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Timing of post-depositional events in the Burano Formation of the Secchia valley (Upper Triassic, Northern Apennines), clues from gypsum–anhydrite transitions and carbonate metasomatism

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Abstract

The Burano Evaporite Formation from the Secchia River Valley is an up to 2200 m-thick sequence composed of meter-to decameter-scale interbeds of gypsum–anhydrite and dolostones with minor halite. The deposit has been affected by a complex array of post-depositional modifications, thermal events and large-scale evaporite dissolution, preventing a satisfactory reconstruction of the environment of deposition. The modifications are intense because these rocks were the main décollement horizon during the formation of the Northern Apennines chain.

The carbonate rocks are massive and-or laminated dolomitic mudstone, wackestone, oolitic packstones and oolitic, peloidal, bioclastic grainstones, which commonly appear as mega-boudins within a sulfate groundmass. The dolostones ($\delta^{18}O = -5.7$ to -3.7‰; $\delta^{13}C = +1.3$ to $+3.0$‰; PDB) have been affected by Mg-metasomatic replacement by magnesite ($\delta^{18}O = -14.0$ to -2.6‰; $\delta^{13}C = -2.6$ to $+1.4$‰; PDB) induced by hydrothermal circulation. Total homogenization temperatures of fluid inclusions in hydrothermal magnesite range from 275 to 310°C.

The anhydrite rocks are characterized by flow structures such as centimeter-scale pseudo-lamination composed of aligned prismatic crystals with transposed isoclinal folds outlined by dolostones fragments. Homogenization temperatures of fluid inclusions in authigenic quartz incorporated into sulfate rocks range from 260 to 305°C (Emilia) and from 230 to 315°C (Tuscany).

The gypsum rocks are composed of xenotopic irregular cloudy crystals and, more rarely, by centimeter-scale idiotopic crystals showing the same structures as the anhydrite rocks. The origin of the gypsum rocks is due to late alteration of anhydrite by migration of sharp hydration fronts. The hydration is a two step process and is revealed by the presence in the gypsum rocks of corroded anhydrite micro-relics and authigenic quartz crystals which include anhydrite.

The role of the Burano Evaporites during the Apennines tectogenesis can be depicted as follows: (a) prevalent deposition of gypsum in the Upper Triassic; (b) gypsum dehydration at burial conditions to form anhydrite (Cretaceous?); (c) syn-tectonic flow of anhydrite rocks, brecciation of dolostones; syn-tectonic growth stage of quartz euhedra at deep burial conditions possibly related to the development of the Oligocene–Miocene greenschist facies Apuane metamorphic complex; (d) hydrothermal deposition of sparry magnesite and partial Mg-metasomatic replacement of dolostones by magnesite; (e) sub-surface dissolution of halite to form thick matrix-supported residual caprock-like anhydrite mega-breccias; (f) complete gypsification

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of anhydrite at sub-surface conditions; and (g) evaporite dissolution at surface exposure producing dolostone breccias with partial calcitization and removal of most clasts ("Calcare cavernoso").

Keywords: Burano Formation; Triassic; Northern Apennines; Anhydrite ↔ gypsum transitions; Thermal evolution

1. Introduction

Sulfate–carbonate deposits carry a large significance in the geologic record: they can be utilized to unravel ancient palaeoclimate and palaeogeographic conditions, may represent a source of mineralizing solutions, may directly influence the conditions of hydrocarbon generation by thermal conductivity changes related to gypsum–anhydrite transition (Jowett et al., 1993) and development of mountain chains by acting as "lubricant" for thrusting (Heard and Rubey, 1966; Helman and Schreiber, 1985).

The study of sulfate deposits has intrigued geologists for a long time, generating remarkable discussion. This is because detailed descriptions of sedimentary features in present-day evaporite setting were not available until the 1970s and because ancient sulfate formations were commonly involved as detachment horizons in the building of mountain chains, with deformation and obliteration of the original structures and textures. This resulted in a common misinterpretation of late deformation features, which were often taken as primary sedimentary structures and textures. As a further complication, gypsum → anhydrite and anhydrite → gypsum transformations can occur because of relatively slight changes of chemical–physical parameters (Hardie, 1967) producing possible significant volume changes (Shearman, 1985) and complex array of structures and textures (Schreiber et al., 1982; Hardie et al., 1985).

New information concerning the complexity of sulfate–carbonate evolution comes from the study of the Burano Evaporites from the Northern Apennines, which were affected by severe post-depositional modification, including thermal events. Sulfates and carbonates carry the signature of these thermal events as indicated by petrography, fluid inclusions and stable isotopes data. The purpose of this paper is to describe the peculiar features of these evaporites and to address the implications of their post-depositional evolution in the framework of the Northern Apennines geologic history.

2. Methods

Sulfate and carbonate rocks were examined using conventional optical methods and X-ray diffraction (XRD).

Microthermometric determinations on fluid inclusions in quartz and magnesite were performed using doubly-polished thin-sections. Measurements in magnesite were done on triphase (liquid + vapor + solid) fluid inclusions generally $<10\ \mu m$ in size. Determinations in quartz were done on biphase (liquid + vapor) and triphase (liquid + vapor + solid) fluid inclusions generally 100–400 μm across. Only syngenetic inclusions were considered using the discriminating criteria of Roedder (1984). Measurements were taken using Linkham (magnesite) and Chaixmeca (quartz) apparatus.

3. Stratigraphy, age and geological setting

The evaporite unit of the Secchia River Valley is mainly composed of meter to decameter alternations of gypsum–anhydrite rocks and dolostones with minor halite at depth (Colombetti and Fazzini, 1986). The inferred total thickness reaches 2200 m in the northernmost zone (Colombetti and Zerilli, 1987). The post-depositional modifications and the strong tectonization that affected these evaporites do not permit a satisfactory reconstruction of the general stratigraphy of the formation: the vertical and lateral continuity of the succession is generally limited to less than a few tens of meters and the most common lithofacies at outcrop are late dissolution breccias. In addition, the carbonate rocks from the Secchia River Valley are completely devoid of recognizable fossils.

Despite the described complex characteristics, the evaporites of the Secchia River Valley are unanimously attributed to the Upper Triassic Burano Anhydrite Formation (Ciarapica and Passeri, 1976; Colombetti and Fazzini, 1986). This formation has been delineated using borehole data from Tuscany,

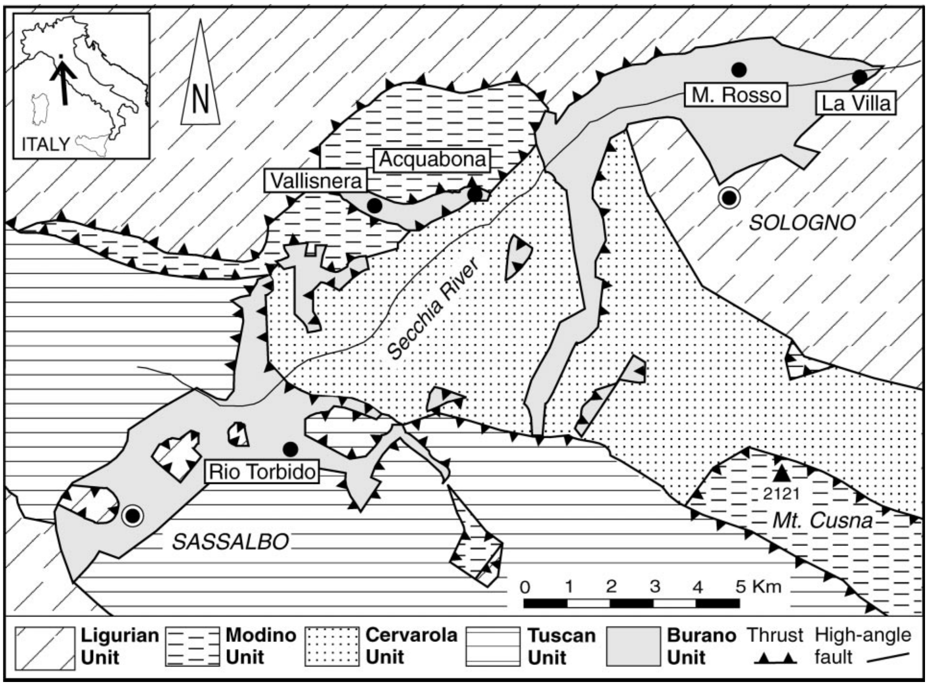


Fig. 1. Schematic geological map of the Secchia River Valley showing the complex setting of the various tectonic units. The Burano Unit includes tectonic fragments of its basement (not differentiated on figure). Simplified from Andreozzi et al. (1987).

Umbria, Marche, Latium and Puglia (Martinis and Pieri, 1963). Considering that anhydrite is the only calcium sulfate found in the boreholes, whereas gypsum prevails at outcrop, the more general term Burano Evaporite Formation is used here. The foraminiferal assemblages of carbonates in the Burano Formation indicate age ranges from Carnian to Norian in Tuscany (Martini et al., 1989) and from Norian to Rhaetian in Umbria (Ciarapica et al., 1987).

In Tuscany the evaporites lie at the base of a more than 2 km-thick carbonate-clastic Mesozoic sequence, the Tuscan Succession or Nappe, deposited during the ingression of the Tethys Sea along the rift system cutting the Variscan orogen and its European foreland (Passeri, 1975). The Burano Formation was the main decollément horizon for the Tuscan Nappe during the NE directed build-up of the Northern Apennines chain (Boccaletti et al., 1987; Carmignani and Kligfield, 1990).

In the study area, the Burano sequence is exposed along the Secchia River Valley structure, which has been interpreted as a transpressional system running transverse to the major tectonic features of the Northern Apennines (Fig. 1; Andreozzi et al., 1987). The evaporite unit is disrupted into thrust slices which are tectonically included into younger allocthonous units. The evaporite thrust slices were detached from the base of the Tuscan Nappe by formation of megatension gashes. These thrust slices were then incorporated into the migrating overlaying Ligurian units during a post-Burdigalian-Langhian deformation phase (Chicchi and Plesi, 1991).

Two lines of evidence indicate that the Burano evaporites in the study area were affected by thermal events possibly related to the development of the greenschist facies Alpi Apuane metamorphic complex, located to the SW of the studied area:

(a) the presence of thrust slices composed of metasediments correlatable to the Apuane metamorphic complex (Calzolari et al., 1987);
(b) the high homogenization temperatures of fluid inclusions in authigenic quartz and magnesite crystallized in the evaporites (see below).

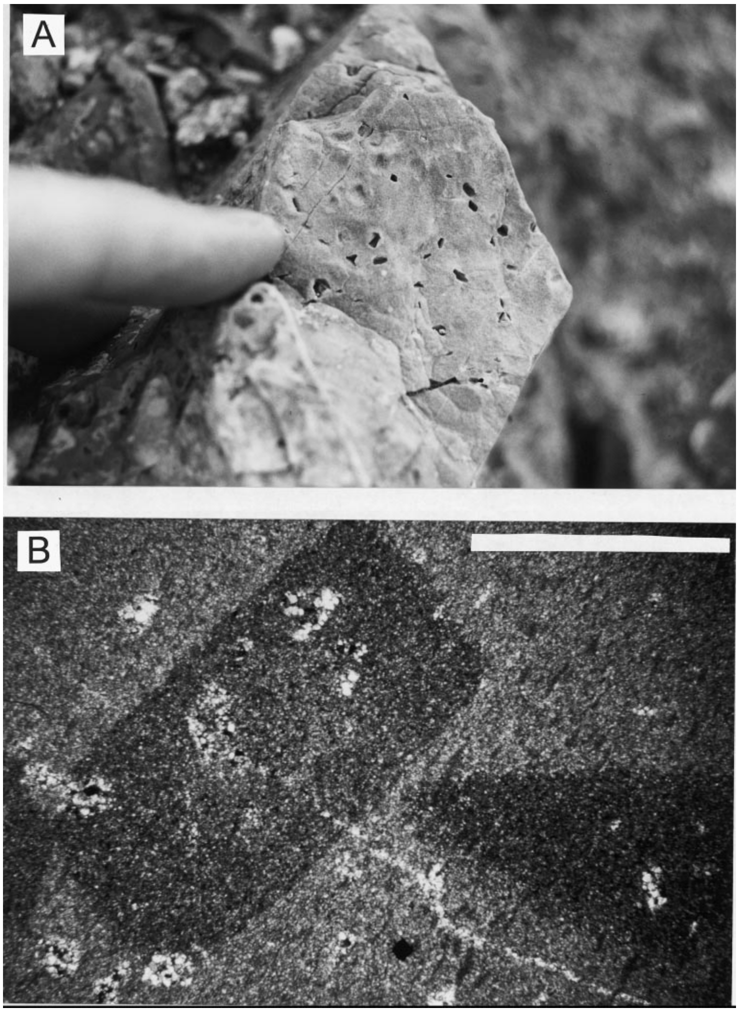


Fig. 2. Some aspects of the dolostones from the Secchia River Valley: (a) Dolomitic mudstone showing rectangular-, lenticular- and triangular-shaped voids after axe-head anhydrite crystals. M. Rosso. (b) Photomicrograph showing a dolomicrite including rectangular- and triangular-shaped areas appropriate to axe-head shapes. The original axe-head anhydrite crystals have been replaced by dark microcrystalline dolomite. Note the bright zones occupied by microsparitic calcite formed by late dedolomitization of the dolostone; plane polarized light, scale bar is 1 cm. Vallisnera.

4. Dolostones

The carbonate rocks are mainly represented by centimeter to decameter dark gray massive dolomitic mudstones (Fig. 2) with rare cross-stratification, flaser, wavy and lenticular bedding, mottled structures and flat lamination. Similar lamination recognized in the Tuscan outcrops has been interpreted as the product of algal activity (Passeri, 1975). In a few cases dolomitized oolitic packstones and oolitic, peloidal, bioclastic grainstones have been identified in dissolution breccias. The mudstones are generally composed of microcrystalline dolomite, which commonly contains millimeter-scale nodules and triangular-, rectangular- or lenticular-shaped voids (Fig. 2a). These voids are commonly filled with light-gray microcrystalline dolomite (Fig. 2b). These cavities and bodies may be interpreted as the results of dissolution or dolomite replacement of former sulfate nodules and axe-head anhydrite crystals (Clark and Shearman, 1980).

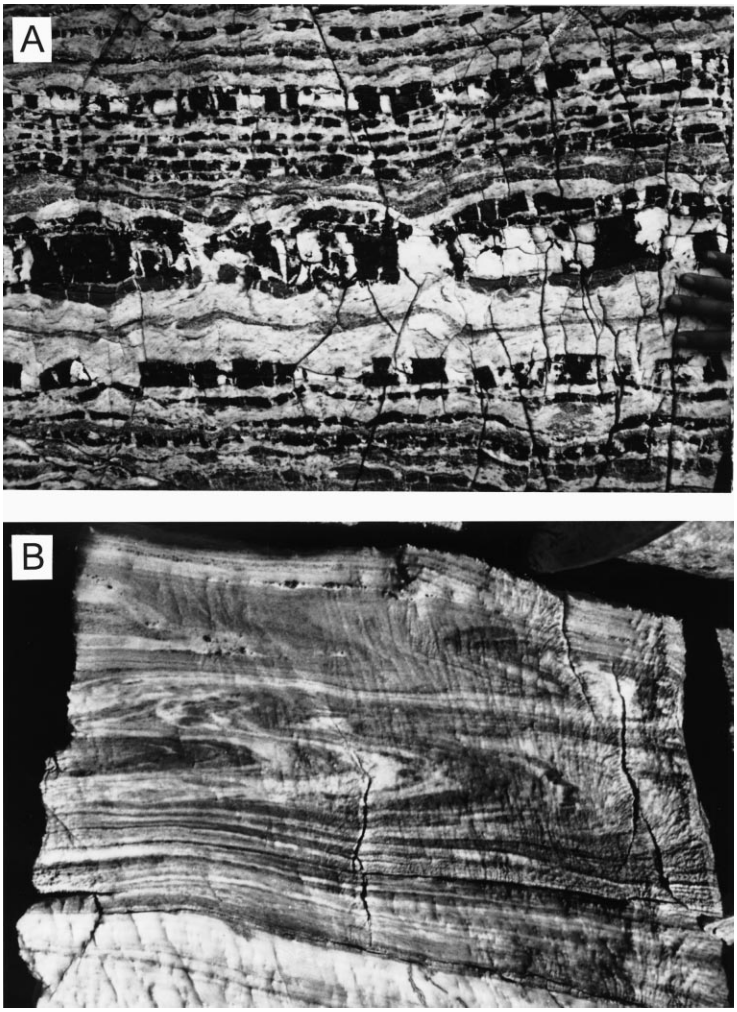


Fig. 3. Outcrop photograph of sulfate–dolomite rocks: (a) Dolostone layers (black) disrupted by boudinage within a gypsum rock after anhydrite. The thin dolostone layers have been completely pulverized to the scale of the single crystal components. Note flow of the incompetent sulfate rock into boudin necks. A hand is visible at right for scale. Rio Torbido. (b) Isoclinal layer-parallel folds in a gypsum rock after anhydrite. Note the crushed thin dolostone layers, which have been disrupted to the scale of the single microcrystalline components. Tip of hammer for scale (upper right corner). Sassalbo.

Due to the strong contrast in competence and "mobility" of the associated rocks during tectonic deformation, the carbonate layers are commonly disrupted and appear as boudins of variable size within a sulfate groundmass (Fig. 3a). The very thin carbonate laminae are commonly strongly sheared and crushed to the scale of single crystalline components (Fig. 3b).

Locally the Burano sequence has been reduced to coarse, angular to spheroidal clast- or matrix-supported vuggy dolostone breccias ("Calcare cavernoso") which, according to Vighi (1958) and Passeri (1975), represent the dissolution product of evaporite layers. The "cavernoso" (vuggy) aspect comes from the partial or total calcitization (dedolomitization) of most of the dolostone breccia clasts followed by dissolution of the calcite replacement. This hypothesis is supported by the presence of calcite after dolomite in unaffected rocks and by the presence of dolomite

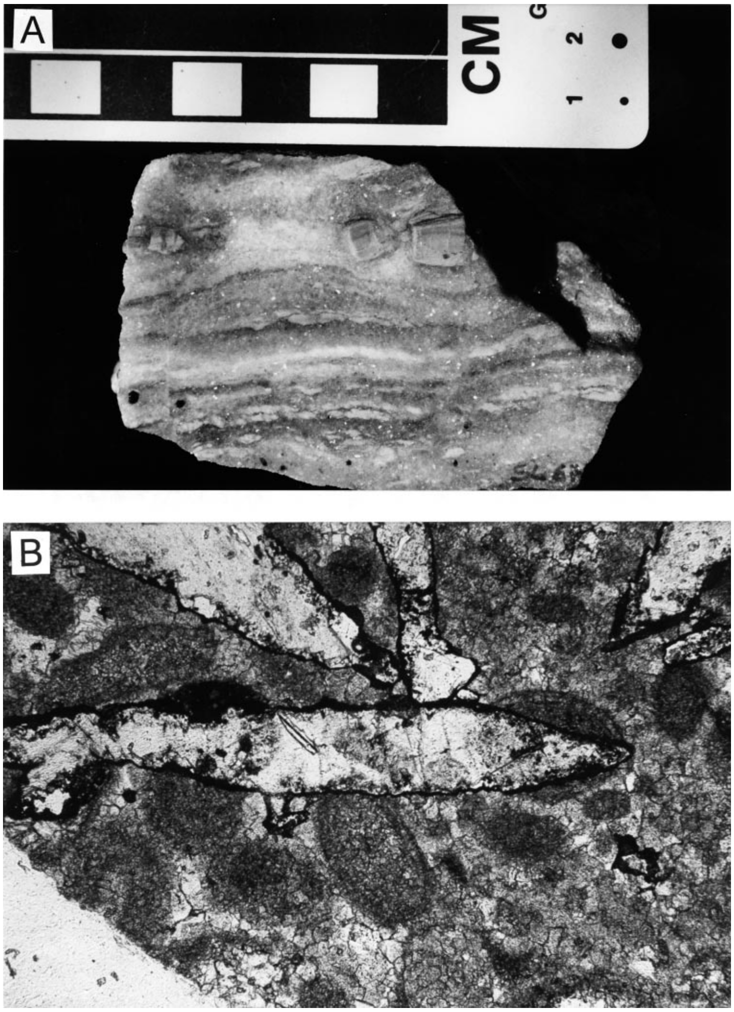


Fig. 4. Magnesite in the Secchia River Valley: (a) Cut slab showing gray colored microcrystalline magnesite boudins within an aligned prismatic anhydrite rock. The authigenic quartz euhedra (black hexagonal spots in the bottom left side) contain magnesite microinclusions. These characteristics suggest a syngenetic or diagenetic origin for the microcrystalline magnesite. Vallisnera. (b) Lenticular sparry magnesite within a dolomitic oolite rock. The ooid ghosts within magnesite crystals indicate that they grew at expense of the host dolostone. Thin section photomicrograph; plane polarized light. Scale bar is 1 mm. Acquabona.

powder partly filling voids formerly occupied by clasts in weathered rocks. The extreme transformation produces masses of residual loose dolomite powder or sand called "Cenerone" (Passeri, 1975).

The dolostones yield $\delta^{18}O$ and $\delta^{13}C$ values of -5.7 to -3.7‰ and $+1.3$ to $+3.0$‰ (PDB), respectively (Lugli et al., 2000). These values are similar to those given by Cortecci et al. (1992) for the metamorphosed Grezzoni dolostones from the Apuane Alps.

5. Magnesite

Magnesite is present in the Burano Formation as light-gray microcrystalline centimeter-thick layers within sulfate rocks (Fig. 4a) and as black, red and brown rocks composed of up to centimeter-scale sparry magnesite crystals. The latter are: (1) fracture-filling aggregates, associated with (2) lens-shaped crystals replacing dolostones to various

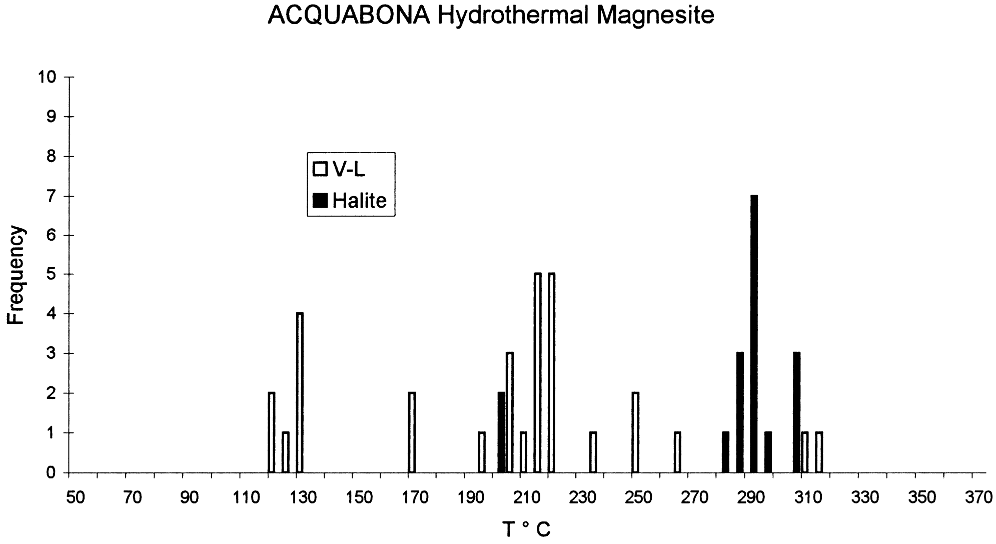


Fig. 5. Frequency histogram relating vapor to liquid homogenization temperatures (v–l) and halite melting temperatures (halite) for fluid inclusions in fracture-filling sparry magnesite from Acquabona.

extents (Fig. 4b). The replacement of dolomite by sparry magnesite in association with fracture-filling magnesite suggests a Mg-metasomatic system induced by hydrothermal circulation of hot, Mg-rich fluids (Lugli, 1996b). The replacement post-dates the growth of the authigenic quartz euhedra (see below) because only dolomite is enclosed within quartz crystals, even in those former dolomite rocks which have been completely replaced by magnesite. Magnesite microinclusions are present only within quartz crystals included in sulfate rocks containing microcrystalline magnesite layers. This suggests that microcrystalline magnesite may be synsedimentary or diagentic in origin.

The magnesite yield $\delta^{18}O$ and $\delta^{13}C$ values of -14.0 to -2.6‰ and -2.6 to $+1.4$‰ (PDB), respectively indicating metamorphic thermal conditions for the Mg-metasomatic replacement of dolostones (Lugli et al., 2000). This hypothesis is supported by the values of the trapping temperatures of fluid inclusions in hydrothermal magnesite. Microthermometric measurements on fluid inclusions from fracture-filling sparry magnesite provided total homogenization temperatures ranging from 275 to 310°C (Fig. 5). As inferred from the model of Carmignani and Kligfield (1990), the maximum depth at which the evaporite were buried was about 10 km in Tuscany during the Oligocene. If we apply a pressure correction relative to 10 km of burial, it follows that magnesite precipitated at 400 ± 50°C from fluids with a calculated composition of $\delta^{18}O = +13.3 \pm 1.2$‰ (Lugli et al., 2000). These values fall into the range of the metamorphic fluid compositions calculated for the Apuane complex ($\delta^{18}O = +7$ to $+16$‰; Benvenuti et al., 1991).

6. Anhydrite

Anhydrite represents roughly less than the 5% of the entire sulfate volume. The anhydrite rocks are gray colored and are characterized by flow structures, which strongly deformed the original sedimentary features (Fig. 6). The result is a spectacular layer-parallel millimeter- to centimeter-scale pseudo-lamination, which actually consists of tight asymmetric to isoclinal folds, commonly recumbent and transposed, outlined by comminuted dolostone fragments (Fig. 3b). A complete, graded, set of structures can be seen in anhydrite layers with different contents of brittle components, such as dolomite. The relatively pure anhydrite layers are deformed into very tight and transposed isoclinal folds, whereas the layers containing variable amounts of dolomite are kinked and more gently folded.

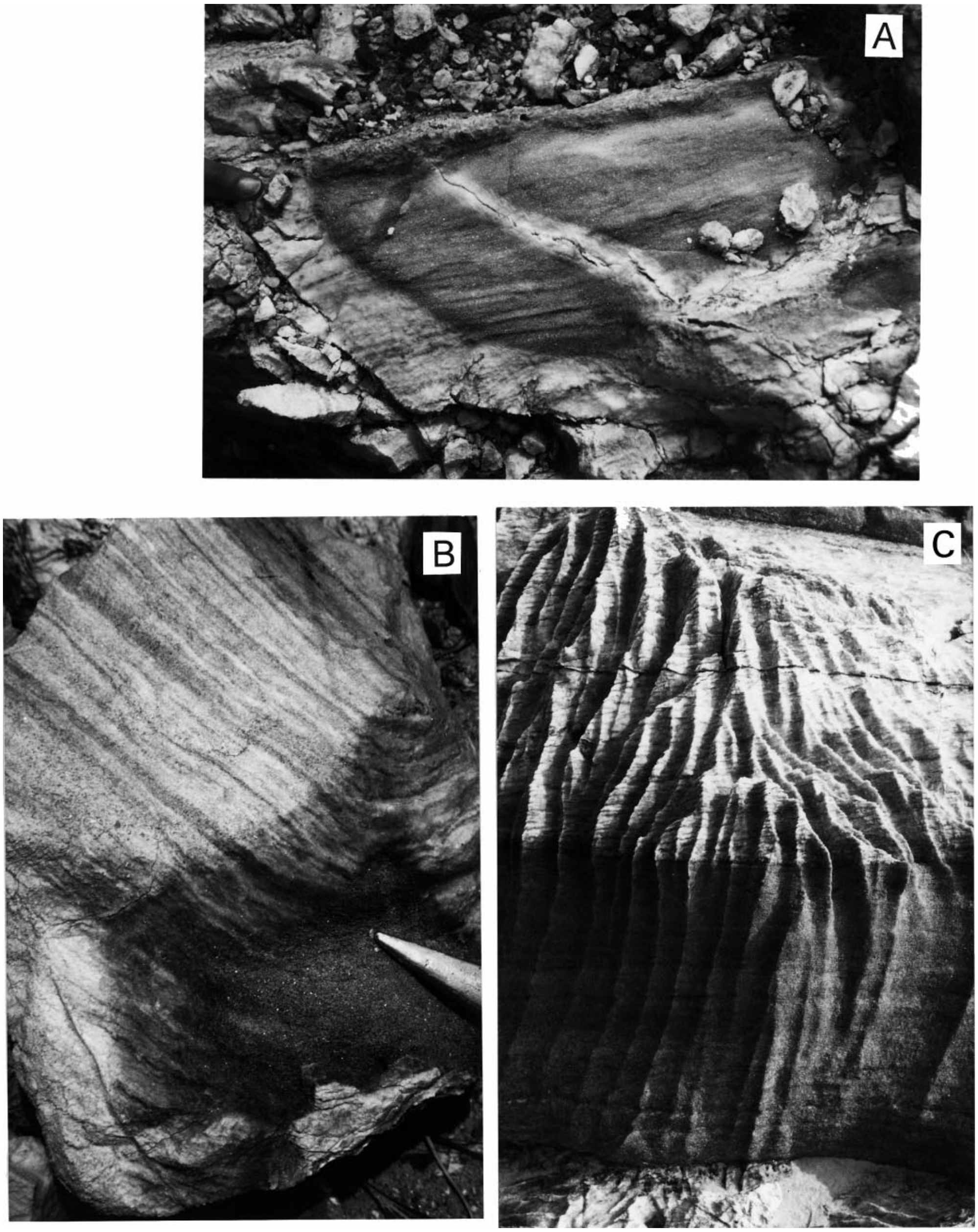


Fig. 6. Outcrop photograph of sulfate rocks: (a) Anhydrite rock (grey) within a gypsum groundmass (white). The boundaries between the two lithotypes are gypsification fronts which develop parallel to fractures and stratification planes. Note that the tiny laminations of anhydrite are not displaced by the gypsification front suggesting that no significant volume changes took place during hydration. A finger is visible for scale (left). Acquabona. (b) Anhydrite rock (grey) in contact with a gypsum rock (white). The boundary between the two lithotypes is a gypsification front. The layering is represented by isoclinal folds outlined by comminuted fragments of dolostone. Note that no dislocation of the pseudo-layering is present across the gypsification front. Tip of hammer for scale. Acquabona. (c) Gypsum pseudo-laminite (top) originated from hydration of an anhydrite pseudo-laminite (bottom of the photograph). The scanty pseudo-lamination consists of transposed isoclinal folds. The anhydrite layer (at bottom) is lens-shaped, 30 cm-thick. The vertical features cutting the outcrop surface are karstic Rillenkarren. M. Rosso.

The most common anhydrite texture is composed of aligned prismatic crystals (Ciarapica et al., 1985), which are up 1 cm in size (Fig. 7). The elongation of the anhydrite crystals is generally parallel to pseudo-lamination. The anhydrite crystals are commonly outlined by a variable rim composed of gypsum, which may represent the first step of hydration (see below for description; Fig. 7a).

No unequivocal undeformed sedimentary features which can be used to reconstruct the environment of deposition have been identified. The described tectonic features could develop from the deformation of both original layering or nodular features, the latter particularly for those rocks showing transposed isoclinal folds.

7. Gypsum

The gypsum rocks are generally white and show the same tectonic lamination structures as the anhydrites (Fig. 6). The gypsum rocks are mostly composed of microcrystalline or xenotopic irregular cloudy ameboid crystals (Ciarapica et al., 1985; Fig. 7b). More rare are rocks composed of centimeter-scale idiotopic crystals. Bertolani and Rossi (1986) reported the widespread presence of fibrous gypsum, but their results appear to be affected by overheating during thin section preparation, as stressed by Holliday (1970).

The origin of the gypsum rocks is always recognizable as being due to late alteration of anhydrite by migration of hydration fronts moving from fractures and strata boundaries (Fig. 6). The hydration genesis is revealed by:

(a) the common observation of sharp hydration fronts separating anhydrite from gypsum rocks showing the same (deformation) structures (Fig. 6);
(b) the common presence of corroded anhydrite micro-relics into the gypsum rocks (Fig. 6b); and
(c) the widespread presence of authigenic quartz crystals, which include anhydrite also in those gypsum rocks completely devoid of anhydrite relics (Lugli, 1996; Fig. 8).

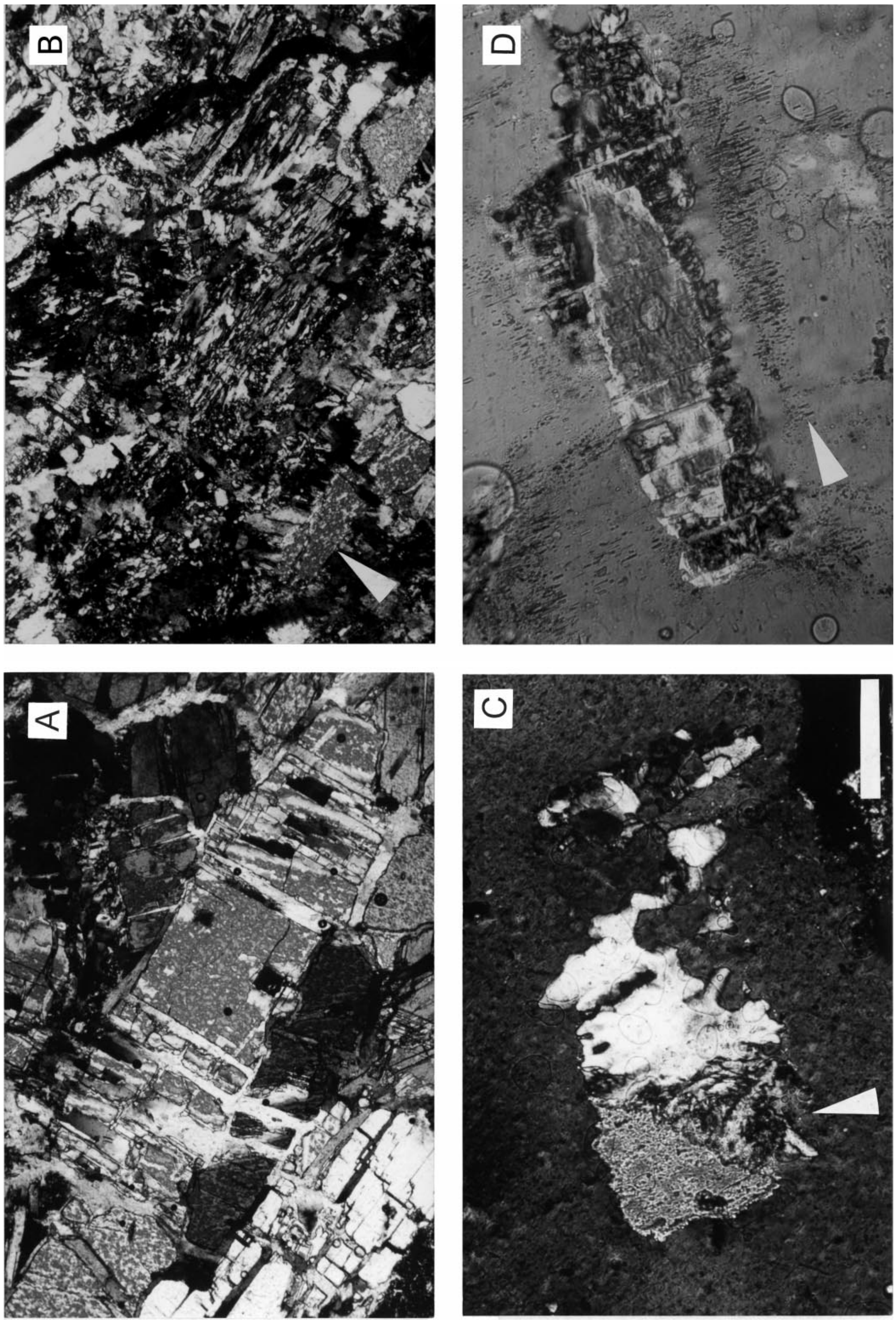
Bertolani and Rossi (1986) suggested that volume increase related to gypsification of anhydrite was responsible for the observed deformation features. On the contrary, because gypsification fronts cut through deformation structures, it follows that hydration clearly post-dates deformation. And moreover, the very fine pseudo-laminations are not disrupted nor displaced across the gypsification fronts (Fig. 6a and b), demonstrating that the anhydrite → gypsum transition occurred with a negligible volume increase. The excess sulfate volume produced by the transition has probably been dissolved away by hydrating fluids, as suggested by Holliday (1970).

Two main gypsification phases can be identified:

(1) *peripheral hydration* of anhydrite along crystals boundaries and cleavage planes (Fig. 7a); this phase occurs when the stability field of gypsum is reached by temperature decrease during progressive exhumation; the formation of gypsum is governed by the available coexisting water and porosity: the volume increase connected with gypsification of the crystal rims progressively seals the rock porosity, fluids cannot penetrate further and hydration stops; the gypsum crystals formed in this phase are generally a few millimeters in size and may contain anhydrite relics. Macrocrystalline gypsum, a few centimeters in size, develop only by hydration of highly porous anhydrite rocks such as those formed as residual phase by halite dissolution (see below for description).
(2) *complete hydration* of anhydrite rocks at outcrop conditions by migration of localized hydration fronts during karstic circulation of water along fractures and strata boundaries (Fig. 6); the gypsum forming in this phase is always the cloudy ameboid type, which is characterized by lattice deformation and defects, suggesting a relatively fast growth and local deformation by volume increase; the unstable cloudy ameboid gypsum appear to recrystallize into larger individuals, which are commonly in optical continuity with the larger crystals formed during the previous phase of peripheral hydration; the lattice reorganization into a more ordered condition leaves tracks of negative crystals (fluid inclusions) within the new gypsum (Fig. 7c and d).

8. Halite

Gypsum mega-breccias after anhydrite which are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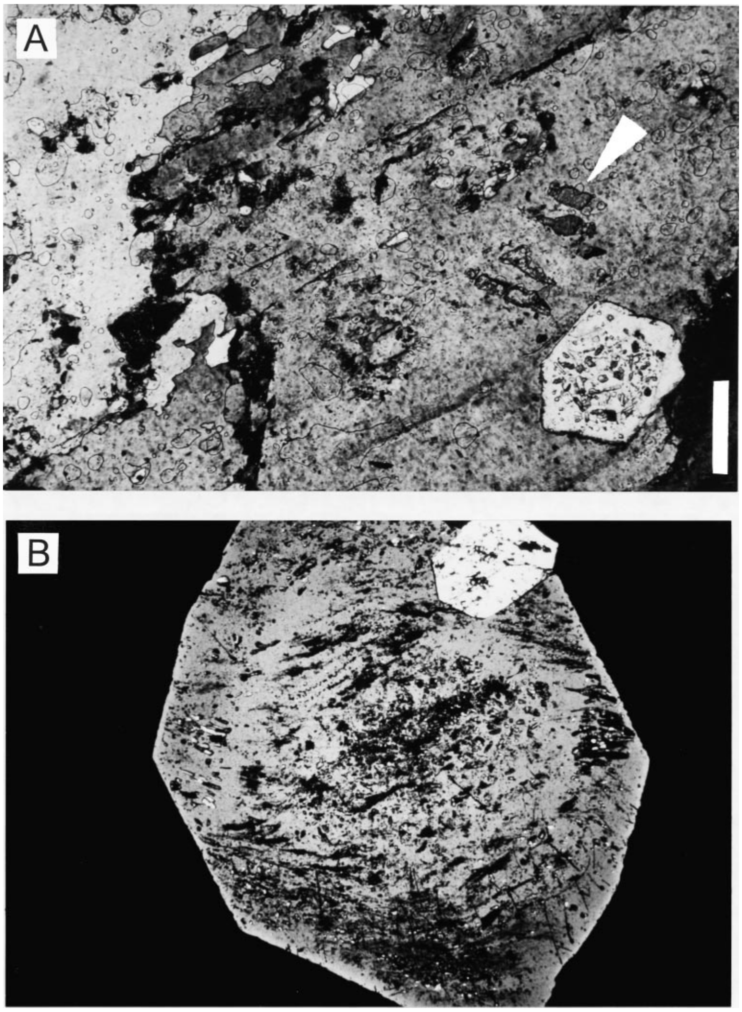

Fig. 8. Photomicrograph of quartz crystals. (a) Quartz crystal (bottom right) within a macrocrystalline gypsum rock. The quartz includes exclusively anhydrite suggesting that the host gypsum represents the product of hydration of an anhydrite precursor. Supporting evidence comes from the presence of some corroded anhydrite relics within the gypsum crystal (arrow); crossed polars. La Villa. (b) Quartz crystal with a penetration twin. The arrangement of the anhydrite and dolomite microinclusions suggests a rotation during the growth. The crystal is 0.5 cm across. Section parallel to *c*-axis; crossed polars. From a residual deposit, Acquabona.

Fig. 7. Photomicrograph of gypsified anhydrite rocks. Scale bar is 0.25 mm and is common for all pictures. (a) Partially gypsified aligned prismatic anhydrite rocks. Note that hydration takes place mostly along grain boundaries and cleavage planes. Some crystals show pressure twinning (bottom of photograph). Crossed polars. M. Rosso. (b) As gypsification continues, the anhydrite crystals are completely replaced by irregular cloudy ameboid gypsum crystals. The gypsum crystal are grouped in domains clearly resembling cleavage flakes of the anhydrite precursor. Some corroded anhydrite relics are still recognizable (arrow). Crossed polars. M. Rosso. (c) Complete hydration of corroded anhydrite relics (left side) within gypsum mega-crystals (in partial optical extinction). The first product of hydration is cloudy ameboid gypsum (arrow) which recrystallize to form larger crystals (white, at center). La Villa. (d) Complete hydration of corroded anhydrite relics (center) into ameboid gypsum (dark rim around anhydrite crystal), which may recrystallize in direct optical continuity with the host gypsum mega-crystal. Note that recrystallization of the strongly deformed ameboid gypsum may occur with formation of new lattice defects, such as negative crystals, within the host gypsum mega-crystal. A train of elongate negative crystals runs around the anhydrite crystal (arrow). Crossed polars. M. Rosso.

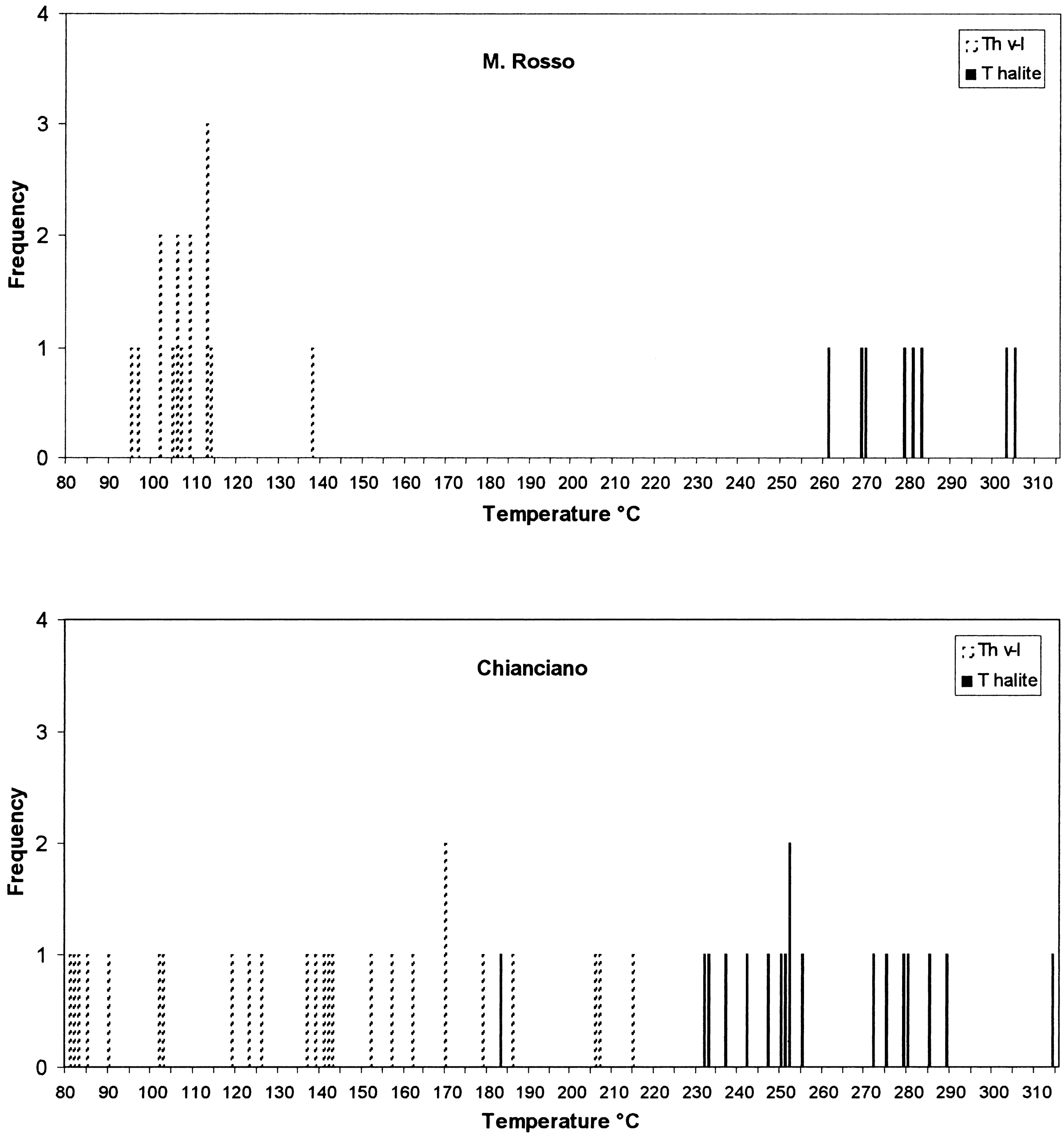

Fig. 9. Frequency histogram relating vapor to liquid homogenization temperatures (v–l) and halite melting temperatures (halite) for fluid inclusions in authigenic quartz crystals from M. Rosso and Chianciano (Tuscany).

more than 200 m thick are present in the northernmost outcrops of the Secchia River Valley, where halite is present at depth, as indicated by boreholes (Colombetti and Fazzini, 1986) and by the presence of salt springs (Colombetti and Fazzini, 1976; Forti et al., 1986). The gypsum mega-breccias are composed of meter to decameter clasts of deformed sulfate-dolostone layers floating in a gypsrudite groundmass

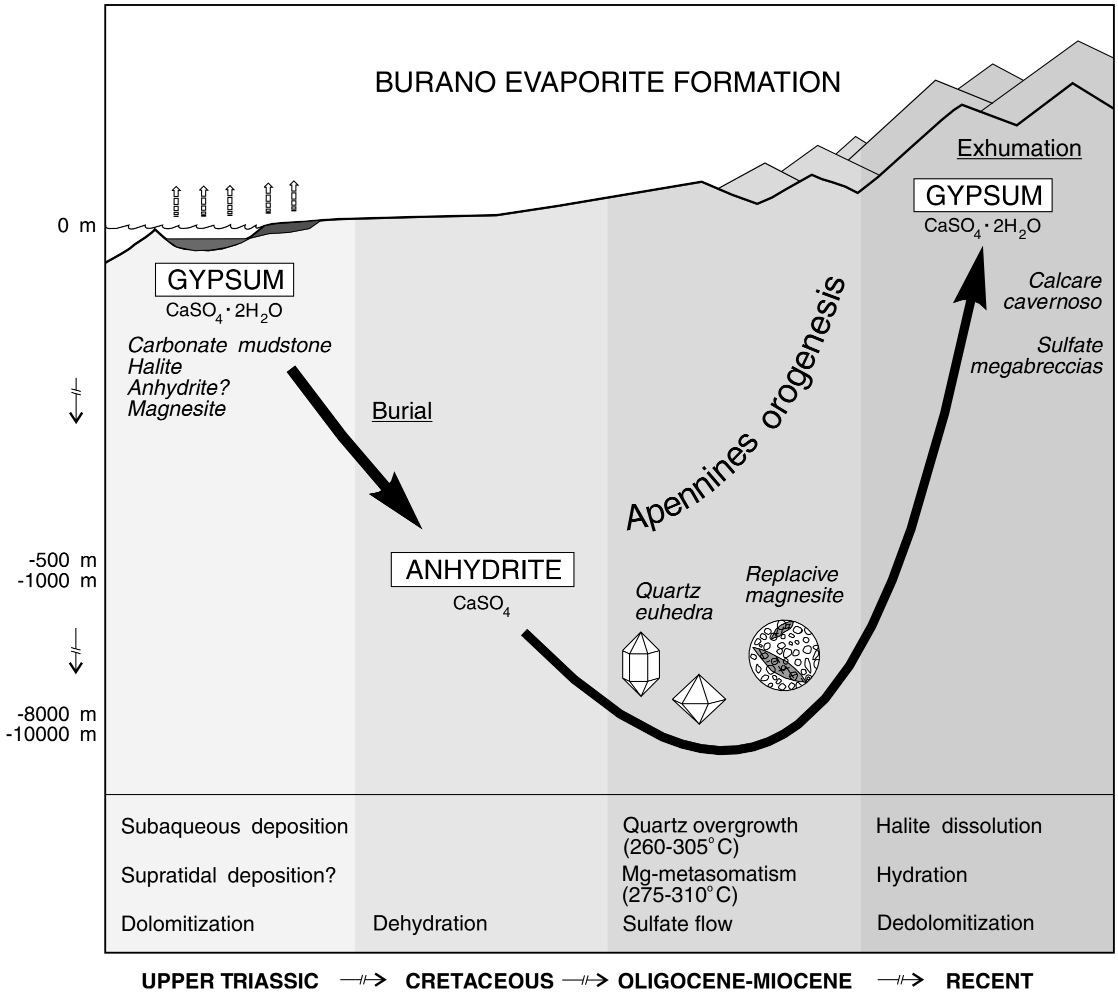

Fig. 10. Tentative reconstruction of the geologic history of the Burano Evaporite Formation. Not to scale. Adapted from the gypsum → anhydrite → gypsum cycle of Murray (1964).

composed of centimeter-scale gypsum crystals including anhydrite relics (Fig. 7c and d). Their origin could be related to caprock-like processes by halite dissolution at sub-surface conditions, because anhydrite and not gypsum was the residual phase (Werner et al., 1988). The clasts may represent relics of dismembered folds and layers which were originally interbedded within a thick, sheared, halite-bearing sequence. The former presence of halite in the area is also inferred from the widespread presence of cubic casts and molds in the associated carbonate and siliciclastic rocks (Lugli and Parea, 1997). Because of the former presence of a large amount of halite, the development of a now vanished diapiric structure in the northernmost area (M. Rosso) cannot be excluded.

9. Quartz euhedra

The anhydrite rocks commonly contain idiomorphic black quartz crystals, which may reach several centimeters in size. The largest quartz crystals are commonly boudinaged. The solid inclusions of the crystals are composed mostly of anhydrite and more rarely of dolomite and magnesite (Lugli, 1996a). The crystals are devoid of gypsum inclusions. The arrangement of solid inclusions within the crystals suggests that some growth phases occurred with rotation of the crystals, possibly induced by flow of the host anhydrite layers (Fig. 8b). These characteristics and total homogenization temperatures of fluid inclusions ranging from 260 to 305°C (Emilia) and from 230 to 315°C (Tuscany; Fig. 9) indicate that some growth phases occurred at deep tectonic burial conditions. These deep tectonic burial conditions could be related to the role of the evaporites as a detachment horizon for the Tuscan Nappe during the Oligocene–Miocene development of the Apuane greenschist facies metamorphic complex (Carmignani and Klingfiel, 1990).

10. The gypsum ↔ anhydrite transitions

The described characteristics of the Burano evaporites suggest a complete gypsum → anhydrite → gypsum cycle for the sulfate of the Burano Formation as described by Holliday (1970; Fig. 10). Evidence for such a sulfate cycle is the observation that the widespread authigenic quartz euhedra included in gypsum rocks from Emilia and Tuscany contain exclusively anhydrite microinclusions, gypsum was never identified (Lugli, 1996a). These characteristics suggest that during the crystals growth the entire sulfate deposit was composed exclusively of anhydrite, whereas it is now composed mostly of gypsum at outcrops.

Considering that anhydrite is known to be deposited only in modern sabkhas (Shearman, 1985) one may assume that most of the evaporite formation originated in such supratidal environments. Unequivocal evidence supporting this explanation, however, is not available. The carbonate–sulfate cycles visible in most outcrops reach stratigraphic thicknesses which are generally up to one order of magnitude greater than those forming in modern sabkhas, where they normally do not exceed one meter (Butler, 1969; Shearman, 1982). In addition, the observation that in most of the cycles the sulfate rocks are greater in volume than the dolostones is unfavorable for a supratidal genesis and would seem to point to a subaqueous origin. On the other hand, the strong deformation which affects the deposit heavily modified the stratigraphic relationships among lithotypes, destroying primary structures and textures. On the above grounds, the question about the environment of deposition of the Burano Formation remains unresolved.

If these considerations are correct, it follows that most of the anhydrite formation probably took place by dehydration of original gypsum due to a geothermal rise in temperature induced by burial conditions (Fig. 10). Because no gypsum is known to be present below 1000 m of depth (Shearman, 1985), the formation of anhydrite at the expense of gypsum could have been completed during the Cretaceous, when the evaporites were buried under about 1000 m of sediments of the Tuscan succession. Considering the general model of Jowett et al. (1993) predicting the depths of gypsum dehydration, the relatively high heat flow regimes in the Triassic rift setting, the burial under carbonate-marls and the presence of halite in some areas, the transition temperature could have been reached at a burial depth of about 500 m. According to the general stratigraphy of the Tuscan Succession (Boccaletti et al., 1987) these conditions would have been reached during the Jurassic.

The subsequent exposure of the sulfate formation caused by the Apennines orogenesis induced the gypsification of anhydrite, as previously described, closing the cycle (Fig. 10).

11. Conclusions

The study of the Upper Triassic Burano Formation has provided us with new insights on the complexity of the geologic evolution of sulfate–carbonate deposits. The petrography and geochemistry of the rocks and their mineralization indicate that the evaporite deposit underwent a complex array of post-depositional modifications including thermal events. These modifications completely obliterated the evaporite sedimentary features. The observed sequence of events reflects the role of the Burano Evaporites as main detachment horizon for the Tuscan Nappe during the Northern Apennines chain formation (Carmignani and Kligfield, 1990). The Burano Evaporites history during the Apennines tectogenesis can be depicted as follows:

(a) prevalent deposition of gypsum in the Upper Triassic, though deposition of anhydrite in same

areas cannot be excluded; thick halite deposits were also precipitated; minor deposition of microcrystalline magnesite took place in localized areas;
(b) gypsum dehydration at burial conditions to form anhydrite; the transition may have been completed during the Cretaceous at burial depths around 1000 m; after the formation of anhydrite, authigenic quartz euhedra crystallized;
(c) syn-tectonic flow of anhydrite rocks, boudinage of dolostones; syn-tectonic overgrowth stage of quartz euhedra at deep burial conditions comparable to the greenschist facies of the Alpi Apuane metamorphic complex (Oligocene–Miocene);
(d) hydrothermal deposition of sparry magnesite and partial or total Mg-metasomatic replacement of dolostones by magnesite;
(e) sub-surface dissolution of halite to form thick matrix-supported residual cap rock-like anhydrite mega-breccias possibly related to diapiric movements;
(f) complete gypsification of anhydrite in subsurface conditions with no significant deformation by volume increase;
(g) evaporite dissolution at surface producing coarse dolostones breccias with partial calcitization and removal of most of the dolomite clasts ("Calcare Cavernoso").

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