exposure of an upper bed surface in a quarry near Brisighella (Lamone Valley) reveals sinuous ridges, depressions and alignments of selenite reminding of surfaces of lava flows (Fig. 18). Locally the matrix of these deposits is so abundant that they can be qualified as pebbly mudstone or diamictites.

The presence of chaotic selenite gypsum was noticed by Ricci Lucchi (1973, p. 145) in this same basin, by Sturani (1973) in Piedmont, and Schreiber (1973, p. 102) in Sicily.

Interpretation. It is evident that the selenite crystals underwent a certain amount of transport; as for the mechanism, we assume a highly viscous, sluggish mass which was frozen by a decrease of slope gradient. Such a mechanism explains the large size of the clasts, the lack of sorting, the abundance of mud, the crystal orientation, the preservation of delicate vegetal remains, the crude reverse grading, the irregular top surface. We observe incidentally that indisputable examples of pebbly mudstones or

Fig. 18. Facies 6: chaotic selenite. Mounds and sinuous alignments of large, flat-lying selenite crystals; compare with autochthonous crystals of overlying cycle on the right, showing stromatolitic limestone and bituminous shale at its base. Monticino quarry, Brisighella.

diamictites with large blocks of gypsum occur in the same position in the same type of depositional cycle in the basal portion of Gessoso-solfifera of Ciminna Basin, Sicily (Bonmarito & Catalano, 1973).

Debris flows may be subaerial or subaqueous (Johnson, 1970; Fisher, 1971; Hampton, 1972; Middleton & Hampton, 1973); in our case, we believe they were produced subaerially by mass wasting and violent rainfalls feeding torrential streams. The lack of hard rock fragments in the streamload can be attributed to the clayey nature of the first emerging formations of the Apennines chain. The source of the selenite clasts was likely represented by levels of massive selenite increasingly exposed by falling sea level and downcutting of fluvial channels.

Character of the cycle

We interpret the above described sequence of facies and events (see summary in Table 1) as a depositional regression leading to infilling of a restricted-marine basin by means of evaporitic, organic and mechanic processes. The major phases of accumulation took place first as subaqueous evaporite precipitation, then as subaqueous to subaerial redeposition of evaporites. The bathymetric character of the cycle leaves little doubt regardless of the ultimate control on its development and the interpretation of some sedimentary mechanisms.

We must remark that the oldest cycle represents the culmination of a regressive trend started in pre-Messinian sediments, while the following ones began with a short transgressive phase. These repeated Messinian transgressions had a peculiar character: the Vena del Gesso Basin was not adjacent to an open sea. The whole Mediterranean was in restricted conditions. Oceanic water came from the Atlantic in limited amounts regulated by a sill: on the way to the Adriatic, its salinity and density were modified by evaporation. Consequently, the sea water which flooded our evaporitic basin was not normal sea water.

The whole sequence of cycles has a general regressive trend as shown by the condensed post-evaporitic sequence.

FACIES AND CYCLE CHANGES IN THE EVAPORITIC FORMATION

Number of cycles (Fig. 3)

Three stratigraphic sections were measured in the evaporitic formation: two of them (A and B) actually represent a single continuous succession located in the Santerno Valley. Section C, located 15 km to the east (along strike) in the Lamone Valley, is closer to the eastern boundary of the basin, i.e. the tectonic sill separating it from Romagna-Marche evaporitic basins.

The number of cycles is the same (thirteen or fourteen) in the two localities, and can be tested by visual correlation in the intervening continuous outcrops; the uncertainty in defining the exact number derives from the difficulty of correlating the thinner basal cycles which are generally covered. Cycles 8–14 in section C were eroded before the Pliocene transgression; they crop out 500 m to the northwest.

Table 1. Depositional cycle of Vena del Gesso Basin

Observed facies	Inferred events	Main depositional processes	Environment	Figures
6 Chaotic gypsum (pebbly mudstone): mixture of selenite crystals of variable sizes in clayey matrix; clay chips, wood fragments, fluidal alignment of clasts.	Subaerial debris flows building out depositional lobes at the mouths of channels cut into emerged selenite beds and older, clayey formations.	Mechanical	Alluvial cone	18, 19
5 Nodular, lenticular and flaser-bedded gypsum: layered, mostly clastic selenite with lenses of siltstone, sandstone and micritic carbonate, deformed by displacive growth of diagenetic structures.	Growth of selenite and algal mats more and more frequently interrupted by sheet floods which carried both selenite fragments and terrigenous material; shoreline progradation, infilling of the lagoon and formation of wide supratidal flats with anhydrite nodules in the vadose zone and primary deposition of acicular gypsum in ephemeral ponds.	Mechanical; important diagenetic changes	Supratidal flat	16, 17
4 Banded selenite: rhythmic sequences of clastic and autochthonous selenite couplets, sometimes associated with muddy carbonate partings and dissolution surfaces.	Evaporitic precipitation of selenite within algal mats interrupted by periods of brine dilution and/or mechanical emplacement of gypsum sand and carbonate mud; increase of average brine concentration and shallowing; possible interplay of waves and fluvial currents in reworking of selenite.	Alternation of organic-chemical and mechanical processes	Shallower lagoon	14, 15
3 Massive selenite: standing up, large selenite crystals (swallow-tail twins) enclosing algal filaments.	Extensive precipitation of primary gypsum: almost continuous, upward growth of selenite within and above algal mats; the algae covered the crystals during minor interruptions of their growth due to small salinity fluctuations.	Organic and chemical	Lagoon, (Supratidal marsh?)	11–13
2 Stromatolitic limestone, stromatolitic selenite, limestone breccia, laminated calc-gypsum sandstone, etc.	Emplacement and growth of algal mats; increased salinity leading to localized evaporite precipitation within the mats; erosion of algal mats by waves and redeposition of intraformational detritus as sublittoral or beach sands. Solution-collapse brecciation of calcareous stromatolites. Sporadic subaerial exposure was possible.	Organic, chemical and mechanical	Lagoon, Beach (Supratidal marsh?)	5–10
1 Bituminous shale: thinly laminated marly clay and silt with sporadic sand laminae and small ripples.	Marine flooding of the lagoon,* density stratification of the water mass, development of anoxic conditions on the bottom, slow settling of terrigenous pelite under probable seasonal control, preservation of organic remains, sporadic reworking by low-energy waves.	Mechanical	Lagoon*	

* Except for the first cycle, when shallowing and restriction of water exchanges occurred in a previous deep-water, open marine basin, transforming part of it into a lagoon.

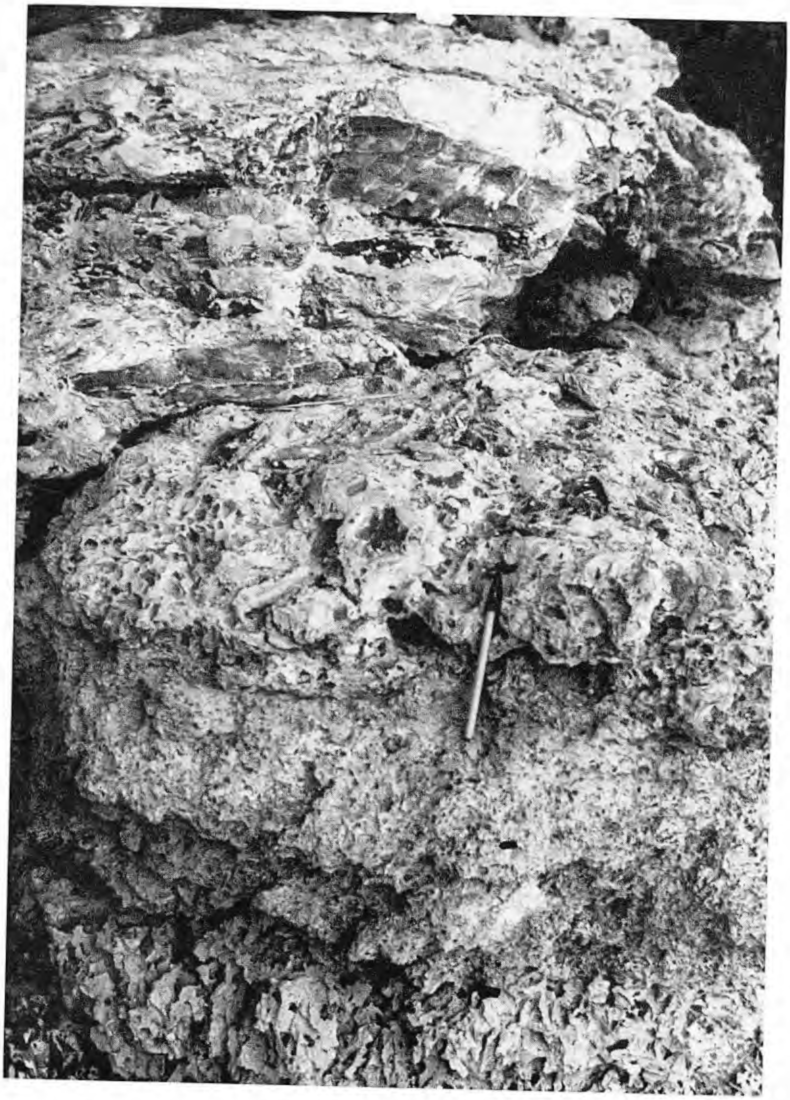

Fig. 19. Transition from facies 4 to facies 6 (marked by the pencil). Coarsening-upward trend, abundant matrix (white) and coarse, flat-lying selenite clasts are evident. Gypsum dissolution left moldic porosity. F. Santerno, Borgo Tossignano.

Two thick beds of chaotic gypsum, interpreted as gravity deposits of debris flow type, are intercalated in the Santerno section:* they were not counted because of their local character and non-cyclical internal organization. Their palaeogeographic value is discussed later.

* The thickest one was recognized along the Sgarba C. during a trip with F. C. Wezel, W. B. F. Ryan and B. C. Schreiber. Thick chaotic lenses of brecciated gypsum (mostly alabastrino) are reported from other Periadriatic evaporite basins (Selli, 1967; Rabbi and Ricci Lucchi, 1968; Parea & Ricci Lucchi, 1972; Ricci Lucchi, 1973).

At least ten cycles very similar to those of Vena del Gesso were counted on a reconnaissance basis in the Gessi Inferiori of Sicily; should a closer inspection reveal the same number as in Vena del Gesso, we could conclude that this is more than a fortuitous coincidence, and that the cycle is the sedimentary expression of geological events affecting a large part of or the entire Mediterranean area.

Vertical changes (Fig. 3)

The thickness of the cycles (which almost coincides with that of gypsum beds in most cases) ranges vertically from 5 to 35 m. The thickest cycles are four and follow each other in the lower-central part of the formation (Fig. 1). Excluding the uppermost, they show an extreme development of autochthonous coarse selenite (facies 3) whereas reworked gypsum (represented chiefly by facies 6 debris flows) does not exceed 10% of cycle thickness. The proportion of clastic gypsum (mostly facies 5) increases up to 80% in overlying thinner cycles. Cycles with more equilibrate ratios between thicknesses of autochthonous and reworked gypsum are lacking as shown by the diagram of Fig. 20. The intensification of mechanical processes in upper cycles suggests that the gypsum detritus was mostly formed at the expense of the lower gypsum beds exposed by regression on the flanks of the basin.

The lowest and least variable thickness values are recorded by bituminous shales (facies 1) and calc-gypsum stromatolites (facies 2); these facies may, however, constitute a whole cycle (see the base of the formation).

Complete, six-member cycles are more frequently found in the upper half of the sections (No. 5 or 6 to No. 14); facies lacking in incomplete cycles are mainly 4 and 5, while facies 3 is the most ubiquitous.

Each facies usually occurs once in a cycle, but some repetitions were noted for facies 3 and 4, and especially for facies 2: two or three levels of algal limestone alternate with bituminous shales (facies 1) in the lowermost cycle, and two alternate with massive selenite (facies 3) in cycle number 4.

Lateral changes

The outcrops can be walked out only along strike for a distance of 15 km. The thickness of individual cycles usually varies by a factor of 1·1–2 for the thickest ones, and of 2–3 for the others. Relative thicknesses of autochthonous and clastic selenite facies change in the same way along the same cycle as well as in different cycles: lateral variations of facies 5 are particularly pronounced.

The highest degree of lateral persistence and thickness uniformity is shown by bituminous shales (a few beds, however, thin out eastwards), the lowest by the various subfacies of facies 2. We could not obtain a systematic pattern for the areal changes of facies 2. The stromatolitic limestone is replaced by a foraminiferal-oncolitic limestone in the Lamone area and the associated shales pass into fossiliferous clays. This suggests the existence of ventilated and turbulent water near the basin margin.

The two huge beds of chaotic gypsum mentioned above have a length of a few kilometres, and wedge out both westward and eastward; the inferred direction of sliding was at about 90°, i.e. normal to the basin axis. This means a lateral slope did exist and influence the sedimentation; we believe it was not a purely local or temporary feature, but the regional slope controlling the dispersion of most clastic gypsum. Notice, for example, that the proportion of clastic gypsum is very high (60–85%) in the two cycles underlying the chaotic beds, which may be connected with a relatively persistent mouth of a torrential stream and a depositional oversteepening. The presence of wood fragments in the coarse chaotic gypsum is significant in this respect.

DISCUSSION

The general environmental setting we propose for the Vena del Gesso Basin (Fig. 21) is a lagoon of varying water depth adjacent to the emerging apenninic chain. Maximum water depth is estimated in the order of some tens of metres (see below); we may therefore speak of shallow-water sediments, but we avoid using the terms shallow basin or shallow lagoon as topographic depth must be distinguished from water depth when wide eustatic fluctuations are possible as in evaporitic basins (see discussion in Hsü, 1973). The model of a shallow lagoon-strandline complex put forward by Hardie & Eugster (1971) for Sicily (Fig. 21) is similar but, in our opinion, it has some limitations: lack of precise stratigraphic control (*auct. cit.*, p. 217) led these authors to assemble features pertaining to two distinct formations (Gessi Inferiori and Gessi Superiori) characterized by somewhat different setting and facies; for the same reason, their facies zonation, although admirably logical, is not supported by real spatial relationships; the occurrence of autochthonous selenite is underestimated which results in a strong bias toward clastic processes; the model does not take into account some dynamic factors; for example, sea level changes, rates of sedimentation, tectonic evolution.

Our interpretation of the Vena del Gesso depositional cycle is based on the following assumptions: interplay of organic (algal), evaporitic and mechanical processes; almost constant rate of subsidence; shallowing ensuing from increasing rate of sedimentation and/or falling of sea level; increasing role, from base to top,* of mechanical processes removing gypsum from basin margins and redepositing it toward the centre (evaporitic cannibalism); predominance of gravity and slope-controlled mechanical processes on wind and waves; erosion of clayey formations in the land resulting in small delivery of coarse terrigenous clastics. Moreover, as stated by Hardie & Eugster (1971) (p. 217), continued exchange with fresher water is necessary to produce the large masses of gypsum and to prevent the precipitation of more soluble salts.

The above assumptions are sufficient to explain the sequence of sedimentary events which form an individual cycle; the repetition of the cycles, on the other hand, was likely triggered by external factors (tectonic or eustatic) operating in the region of the sill between the Mediterranean and the Atlantic (see Hsü *et al.*, 1973; Selli, 1973; and others).

Depth changes produced by local evaporation (the evaporative drawdown of Maiklem, 1971) are expected in a restricted shallow water body: this factor should be regarded as the most significant in the internal dynamics of the cycle, but its effect is not easily discernible from that of the sedimentation rate. Was shallowing the effect or the cause of excess sedimentation and basin fill? We suppose that both evaporative drawdown and excess sedimentation acted as concomitant causes to produce the same effect.

Local tectonic movements were not considered in the model; they might have

* Not only the single cycles, but also the whole succession show this trend.

played a role as well (e.g., tilting of basin margin, triggering of slides and debris flows on unstable slopes), but not a major one. The occurrence of the same basic type of depositional cycle in widely separated basins (northern Apennines and Sicily) is a strong argument against it.

An implication of our scheme is that the maximum water depth in the lagoon was reached at the start of each cycle (euxinic stage); as for the absolute value of this depth, several lines of reasoning can be followed. The absence of algal mats could be taken as an indication of deposition below the photic zone (see Schreiber *et al.*, in press), but to put a figure for this depth (which already falls in a wide range in open sea) is meaningless in an euxinic setting where the regulating factors (thickness of the anoxic layer, concentration of suspended organic matter and poisoning products, etc.) are unknown. The presence of low-energy oscillation ripples implies few metres of water, but the examples we saw are few and not very clear. If we assume, according to Schmalz (1969), a sedimentation rate in large excess of subsidence rate, a depth in the order of gypsum bed thickness should be inferred (some to 30 m). We can indeed recognize that sedimentation exceeded subsidence during the evaporitic stage but, unfortunately, we know neither of the two rates. An integrated palaeo-ecological approach, successfully employed in other areas for these sediments (Sturani, 1973, 1975; Sturani & Sampo', 1974) would certainly help to solve this problem. We think at the moment that some tens of metres represent a reasonable estimate for maximum water depth in Vena del Gesso Basin.

Our zonation of gypsum facies differs from that of Hardie & Eugster (1971), particularly in regard to the relative positions of autochthonous and clastic selenite and the mechanism and direction of transport. The following comparison does not mean that we give a different interpretation of the same facts; the depositional setting of the two basins was not necessarily the same (see, for example, the importance of balatino in Sicily). Hardie & Eugster (1971) put the major emphasis on storm wave action and place the selenite in quiet lagoonal water adjacent to a littoral belt of gypsum sand. We think that this situation may hold for a certain stage of our cycle represented by relatively thin gypsum sandstone bodies with wave lamination (facies 2), but not for the most important episodes of cannibalistic accumulation of gypsum (facies 5 and 6). The sedimentological characters of these deposits, discussed above, suggest to us mass transports with little abrasion of clasts and rapid entombment with no winnowing. Torrential flash floods emptying into a quiet water body provide the suitable mechanism. This requires a sizable source of gypsum clasts of a wide size range located in nearshore and coastal areas. Autochthonous selenite exposed to erosion and gypsum sand already prepared by waves could provide the source material. In this respect, evidence of mechanical disturbance in stromatolitic selenite seems to indicate that it could grow not only in quiet basinal water but also near shore. Most important of all, the dynamics of the regressive cycle implies the areal expansion of emerged selenite flats.

We do not deny, in principle, the presence of storm layers advocated by Hardie & Eugster (1971); we just point out that modern analogues referred to by these authors occur in tidal flats exposed to the ocean. More should be known about the sedimentary features of such deposits and the importance of storm action in other environmental settings, particularly in inland seas with topographical differentiation providing physical barriers for water circulation.

Our conclusion concerning the main mode of mechanical emplacement of gypsum

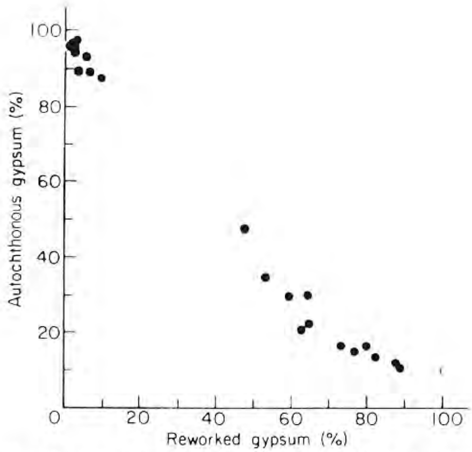

Fig. 20. Plot of thickness of autochthonous versus reworked selenite gypsum in each cycle of studied sections showing an inverse relation. Had the clastic gypsum been introduced from outside the basin, a lack of correlation might have resulted. Autochthonous and reworked gypsum as percent of cycle thickness.

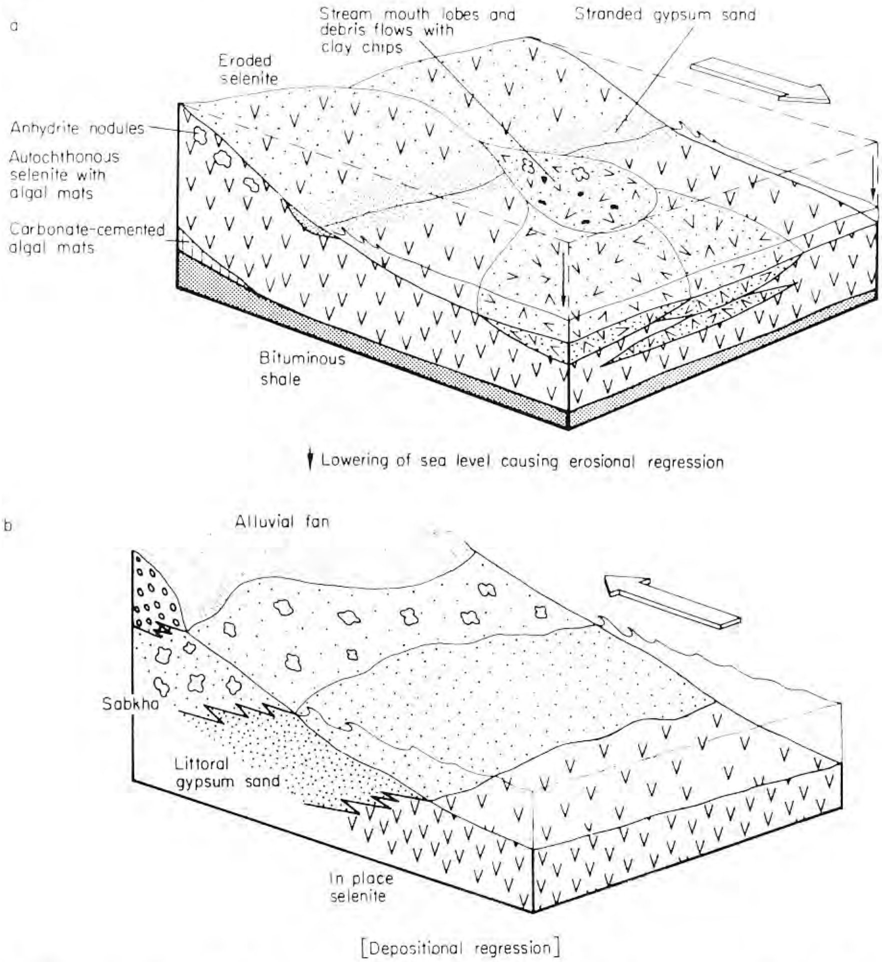

Fig. 21. Conceptual model of deposition in Vena del Gesso Basin (a) as compared with Hardie & Eugster (1971) model for Sicily (b). Large arrows indicate dominant transport direction of clastic gypsum.

in the Vena del Gesso Basin are: (1) autochthonous selenite and littoral gypsum sand were removed and carried basinward by slope-controlled flows (fluvial currents and debris flows); tongues of clastic gypsum initially advanced from the mouths of torrential streams and bypassed areas where selenite kept on growing (Fig. 21); (2) removal of gypsum was intensified by increased subaerial exposition of marginal depositional areas in connection with sedimentary buildup and relative fall of sea level; eventually, shallow alluvial cones mostly made of reworked selenite encroached on the basin area.

The same cannibalistic mechanism likely led to deposition of gypsum turbidites in deeper basins (Parea & Ricci Lucchi, 1972; Ricci Lucchi, 1973, 1975).

We admit that more factual evidence is needed to prove this model, and that the lack of modern selenite basins is a serious drawback in this respect; our aim is to propose a working hypothesis in the light of the renewed interest for the study of evaporite facies.

AKNOWLEDGMENTS

This paper is dedicated to the memory of Carlo Sturani, geologist and palaeontologist, who perished during his field work in a gypsum quarry in Piedmont; this work was greatly stimulated and influenced by his new findings and ideas.

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