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Facies analysis of the Trypali carbonate unit (Upper Triassic) in central-western Crete (Greece): an evaporite formation transformed into solution-collapse breccias

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ABSTRACT

The Trypali carbonate unit (Upper Triassic), which crops out mainly in central-western Crete, occurs between the parautochthonous series (Plattenkalk or Talea Ori-Ida series, e.g. metamorphic Ionian series) and the Tripolis nappe (comprising the Tripolis carbonate series and including a basal Phyllite–Quartzite unit). It consists of interbedded dolomitic layers, represented principally by algally laminated peloidal mudstones, foraminiferal, peloidal and ooidal grainstones, as well as by fine-grained detrital carbonate layers, in which coarse baroque dolomite crystals and dolomite nodules are dispersed. Baroque dolomite is present as pseudomorphs after evaporite crystals (nodules and rosettes), which grew penecontemporaneously by displacement and/or replacement of the host sediments (sabkha diagenesis). However, portions of the evaporites show evidence of resedimentation. Pre-existing evaporites predominantly consisted of skeletal halite crystals that formed from fragmentation of pyramidal-shaped hoppers, as well as of anhydrite nodules and rosettes (salt crusts). All microfacies are characteristic of peritidal depositional environments, such as sabkhas, tidal flats, shallow hypersaline lagoons, tidal bars and/or tidal channels. Along most horizons, the Trypali unit is strongly brecciated. These breccias are of solution-collapse origin, forming after the removal of evaporite beds. Evaporite-related diagenetic fabrics show that there was extensive dissolution and replacement of pre-existing evaporites, which resulted in solution-collapse of the carbonate beds. Evaporite replacement fabrics, including calcitized and silicified evaporite crystals, are present in cements in the carbonate breccias. Brecciation was a multistage process; it started in the Triassic, but was most active in the Tertiary, in association with uplift and ground-water flow (telogenetic alteration). During late diagenesis, in zones of intense evaporite leaching and brecciation, solution-collapse breccias were transformed to rauhwackes. The Trypali carbonate breccias (Trypali unit) are lithologically and texturally similar to the Triassic solution-collapse breccias of the Ionian zone (continental Greece). The evaporites probably represent a major diapiric injection along the base of the parautochthonous series (metamorphic Ionian series) and also along the overthrust surface separating the parautochthonous series from the Tripolis nappe (Phyllite–Quartzite and Tripolis series). The injected evaporites were subsequently transformed into solution-collapse breccias.

Keywords Dolomites, evaporites, peritidal environment, sabkha diagenesis, solution-collapse breccias, Upper Triassic.

INTRODUCTION

Evaporite replacement fabrics within carbonate strata and residual textures created by dissolution of evaporites are of great economic and scientific interest (e.g. Ulmer & Laury, 1984; Scholle *et al.*, 1992, 1993; Ulmer-Scholle & Scholle, 1994; Warren, 1996, 1997; Friedman, 1997). These fabrics include calcitized and silicified evaporite crystals and nodules, calcitized dolomite crystals and rocks, and quartz euhedra (Folk & Pittman, 1971). However, the most common fabrics related to evaporite dissolution and diagenesis are solution-collapse breccias and rauhwackes, which can be difficult to differentiate from tectonic or other type of breccias (Stanton, 1966; Swennen *et al.*, 1990). Solution-collapse breccias result from the dissolution of massive evaporite strata, which creates cavities. Thus weakened, the overlying interbedded carbonate facies collapses creating breccias (Scholle *et al.*, 1993; Warren, 1997).

The Trypali carbonate unit crops out mainly in central and western Crete and is intercalated between the parautochthonous unit (Plattenkalk or Talea Ori-Ida series) and the Tripolis nappe (Phyllite–Quartzite and carbonate Tripolis series; Fig. 1). Along most horizons, the Trypali carbonate unit is strongly brecciated. Several contrasting interpretations have been proposed for the carbonate breccias of the Trypali unit (Kuss & Thorbecke, 1974; Creutzburg & Seidel, 1975; Xavier, 1976; Kopp & Ott, 1977; Jacobshagen *et al.*, 1978; Dallwing & Kuss, 1982; Krahl *et al.*, 1983, 1986; Karakitsios, 1987).

The parautochthonous unit in Crete represents the metamorphic equivalent of the Ionian zone, in NW Greece, and the Trypali carbonate breccias are very similar in appearance to the Triassic breccias–rauhwackes of the Ionian zone. The Triassic breccias–rauhwackes are the first documented case of overthrust-zone breccias with an evaporitic origin (Karakitsios & Pomoni-Papaioannou, 1998). Thus, the question arose as to whether the Trypali carbonate breccias could also have originated from pre-existing evaporites. The present study was undertaken to define the

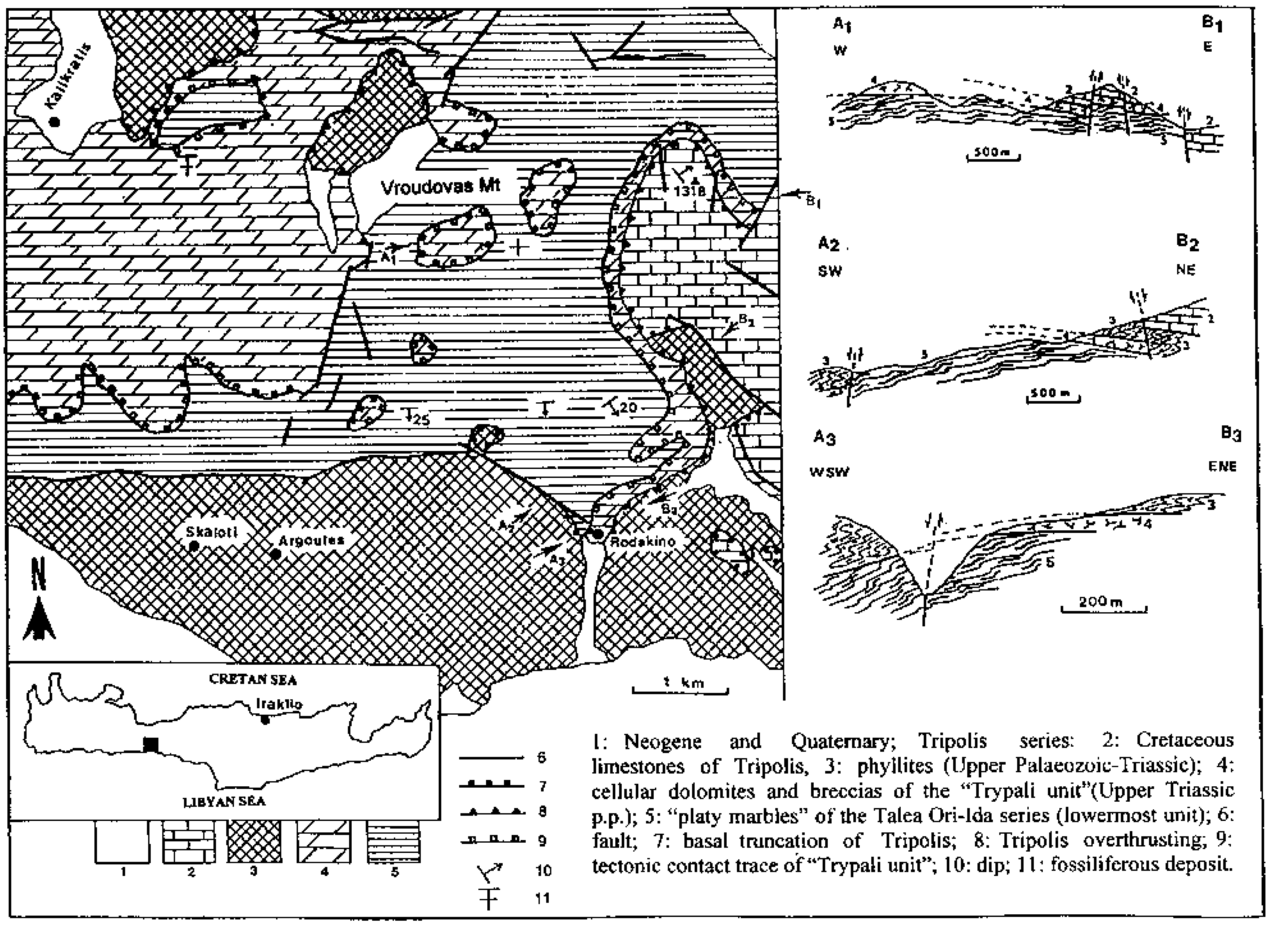


Fig. 1. Geological map and structural cross-sections of the Rodakino region (modified from Karakitsios, 1987). The black square on the inset map indicates the field area.

origin of the Trypali carbonate breccias and to determine the possible timing of brecciation.

Many authors have studied similar breccia formations in the Alpine system (Goguel, 1936; Bruckner, 1941; Ricour, 1962; Sturani, 1963; Warrak, 1974; Grandjacquet & Haccard, 1975; Bourgois, 1979). Re-examination of their origin, considering the possibility that they are of evaporite solution-collapse origin, is worthwhile. Such studies should take into consideration the significant role that the evaporitic horizon played in the tectonic evolution of the sedimentary cover in the context of the Alpine orogenesis. This includes halokinesis, detachment, diapirism and brecciation of evaporites (Karakitsios *et al.*, 2001).

GEOLOGICAL SETTING

Porous breccias that locally contain concentrations of gypsum are very common in the Trypali carbonate unit (Creutzburg & Seidel, 1975). However, field criteria and simple stratigraphic analysis provide no clear evidence for the origin of these breccias.

A detailed facies analysis of the Trypali unit was undertaken in the Rodakino area of mid-western Crete (Fig. 1). The study area was remapped in order to find genetic relationships between the porous breccias and other units. The lowermost structural units of the Cretan Nappe pile are exposed within the Kalikratis–Vroudovas mega-anticline. The parautochthonous unit (Plattenkalk or Talea Ori-Ida series) is tectonically overlain by the porous breccias, which is in turn tectonically overlain by either the Phyllite–Quartzite unit (most frequently) or the Tripolis carbonate unit (rarely). The upper two units are probably allochthonous, although there is some controversy concerning their original relative palaeogeographic relationships (Karakitsios, 1982, 1986 and references therein). In Crete, the Tripolis carbonate series includes shallow-marine, generally fossiliferous limestones and dolomites (with local stromatolitic horizons) ranging in age from Upper Triassic to Upper Eocene (Karakitsios, 1979, 1986). The Phyllite–Quartzite series is Upper Palaeozoic–Triassic in age (Krahl *et al.*, 1986) and includes siliciclastics, carbonates and basic volcanics, which have undergone polyphase deformation and low-grade regional metamorphism. In this paper, the Phyllite–Quartzite unit corresponds to the basal stratigraphic division of the Tripolis carbonate series (Bonneau & Karakitsios, 1979). The whole entity, which includes the Tripolis carbonate series and the Phyllite–Quartzite series, is referred to here as the 'Tripolis nappe'. The parautochthonous unit (Plattenkalk or Talea Ori-Ida series) consists of a sequence of platy cherty marbles (almost entirely devoid of terrigenous debris), which have also undergone deformation and low-grade regional metamorphism. Only the lowest and highest parts of the sequence are dated: Epting *et al.* (1972) reported Norian ages for the basal stromatolitic dolomites, whereas the top of the sequence is dated as Oligocene by deformed *Globigerina*-bearing metamarls in eastern Crete and the Psiloritis Mountains (Fytrolakis, 1972; Bonneau, 1973). In the study area, the platy cherty marbles are estimated to be over 600 m thick, whereas the porous breccia formation does not exceed 200 m. Yellow saccharoidal gypsum, associated with the breccia, is sometimes observed (i.e. NW of Kalikratis; Karakitsios, 1979).

The Trypali unit includes, in its lower parts, cellular dolomite (yellow, grey or reddish), which is less than 20 m thick. The breccias gradually follow the cellular dolomite, are grey/black and consist of calcareous dolomitic clasts with algae and cements. No internal stratification is visible, except in the uppermost horizons. These horizons also contain oolitic clasts and sometimes pass laterally into either cavernous dolomites or oolitic dolomites. The cavernous dolomites occur close to Kalikratis and contain *Glomospirella friedli* Kristan-Tollmann of Upper Triassic age (Karakitsios, 1987). The oolitic dolomites are stratified and occur 1 km SE of Kalikratis. They contain an undeterminable conodont assemblage (Karakitsios, 1987).

It has not been possible to determine the metamorphic grade of the Trypali unit; except for the albite and quartz that formed diagenetically in its lower part (i.e. the cellular dolomite), no other crystals with any metamorphic significance have been observed.

METHODS OF STUDY

Detailed microfacies analysis was carried out in four stratigraphic sections located in the Kalikratis–Vroudovas mega-anticline (Fig. 2). Thin sections were stained with Alizarin red S to differentiate calcite, dolomite and dedolomite. Staining with potassium ferricyanide did not reveal the presence of iron in the dolomite or calcite.

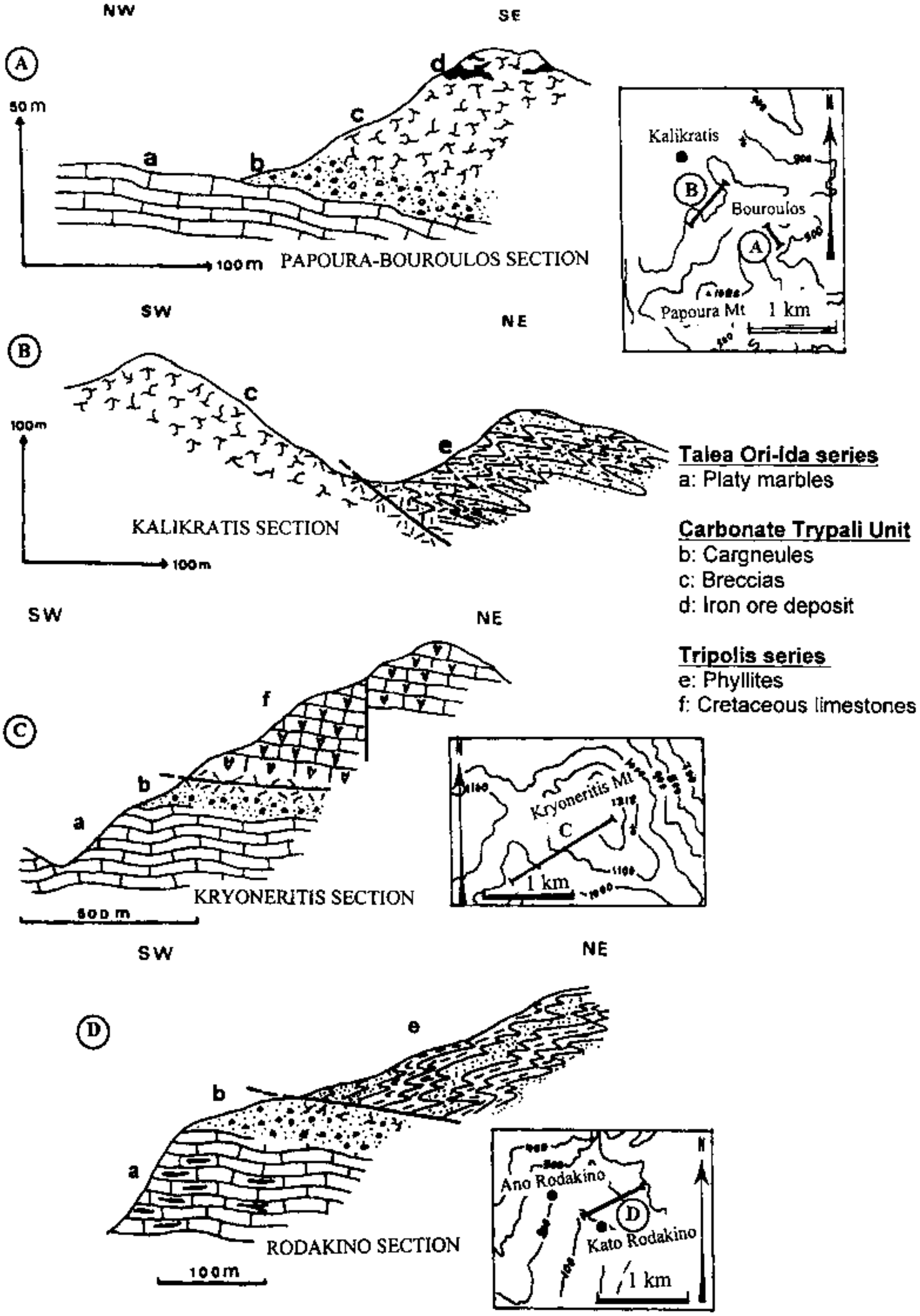
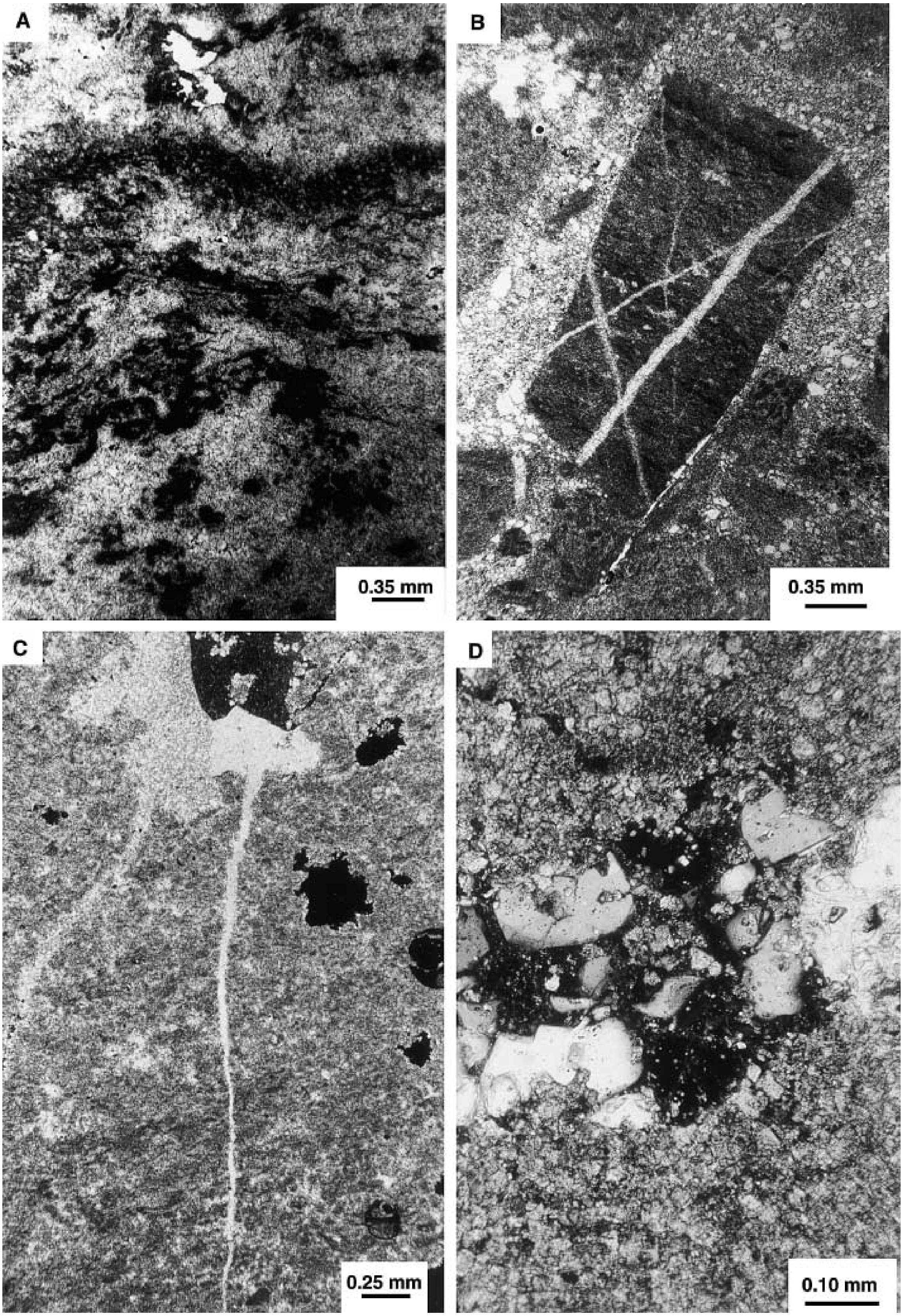


Fig. 2. Geological sections of the Rodakino region (modified from Karakitsios, 1979).

Fig. 3. Algally laminated peloidal mudstones. (A) Algally laminated peloidal mudstones consisting of laterally linked microdomal structures. Dark, irregularly undulated and crinkled laminae, consisting of crypto-microcrystalline dolomite, alternate with lighter laminae consisting of fine-grained dolomicrosparite. Because sediments have been affected by intense dolomitization and recrystallization, only relic structures are observed. Plane-polarized light. (B) Breccia clast of algally laminated (planar) peloidal mudstone with small bird's eye-type cavities. Plane-polarized light. (C) Pseudomorph after an evaporite nodule, with extinction patterns revealing a radial arrangement of the crystals. Crossed polars. (D) Quartz euhedra filling the fractures show a tendency for radial arrangement. The area that is at extinction is later poikilotopic calcite. Crossed polars.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X-ray diffraction analysis of the upper part of the Papoura–Bouroulos section (Fig. 2A) was carried out in order to determine the mineralogy of part of the stratigraphic section (e.g. dolomite vs. dedolomite) and identify associated Fe oxides (Karakitsios, 1979).

FACIES ANALYSIS

Six main lithofacies are recognized in the Trypali carbonate unit; these are algally laminated peloidal mudstones, peloidal grainstones, bioclastic grainstones, ooid grainstones, as well as Fe oxide-enriched, fine-grained detrital carbonate, in which coarse baroque dolomite crystals and dolomite nodules float. Considerable brecciation has occurred along most horizons, forming solution-collapse breccias and/or rauhwackes, and disrupting primary depositional textures.

Reddish intervals of calcareous shales or reddened, vuggy, coarsely crystalline limestones are commonly associated with zones of intense leaching and brecciation. In faulted areas, travertine-like calcium carbonate deposits are present along or in the immediate vicinity of fractures.

Algally laminated peloidal mudstones

The mudstones are algal biolithites consisting of laterally linked microdomal and planar types (Fig. 3A and B). Texturally, both domal and planar laminae consist of dark, mm-thick, irregularly undulating and crinkled laminae that alternate with lighter laminae (Fig. 3A). Dark laminae consist of crypto-microcrystalline dolomite with small floating pellets, whereas lighter laminae consist of fine-grained saccharoidal dolomicrosparite. In places, a pelmicrite formed as a result of compaction. Sparse ostracods and pseudomorphs after nodules and rosettes of evaporites occur locally (Fig. 3C). However, as a result of dolomitization and recrystallization, pre-existing textural characteristics of the nodules and rosettes have been obliterated.

Desiccation cracks are common (Fig. 3C), and commonly start from the evaporite nodule and extend into the matrix, following variable directions. Desiccation crack systems have been further enlarged resulting in *in situ* brecciation. The cracks are filled by calcite spar. Quartz euhedra are associated with the mineral fillings of the cracks, but are absent in the brecciated host rock. Quartz euhedra often show a radial arrangement (Fig. 3D) and contain tiny anhydrite relics.

Peloidal grainstones

The peloidal grainstone lithofacies is made up of brownish, fine- to medium sand sized, organic-rich material, as well as cryptocrystalline peloids, with varying admixtures of small ooids. Most peloids are uniform, ovoid and dark, with indistinct outlines and are probably faecal in origin (Fig. 4A). Sparse bioclasts (molluscs, echinoderms and ostracods) occur locally (Fig. 4B).

The nature and origin of some peloids are quite variable. Small peloids are probably of algal origin, whereas some larger spherical and elliptical types display faint oolitic structures, suggesting that they may be micritized ooids. Prismatic, sand grain-sized peloids may be micritized fragments of molluscs. However, because of strong dolomitization and recrystallization, primary textural characteristics of pre-existing allochems are not preserved.

Peloids are well sorted and form a grain-supported texture. The cement consists of finely crystalline anhedral dolomite (Fig. 4C). In some horizons, the peloidal grainstones have undergone intense compaction, followed by cementation and then micritization of the cement, probably as a result of calichification. In some cases, the sediments have the appearance of mudstone layers with the grains barely visible. Often peloids were strongly deformed during early diagenesis, becoming elongated and subparallel to one another. Fractures are filled by poikilotopic spar.

Bioclastic grainstones

The bioclastic grainstone lithofacies is composed of sand-sized bioclastic debris with minor amounts of coated grains (ooids and pisoids) and peloids. The bioclastic debris consists of benthonic foraminifera that have been heavily micritized, making identification difficult. However, some appear to have been *Glomospirella* sp. (Fig. 5).

Usually, the bioclastic grainstones are poorly compacted, suggesting that cementation occurred soon after deposition. Individual grains are cemented together by either micrite or isopachous cement, which probably formed under vadose conditions (Harrison, 1977). Many bioclasts were coated with alternating laminae of micrite and sparite cement before the main phase of sparry cementation occurred. Comparable accumulations of coated bioclastic material are deposited, probably during storm events, in modern supratidal beach ridges of the Persian Gulf (Purser &

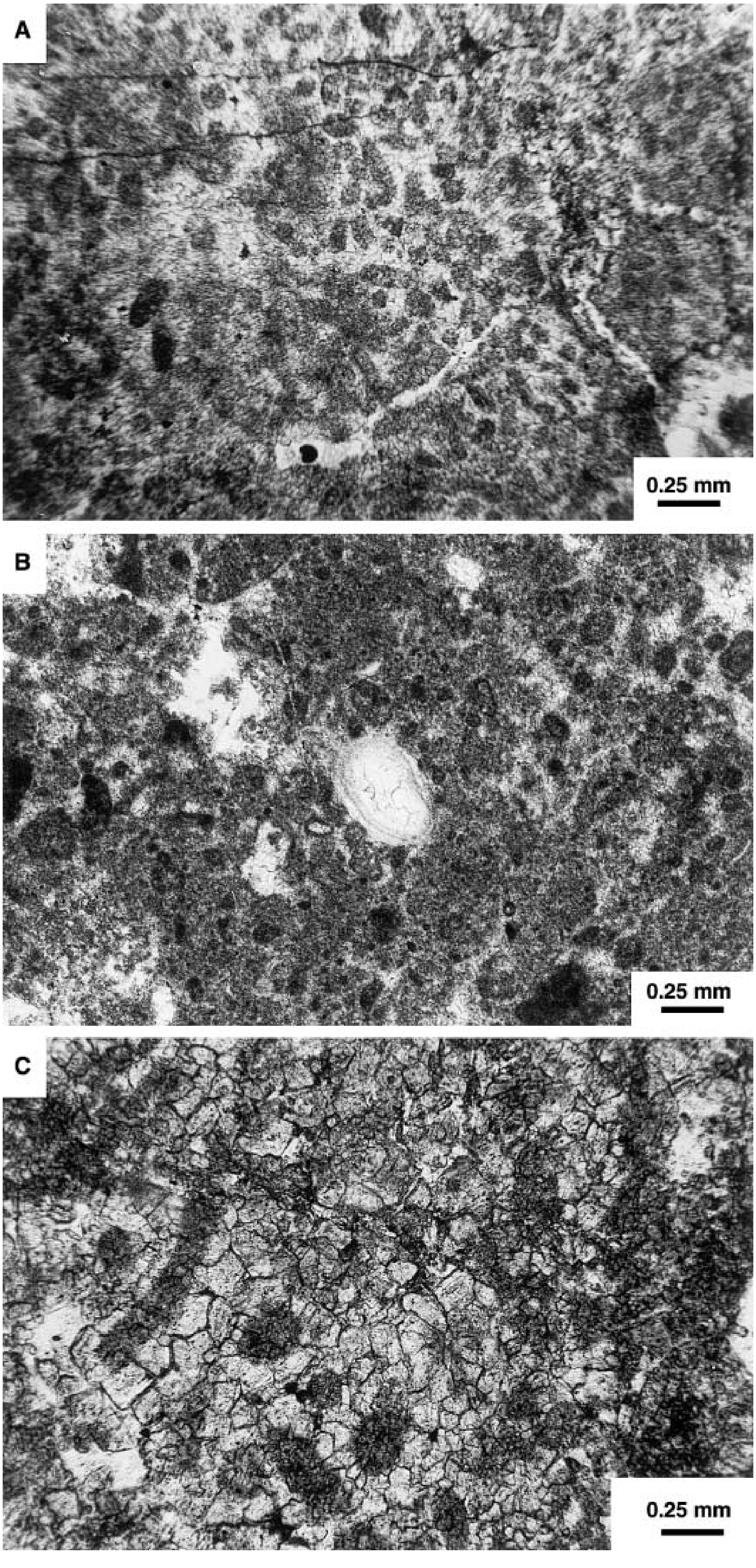


Fig. 4. Peloidal grainstones. All photographs taken with plane-polarized light. (A) Peloidal grainstone made up of brownish, fine to medium sand sized, organic-rich, cryptocrystalline peloids. Peloids are ovoid, ellipsoid or prismatic in shape, indicating different origins. Owing to strong dolomitization and recrystallization, primary textural characteristics of the pre-existing allochems are not preserved. Peloids are cemented by dolosparite. (B) Peloidal grainstone contain varying admixtures of bioclasts. An ostracod shell is shown in the centre. (C) Peloids surrounded by finely crystalline anhedral dolomite. Prismatic grains probably represent micritized molluscs.

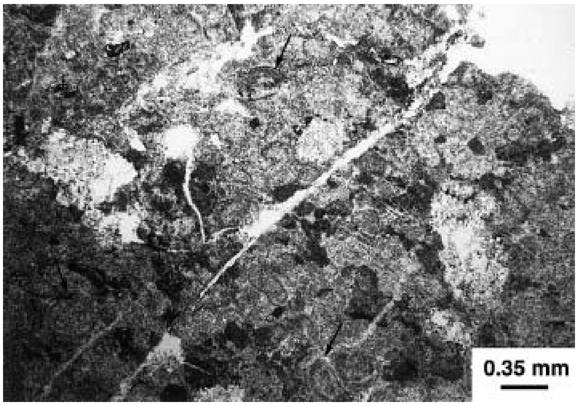


Fig. 5. Bioclastic grainstone consisting predominantly of benthonic foraminifera (*Glomospirella* sp.?). Many foraminifera are coated with alternating laminae of micrite and sparite (arrows). Plane-polarized light.

Loreau, 1973). Percolation of sea water below the surface of the sediment also causes cementation to proceed under vadose conditions.

Ooidal grainstones

The ooidal grainstone lithofacies is composed predominantly of very fine to fine sand-sized, ellipsoidal to spheroidal micritic grains (100–200 μm). Most grains exhibit no internal structure, but some have smoothly laminated cortices with a radial crystal arrangement (Fig. 6A). Nuclei within the ooids are not recognizable.

Composite ooids and grapestones of well-cemented ooids occur as well (Fig. 6B). They are less than 600 μm in size and are commonly coated by alternating laminae of micrite and sparite.

Very finely crystalline anhedral dolomite cement fills the intergranular pores. In places, coarsely crystalline dolomite cement borders the ooids. In the latter case, cementation is only partial, and the rock has large cavities sometimes filled with poikilotopic calcite. Ooids are frequently surrounded by a vadose silt-type sediment, possibly remnants from carbonate and evaporite dissolution (Fig. 6C).

The ooids are often deformed and ruptured, presumably as a result of contraction and stretching (Fig. 6D), producing spastoliths (Cayeux, 1935; Carozzi, 1961; Assereto & Benelli, 1971; Conley, 1977). In some horizons, the ooids retain their primary circular or elliptical shape. Some spastoliths are deeply penetrated by wedge-like open cracks, whereas others are joined to one another by irregular, elongate and delicate projections. Unaffected ooids are always associated with strongly deformed ones (Fig. 6D). Deformation probably occurred during late diagenesis, when compressional tectonics affected the area. Cementation may control the degree to which specific ooids were deformed.

The grapestones are texturally similar to beachrock forming today in the Persian Gulf by wave action (Evamy, 1973; Purser & Loreau, 1973).

Detrital carbonate sediments with dolomite pseudomorphs after evaporites

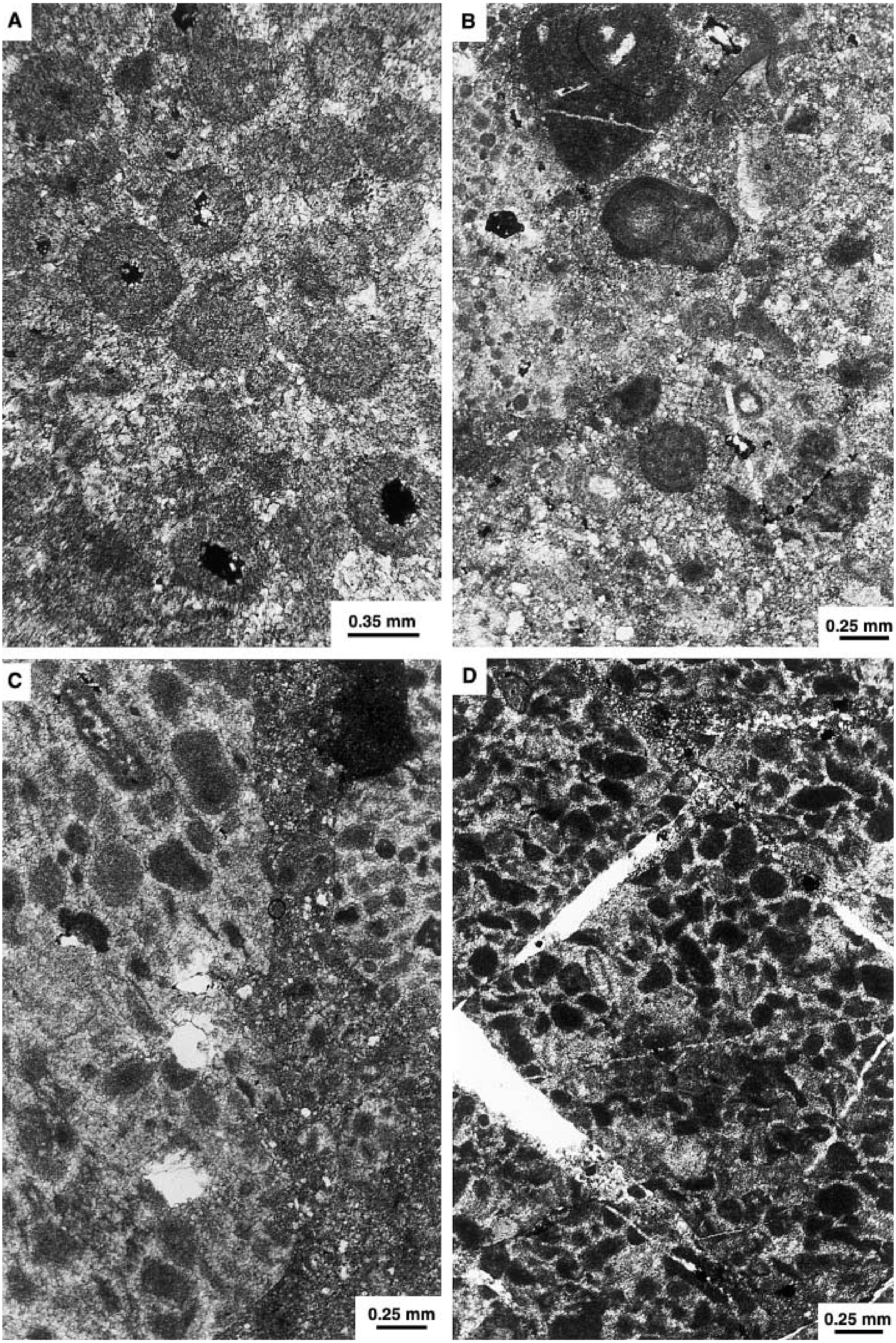
In this lithofacies, laminae of dolomite crystals of variable size (averaging between 20 μm and 1 mm), with prismatic and cubic habits (Fig. 7A), alternate with laminae of Fe oxide-rich grains and argillaceous material, dispersed in a microcrystalline dolomitic matrix (45–90 μm; Fig. 7B).

Dolomite nodules and rosettes, consisting of radially arranged crystals, and coarse intraclasts of the interbedded peritidal carbonate facies are present locally. Dolomite crystals show the optical characteristics of baroque dolomite (e.g. irregular crystal contacts, intense pleochroism and wavy extinction; Fig. 7C). The host argillaceous sediment is commonly reduced to pockets or thin films between crystals.

Cubic dolomite crystals are characterized by internal zonation, containing tiny inclusions of the host argillaceous sediment (Fig. 8A). Inclusions are parallel to the cubic crystal faces. Prismatic dolomite crystals, however, are characterized by ragged stair step-type outlines (Fig. 8B). In places, they are orientated parallel to the depositional fabric. Microscopic inclusions of anhydrite are concentrated in the cores of the crystals.

This facies is characterized by abundant quartz euhedra, either as sparse crystals (Fig. 8C) or in the form of rosettes (Fig. 8D). Quartz crystals contain tiny anhydrite relics (Fig. 8C and D). In

Fig. 6. Oolitic grainstones. All photographs taken with plane-polarized light. (A) Ooids with smoothly laminated cortices and radial arrangement. Nuclei within the ooids are not recognizable; some are opaque grains. (B) Sparse composite ooids and grapestones in a microclastic matrix. Breccia clasts of oolitic grainstones in a vadose silt-type material, possibly derived from carbonate and evaporite dissolution. (C) A vadose silt-type sediment introduced between the breccia clasts of ooidal grainstone. (D) Distorted ooids (spastoliths) resulting from contraction and stretching; ooids have lost their primary circular or elliptical shape. Ooids are well compacted, and some are joined to one another by irregular, elongate microstylolitic projections.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addition, the facies is characterized by the ubiquitous presence of microscopic euhedral pyrite crystals, which occur in places as small framboids.

A network of sinuous hair-like cracks occurs within the sediments. The cracks are filled by either poikilotopic calcite spar or mechanically introduced vadose silt. In places, the calcite spar has been further replaced by authigenic dolomite rhombs. Sedimentary structures (e.g. ripple-marks and cross bedding) favour a detrital origin for this facies, either fluvial or aeolian. However, the depositional texture has in places been obliterated by the growth of dolomite crystals.

Cubic and prismatic dolomite crystals are pseudomorphs after displacively and/or replacively grown evaporite crystals, halite and anhydrite respectively. Cubic dolomite crystals predominate and pseudomorph fragmentary surface-grown halite crystals or reworked material from bottom-growing crusts (Shearman, 1970; Kendall, 1984). In the same sense, dolomite nodules and rosettes are interpreted as pseudomorphs after anhydrite. The evaporitic origin of the carbonate sediments is further supported by the presence of quartz euhedra and rosettes (Folk & Pittman, 1971). Primary growth of evaporites occurred penecontemporaneously, but the crystals continued to grow diagenetically. Owing to the progressive growth of evaporite crystals and nodules/rosettes, the primary textural characteristics of the parent argillaceous sediments have been obliterated. Baroque dolomite has pseudomorphed pre-existing evaporites, which have grown by pushing aside the fine-grained and organic-rich matrix or have been resedimented. Desiccation, during early diagenesis, was responsible for the development of thin cracks. Owing to pedogenic alteration during late diagenesis, the above-described facies tends to be progressively assimilated by a homogeneous dolomicrosparitic matrix (calcrete floating texture).

Solution-collapse breccias

Breccia fragments are mainly dolomitic and correspond lithologically to the Trypali carbonate unit microfacies (Fig. 9A). Clasts are angular to subrounded and poorly sorted, and are chaotically distributed in a matrix of limonitic clay, microclastic material and porous saccharoidal calcareous dolomite matrix (Fig. 9B). This matrix was probably derived from the dissolution of large volumes of interbedded carbonate and evaporite beds. Baroque dolomite is found along discontinuities. Concentrations of quartz and Fe oxides surrounding the breccia clasts form thick coatings in places (Fig. 9C).

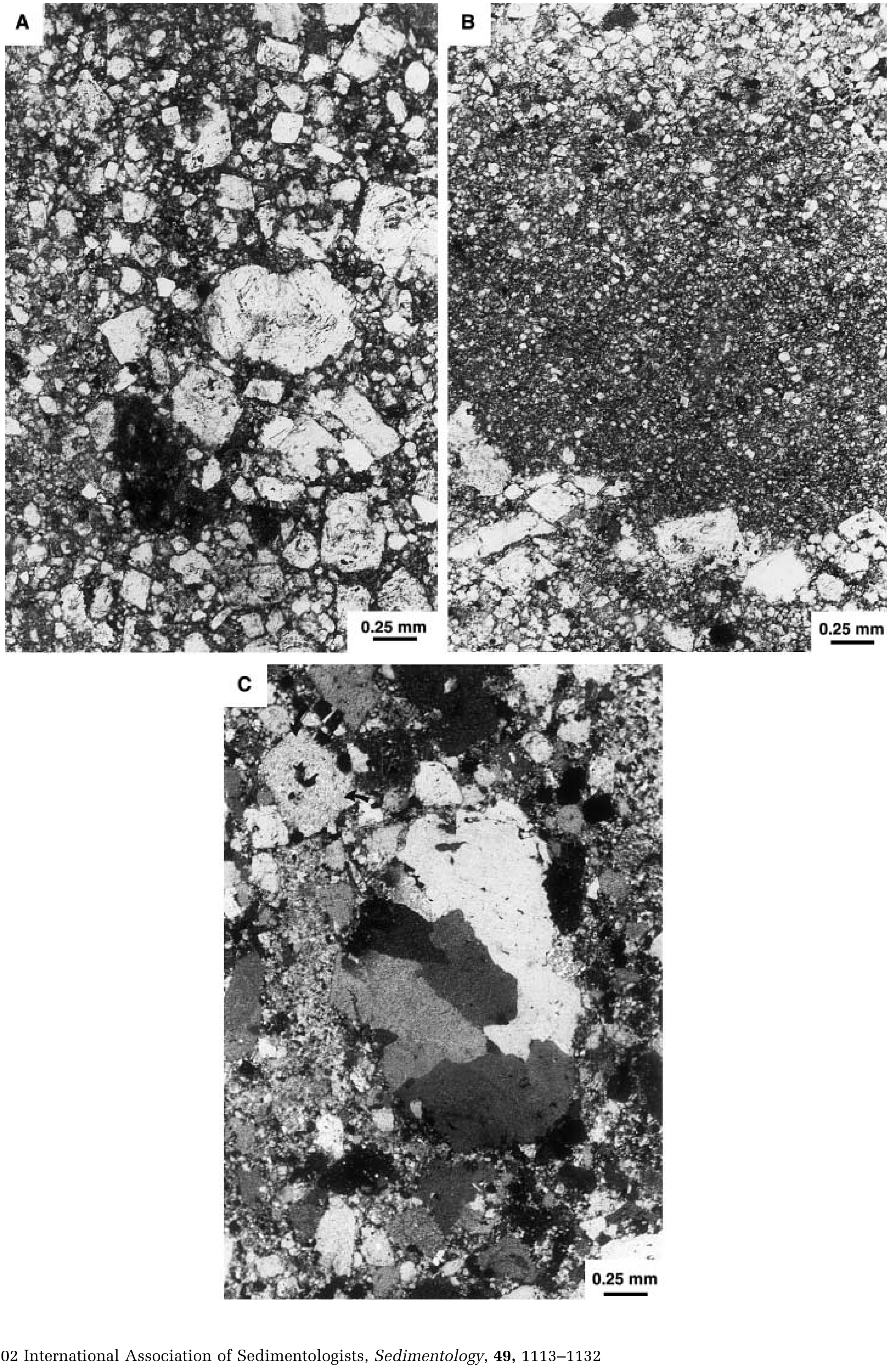
The original highly soluble evaporite minerals were either leached to form open pores or replaced by baroque dolomite (Fig. 9D) or megaquartz (Fig. 9D; Scholle *et al.*, 1992). Dolomite spar shows clear evidence of replaced evaporites (Harwood, 1980), such as the characteristic rectangular, stepped outlines of anhydrite. Nodules consist of megaquartz with radial extinction under crossed nicols. Inclusions of anhydrite are common within the authigenic quartz euhedra (Fig. 8D).

Calcitization of areas of pervasive earlier evaporite replacement results in floating fabrics. These fabrics show extremely loosely packed and unsupported grains or clasts floating within calcite spar (Scholle *et al.*, 1992, 1993). The fact that evaporite inclusions are rarely observed within the calcite spar suggests that dissolution of evaporites has occurred. According to Scholle *et al.* (1993), the scarcity of evaporite inclusions in the sparry calcite cements may indicate that most calcitization took place by a multistage process involving evaporite dissolution, followed by later filling of open pore spaces. Calcite spar is later replaced by dolomite rhombs (Fig. 9E). Owing to later epigenetic dolomitization, calcite spar tends to be assimilated by Fe oxide-rich dolomites.

Silicification, either in the form of nodules or as scattered crystals, followed evaporite precursors, as it is observed only in the matrix and not in the clasts (Fig. 8C and D). This indicates that silicification took place at an earlier stage, before the complete dissolution of anhydrite (Scholle *et al.*, 1992; Ulmer-Scholle & Scholle, 1994).

Intervals of reddish calcareous shale or vuggy limestone are commonly associated with zones of intense leaching and brecciation. As Scholle *et al.*

Fig. 7. Dolomitized detrital carbonate sediments. (A) Cubic and/or prismatic dolomite pseudomorphs after displacively and/or replacively grown evaporites in a Fe oxide-rich, argillaceous microcrystalline dolomitic matrix. Plane-polarized light. (B) Laminae of dolomite crystals of variable size (lowermost part) alternate with laminae of Fe oxide-rich grains and argillaceous material in a microcrystalline dolomite matrix. Plane-polarized light. (C) Pseudomorph after an evaporite nodule consisting of baroque dolomite. Pre-existing evaporite crystals were prismatic and radially arranged. Note a prismatic dolomite pseudomorph after anhydrite (arrow). Crossed polars.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(1993) stated, reddish calcareous shales accumulate as insoluble residue, marking zones of intense leaching and brecciation, and its particular prominence reflects more prolonged exposure and/or more intense alteration.

ENVIRONMENT OF DEPOSITION

Microfacies analysis shows that the Trypali unit was deposited in a peritidal environment under hypersaline to evaporitic conditions. This environment included sabkhas, tidal flats, shallow hypersaline lagoons, tidal bars and/or tidal channels. Algally laminated peloidal mudstones formed on peritidal flats dominated by blue-green algae. These fine-grained sediments are characterized by widespread displacive and/or replacive evaporite growth (Assereto & Benelli, 1971).

The grainstone facies, so commonly observed in the Trypali sequence (peloidal, bioclastic and ooidal grainstones), are assumed to have been deposited in high-energy environment (barrier complexes, tidal bars/tidal channels). However, this assumption must not be accepted without scepticism, as the grainstone fabric may have formed diagenetically, from desiccation–shrinkage and evaporite dissolution processes (Mazzullo & Birdwell, 1989). Radial ooids and grapestones can also be deposited in low-energy and high-salinity lagoonal environments (Winland & Matthews, 1974; Hird & Tucker, 1988).

Baroque dolomites, which are the principal component of the detrital carbonate facies, are interpreted to be pseudomorphs after displacively and/or replacively grown evaporites (salt crusts) that have subsequently been eroded and transported shoreward by storm waves and currents into very shallow strandline lagoonal environments (Hardie & Eugster, 1971). Vai & Ricci Lucchi (1977) proposed that evaporites can also be removed from the basin margins and transported towards the centre by slope-controlled currents and gravity flows. Both models were combined by Kendall (1984), who applied Hardie & Eugster's (1971) model to periods of transgression and Vai & Ricci Lucchi's (1977) model to periods of regression. According to Peryt (1994), the provenance of coarse-grained clastic sulphates is possibly related to periodic high-energy erosive and resedimentation events, or to brecciation caused by salinity fluctuations and the dissolution of halite.

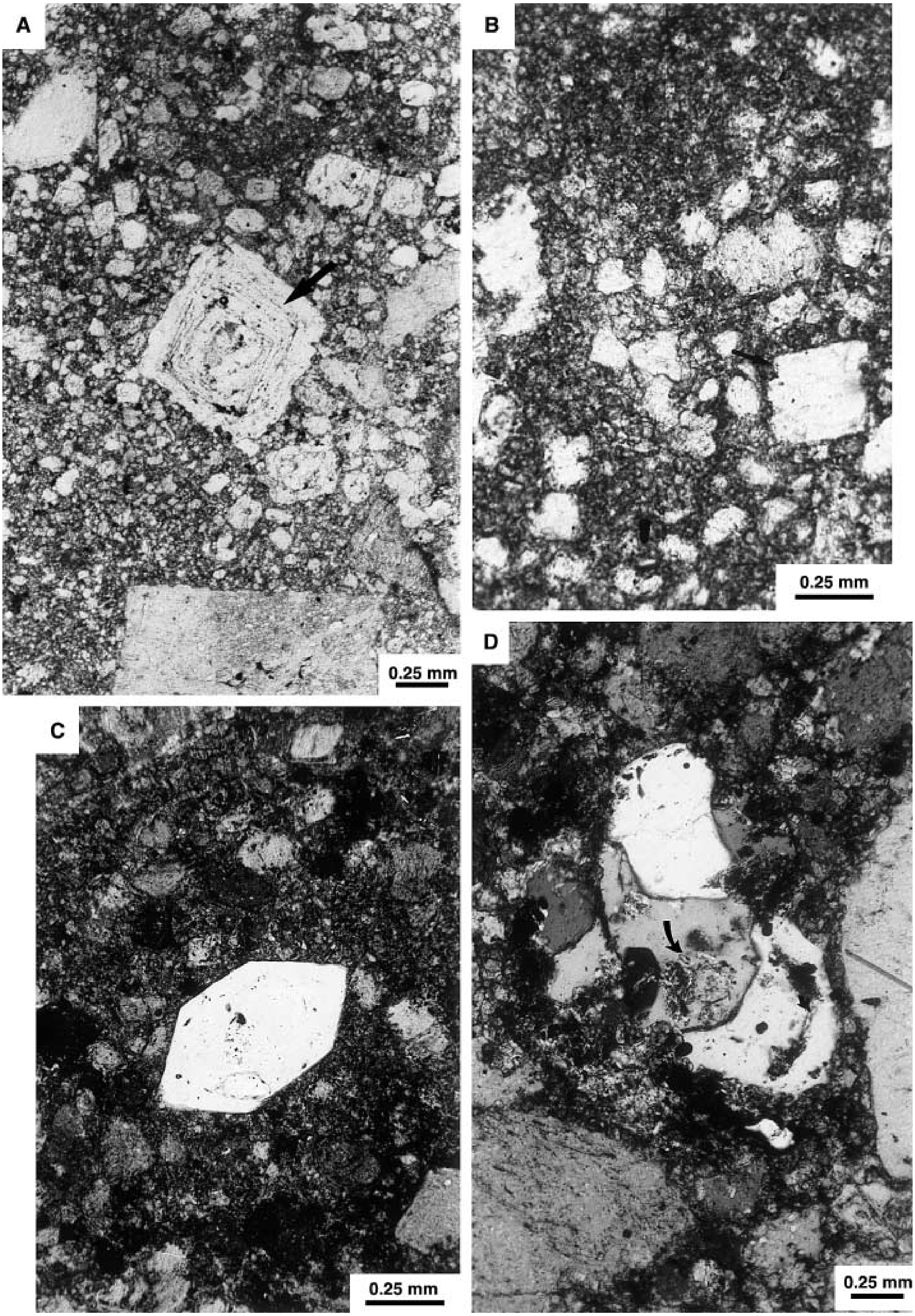
DIAGENETIC EVOLUTION

Near-surface syndepositional alteration of the studied peritidal formations, which took place during the early stages of burial, is difficult to differentiate from later burial diagenesis and diagenesis associated with Tertiary uplift.

Early diagenetic processes within the Trypali sequence were dominated by hypersaline groundwaters or restricted marine porewaters (brines). At surface or near-surface conditions, the waters percolated through the sediments. During sea-level lowstands, supratidal surfaces were subaerially exposed, and percolating meteoric waters caused extensive leaching of sediments (Clark, 1980). Subsequently, sediments underwent sabkha diagenesis, involving interstitial emplacement of evaporite minerals and dolomitization. Nodules, rosettes and sparse crystals of evaporites grew displacively and/or replacively within the carbonate sediments. Evaporite minerals are not preserved, except as inclusions, as they have been totally dissolved, calcified or silicified. However, evaporites were clearly present in the past. Evidence for prior evaporites includes areas composed of coarsely crystalline dolomite, pseudomorphs after prismatic anhydrite crystals, which form a characteristic mosaic texture (Fig. 10A) or a radial arrangement. In places, pseudomorphs after anhydrite laths with felted textures are present (Fig. 10B). In areas of more restricted circulation, salt crusts developed by displacive growth of anhydrite and halite in detrital carbonate sediments of fluvial or aeolian origin.

Early dolomitization by the same hypersaline fluids that produced the evaporites (evaporative reflux dolomitization) formed very fine to fine crystalline planar (subhedral) mosaic dolomite (Amthor & Friedman, 1991) similar to that described from modern tidal flat/sabkha sequences in

Fig. 8. Dolomitized detrital carbonate sediments. (A) Cubic dolomite crystal characterized by internal zonation defined by tiny inclusions of the host sediment (arrowed). Such crystals are interpreted as pseudomorphs after fragmentary surface-grown pyramidal hopper halite crystals. Note coarse prismatic crystal at the bottom of the photo. Plane-polarized light. (B) Prismatic dolomite crystals characterized by ragged outlines similar to the stair-step crystal habit of anhydrite (arrow). Plane-polarized light. (C) Authigenic euhedral megaquartz containing tiny inclusions of anhydrite. Crossed polars. (D) Quartz nodule with radially arranged quartz crystals. Note anhydrite relics (arrow). Crossed polars.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the Persian Gulf (Shearman, 1966; Butler, 1969; Kinsman, 1969; McKenzie, 1981; Butler *et al.*, 1982; Patterson & Kinsman, 1982). However, dolomitization resulting from sea-water circulation near the mixing zone cannot be excluded (Folk & Siedlecka, 1974; Magaritz *et al.*, 1980; Pierre *et al.*, 1984), although the mixing-zone model has several serious weaknesses for evaporite-related dolomites (Hardie, 1987; Magaritz, 1987). Freshwater lenses can extend laterally into submarine deposits and shift their positions with trangressions and regressions (Dunham & Olson, 1978) and, according to Zenger (1981), could be responsible for widespread dolomitization in the past. Therefore, penecontemporaneous dolomites of the Trypali Formation may have formed during periods of sea-level highstands (Peryt & Scholle, 1996). However, they show no evidence for early calcitization and/or redolomitization reactions during periods of subsequent sea-level lowstands. The influence of freshwater on syndepositional dolomitization has been well established in the Main Dolomite (Zechstein, Upper Permian), suggesting that similar relationships may be characteristic of other evaporite-associated dolomites as well (Peryt & Magaritz, 1990).

The existence of dedolomite horizons, especially in the upper part of the Trypali sequence, as well as vein calcites and calcareous cements, is evidence in favour of groundwater movement through the carbonate sediments (Fig. 10C). Dedolomite appears as anhedral, coarse sand-sized crystals, which include relic dolomite crystals in their core. According to Back *et al.* (1983), groundwaters are responsible for the initial dissolution of calcite, dolomite and gypsum (or anhydrite) at varying rates. Saturation of these solutions with calcite and dolomite, and progressive dissolution of gypsum, causes additional dissolution of dolomite followed by precipitation of calcite (dedolomite). Therefore, calcite precipitated in voids created after evaporite dissolution (Fig. 10D).

As the sediments were buried, porewater composition evolved, and a spectrum of diagenetic processes took place. Extensive cementation and replacement by gypsum, resulting from the injection of large volumes of $CaSO_4$-rich water, followed the dehydration of gypsum to anhydrite.

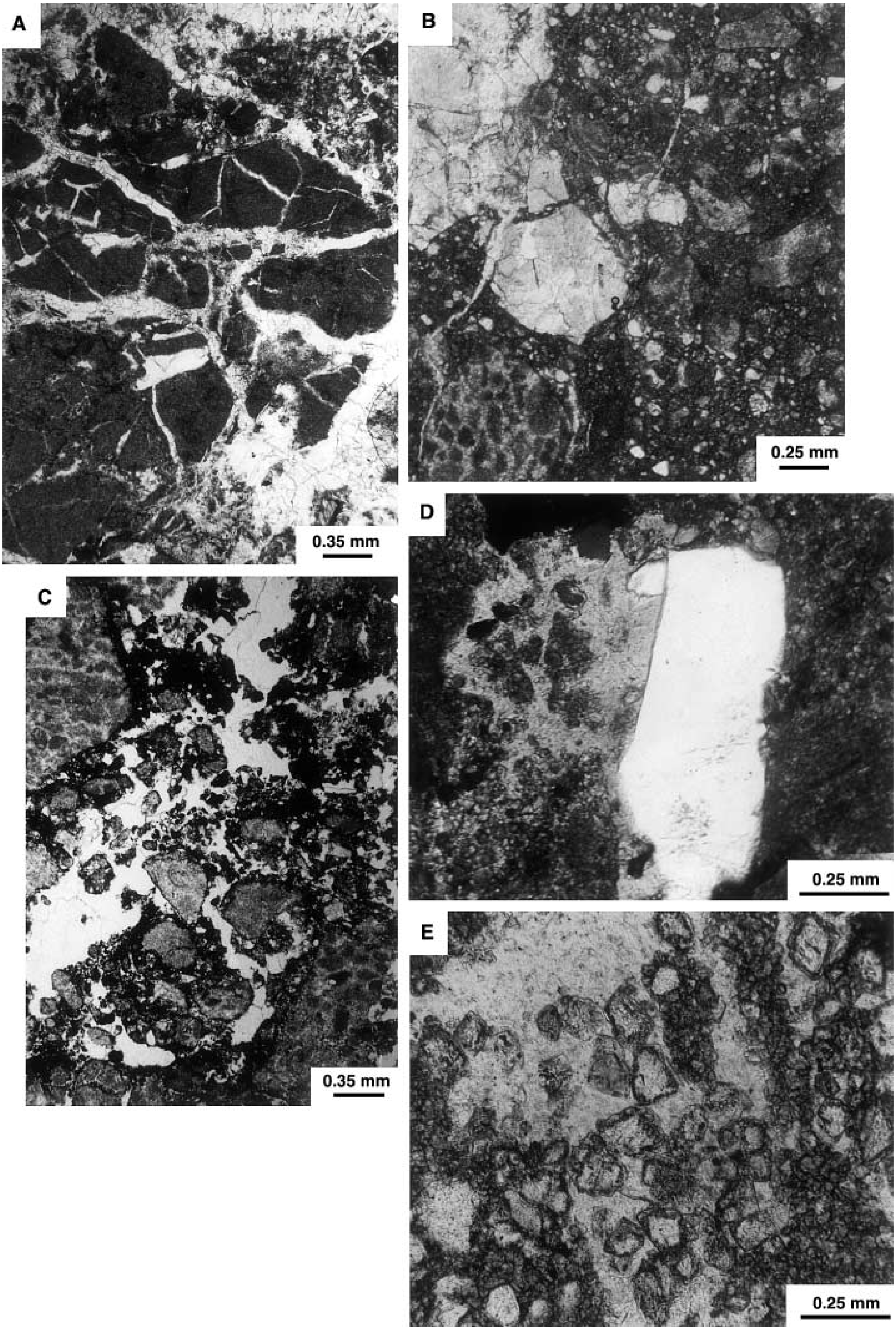
During progressive Tertiary uplift of the Trypali unit, the following sequence of diagenetic processes took place: (1) gypsum precipitation; (2) dehydration of gypsum to anhydrite; (3) early silicification of anhydrite before complete dissolution of anhydrite; (4) dissolution of anhydrite resulting in small-scale brecciation; (5) hydration of remaining anhydrite, which produced coarse poikilitic gypsum crystals; (6) dissolution of gypsum resulting in further collapse brecciation; (7) dedolomitization, calcite replacement of preserved evaporites and/or precipitation of calc-spar in voids.

ORIGIN OF THE SOLUTION-BRECCIAS

The timing of solution-breccia formation is problematic, particularly whether the breccias are synsedimentary or late diagenetic (Scholle *et al.*, 1993). Very early in the diagenetic evolution of the sediments, thin desiccation cracks developed in the host sediment (Fig. 9A). Where solution-collapse was incomplete, a dense network of fractures formed (Assereto & Benelli, 1971). Owing to progressive evaporite dissolution, enlargement of the cracks resulted in *in situ* brecciation (the breccia clasts fit together well; Fig. 9A).

Brecciation was a multistage process, which started in the Triassic, but mainly took place in association with Tertiary uplift and renewed groundwater flow (telogenetic alteration). Initial small-scale brecciation was related to exposure episodes during the formation of the Trypali sequence in a peritidal environment, as a result of periodic seasonal desiccation. In this setting, meteoric removal of intrastratal evaporites may produce extensive *in situ* breccias, resulting from stratal weakening and subsequent structural collapse. However, most diagenetic processes, including anhydrite hydration, dissolution of gypsum and replacement, as well as precipitation

Fig. 9. Solution-collapse breccias. (A) A network of thin desiccation cracks developed in the host mudstone. Solution enlargement resulted in *in situ* brecciation. Note how breccia clasts fit together. Plane-polarized light. (B) Rauhwackes with boxwork fabric. Clasts are surrounded by thick coatings of Fe oxides trapping some detrital quartz crystals. Pores formed by the leaching of evaporites are filled by sparry calcite. Plane-polarized light. (C) Clasts chaotically distributed in a matrix consisting of limonitic clay, microclastic material and porous saccharoidal calcareous dolomite matrix. Dolomite pseudomorphs after evaporite nodules and rosettes are common (left). Plane-polarized light. (D) Prismatic megaquartz and sparry calcite replacing pre-existing evaporites. Crossed polars. (E) Calcite spar further replaced by dolomite rhombs. Plane-polarized light.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of calcite spar, seem to be relatively recent (cf. Scholle *et al.*, 1992). The process that occurred closest to the surface was calcite replacement of evaporites and precipitation of calcite spar and, as Scholle *et al.* (1993) suggested, these were probably ongoing processes related to the influx of meteoric fluids.

During late diagenesis, in zones of intense leaching and brecciation, the solution-collapse breccias were transformed to rauhwackes, as a result of partial dissolution of the breccia clasts, with a characteristic boxwork fabric (Fig. 9C). By progressive diagenesis, breccia clasts became surrounded by a thin irregular coating of pedogenic origin, with characteristic protuberances and alveolar-like structures (Wright & Wilson, 1987; Wright *et al.*, 1988).

Solution-collapse breccias related to modern surficial or telogenetic alteration have been documented by Smith (1974) and Sarg (1981) and described further by Scholle *et al.* (1992, 1993).

ANALOGOUS OCCURRENCES OF SOLUTION-COLLAPSE BRECCIAS IN THE EXTERNAL HELLENIDES

The Triassic breccias of the Ionian zone in western Greece are typical evaporite dissolution-collapse breccias (Karakitsios & Pomoni-Papaioannou, 1998). The carbonate formations that produced the breccia also formed in a very shallow, restricted, hypersaline, lagoonal setting and evolved into sabkha sequences during a lowstand episode. Brecciation patterns are analogous with those of the Trypali breccias. Brecciation started soon after deposition, leading to *in situ* breakage of the carbonate beds. Subsequently, a major brecciation event occurred, which affected the still poorly lithified carbonate fragments, as a result of progressive dissolution of evaporites by meteoric water. However, the majority of the initial evaporitic sediments were brecciated after the emplacement of the tectonic units, so that halokinetic phenomena (which occurred from the Upper Liassic in the Ionian Zone; Karakitsios, 1990, 1992, 1995) were possible as well as diapirism during the Early Miocene overthrusting of the Tripolis nappe. This diapirism is inferred from the presence of small gypsum bodies, which crop out close to the tectonic surfaces, and implies that the parautochthonous series was also underlain by Carnian evaporites along which it became detached during the main orogenic phase (Early Miocene) that affected the parautochthonous series. Carnian evaporites are well-known throughout the Ionian zone of the Greek mainland and the Alpine region in general.

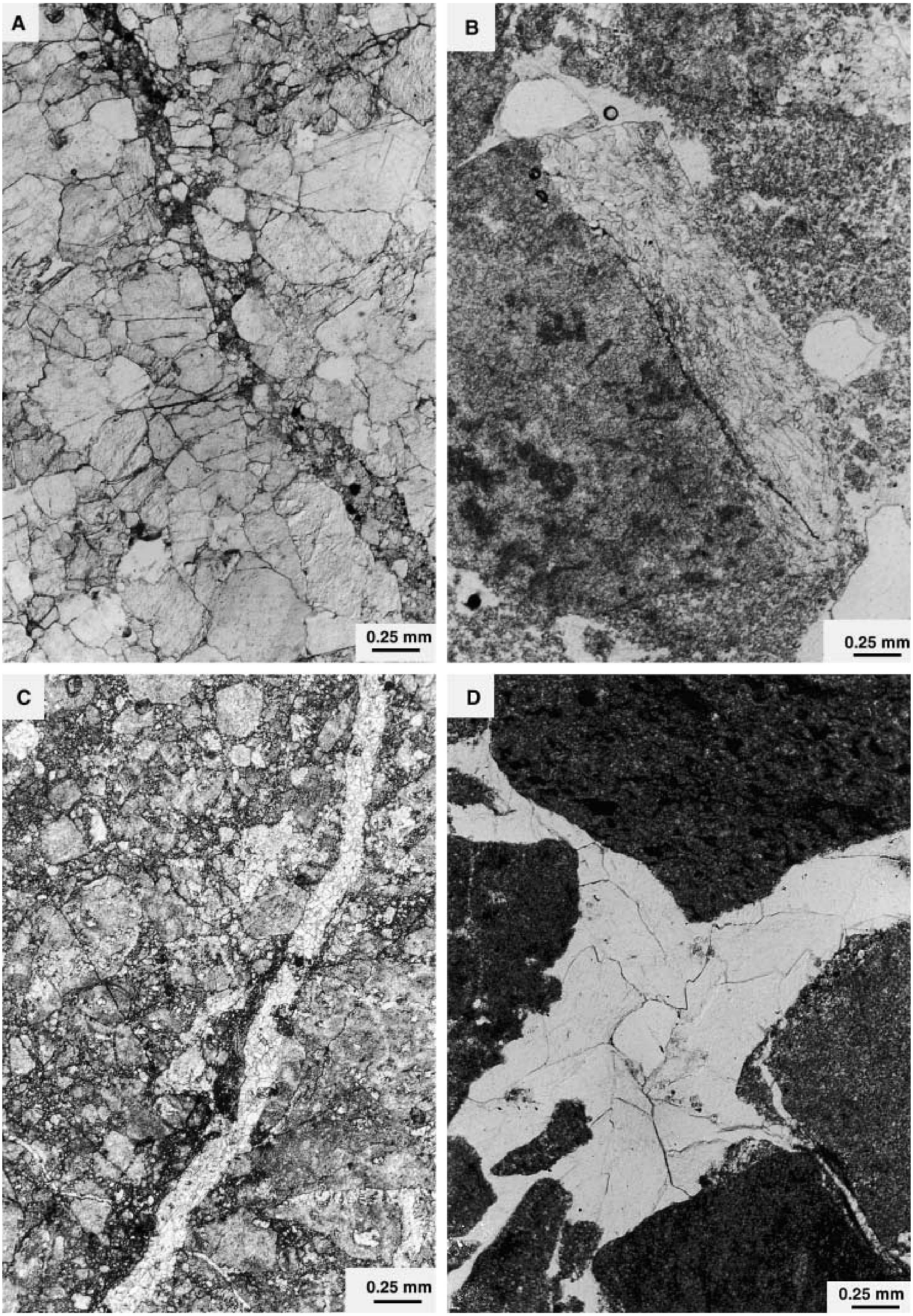
As discussed previously, the porous carbonate breccias (Trypali unit) intercalated between the parautochthonous unit and the Tripolis nappe (Phyllite–Quartzite unit and carbonate Tripolis unit) correspond to an initially evaporitic formation, which was transformed into solution-collapse breccias. This interpretation is strengthened by the fact that the parautochthonous unit represents the metamorphic equivalent of the Ionian zone. The Triassic age of the associated dolomites, the metamorphic overprint (Seidel, 1978), as well as their tectonic position on top of the parautochthonous unit and under the Phyllite–Quartzite unit, confirm the assignment of the solution-collapse breccias to Carnian evaporites that are very likely to occur at the base of the parautochthonous unit (Hall & Audley-Charles, 1983). Undated gypsum bodies are known from the Phyllite–Quartzite series of Crete and are considered to be remnants of Carnian evaporites. Rauhwackes (cargneules) associated with gypsum and dolomitic solution-collapse breccias are also observed at the lower part of the Tripolis nappe in Peloponnesus (De Wever, 1975; Pomoni-Papaioannou & Carotsieris, 1993).

The fact that breccias of evaporitic origin occur for more than 700 km at the base of the external nappes of Hellenides leads us to consider that the analogous carbonate formations of the Alpine system, found at the base of tectonic nappes, may also result from vanished evaporites.

CONCLUSIONS

The Trypali unit is a peritidal carbonate that has suffered *in situ* solution-collapse brecciation. It consists of interbedded layers of dolomitized algally laminated peloidal mudstones, as well as

Fig. 10. Dolomite pseudomorphs after evaporites. All photographs taken with plane-polarized light. (A) Coarse crystalline dolomite pseudomorphs after pre-existing anhydrite crystals (mosaic texture). (B) Pseudomorphs of dolomite after anhydrite laths with felted texture. (C) Calcite cements indicate incipient dedolomitization (staining by Alizarin red S). (D) Late calcite spar filling voids created by evaporite dissolution.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foraminiferal, peloidal and ooidal grainstones, deposited in a variety of environments, including sabkhas, tidal flats, shallow hypersaline lagoons, tidal bars and/or channels. The lagoons acted as evaporating basins in which evaporites frequently formed and became incorporated into the carbonate sediments.

Fe oxide-rich, fine-grained dolomite layers within the sequence are of detrital origin (fluvial or aeolian), and some seem to be resedimented (e.g. eroded and transported from neighbouring horizons, possibly by storm waves and currents during periods of transgression). Dispersed baroque dolomite crystals, either prismatic or cubic, represent pseudomorphs after anhydrite and halite respectively. Evaporites grew penecontemporaneously by displacement and/or replacement of detrital carbonate sediments.

Diagenetic processes started very early by displacive and/or replacive growth of nodules, rosettes and sparse crystals of evaporites within the carbonate sediments, which were penecontemporaneously dolomitized. Continual dissolution of evaporites by meteoric water caused further brecciation. However, most brecciation was during post-Pliocene to Recent subaerial exposure of the breccias, resulting from soil-forming processes. In zones of intense leaching and brecciation, porous carbonate breccias were formed (rauhwackes, cargneules).

Late diagenetic processes were related to the influx of meteoric fluids during uplift and include gypsum precipitation, dehydration of gypsum to anhydrite, dissolution of anhydrite, replacement and precipitation of calcite spar, which cements the carbonate material of the breccias. Evaporite replacement fabrics, including calcitized and silicified evaporite crystals, are recognized in the calcite spar. Silicification of anhydrite took place before complete dissolution of anhydrite, whereas calcite precipitation in voids probably occurred after evaporite dissolution.

The origin of analogous breccia formations at the base of the Alpine nappes should be reconsidered, as they may also originate from evaporite solution-collapse.

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