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H. DRINIA

DEPOSITIONAL SYSTEMS AND PALEOGEOGRAPHICAL EVOLUTION OF APOSTOLI BASIN, CENTRAL-WEST CRETE

Χ. ΝΤΡΙΝΙΑ

ΑΠΟΘΕΤΙΚΑ ΣΥΣΤΗΜΑΤΑ ΚΑΙ ΠΑΛΑΙΟΓΕΩΓΡΑΦΙΚΗ ΕΞΕΛΙΞΗ ΤΗΣ ΛΕΚΑΝΗΣ ΤΩΝ ΑΠΟΣΤΟΛΩΝ, ΚΕΝΤΡΟΔΥΤΙΚΗ ΚΡΗΤΗ

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DEPOSITIONAL SYSTEMS AND PALAEOGEOGRAPHICAL EVOLUTION OF APOSTOLI BASIN, CENTRAL-WEST CRETE*

by

H. DRINIA**

I. INTRODUCTION

The island of Crete is the southernmost emerged part of the Hellenic Arc, an arcuate segment of the active convergent boundary between the African and Eurasian lithospheric plates in eastern Mediterranean (Fig. 1a) (ANGELIER *et al.*, 1982; DE BOER, 1989).

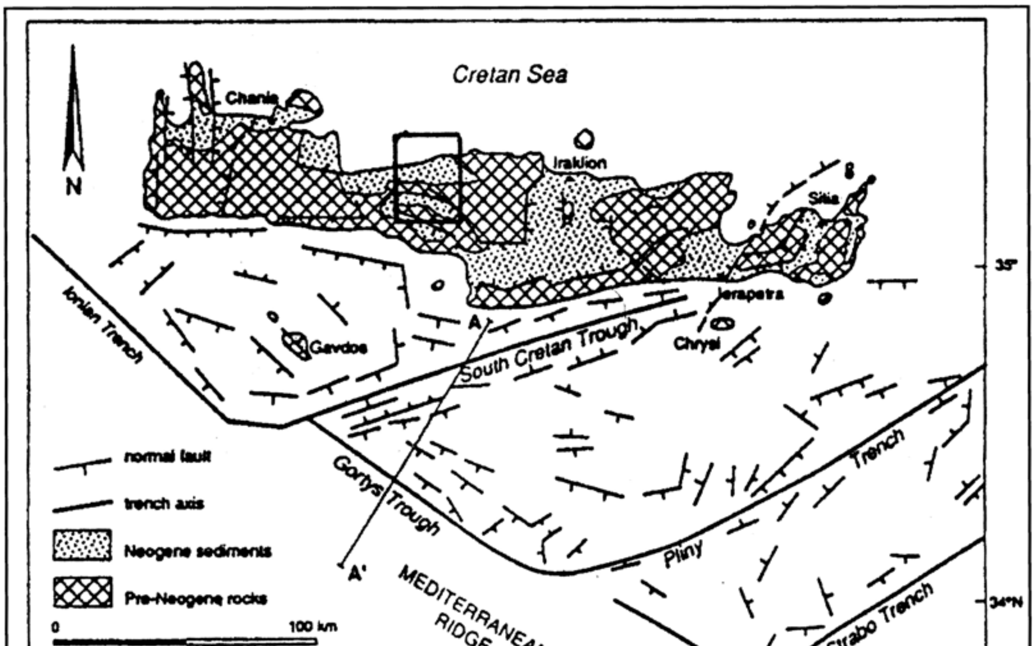

Fig. 1a. Geological map of the south Hellenic Arc where the location of Rethymnon Province is depicted (after ANGELIER *et al.* 1982; MASCLE *et al.* 1982; FORTUIN & PETERS 1984).

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** Dept. of Geology, Section of Hist. Geology-Paleontology, University of Athens, 157 84 Panepistimiopolis, Athens, Greece. E-mail address: cntrinia@geol.uoa.gr

The tectonic-sedimentary regime of Apostoli Basin in Rethymnon Province of the central-west Crete is corresponding to a tectonic graben. Alluvial conglomerates, originating from the elevated Alpine relief which is found northwards and northeastwards of this graben, are dispersing into it by mass flows and by braided-river currents. Afterwards and due to the invasion of the sea from the south, marine deposits are covering the coarse-grained continental deposits. No unconformities have been noticed.

The stratigraphy and palaeontology of these sediments have been extensively studied for many years (KUHN, 1936; RALLI, 1940; SYMEONIDIS, 1969; MEULENKAMP, 1969; DE BRUIJN & MEULENKAMP, 1972; MELENTIS, 1974; GEORGIADES-DIKEOULIA, 1974, 1979; SYMEONIDIS & SONDAAR, 1975; MEULENKAMP, 1979; DRINIA, 1996; DRINIA *et al.*, 1997).

MEULENKAMP (1969) who mapped three Neogene formations, each one corresponding to different environmental conditions, has established the lithostratigraphical scheme of the area for the first time.

The Neogene succession of Apostoli Basin includes coarse-grained alluvial deposits (Pandanassa Formation) and conglomerates with alternations of siliciclastic or carbonate shallow-marine sediments (Apostoli Formation). Going-upwards in the succession, the marine facies gradually increase in thickness and go into the overlying bioclastic limestones of Rethymnon Formation (Fig. 1b).

The basin evolution was in fact controlled by two fault systems (Fig. 1c): an E-W oriented system, and a N-S trending system that played a more local role, controlling rapid lateral variations in facies as well as some deformation in basin floor. At the initial stage of basin development, sedimentation was influenced by contemporaneous tectonism, with differential subsidence of the basin floor.

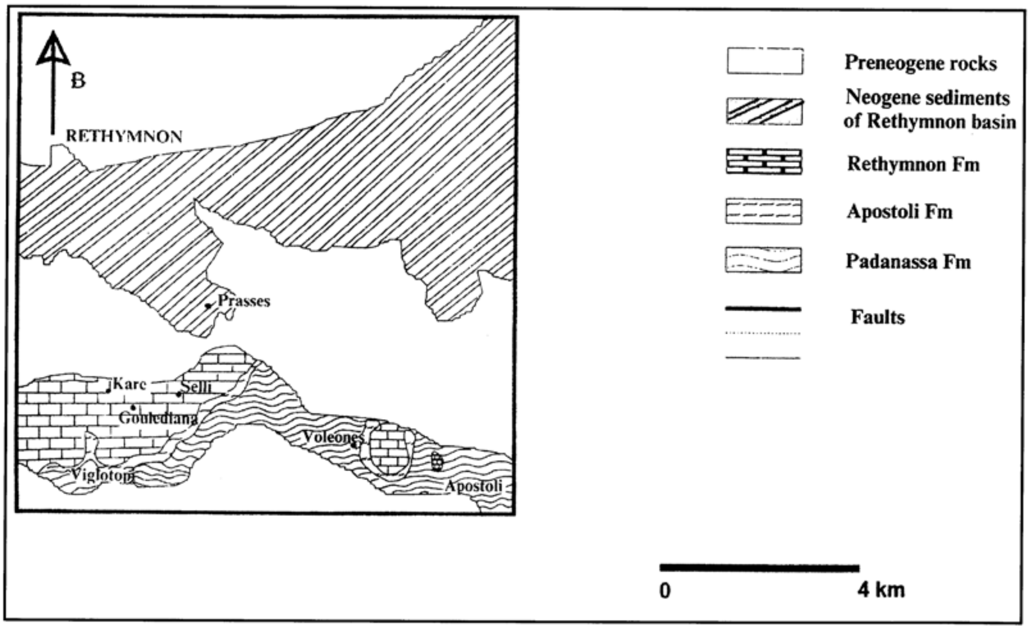

Fig. 1b. Geological map of the studied area (after MEULENKAMP (1969), modified).

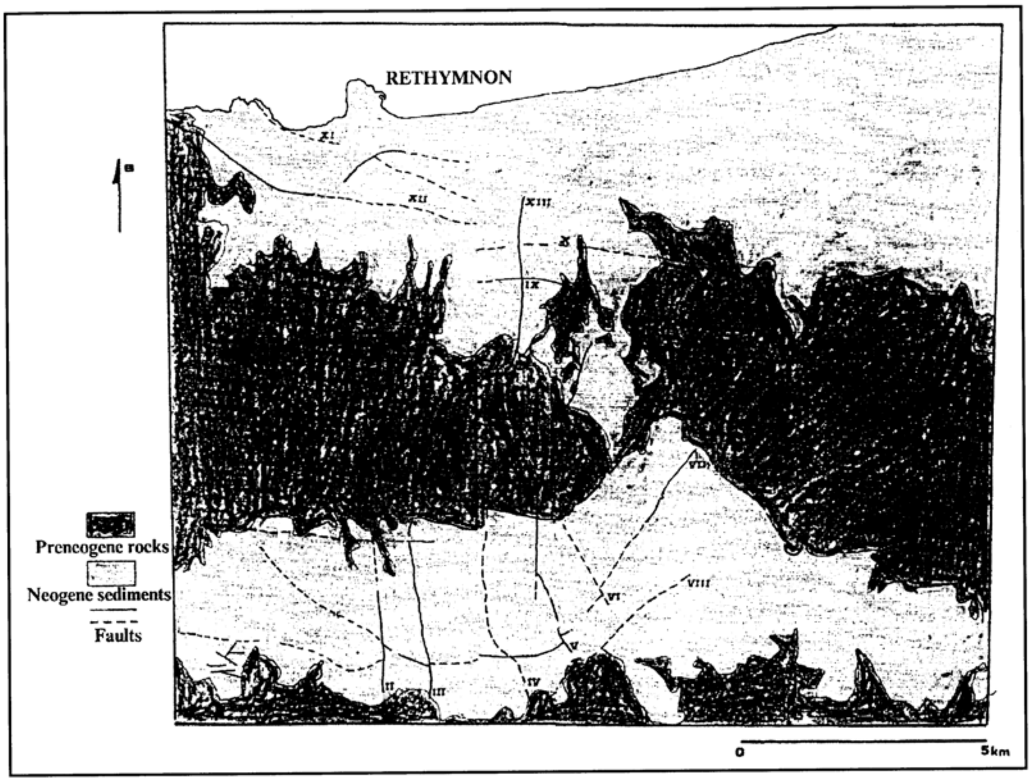

Fig. 1c. Tectonic map of the studied area.

For the biostratigraphical dating of the marine deposits of Apostoli Basin, a qualitative analysis based on calcareous nannofossils has been carried out (DRINIA *et al.*, 1997, DRINIA *et al.*, 1998). This analysis led to the biostratigraphic correlation of the studied sediments with the biozones CN7a-b (OKADA & BUKRY, 1980) and NN9 (MARTINI, 1971) indicating that the marine sedimentation set out during Early Tortonian times.

Although the geology and stratigraphy of the Apostoli Basin have been described, the facies, sedimentary environments and palaeogeography of these rocks are poorly understood.

This study was designed to 1) conduct facies analysis in order to interpret sedimentary environments, 2) determine the characteristics, lateral relationships, vertical stacking patterns and controls on development and 3) reconstruct the palaeogeography.

II. METHODS OF STUDY

The entire stratigraphic sequence of Apostoli Basin was measured in seven sections ranging in thickness from 60 to 400 m. These sections are lying along an east-west running ridge which exposes a great part of the stratigraphy of the basin. Only two sections have the complete thickness of the Early-Late Tortonian Pandanasa-Apostoli and Rethymnon Formations, the other five are partial sections. The total columnar section measured is about 1810 m in thickness. Detailed measurements of sedimentological characteristics (grain size and shape, composition, maximum clast size, primary and secondary sedimentary structures, bed geometry etc) were made on a centimetre scale in all sections using realistic symbols.

A bed-by-bed correlation was made using key beds and sequential orders.

Sedimentary facies will be discussed in terms of their general features of texture, fabric, sedimentary structures and palaeocurrent patterns on a basin-wide scale. Sedimentary environments were inferred on the basis of geometry, facies sequences, facies associations and paleocurrent analysis.

III. FACIES ANALYSIS

Though Apostoli lithostratigraphy is fairly well known, beside some determinations of clast origin, the sediments themselves have received little attention and palaeocurrent patterns are almost unknown. Based on vertical arrangements of the deposits in the large scale sequences, five major Depositional Systems can be recognized on the basis of shared sedimentological and palaeontological features and by the spatial relationships. The term "facies" is used here to denote the assemblage of beds deposited within a depositional system. A «depositional system» comprises a sedimentary environment together with the processes that may operate within it. Individual depositional processes form beds.

The recognized depositional systems are categorized as follows: 1. Alluvial system, 2. Brackish-lacustrine (transitional) system, 3. Shoreface system, 4. Inner shelf system and 5. Carbonate platform.

The bioclastic limestone of Depositional System 5 always form the cap of the underlying marly deposits of Depositional System 4 (Fig. 2a, b). The Depositional System 3 which is composed of coastal conglomerates and the basal part of Depositional System 4 (*Heterostegina* sands) overlie the fresh water - brackish deposits of Depositional System 2. Depositional Sustems 2 and 3 are wedging towards the north resulting in their absence in Rethymnon Basin.

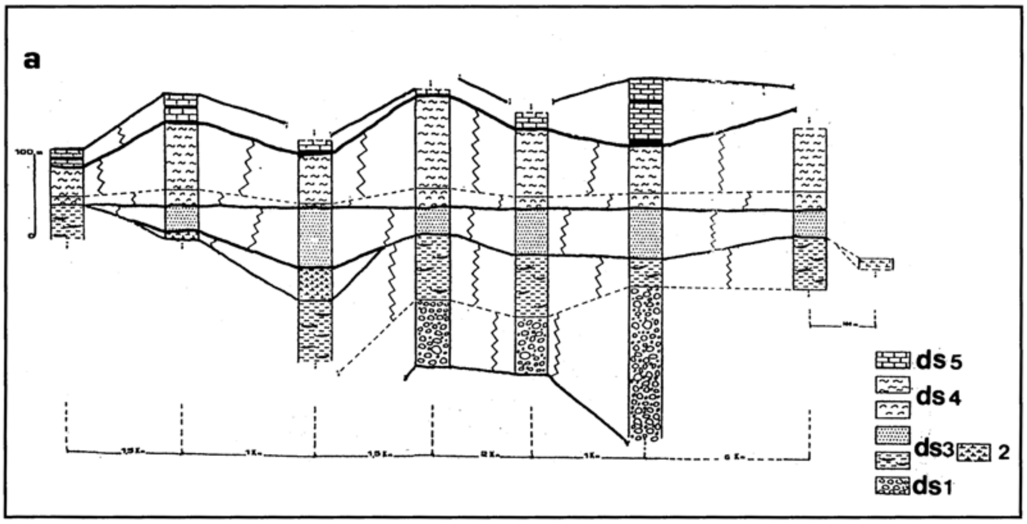

Fig. 2a. Lithostratigraphical correlation of the studied sections.

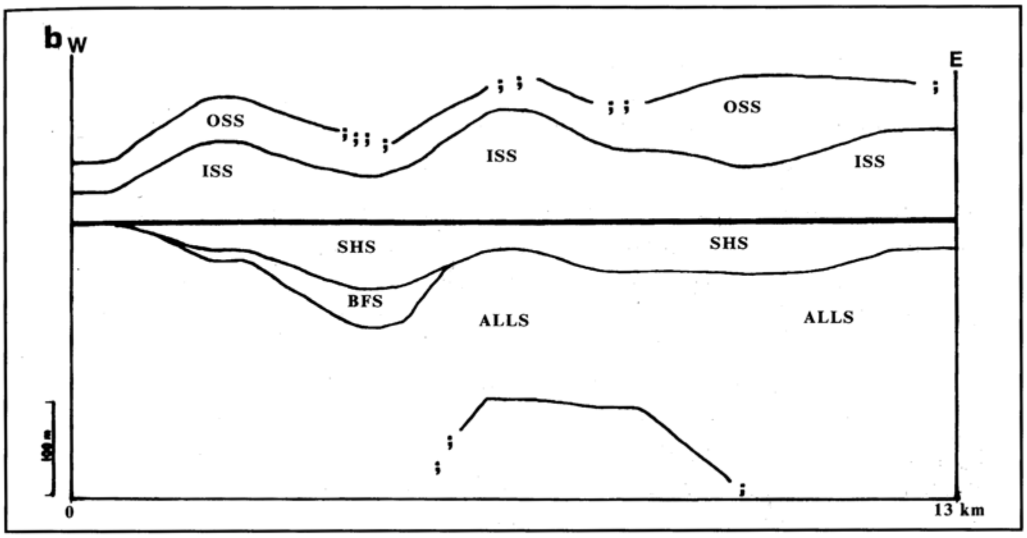

Fig. 2 b. Stratigraphical cross- section of the studied basin which shows the distribution of the depositional systems.

The coarse-grained alluvial deposits of Depositional System 1 dominate in the east part of the basin. Westwards, their thickness decreases gradually, passing into the fluvial deposits. Coarse-grained alluvial conglomerates are present again along the west margin of the basin, which are attributed to a tectonic origin.

The transitional sediments of Depositional System 2 are well documented in the west part of the basin whereas in the east part only small occurrences have been found. Moreover, the shoreface deposits, and in particular the beachface conglomerates are shown in the west part of the basin.

An unconformity is not present in these intervals, suggesting that the magnitude of the relative sea-level excursion was small (<10m) and that the relative sedimentation rate tracked this fall.

Depositional System 1: Continental-fluvial deposits (ALLS)

This Depositional System lies above the Alpine basement and has a varied thickness ranging from 40 to 210m. The deposits, which constitute this system, have been categorized in two units based on their grain size. The coarse-grained sediments are mainly composed of conglomerates and sandstones whereas clayey sediments mainly compose the fine-grained deposits.

Description:

Matrix-supported conglomerates (Fig. 3a): These conglomerates which constitute the basal part of Depositional System 1, are composed of pebbles, cobbles and some large "outsize" boulders. Conglomerate beds range in thickness from 0.3 to 5 m. The conglomerates show disorganized, matrix-filled framework. Matrix generally consists of coarse sand and granules. Individual beds are unstratified and display sheet-like geometries. Where it was possible, palaeocurrent directions were measured indicating a south, southwestward transport direction. Their basal contacts are slightly erosive to non-erosive. Some units are locally capped by thin lenses of plane- to cross-stratified

Fig. 3a. Debris flow deposits.

coarse-grained sandstones and pebble conglomerates.

Clast-supported conglomerates (Fig. 3b): This facies consists of conglomerates with minor interbedded sandstones and pebbly sandstones. The conglomerates are moderately to well sorted, comprising subrounded to subangular pebbles and cobbles. Invariably, they are clast-supported and tightly packed. Basal surfaces of the beds are sharp and irregular with relief of up to 0.3 m. Beds are generally ungraded, though normally grading is locally present. Imbrication is occasionally developed at the top of beds. Intercalations of sandstone and mudstone are ofter lenticular. The conglomerates are commonly capped by medium to coarse grained sandstones up to 0.3 m thick which are usually parallel laminated or display low angle planar cross-stratification.

Cross-stratified conglomerates (Fig. 3c): This facies comprises mostly clast-supported conglomeratic beds, 2 to 5m thick and 1 to 5 m wide. The conglomerates commonly display imbrication and contain cross-stratified sandstone lenses. Both planar and trough cross bedding are conspicuous in transverse and longitudinal sections, and plane bedded units commonly show clast imbrication and occasional local fining upwards.

Litharenitic sandstones: This facies comprises fine- to coarse-grained, granule-bearing litharenitic sandstones, dominated by plane-parallel stratification and low-angle cross-stratification. Normal grading is occasionally developed. Sandstone beds are frequently rippled cross-laminated. Beds may be isolated or amalgamated to form composite laterally extensive sequences up to 20 m thick, which consist of a large number of stacked, sheet-like beds and contain minor interlayers of conglomerate or mudstone. Individual beds range between 0.5-1.5 m in thickness and have sharp or

Fig. 3b. Stream-flow conglomerates.

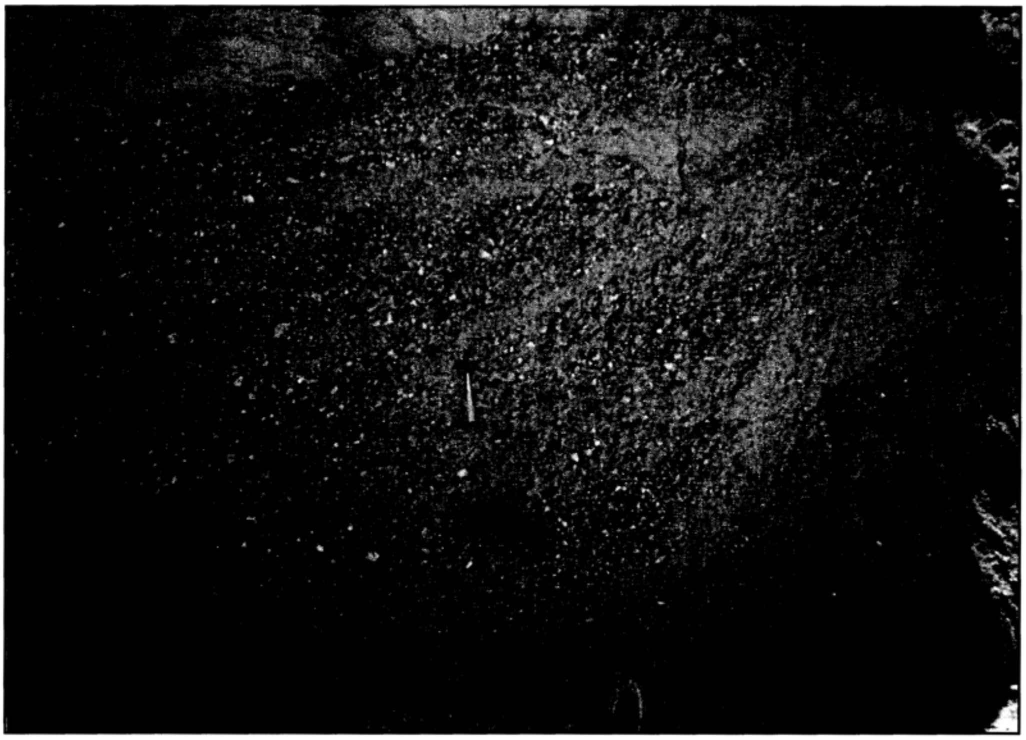

Fig. 3c. Conglomeratic channel.

mildly irregular basal bedding contacts.

Mudstones (Fig. 3d): This facies comprises mudstones often with plant roots (seat-earth horizons) and coal layers, which cap the sedimentary sequences of the other four facies, particularly near the top of the subaerial facies assemblages. Individual units range in thickness from 0.1 to 4.0 m and can either extend laterally for hundreds of metres or are abruptly truncated within a few metres by sandstones.

Sandstone/siltstone intervals generally are internally structureless, but in a few places horizontal laminae or asymmetrical ripple cross-laminae are present. Interbedded mudstones are red or light green and rarely exceed 1 m in thickness. Contacts between sandstone/siltstone and mudstone beds can be either gradational or sharp. Invertebrate burrows and pedogenic carbonate nodules are common (Fig. 3e).

Interpretation:

The characteristic facies and the presence of typical indicators of subaerial exposure (root traces, paleosols) suggest that Depositional System 1 formed on an alluvial plain. The matrix-supported conglomerates are considered to represent debris flow deposits based on the texture, the lack of organized fabric and the negligible percentage of sediment finer than silt in the matrix. The associated finer-grained capping resulted from stream-flow processes following debris-flow deposition on the fan surface. The clast-supported conglomerates are significantly better sorted, better graded and thinner than the matrix-supported conglomerates. They are interpreted to represent deposition from poorly confined sheetflows. Evidence for current processes in the conglomerate includes imbrication, the fining-upward trend (decaying flood flows) and erosional surfaces.

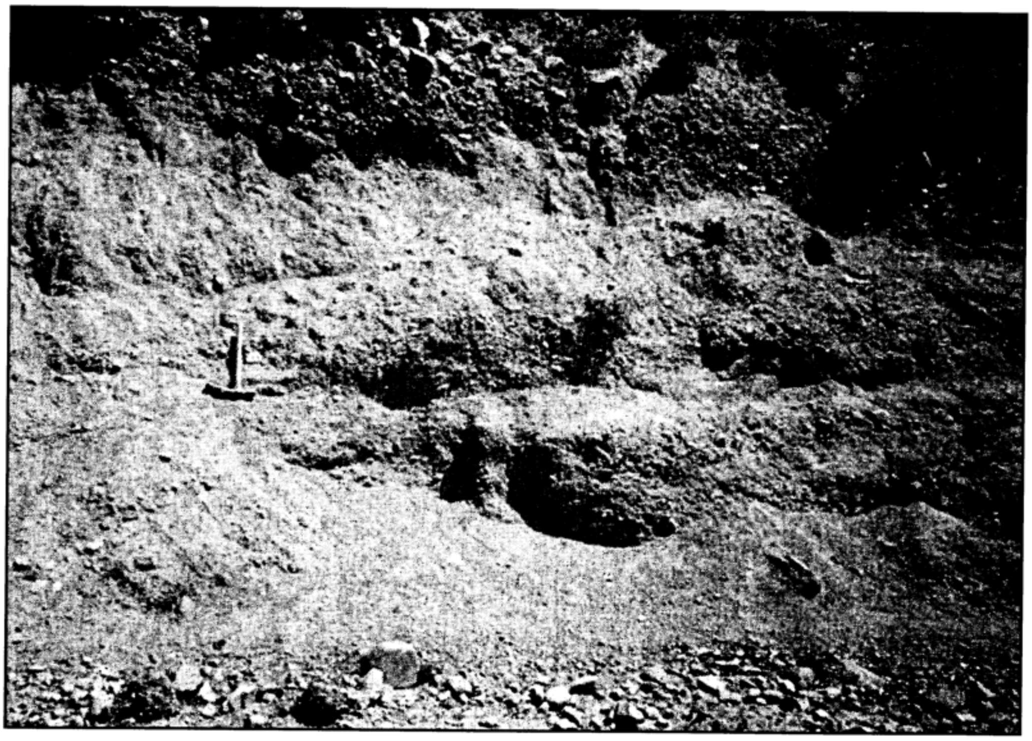

Fig. 3d. Fine-grained floodplain deposits with caliche interbeds.

Fig. 3e. Intensely stratified nodular limestones.

The sandstone tops are thought to represent the development of upper flow regime plane-bed conditions during waning flood stage. This Facies is thought to record ephemeral flood sedimentation in an alluvial fan environment, with features typical of sheetflow deposits in very shallow channels. The presence of large-scale stratification and erosional relief together with the limited lateral extent of the cross-stratified conglomerates suggests deposition by streamflow processes in confined channels.

Litharenitic sandstones require a lower depositional energy with respect to those of the aforementioned facies.

The lack of channelization, large lateral extent, little thickness variation and dominance of horizontal laminae together with their mainly coarse grain size suggests that the deposition has been due to a multitude of sandy sheetfloods (unconfined floodflows) on the gravelly surface of a fan sector that was temporarily abandoned by the gravel-bed distributary channels due to advanced aggradation. The rippled tops suggest reworking by decelerating flood currents. From the point of view of the sediment dispersal pattern on an alluvial fan, this facies might then represent "interlobe deposits".

Mudstones are thought to have been deposited from slack-water suspension settling combined with intermittent traction during floods. It can be proposed that they correspond to floodplain deposits. Plant growth and development of peat-forming mires were possible due to limited clastic influx.

The presence of calcareous palaeosols suggests a relatively dry, probably semiarid palaeoclimate (REEVES, 1970; CERLING, 1984).

Depositional System 2: Transitional facies (BFS)

This depositional system corresponds to the transition between the continental and the marine deposits. It is mainly developed in the western part of the basin and its thickness decreases progressively eastwards disappearing almost completely. Small occurrences of these deposits have been also found in the eastern side of the basin.

Description:

Depositional System 2 is mainly composed of fresh - water limestone beds with coal seams in between and brackish intercalations of sandy oyster banks.

The *fresh-water limestones* (Fig. 4a, b) are often platy or laminated with maximum thickness of about 30 m. Coal seams are often found intercalated between limestone beds. Amongst the fossil contents of the fresh-water deposits, Planorbidae, Melanids, *Terebralia*-like gastropods and plant remains predominate.

Sandy Oyster banks (Fig. 4c): These beds are composed of closely packed oysters, more or less parallel to the bedding plane. The oysters are often very big (up to 40 cm length) and are stacked upon each other with a silty matrix in between.

Interpretation

The sequence of the lacustrine carbonates is interpreted as a low-energy carbonate pond. Lacustrine carbonates (Fig. 4b) are due to inorganic precipitation. Inorganic precipitation producing lime muds, mostly takes place through evaporation, but CO_2 loss, as a result of plant photosynthesis or pressure-temperature changes, and mixing of fresh stream water with saline lake water, also cause carbonate precipitation.

As far as the sandy oyster banks are concerned, according to DEMARCQ & DEMARCQ (1989) these are favored where mixing of fresh-water with marine water is taking place. Therefore their development is connected to brackish palaeoenvironmental conditions.

Fig. 4a. Coal seams in the contact of two freshwater limestone beds.

Fig. 4b. Freshwater limestones.

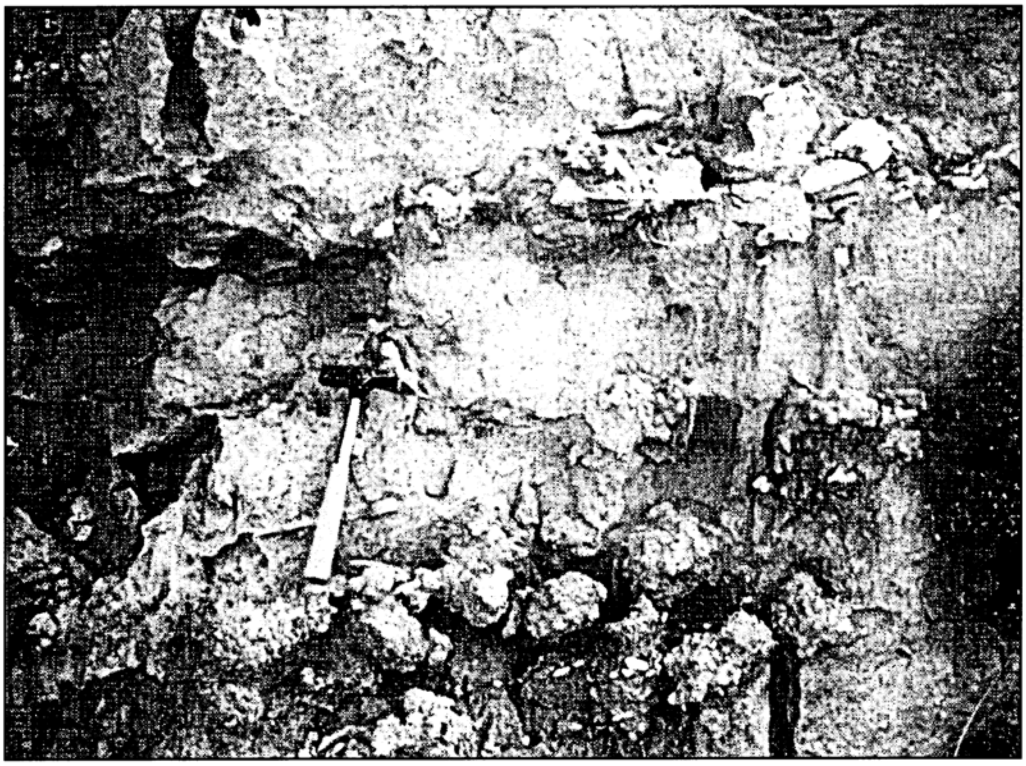

Fig. 4c. Oyster banks from the transitional deposits.

Depositional System 3: Shoreface deposits (SHS)

The shoreface depositional system consists of three facies that overlie the transitional depositional system. These facies include 1. Concretionary sandstones, 2. Interbedded conglomerates and sandstones, and 3. Hummocky-cross-stratified sandstones.

Description:

Concretionary sandstones (Fig. 5a): This facies consists of brownish, partly unconsolidated, fine-grained sandstones. Trough-cross stratification and horizontal lamination are the main sedimentary structures but ripple-laminated horizons are also present. The most remarkable feature of this facies is the presence of spherical to oval or oblong concretions, ranging in size from 10 cm to approximately 50 cm along the longest diameter, which are slightly parallel to the bedding (Fig. 5a). The concretions tend to weather positively, giving the sandstone a characteristic knobby appearance.

Highly elongated sandy concretions are found into loose deposits in the eastern part of the basin. They are shaped like rods and thin blades and are fragile. Concretions excavated and removed from outcrop have lengths of up to 30 cm and have remarkably uniform orientation.

Interbedded conglomerates and sandstones (Fig. 5b): Well-defined, gently inclined, seaward dipping layers of alternating sandstones and conglomerates constitute this facies.

Sandstones are moderately to well-sorted, medium to very coarse-grained showing either horizontal or low-angle parallel lamination and common *Skolithos* burrows.

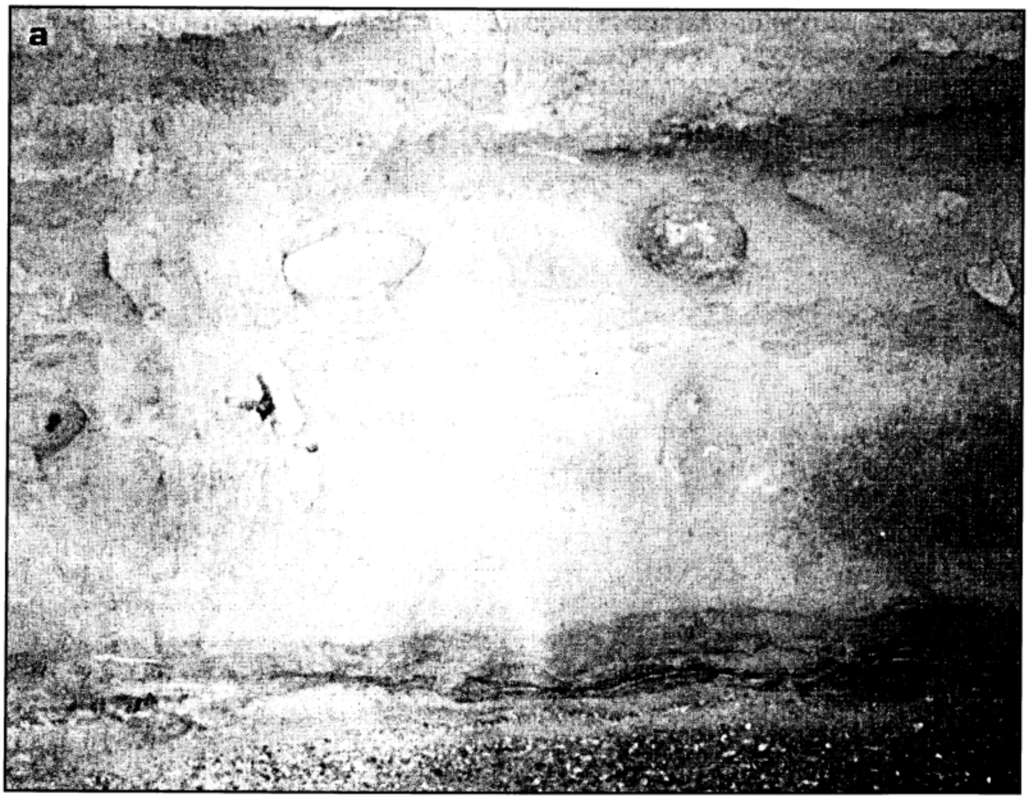

Fig. 5a. Fine-grained concretionary sandstones.

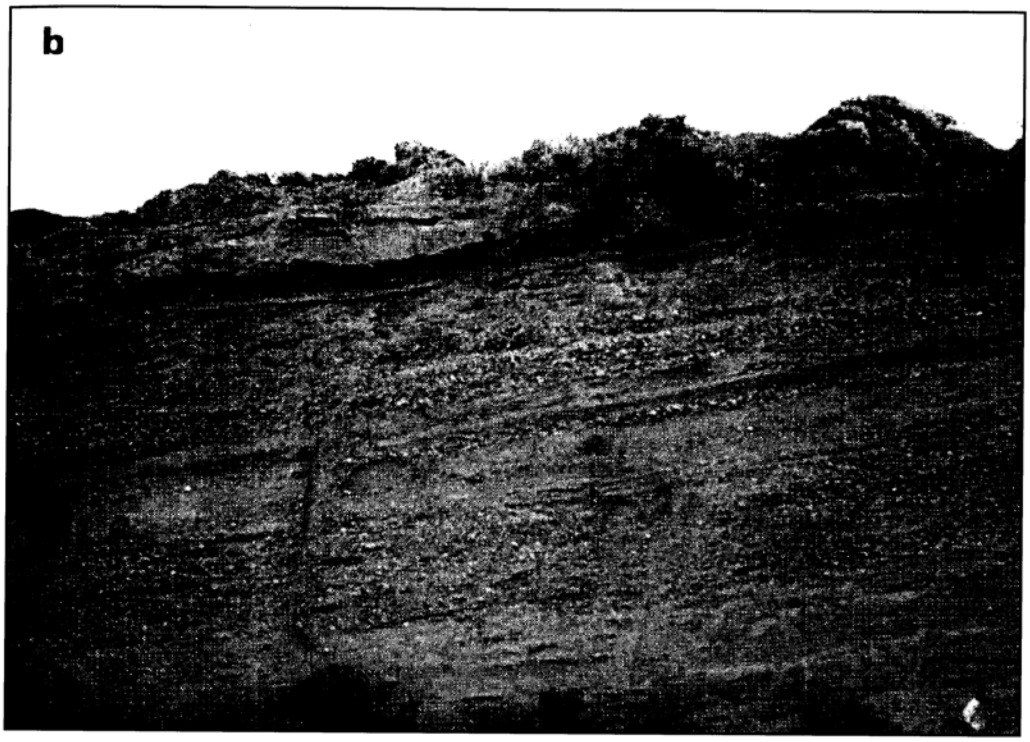

Fig. 5b. Beachface sandstones and conglomerates from the shoreface deposits.

Conglomerates occur as laterally persistent, one-clast thick layers and less commonly, as thicker sharply based tabular units. Most of the thicker, tabular units have an ungraded clast-supported framework of spherical to rod-shaped pebbles and cobbles, with a matrix of sand and small pebbles.

Hummocky cross-stratified sandstones (Fig. 5c): They are represented by fine-to coarse-grained beds with horizontal to low-angle stratification and swalley or hummocky cross-stratification. The individual beds are lenticular, showing flat or slightly irregular, erosive bases and low-relief undulatory tops. Thin, wave-rippled sandstones occasionally cap them.

Interpretation

Concretions are thought to have grown after deposition of the host rock, under low or moderate sedimentation rates, by precipitation of calcite from ground water actively moving in the direction of the regional subsurface drainage (MCBRIDE *et al.*, 1994). In particular, the highly oriented concretions could constitute a useful tool for reliably inferring the regional paleoslope and paleo-groundwater flow directions

The interbedded conglomerates and sandstones facies is being interpreted as foreshore/upper shoreface deposits or mixed, sand-gravel "depositional" beaches. The one-clast thick gravel layers and the pavements of clasts with lithophage cappings, seem to reflect variable reworking of fan-derived gravels by storm waves. Storm wave conditions are further supported by the presence of hummocky-cross-stratification. Accord-

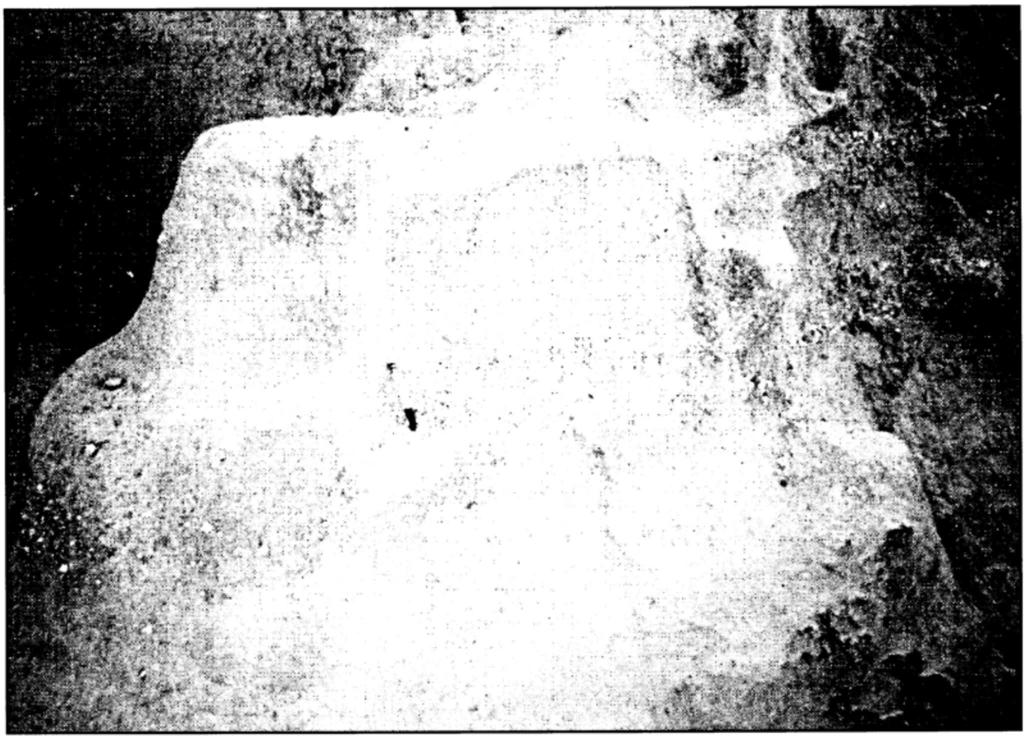

Fig. 5c. Trough-cross stratified, bioturbated shoreface sandstones with laterally continuous gravel interbeds.

ing to HARMS *et al.* (1975) the long, low, undulating hummocky cross stratification is produced by storm waves, below fair weather wave base. HAMBLIN & WALKER (1979) and WRIGHT & WALKER (1981) suggested for the origin of this structure that a storm of hurricane proportion could entrain sand in very shallow water creating a density current. This density current as originally proposed by HAYES (1967), transport sands offshore. After the deposition of these sands under the influence of strong oscillatory flows (i.e. above storm wave base but below fair weather wave base), storm waves of the same storm which created the density current, subsequently reworked the sands creating hummocky-cross-stratification to the depth of storm wave base.

Depositional System 4: Inner shelf deposits (ISS)

The inner shelf depositional system gradationally overlies the shoreface depositional system and is characterized by the presence of two facies, which are: 1. The *Heterostegina* sands and 2. Grey-bluish fossiliferous marine marls.

Description:

Heterostegina sands (Fig. 6a): The facies of *Heterostegina* sands, due to its lateral continuity, serves as marker bed for local correlation. The relative thickness of the *Heterostegina* sands varies strongly from one place to the other from 2.50 to 40 m. Within these *Heterostegina* sands there are scattered Echinoids (*Clypeaster*) and Pectinidae.

Grey-bluish fossiliferous marine marls (Fig. 6b): This facies comprises bluish, fossiliferous marls with occasional lenses or layers of fine to very fine-grained sandstones.

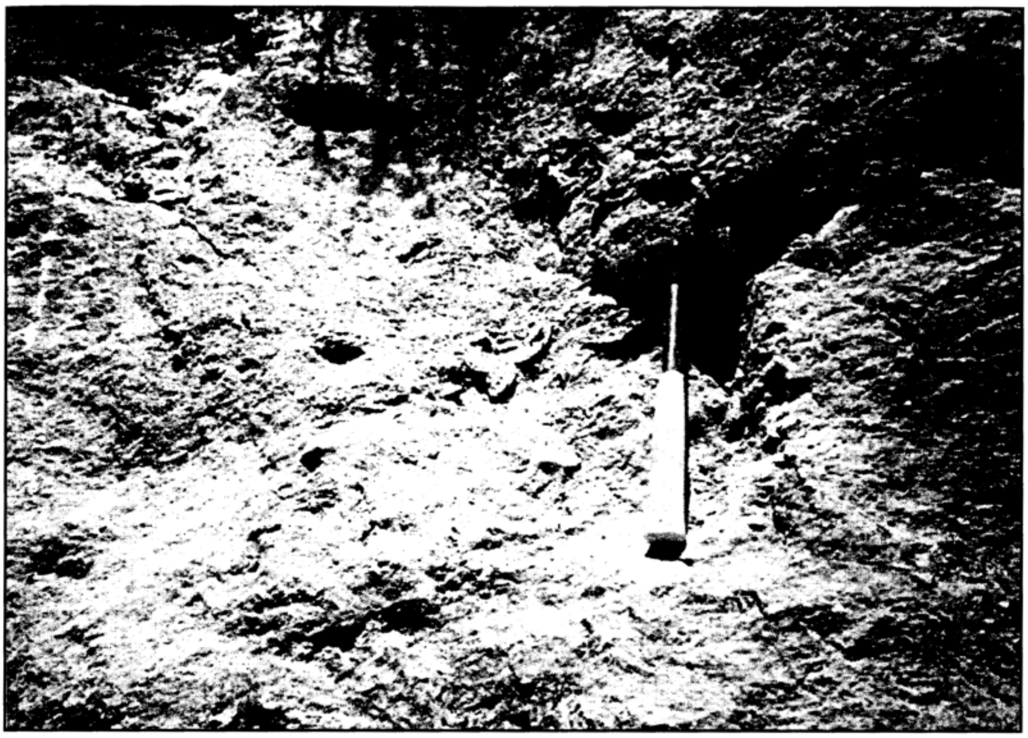

Fig. 6a. A *Heterostegina* sandstone bed which contains scattered *Clypeaster*.

Fig. 6b. Grey-bluish fossiliferous marine marls.

The grey and bluish marls and clays yield a rich mollusc fauna, whose composition is fundamentally the same in all sections. Partly, these marls above the *Heterostegina* beds show a strong sandy development.

Amongst the numerous genera, *Conus, Murex, Arca, Ancilla, Dentalium, Natica, Vermetus, Turritella, Chlamys, Corbula, Ostrea* and *Pecten* are common (SYMEONIDIS, 1969, GEORGIADES-DIKEOULIA, 1974). Specimens of *Pecten latissima* may reach a diameter of up to 30 cm. Incidentally *Ancilla glandiformis*, "index fossil" of the Tortonian is found. *Clypeaster* and *Scutella* represent Echinids. Brachiopods of small dimensions, like *Argyrotheca* cf. *dertomutinensis, Megerlia oblita, Terebratula sinuosa*, have been found in the lower strata of the clayey marls (GEORGIADES-DIKEOULIA, 1974). They are representatives living in quiet sea bottoms or in deeper seas.

Interpretation

The *Heterostegina* sands constitute a skeletal concentration which has been formed during episodes of low net sedimentation, during brief or prolonged intervals of sediment starvation, dynamic bypassing, winnowing or erosional reworking (sensu KIDWELL *et al.*, 1986). According to KIDWELL (1989, 1991) and BANERJEE and KIDWELL (1991), similar deposits to that of the *Heterostegina* sands represent high rates of shell production indicating rapidly generated storm and mass-mortality event concentrations.

The mud-dominated facies is thought to represent open marine (shelf) environment. The fossiliferous marls indicate deposition from suspension in a quiet environment, which has hardly been influenced by waves or other currents. Waning sand-laden traction currents (deposition of the sandstone beds) occasionally interrupted the deposition of mud by suspension.

Depositional System 5: Carbonate platform (OSS)

This depositional system always forms the cap of the infilling of the Apostoli Basin and consists of one facies: the bioclastic limestones.

Description:

This facies is characterized by the presence of alternating marls and bioclastic limestones, which are partly stratified and often resemble reef deposits. Limestones are bioclastic calcarenites/calcirudites dominated by coralline algae and bryozoans (DRINIA *et al.*, 1998). They also contain abundant disarticulated and reworked gastropods, bivalves, brachiopods arranged in crudely horizontal thin beds or laminae. *Heterostegina* may be still present. Both sorting and grading are typically poor or absent.

The intercalated marls and clays are of grey or bluish colour and partly they may be finely laminated. They are commonly lacking the rich macrofossil assemblage. Thin conglomeratic and sandy intercalations may be present within the marls and clays.

Interpretation

The abundant evidence of reworking of bioclastic material and rapid interbedding with marls suggest that these were also introduced to the depositional site by high-energy currents. The poor sorting, however, indicates that the sediment may not have endured significant in situ reworking and that deposition was rapid.

The absence of reef-building corals and the appearance of highly calcareous facies representing by the coralline algae-bryozoans facies association suggest the prevalence of cooler conditions.

Temperate shelf carbonates frequently contain very high concentrations of siliciclastic sand (NELSON, 1988), the bulk of which is usually derived through lateral transfer from adjacent facies belt.

IV. PALAEOGEOGRAPHIC RECONSTRUCTION

As biostratigraphy does not allow precise correlation, nor highlights lateral lithofacies variations, which is often the case of fluvially-dominated basins with a lack of fossils, correlation is based on key marker horizons or beds. A key marker horizon (*Heterostegina* sands) is present over the whole study area and is used to delimit the regional correlations. Locally, using correlatable surfaces of a lesser extent performs detailed analysis.

The detailed lithostratigraphical and tectonic analyses, which were carried out in Apostoli Basin, led to some important conclusions, related to environmental and lithological changes, which took place during Late Serravallian-Late Tortonian times. These changes are depicted in five paleogeographical sketch maps where the studied facies associations are shown (Fig. 7).

? Late Serravallian: During that timespan the tectonic activity which took place resulted in the formation of Apostoli basin (Fig. 7a). The sediments deposited that period are characterised by high-energy sedimentation pattern. Imbrication structures indicate that the source rock of the sediments deposited was situated north and northeastwards of the basin. Due to the transportation pattern, in the eastern part of the basin coarse-grained fanglomeratic deposits are found which laterally are passing into finer-grained, laterally persistent floodplain and channel deposits. During that period the climate was subtropical with low to medium temperatures.

Early Tortonian: During that timespan, a general transgression affected the island of Crete (Fig. 7b). Secondary N-S normal faults are causing the differential submergence of the basin of Apostoli. The subtropical climate, which was dominating the previous timespan progressively, changed into tropical. The studied region is characterized by lower energy sedimentation pattern. In the west part of the basin, the sea invasion over the fluvial deposits resulted in the deposition of lacustrine and brackish sediments whereas in the eastern part shoreface deposits are observed. As the submergence of the basin was not homogeneous, the sea invasion in the west part of the basin was fast due to the higher rate of submergence resulting in the formation of well-developped beach deposits. Eastwards, beachconglomerates do not appear as there the sea invasion was lower.

Middle Tortonian: During that period, the continuous sea invasion and the exhaustion of the source rocks northwards and northeastwards of the basin, resulted in the deposition of marine marls (Fig. 7c). Along the northeastern margin of this basin, carbonate shelf and reef deposits are growing, indicating that the environment there remained shallow. The inactivation of the north marginal fault, the emergence of the Apostoli basin, the shortage in clastic sediments (Fig. 7d) in addition with the prevailing climatic conditions caused the deposition of shallow marine limestones.

Late Tortonian: The northward tilting of Crete took place resulting in the uplift and erosion of the Neogene deposits of Apostoli Basin and their redeposition as marly breccias in the deepest parts of Rethymnon basin (Fig. 7e).

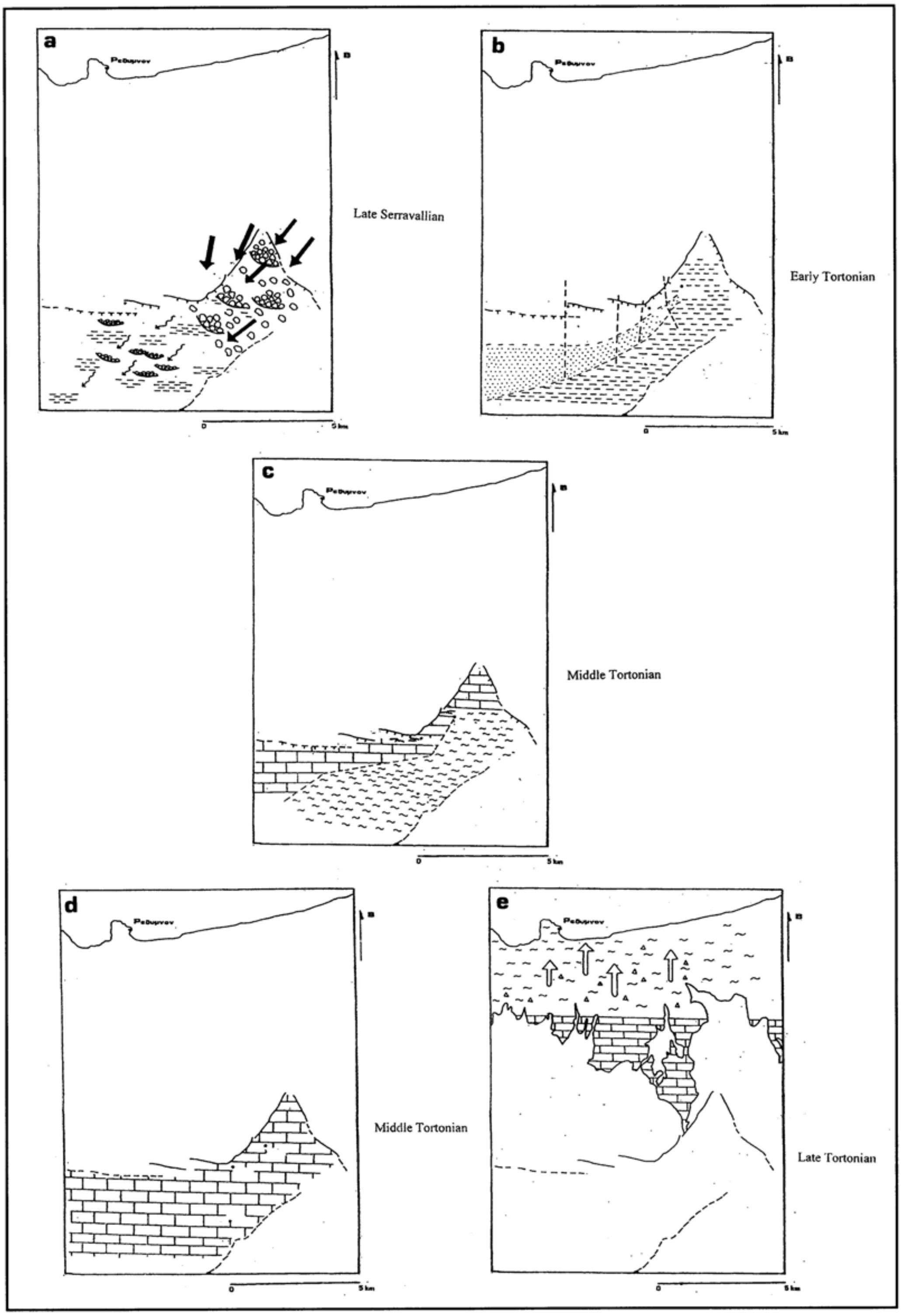

Fig. 7. Paleogeographical reconstruction of the studied area during a. Late Serravallian, b. Early Tortonian, c., d. Middle Tortonian, e. Late Tortonian.

CONCLUSIONS

The lithostratigraphical and sedimentological analyses of the deposits of Apostoli Basin gave the following results:

i. The tectonic-sedimentary regime of Apostoli Basin is corresponding to a tectonic graben where great part of its sediment fill has been originated from the elevated Alpine relief which is found northwards and northeastwards of the graben.
ii. The recognised depositional systems are categorized as follows: 1. Alluvial system, 2. Brackish-lacustrine system, 3. Shoreface system, 4. Inner shelf system and 5. Outer shelf system.
iii. An unconformity is not present in these intervals, suggesting that the magnitude of the relative sea-level excursion was small (<10m) and that the relative sedimentation rate tracked that fall.
iv. The following discussion outlines a simple scenario for the stepwise evolution of the depositional systems: The evolution of the sedimentary fill of Apostoli Basin started when subsidence of the basin took place and coarse grained clastic sediments originating from the elevated pre-Neogene basement were transported and deposited forming debris-flow and stream-flow deposits. The invasion of the sea from the south and the gradual decrease of the clastic sediment supply from the northeast, resulted to the deposition of the transitional sediments of the brackish-lacustrine system to the west, and of the shoreface deposits to the east. The continuous erosion of the palaeorelief and the climatic change towards warmer conditions are the responsible conditions for the change in the sedimentation regime. Thus, marls and bioclastic limestones gradually covered Apostoli Basin.

ABSTRACT

The tectonic-sedimentary regime of Apostoli Basin, central-west Crete, is corresponding to a tectonic graben where great part of its sediment fill has been originated from the elevated Alpine relief which is found northwards and northeastwards of the graben. Based on the vertical arrangement of the deposits in Apostoli Basin, five major Depositional Systems have been recognized which are categorized as follows: 1. Alluvial system, 2. Brackish-lacustrine (transitional) system, 3. Shoreface system, 4. Inner shelf system and 5. Carbonate platform.

The detailed lithostratigraphical and tectonic analyses, which were carried out in Apostoli Basin, led to important conclusions, related to environmental and lithological changes, which took place during Late Serravallian-Late Tortonian times. These changes are depicted in five palaeogeographical sketch maps where the studied facies associations are shown. During Late Serravallian - Late Tortonian times, the tectonic/sedimentary setting was one of graben, with most of the sediments being shed from a fault-bounded upland area to the north.

Important features for this trough is that it received coarse alluvial fan conglomerates from active fault-lines mainly on its northern margin, and that the coarse alluvial facies interfinger with coastal plain and marginal marine facies. The marginal marine facies become more abundant upward in the succession and culminate with the overlying bioclastic limestones, documenting the important Tortonian marine transgression of the region. No unconformities have been noticed.

ΠΕΡΙΛΗΨΗ

Το τεκτονοϊζηματογενές καθεστώς της λεκάνης των Αποστόλων, του νομού Ρεθύμνης στην νήσο Κρήτη, αντιστοιχεί σε μία τεκτονική τάφρο της οποίας το μεγαλύτερο μέρος του ιζηματογενούς πληρώματος προέρχεται από το ανυψωμένο Αλπικό ανάγλυφο βορείως και βορειοανατολικά αυτής.

Με βάση την κατακόρυφη διευθέτηση των αποθέσεων της Λεκάνης των Αποστόλων, αναγνωρίστηκαν πέντε κύρια αποθετικά συστήματα: 1. Το αλλουβιακό σύστημα, 2. Το υφάλμυρο-λιμναίο (μεταβατικό) σύστημα, 3. Το παράκτιο σύστημα, 4. Το σύστημα εσωτερικής κρηπίδας, 5. Το σύστημα ανθρακικής πλατφόρμας.

Από την λεπτομερή λιθοστρωματογραφική, βιοστρωματογραφική και τεκτονική ανάλυση που διεξήχθη στη Λεκάνη των Αποστόλων, προέκυψαν σημαντικά στοιχεία για τις περιβαλλοντικές και λιθολογικές μεταβολές που έλαβαν χώρα κατά τη διάρκεια της περιόδου από το Ανώτερο Σερραβάλλιο έως το Ανώτερο Τορτόνιο. Αυτές οι μεταβολές διαδραματίστηκαν σε πέντε φάσεις, οι οποίες κάθε μια απεικονίζεται σε έναν παλαιογεωγραφικό χάρτη πάνω στον οποίον φαίνονται τα διάφορα αποθετικά συστήματα.

REFERENCES

ANGELIER, J. (1976). Sur la néotectonique de l' arc égéen externe: les failles normales Est-Ouest et l' extension sudmeridienne crétoise. *C.R. Acad. Sci. Paris*, (D), 282, 413-416.

ANGELIER, J., DUMONT, J.F., KARAMANDERESI, H., POISSON, A., SIMSEK, S. & S. UYSAL (1981). Analyses of fault mechanisms and expansion of southwestern Anatolia since the Late Miocene. *Tectonophysics*, 75, T1-T9.

ANGELIER, J., LYBERIS, N., LE PICHON, X., BARRIER. E. & P. HUCHON (1982). The tectonic development of the Hellenic Arc and the Sea of Crete: a synthesis. In. *Geodynamics of the Hellenic Arc and Trench* (Ed. by X. LE PICHON, S.S. AUGOUSTITHIS & J. MASCLE), *Tectonophysics*, 86, 159-196.

AUBOUIN, J. (1971). Reflexion sur la tectonique de faille plio-quaternaire. *Geol. Rdsch.*, 60, 833-848.

AUBOUIN, J. & J. DERCOURT (1965). Sur la géologie de l' Egée: regard sur la Créte (Grèce). *Bull. Soc.Geol. France*, (7), t. VII, 787-821.

BANERJEE, I. & S.M. KIDWELL (1991). Significance of molluscal shell beds in sequence stratigraphy: an example from the Lower Cretaceous Mannville Group of Canada. *Sedimentology*, 38, 913-934.

CERLING, T.E. (1984). The stable isotopic composition of modern soil carbonate and its relationship to climate. *Earth Planet. Sci. Lett.*, 71, 229-240.

COHEN, A.S. (1982). Paleoenvironments of root casts from the Koobi Fora Formation, Kenya. *J. Sedim. Petrol.*, 52, 401-414.

DE BOER, J.Z. (1989). The Greek enigma: is development of the Aegean orogeny dominated by forces related to subduction? *Mar. Geol. 87*, 31-54.

DE BRUIJN, H. & J.E. MEULENKAMP (1972). Late Miocene rodents from the Pandanassa formation (prov. Rethymnon), Crete, Greece. *Proc. Koninklijke nederlanden Akademie van Wetenschappen, North-Holland publishing Company edit.*, Amsterdam, ser. B, vol. 75, 54-60.

DEMARCQ, G. & H. DEMARCQ (1989). Biostrome à Crassostrea du Quaternaire recent (Senegal), comparaison avec ceux du Miocène (bassin rhodanien). *Geologie Mediterranéenne*, XVI, 3-15.

DRINIA, H. (1996). Late Cenozoic clastic sedimentation in West Crete-Apostoli Basin (Rethymnon Province). *PhD Thesis*, University of Athens, 187p., Athens.

DRINIA, H., TRIANTAPHYLLOU, M.V. & M.D. DERMITZAKIS (1997). Cyclic sedimentation and biostratigraphic-paleoecological analysis of the marine sediments of Potami section (Apostoli Basin-Rethymnon Province, Crete). *Proceedings of the 5th Hellenic Symposium of Oceanography and Fishery*, vol. 1, 419-422.

DRINIA, H., TRIANTAPHYLLOU, M.V. & M.D. DERMITZAKIS (1998). Sedimentary facies analysis and biostratigraphical implications of the fluvio-marine sediments of central-west Crete. *R.C.M.N.S. Congress, May 27-29, 1998*, Patras.

FORTUIN, A.R. & J.M. PETERS (1984). The Prina complex in eastern Crete and its relationship to possible Miocene strike-slip tectonics. *J. Struct. Geol.*, 6, 459-476.

GEORGIADES-DIKEOULIA, E. (1974). Les brachiopodes du Miocène moyen de l' île de Crète (Aghii Assomati, Rethymnon). *Ann. Geol Pays hell.*, Athens, tome hors serie, fasc. I, 449-455.

GEORGIADES-DIKEOULIA, E. (1979). Paleontological and biostratigraphic survey of the marine Miocene of the Apostoli section, province of Rethymnon (Crete). VIIth International Congress on mediterranean Neogene (Athens, 1979). *Ann. geol. des Pays hellèniques*, Athens, tome hors serie, fasc. I, 449-455.

GOUDIE, A.S. (1973). *Duricrusts in Tropical and Subtropical Landscapes*. Clarendon Press, Oxford.

HAMBLIN, A.P. & R.C. WALKER (1979). Storm-dominated shallow marine deposits: The Fernie-Kooterray (Jurassic) transition, Southern Rocky Mountains. *Canadian Jour. Earth Sci.*, 16, 1673-1690.

HARMS, J.C., SOUTHARD, J.B., SPEARING, D.R. & R.G. WALKER (1975). Depositional environments as interpreted from primary sedimentary structures and stratification sequences. Short Course, *Soc. Econ. Paleont. Miner.*, Tulsa, 2, 161p.

HAYES, M.O. (1967). Hurricanes as geological agents: case studies of hurricanes Carla, 1961 and Cindy, 1963. *Rept. Invest.*, 61, 1-50.

KIDWELL, S.M. (1989). Stratigraphic condensation of marine transgressive records: origin of major shell deposits in the Miocene of Maryland. *The journal of Geology*, 97, 1-29.

KIDWELL, S.M. (1991). Condensed Deposits in siliciclastic sequences: Expected and observed features. In: *Cycles and Events in Stratigraphy* (Ed. by EINSELE *et al.*), Springer-Verlag Berlin-Heidelberg, 682-695.

KIDWELL, S.M., FURISCH, F.T. & T. AIGNER (1986). Conceptual framework for the analysis and classification of fossil concentrations. *Palaios*, 1, 228-238.

KLAPPA, C.F. (1980). Rhizoliths in terrestrial carbonates: classification, recognition, genesis and significance. *Sedimentology*, 27, 613-629.

KOPP, K.O. & D. RICHTER (1983). Synorogenetische Schuttbildungen und die Eigenstandigkeit der Phyllit-Gruppe auf Kreta. *Neues Jb. Geol. Palaont. Abh.*, 165, 228-253.

KUHN, O. (1936). Die Korallen und Bryozoen des Tegels von Kreta. *Pract. Akad. Athinon*, 11, 171-181, Αθήνα.

LE PICHON, X. & J. ANGELIER (1979). The Hellenic Arc and Trench System: a key to the neotectonic evolution of the Eastern Mediterranean. *Tectonophysics*, 60, 1-42.

LEES, A. (1975). Possible influences of salinity and temperature on modern shelf carbonate sedimentation. *Mar. Geol.*, 19, 159-198.

MAKRIS, J. (1977). Geophysical investigations of the Hellenides. *Hamb. Geophys. Einzelschr.*, 34, 124p.

MARTINI, E. (1971). Standard Tertiary and Quaternary calcareous nannoplankton zonation. In: Farinacci, A. (Ed.). *Proc. II Plankt. Conf. Roma*, 1970, Roma (Technoscienza), 2, 738-785.

MASCLE, J. & J. MARTIN (1990). Shallow structure and recent evolution of the Aegean Sea: a synthesis based on continuous reflection profiles. *Mar. Geol.,* 94, 271-299.

MASCLE, J., JONGSMA, D. *et al.* (1982). The Hellenic margin from eastern Crete to Rhodos: preliminary results. In: Geodynamics of the Hellenic Arc and Trench (Eds Le Pichon, x., Augustithis, S.S. & Mascle, J.) *Tectonophysics*, 86, 133-147.

MCBRIDE, E.F., DANE PICARD, M. & R.L. FOLK (1994). Oriented concretions, Ionian coast, Italy: evidence of groundwater flow direction. *Journal of Sedimentary Research*, A64, 535-540.

MCKENZIE, D.P. (1972). Active tectonics of the Mediterranean region. *Geophys. J.R. Astron. Soc.*, 30, 109-185.

MCKENZIE, D.P. (1978). Some remarks on the development of sedimentary basins. *Earth Planet. Sci. Lett.*, 40, 23-32.

MERCIER, J.L., SOREL, D. & K. SIMEAKIS (1987). Changes in the state of stress in the overriding plate of a subduction zone: the Aegean arc from the Pliocene to the present. *Annales Tectonicae*, 1, 20-39.

MELENTIS, J.K. (1974). Palaontologische Ausgrabungen in den Hohlen des Gebietes von Rethymnon, Kreta. *Sci. Ann. Sci. Fac. Un Thess*, 14, 17-24.

MEULENKAMP, J.E. (1969). Stratigraphy of Neogene deposits in the Rethymnon province, Crete, with special reference to the phylogeny of uniserial *Uvigerina* from the Mediterranean region. *Utrecht Micr. Bull.*, 2, 168p

MEULENKAMP, J.E. (1979). Lithostratigraphy and relative chronostratigraphic position of the section Apostoli and Potamidha 1 and 2. *Utrecht Micr. Bull.*, 21, Utrecht.

MEULENKAMP, J.E., WORTEL, M.J.R., VAN WAMEL, W.A., SPAKMAN, W. & HOOGERDUYN STRATING, E. (1988). On the Hellenic subduction zone and the geodynamic evolution of Crete since the late Middle Miocene. *Tectonophysics*, 146, 1-13.

NELSON, C.S. (1988) (Ed.). Non-tropical shelf carbonates –modern and ancient. *Sediment Geol.*, 60, 355 p.

OKADA, H. & D. BUKRY (1980). Supplementary modification and introduction of code numbers to the low latitude coccolith biostratigraphic zonation. *Marine Micropal.*, 5, 321-325.

PAPAZACHOS, B.C. & P.E. COMNINAKIS (1978). Deep structure and tectonics of the Eastern Mediterranean. *Tectonophysics*, 33, 285-296.

PETERS, J.M. (1985). Neogene and Quaternary vertical tectonics in the south Hellenic Arc and their effection on concurrent sedimentation processes. *Gua paper of Geology*, Amsterdam, Series 1, No 23, 230p.

POSTMA, G., FORTUIN, A.R. & W.A. VAN WAMEL (1993). Basin-fill patterns controlled by tectonics and climate: the Neogene "forearc" basins of eastern Crete as a case history. In: *Tectonic Controls and Signatures in Sedimentary Successions* (Ed. by L.E. Frostick and R.J. Steel), *Spec. Publ. Int. Ass. Sed*., 335-362.

RALLI, Z. (1940). Beitrage zur Kenntnis des Neogens in Kreta. *Prakt. Akad. Ath.*, 15, S. 443-448, Athens.

REEVES, C.C. (1970). Origin, classification and geologic history of caliche on the southern High Plains, Texas and eastern New Mexico. *J. Geol.*, 78, 352-362.

SYMEONIDIS, N.K. (1969). Das Miozan in Bereich von Boliones (Landkreis Rethymnon-W. Kreta). *Ann. Geol. Pays hellen.*, Athens, ser. 1, t. XXI, 30-34.
SYMEONIDIS, K. & P.Y. SONDAAR (1975). A new otter from the Pleistocene of Crete. *Ann. Geol. pays Hellen.* XXVII, 11-24.
WRIGHT, M.E. & R.G. WALKER (1981). Cardium Formation (Upper Cretaceous) at Seebee, Alberta - storm transported sandstone and conglomerate in shallow marine depositional environments below fairweather wave base. *Canadian Jour. Earth Sci.*, 18, 795-809.