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STUDY OF THE SANDY CARBONATE CLASTIC SEDIMENTS OF THE KALAMAVKA FORMATION (UPPER MIOCENE, E. CRETE)

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STUDY OF THE SANDY CARBONATE CLASTIC SEDIMENTS OF THE KALAMAVKA FORMATION (UPPER MIOCENE, E. CRETE)*

by

H. DRINIA**

1. INTRODUCTION

In eastern Crete, the Neogene sedimentary evolution of the Ierapetra basin has been studied in detail (FORTUIN 1977, 1978). The stratigraphy of the Ierapetra region is rather complicated by tectonic movements during the period of sedimentation, especially during the Late Serravallian when the break-up stage of Crete from the European Landmass started. During that period, Neogene basins were formed due to the strong vertical crustal movements. FORTUIN (1977, 1978), in his contridution to the interpretation of the structural and depositional settings of the Neogene sedimentary basin fills, studied thoroughly the Ierapetra region. On the basis of detailed mapping and faunal datings, he subdivided the basin fill of the Neogene Ierapetra basin into nine formal rock units: eight formations and one complex.

1.1. Scope of the present study

In this study, we have restricted ourselves to the detailed study of one of the eight formations of FORTUIN (1977): the Kalamavka Formation (Late Serravallian - Early Tortonian). This formation has been selected for the reason that its depositional timing (Late Serravallian - Early Tortonian) coincides with the initiation of the break-up stage of the Aegean crust due to intense extensional tectonics (ANGELIER, 1979), and therefore, with the onset of the «modern history» of the Aegean region (MEULENKAMP, 1985). As a result it is to be expected that many lithostratigraphical and paleogeographical variations must have taken place during that timespan. The Kalamavka Formation is thought to be a representative rock unit, which depicts the prevailing sedimentary pattern during that period.

Thus the purpose of this work is to interpret the depositional envirnonment of the sediments belonging to the Kalamavka Formation and its changes through time. The interpretation is mainly based on the prevailing sedimentation pattern during deposition.

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1.2. Methodology

In order to accomplish the aim of the present study, the following steps have been taken:

1. Sedimentological field description of the sediments belonging to the Kalamavka Formation.
2. Petrographic description of approximately 30 thin sections, which cover the stratigraphy of the Kalamavka Formation.

2. GEOLOGICAL SETTING OF CRETE

In order to understand the sedimentation and the tectonic evolution of Crete, during the Late Cenozoic Era, it is important to take into consideration its plate tectonic setting.

The Late Cenozoic evolution of Crete has been controlled by the northward subduction of the African plate beneath the Aegean lithosphere (MAKRIS, 1977; McKENZIE, 1978a; PAPAZACHOS & COMNINAKIS, 1978; LE PICHON & ANGELIER, 1979). As the African plate moves northwards, strike slip displacements along the Dead Sea fault zone causes compression between the Arabian and the Eurasian plates (MOLNAR & TAPPONIER, 1975). This process results in a crustal thickening of E. Turkey. As a result, the Aegean and Anatolia plates are being pushed westwards causing the extension of the Aegean region towards the eastern Mediterranean (gravitational-spreading), (McKENZIE, 1972; McKENZIE, 1978a; LE PICHON & ANGELIER, 1979; ANGELIER *et al.*, 1981). The gravitational spreading of the Aegean region towards the eastern Mediterranean is evidenced by the presence of a dense pattern of normal faults (Upper Miocene) and horst and graben structures (McKENZIE, 1972; McKENZIE, 1978; LE PICHON & ANGELIER, 1979; ANGELIER *et al.*, 1981).

Although the Aegean region is characterized by extensional testonics resulting in a steady subsidence, the Hellenic arc and consequently the island of Crete, has an elevated position relative to the Cretan Sea in the north. The elevated position of Crete seems to be contradicted by the extensional tectonics and the subsequent subsidence which began to act upon the Aegean region in the Late Miocene. However, geological data support the idea that compressional tectonics may have played a greater role in Crete than in the rest of the Aegean region.

According to MEULENKAMP *et al.* (1988), the Neogene of Crete is characterized by periods of universally directed extension alternating with periods of approximately NE-SW oriented compression. This particular situation in the tectonic regime of Crete can be explained if we concider that the extensional regime in the Aegean lithosphere gave rise to the generation of south-dipping, low-angle shear zones (see LISTER *et al.*, 1984). Along these zones, a supracrustal slab was formed and started to slide in a southward direction, driven by gravity (SIMPSON & SCHMID, 1983; LISTER et al., 1984). Above the «detachment plane» of this supracrustal slab, the extensional faulting resulted in the crustal thinning and finally, in subsidence of the crust, leading to the generation of the Sea of Crete (LISTER *et al.*, 1984). On the other hand, the frontal part of the supracrustal slab may be affected by compression as dissects Crete and meets the bulge of the Ionian plate (eastern Mediterranean, a part of the African plate), (MEULENKAMP *et al.*, 1988). The consequent folding and thrusting, which acted upon Crete, are thought to be the processes responsible for the uplift of Crete.

3. IERAPETRA REGION

3.1. Regional setting

The Ierapetra region is located in eastern Crete and occupies the area of the Ierapetra and Merabellou districts of the Prefecture of Lasithi (FORTUIN, 1977).

The Neogene rocks of the Ierapetra region extend over an area of 500 km^2 and consist of coarse clastic sediments at the base which pass upwards into marine marls, sands and limestone, (FORTUIN, 1977). They are underlain by the pre-Neogene rocks, which form a complex structure of an autochthonous basement of Permian-Oligocene age (Plattenkalk Series) overlain by four allochthonous units (Phyllite-Quartzite, Tripolitza, Pindos and Sub-Pelagonian) (BAUMAN *et al.*, 1976). After the emplacement of this nappe pile in the Oligocene-Early Miocene times (MEULENKAMP, 1971; ANGELIER, 1979), strong block-faulting along E-W and NE-SW directions affected the whole region and formed small sedimentary basins in which the complex interaction between the faults resulted in the frequent change of land-sea distribution (DROUGER & MEULENKAMP, 1973; MEULENKAMP, 1979) This complicated pattern of land and sea during the Late Cenozoic caused rapid lateral and vertical changes in the lithology (FORTUIN, 1977). Besides, the stratigraphy of the Ierapetra region became more complicated in the Messinian when the Messinian salinity crisis and its consequences had a strong impact upon sedimentation.

It should be pointed out that the present topography of the Ierapetra region reflects some important Late Pliocene-Quaternary movements along faults. The most striking tectonic feature of the present day morphology of the Ierapetra region is the central NE-SW depression with its eastern margin bounded against the Quaternary Ierapetra fault (La fosse d'Ierapetra: ANGELIER, 1976; ANGELIER, 1977).

3.2. Stratigraphy of the Ierapetra region

FORTUIN (1977) subdivided the Neogene of the Ierapetra region into nine formal rock units: eight formations and one complex, each one corresponding to different environmental conditions. The Neogene sediment distribution of the Ierapetra basin is shown in Fig. 1. The main characteristics of these formational units are cited below (from bottom to top, Fig. 2):

1. **Mithi Formation** (150 m thick): Conglomerates of poorly sorted pebbles with a reddish or greyish weathering colour. This formational unit has not been dated because of the lack of datable material in these deposits.
2. **Males Formation** (350 m thick, ?-Late Serravallian): Alternations of mature conglomerates, sandstones and clayey marls. On top of this succession, marly deposits predominate forming the Parathiri Member.
3. **Prina Complex** (350 m thick, Late Serravallian-Early Tortonian): Stratified breccias and breccio-conglomerates and conglomerates with fine-grained interbeds. Partly, marine boulder conglomerates with regular intercalations of well-sorted calcareous sandstones predominate.
4. **Fothia Formation** (450 m thick, Late Serravallian-Early Tortonian): Irregularly stratified, polymict conglomerates with ill-sorted and poorly rounded pebbles, alternating upwards with sands and marly deposits. This formational unit is found only east of the Ierapetra fault (Fig. 1).

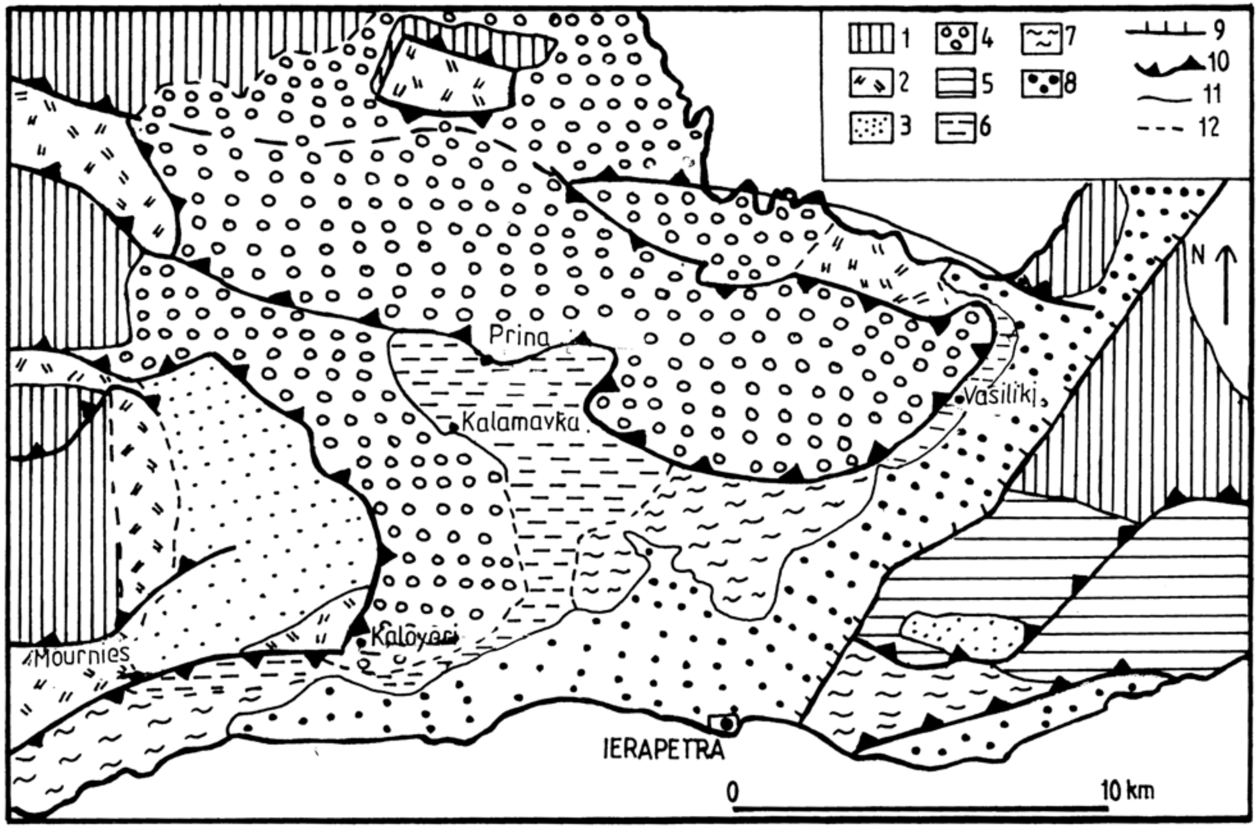


Fig. 1: Simplified geological map of the central part of the Ierapetra region (after FORTUIN, 1977; modified by POSTMA, pers. comm.)
1. Tripolitza Series; 2. Subpelagonian Series; 3. Mithi and Males Formations; 4. Prina Complex; 5. Fothia Formation; 6. Kalamavka Formation; 7. Makrylia Formation; 8. post-Tortonian sediments; 9. normal faults; 10. thrust faults; 11. tectonic contact; 12. stratigraphic contact.

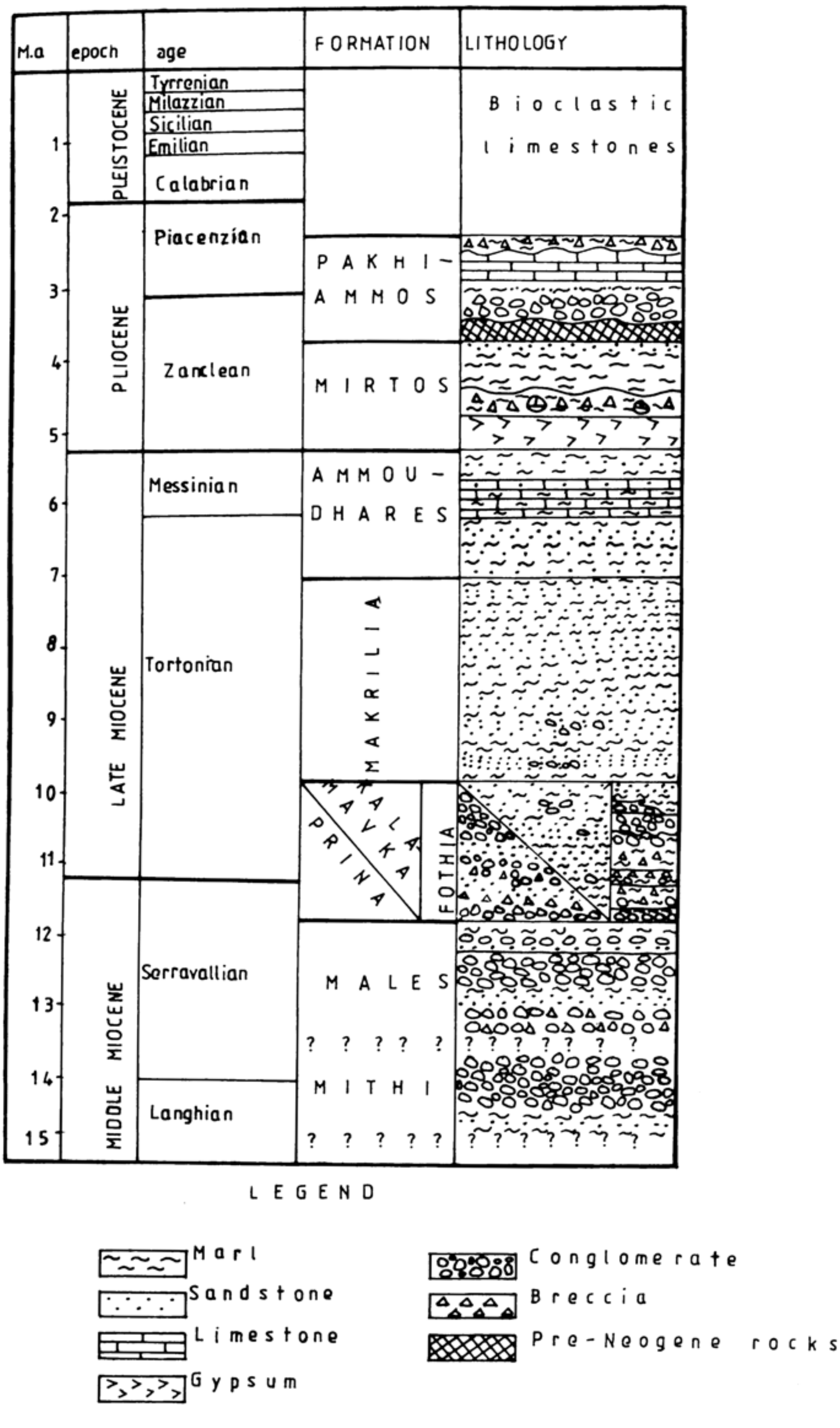


Fig. 2: Generalized stratigraphic column of the Ierapetra region.

5. **Kalamavka Formation** (300 m thick, Late Serravallian-Early Tortonian): Rhythmically alternating marls and calcareous sandstones. Pebbly mudstone intercalations as well as other conglomeratic bodies are common in different levels.

6. **Makrylia Formation** (450 m thick, Early Tortonian): Marine bluish marls alternating with brownish, graded sands (turbidites).

7. **Ammoudhares Formation** (50-100 m thick, Late Tortonian-Messinian): Yellow-grey, highly calcareous, homogeneous or laminated marls, alternating with sandy bioclastic limestones. Sponge spicules are abundant in the laminated marls.

8. **Mirtos Formation** (60 m thick, Early Pliocene): Heterogeneous deposits of gypsum, white and greyish marls, marl breccias and sands.

9. **Pakhiammos Formation** (30 m thick, Middle Pliocene): Cavernous, micritic limestones, marl breccias and whitish marls.

In some parts of the Ierapetra region, especially along the south coast, post-Neogene rocks are found to form large terraces at various heights (FORTUIN, 1977).

3.3. Tectono-sedimentary history of the Ierapetra region

According to MEULENKAMP (1979) and DROOGER and MEULENKAMP (1973), the Neogene sedimentary history of the Ierapetra region started with the deposition of the Mithi Formation (the timing of which has not been defined). During that time, the region was part of a continental borderland, situated at the southern margin of the South Aegean Landmass (DROOGER & MEULENKAMP, 1973). On top of this formation, conglomerates, sandstones and clays of the Males Formation were laid down into a large, east to west flowing, fluvial drainage system.

In the Late Serravallian, the fluvial sedimentation ceased because of the gradual submergence of the area which was caused by strong blockfaulting due to crustal tension (DROOGER & MEULENKAMP, 1973). As a consequence, fossiliferous, shallow marine marls (Parathiri Member) were deposited on top of the Males Formation.

During the same period, the break-up stage of the Southern Aegean Landmass started (DROOGER & MEULENKAMP, 1973; MEULENKAMP, 1985; MEULENKAMP *et al.*, 1988). As a consequence, a N-S shortening affected the Ierapetra region. During the Late Serravallian-Early Tortonian period, compressional tectonics affected the Ierapetra region resulting in the formation of a major, approximately E-W oriented, thrust fault (POSTMA, pers. comm.; Fig. 3). Thrusting caused the uplift of the northern part of the region and exotic blocks and coarse clastics of continental to littoral origin started to accumulate south of the thrust fault (Prina Complex). The continuous accumulation of sediment there and the imposed weight of the thrust mass (isostatic loading) caused flexure and gradual subsidence of the crust and the formation of a graben-like depression in the central part of the region, which had an open marine connection in the south (FORTUIN, 1978). Due to the main thrust fault, other secondary thrust faults were formed (Fig. 3), which deformed the already continental to littoral sediments of the Prina Complex and caused the deposition of fluvio/marine conglomerates (still Prina Complex) and calcareous mudstones and sandstones (Kalamavka Formation).

East of the Ierapetra fault, the lithostratigraphic succession is different (FORTUIN, 1977). Instead of the Prina Complex, the Fothia Formation is deposited next to the fault (Fig. 1).

In the Early Tortonian, in response to further subsidence, a deeper basin was

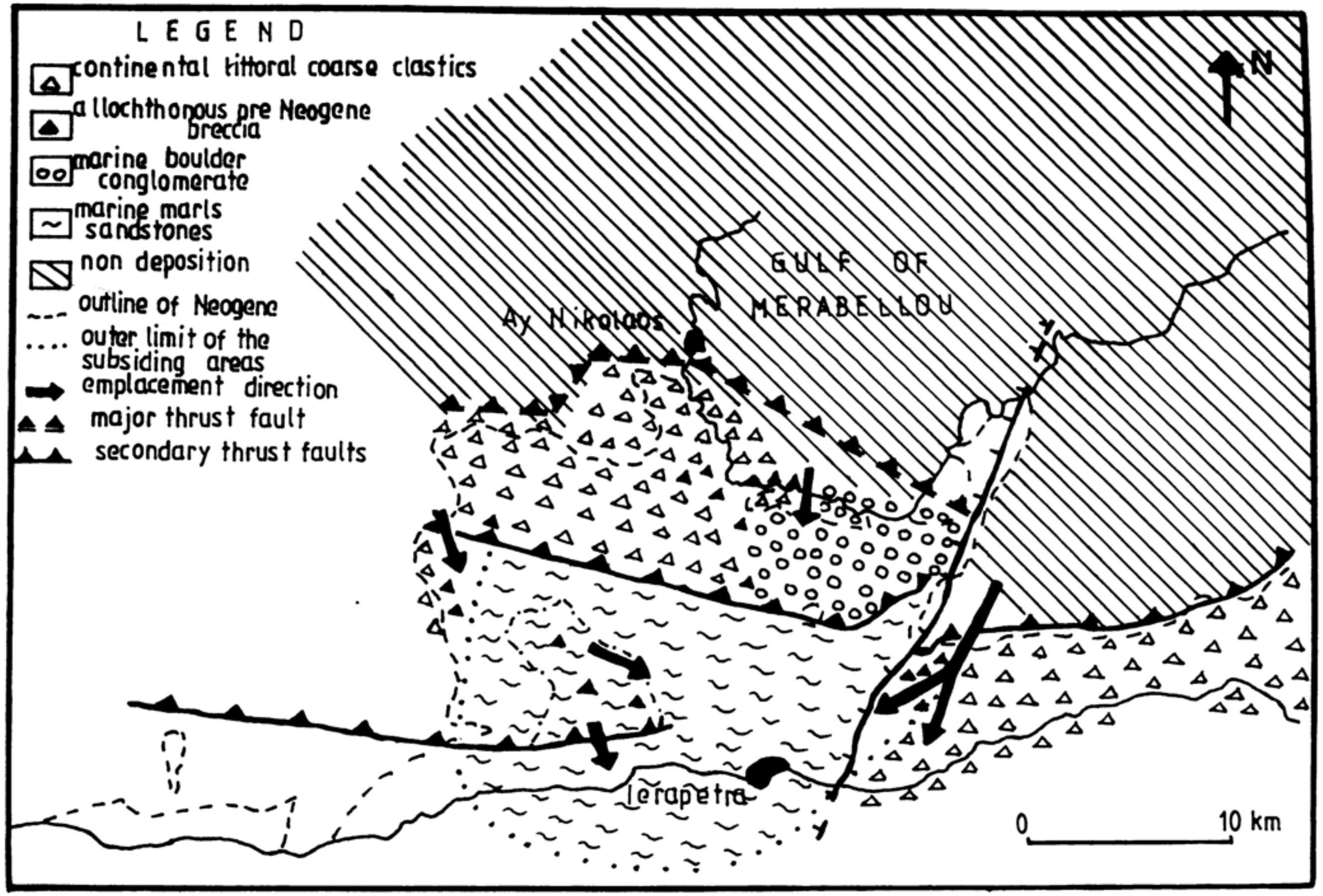


Fig. 3: Paleogeographical reconstruction of the Ierapetra region during the Late Serravallian-Early Tortonian. The activation of the thrust fault caused uplift and denudation of the northern part and subsidence (due to isostatic loading) of the southern part. In the beginning, mainly continental to littoral coarse clastics were accumulated next to the fault (Prina Complex). Further to the south, more pronounced subsidence (due to activation of secondary thrust faults) resulted in the deposition of fluvio/marine conglomerates (still Prina Complex) and marine marls and sandstones of the Kalamavka Formation.

formed which was filled with marl and a few turbiditic sandstones and extended over the south coast areas (Makrylia Formation), (FORTUIN, 1977).

The Messinian is characterized by the gradual emergence of the area, which resulted in the «Messinian facies» and is attributed to the Late Miocene salinity crisis of the Mediterranean sea (HSÜ et al., 1976). Before the end of the Messinian, marine conditions returned again.

Finally, during the Early Pliocene, marl breccias were deposited, indicating submarine mass transport (FORTUIN, 1977). In the Middle Pliocene, a renewed uplift started and by the end of the Pliocene, the whole area had emerged (DROOGER & MEULENKAMP, 1973).

From the previously discussed structural evolution of the Ierapetra region, it is evidenced that a big change in its tectonic regime occurred in the Late Serravallian times: The N-S extensional phase which acted on Crete and was evidenced by the deposition of mature, gravelly braided river facies (Males Formation) switched to a N-S compressional phase which caused the deposition of the Prina Complex (immature carbonate clastics) and the Kalamavka Formation (rhythmical alternations of calcareous mudstone and sandstone).

4. KALAMAVKA FORMATION

4.1. Stratigraphy and general characteristics

The Kalamavka Formation is a rock unit with a limited geographical extension (20 km E-W and 10 km N-S). It mainly covers the area between the villages of Kalamavka-Prina-Kaloyeri (FORTUIN, 1977), (Fig. 1), and is also found in a narrow E-W strip between Kaloyeri and Mournies and around the village of Vassiliki, NE of Ierapetra (FORTUIN, 1977). The Kalamavka Formation is well developed near the Kalamavka village (over 350 m thick), (type section of the Formation). The type section (which has been studied in detail in this work) is exposed along the road from Kalamavka to Prina, 12 km NW of Ierapetra (FORTUIN, 1977). (Fig. 4).

The Kalamavka Formation developed during the Late Serravallian-Early Tortonian times, when the extensional phase which acted on Crete switched to a N-S compressional phase. It is found southwards of the thrust fault which delimits the northern uplifted deposits from the southern subsiding areas (Fig. 3). It usually overlies the marly deposits of the Parathiri Member (Males Formation) (Fig. 2). As far as the Prina Complex is concerned, FORTUIN (1977, 1978) suggested that it can either underlie or interfinger with the Kalamavka Formation. Field data show that the contact between the Prina Complex and the Kalamavka Formation is either of a tectonic or sedimentary nature. The Kalamavka Formation is overlain by, or it is a lateral equivalent of the brownish graded sands and the marine marls of the Makrylia Formation (Fig. 2).

The Kalamavka Formation is characterized by predominantly marine fine-grained clastics (FORTUIN, 1977). Its submature sediments possibly originated from both the uplifted basement (the Mesozoic Tripolitza limestone) found NW of the major thrust fault and partly from the adjacent coarse-grained Prina Complex. Paleocurrent measurements indicate a SE directed transport of sediments (FORTUIN, 1977).

The studied section (type section of the Kalamavka Formation) consists of alternating, bluish-grey fossiliferous marls and dark grey, strongly lithified, calcareous sandstones. Its basal, predominantly marly beds (section AB Fig. 4), which conforma-

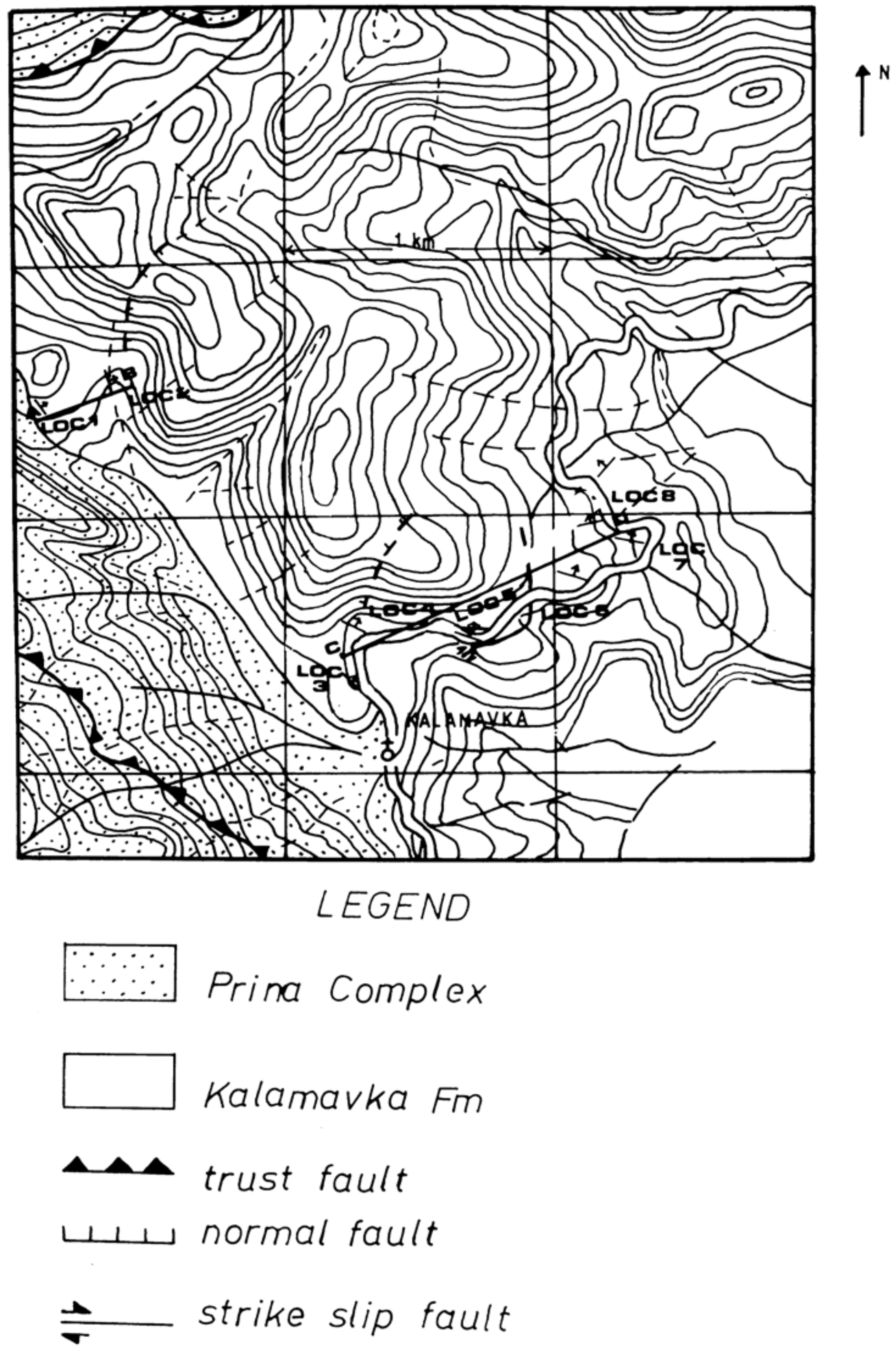


Fig. 4: Geological map of the studied region, indicating the studied cross-sections AB and CD (scale 1:50.000).

bly overlie breccio-conglomerates of the Prina Complex, are overlain by thin to thick, partly amalgamated sandstones (section CD Fig. 4). In the lower and middle part of the Formation, there are some conglomeratic bodies similar to those found in the Prina Complex. The whole section has an average dip 30° NE and forms a crude coarsening-upward trend.

4.2. Petrographic and biostratigraphic comments

Generally, the Kalamavka sandstones are lithic sandstones, relatively low in quartz and feldspars, and contain a variety of rock fragments. These sandstones are, mostly, very fine to fine and calcareous. The rock fragments are usually of sedimentary or secondary diagenetic origin, (although there may be some transported metamorphic fragments), chiefly limestone and chert. Micritic limestones are the most common types of sedimentary rock fragments. These calcareous sandstones are usually fossiliferous with the most common fossils being foraminifera. Other fossils such as fragments of gastropods and ostracod valves also occur.

The fossils that have been identified are the uniserial *Uvigerina* and some planktonic foraminifera, mainly Globigerinidae. The identified fossils are in complete agreement with those that FORTUIN (1977) found, which are the following:

– *Uvigerina melitensis* or U. ex. interc. *pappi melitensis* usually found in the lower part of the studied section.

– *Uvigerina praeselliana* which together with *Uvigerina gaulensis* are found in the higher levels of the type section.

– And finally, the primitive *Uvigerina selliana.*

These *Uvigerina* specimens suggest a Late Serravallian-Early Tortonian depositional age for the Kalamavka Formation (FORTUIN, 1977). This assumption is supported by the fact that *Globorotalia menardii* has also been detected (FORTUIN, 1977).

The previously mentioned faunal data indicate deposition in an open marine environment at an approximate depth of 100 to 200 m (MURRAY, 1973).

This conclusion is also supported by the marine burrows which have been found in the Kalamavka sediments. Burrows are of the *Scolithos* and *Cruziana Ichnofacies,* that belong to the marine rȩalm.

4.3. Sedimenary facies: Description and Interpretation

The studied section of the Kalamavka Formation has been divided into five facies, each one identified by its field aspect, physical and biological sedimentary structures, grain size and lithology. These facies are as follows (Fig. 5):

Facies 1: Calcareous mudstone
Facies 2: Alternations of very thin-bedded, laminated sandstone and mudstone.
Facies 3: Fine to medium-grained, thin-bedded sandstones.
Facies 4: Medium to coarse-grained, thin to thick-bedded, hummocky-cross-stratified sandstones.
Facies 5: Debris flow lobes.

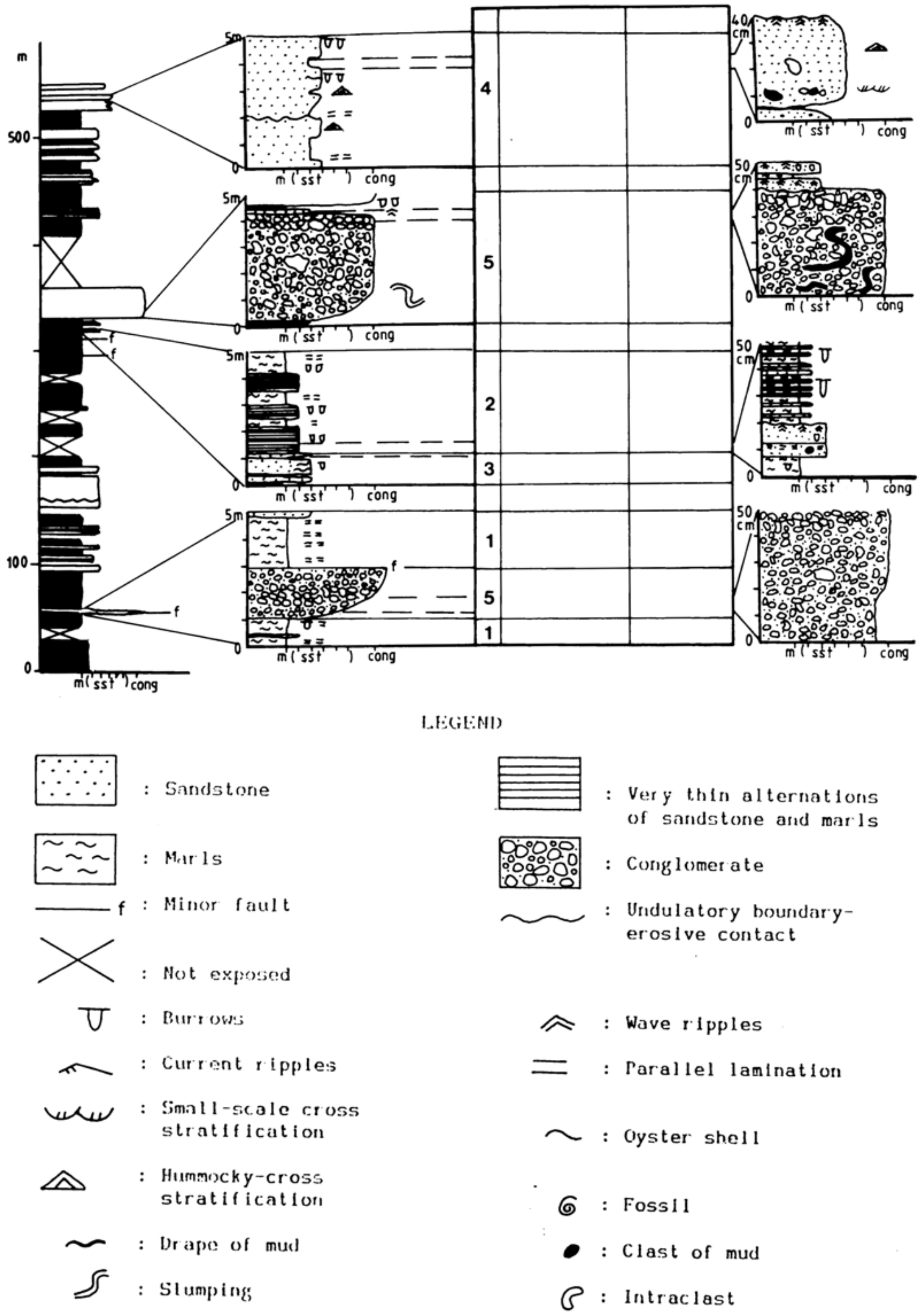


Fig. 5: Vertical profile through the Kalamavka Formation (type section).

FACIES 1

Description

Facies 1 (Fig. 6, Fig. 7a, Fig. 7b, Fig. 7c) comprises bluish, fossiliferous, calcareous mudstones with occasional lenses or layers of fine to very fine grained sandstone (Fig. 7a). The mudstone is generally massive but in places thin laminations are visible (Fig. 7b). The sandstone beds are very thin and increase in abundance and thickness as Facies 1 grades into Facies 2. The sandstone layers are usually massive but parallel lamination, ripple cross-lamination, lenticular and wavy bedding also occur.

Due to the strong bioturbation most commonly of the *Scolithos Ichnofacies* (Fig. 7c) which affected the sediments of Facies 1, the lower and upper surfaces of the thin sandstone layers are frequently indistinct.

Facies 1 dominates mainly the basal part of the studied section.

Interpretation

The mud-dominated Facies 1 is thought to represent open marine (shelf) environment. The fossiliferous and burrowed mudstones indicate deposition from suspension in a quiet environment which has hardly been influenced by waves or other currents. The deposition of mud by suspension was occasionally interrupted by waning sand-laden traction currents (deposition of the sandstone beds).

FACIES 2

Description

Facies 2 (Fig. 8, Fig. 9a, Fig. 9b, Fig. 9c) consists of very thin to thin-bedded and very fine to fine-grained sandstones found embedded in shelf mud.

All these sandstone beds begin with a sharp base and mostly grade upwards into overlying mud layers. The sandstone:mudstone ratio is usually 1:1 and the average thickness of the beds is 1 to 2 cm. The sandstone beds are either evenly laminated or are developed as laminated rhythmites (sensu REINECK & SINGH, 1972), (Fig. 9a), in which the lower laminae are thicker and coarser grained and grade upwards into thinner and finer-grained laminae. The upper contact of each bed with the intercalated mudstone is sharp, yet there are some sandstone beds with wave-rippled tops.

On the surface of the very thin-bedded sandstones, there are some curvilinear, randomly distributed imprints which are possibly traces of crab (Fig. 9b) (FORTUIN, 1977). Primary sedimentary structures throughout Facies 2 are reworked by strong, mainly vertical, bioturbation (Fig. 9c).

Facies 2 is dominating in the southern part of the basin and usually overlies the massive mudstone of Facies 1. Locally, it is characterized by a crude fining-upward trend.

Interpretation

According to WALKER (1979), the mechanism for the transport and deposition of sand offshore is by density driven turbidity currents which evolve from storm-generated currents and can transport and deposit sediment well below storm wave-base.

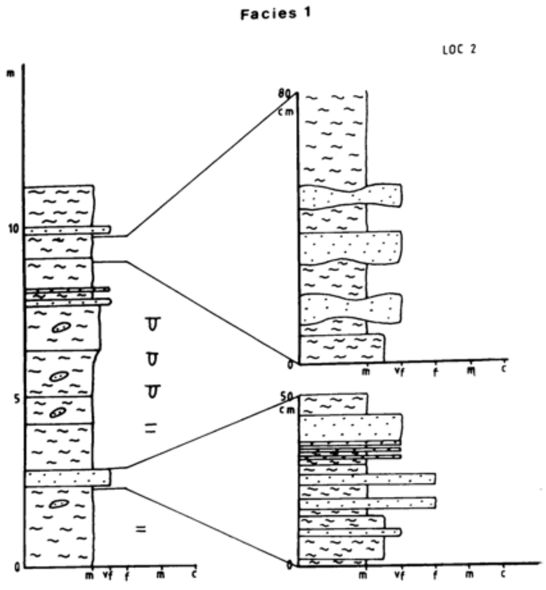
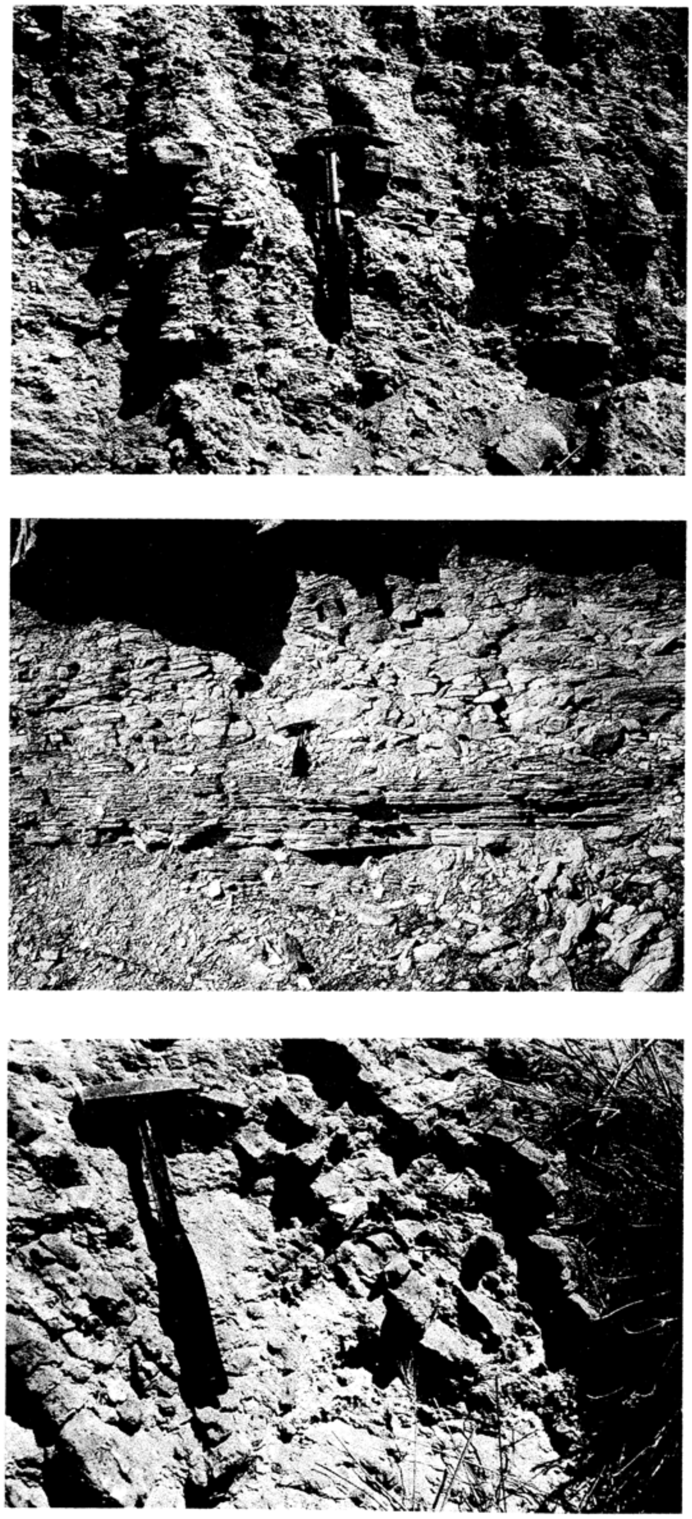


Fig. 6: Selected vertical log through Facies 1.



A

B

C

Fig. 7: (A) Calcareous mudstone with layers of very fine grained sandstone. (B) Very thin laminated calcareous mudstone. (C) Bioturbated Facies I *(Scolithos Ichnofacies).*

HAMBLIN & WALKER (1979) and LECKIE & WALKER (1982) worked on offshore/shelf facies which include sandstone beds 1-2 cm thick, characterized by parallel-lamination grading upwards into wave ripple lamination and interpreted them as originating from storm-generated turbidity currents which escaped beyond storm wave base and deposited sediment in the offshore-shelf area.

The crude fining-upward trend of such deposits is thought to be due to the declining energy of successive, episodical currents. That is, in the beginning, when the energy level of the storm-generated current is high, only sand in the form of parallel laminae is deposited, so that laminated sandstone beds are produced. Later, with a decrease in wave energy, finer-grained, wave cross-stratified sediments and finally mud with rather ill-defined laminae are laid down, forming the observed fining upward, small-scale sequences.

FACIES 3

Description

Facies 3 is characterized by fine to medium grained, thin to medium bedded, moderately sorted sandstones (Fig. 10, Fig. 11a, Fig. 11b, Fig. 11c). It usually grades into Facies 4 and is laterally persistent.

Generally, the base and the top of each sandstone bed of Facies 3 are sharp and smooth surfaces but they can also be disrupted by moulds or burrows.

The base of many sandstone beds of this Facies usually show a distinct laminated interval with some scattered outsized pebbles. This laminated interval is covered by wave rippled sand (Fig. 11a and Fig. 11b). The sandstone beds are separated by thin marly horizons or by very thin, strongly bioturbated alternations of mudstone and wave-worked, very fine-grained sandstones (Fig. 11c). Otherwise, they are amalgamated.

In some beds, granules and pebbles are either scattered throughout the entire thickness of the bed or are concentrated as discontinuous streaks along laminae and basal erosive surfaces.

Interpretation

The type of stratification present in these sandstone beds is thought to be indicative of sedimentation in the offshore-transition zone: the flat lamination being the product of storm produced ebb-surge currents (ELLIOTT, 1978) and the abundance of wave rippled cross lamination that occur between the storm generated beds being indicative of a return from storm to fair weather conditions. In other words, high energy conditions («storms») alternated with periods of lower energy («fair weather» conditions). The wave rippled sandstone cappings and the bioturbated alternations of mudstone and very fine sandstone possibly represent sand reworking by waning storm currents and fairweather sedimentation punctuated by minor storms respectively (MAEJIMA, 1988). The accumulation of pebbles into the sandstones suggests effective segregation of larger clasts from sands and is interpreted to be the result of wave processes related to storms (MAEJIMA, 1988).

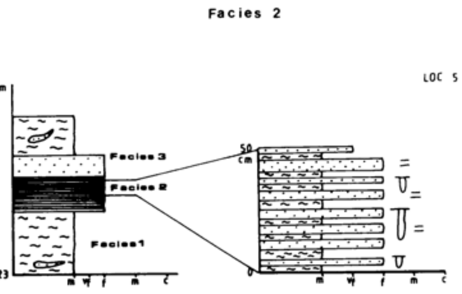
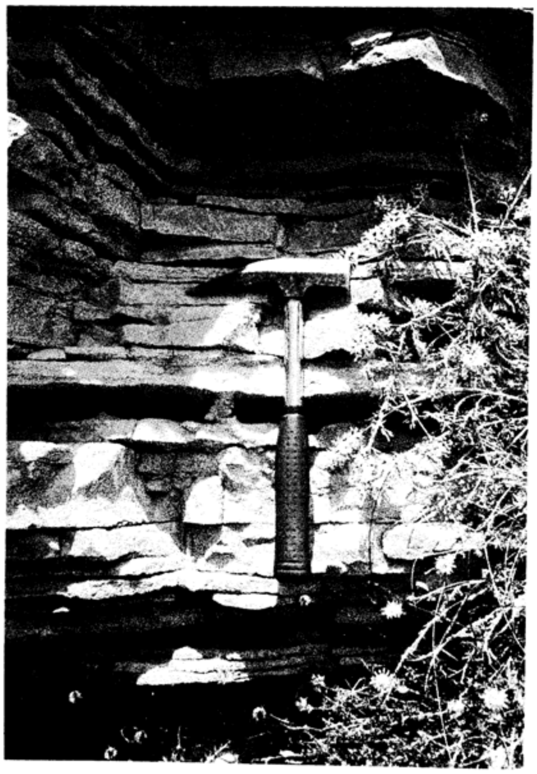


Fig. 8: Selected vertical log through Facies 2.


B

A


Fig. 9: (A) Alternations of very thin-bedded sandstone and mudstone, parallel-bedded and varve-like in appearance. (B) Curvilinear imprints on the surface of very thin bedded sandstones. (C) Reworking of Facies 2 by strong, mainly vertical bioturbation.

C


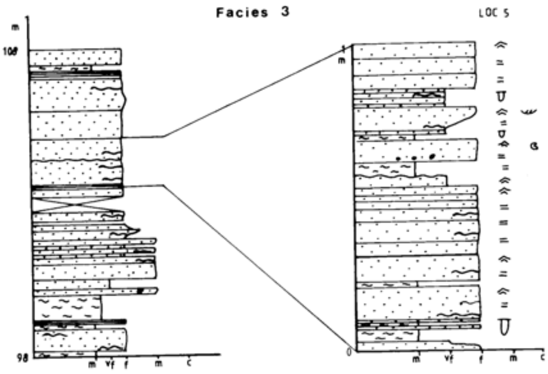
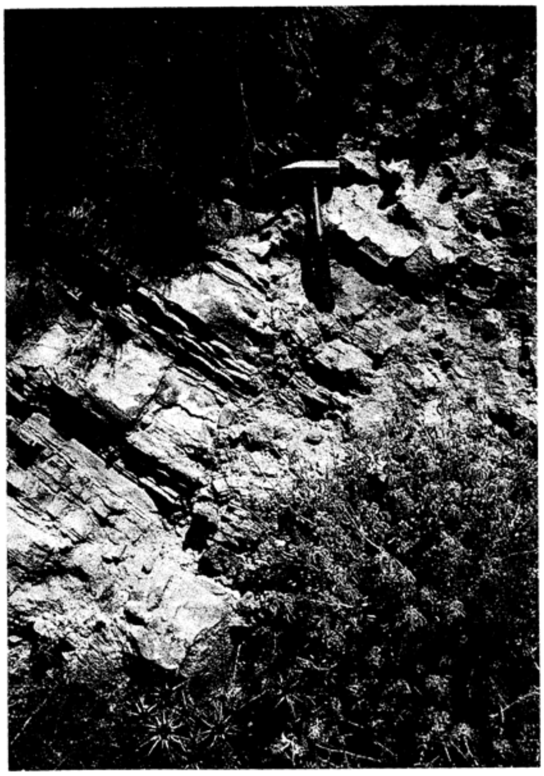


Fig. 10: Selected vertical log through Facies 3.

A

Fig. 11: (A) Medium to fine-grained, laminated sandstone bed. (B) Wave rippled top of a medium-grained sandstone. (C) Medium-bedded sandstones separated by very thin, strongly bioturbated alternations of mudstone and sandstone.

C



B

FACIES 4

Description

Facies 4 (Fig. 12, Fig. 13a, Fig. 13b, Fig. 13c) follows Facies 3 gradationally in a lateral and vertical sense, and consists of medium to coarse grained, medium to thick-bedded sandstones and bioturbated mudstones (up to 5 cm thick) (Fig. 13a). These deposits are elongate, lenticular units, ungraded and poorly sorted. The sandstones contain hummockly-cross-stratification. This structure consists of low-angle, gently undulating laminations. The base of these HCS beds is usually sharp whereas the top commonly show small-scale symmetrical ripples. The HCS beds become amalgamated upward in the sequence, forming a sand body of 2-3 m thick. The top of this amalgamated sand body is very undulatory and partly reworked (wave ripple cross-stratification), whereas the base is characterized by load structures (Fig. 13b).

Outsized pebbles are scattered throughtout the amalgamated, sandy beds or occur concentrated as discontinuous stringers along the internal scour surfaces, forming traction carpets (Fig. 13c). Some of these clasts show imbrication indicating current direction to the SE.

The mudstone intercalations which have developed between the sandstone beds are homogenized due to bioturbation (*Rhizocorallium*). Bioturbation is almost absent where there is predominance of coarse sand.

Facies 4 is common in the upper part of the type section.

Interpretation

Facies 4 is characterized by the presence of hummocky-cross-stratification. According HARMS *et al.,* (1975, p. 87-88), the long, low, undulating HCS 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 can entrain sand in very shallow water creating a density current. This density current, as originally proposed by HAYES (1967a), 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 HCS to the depth of storm wave base. As the storm abates, normal fair weather deposition of mudstone would resume (deposition of the bioturbated mudstone intercalations).

Upwards in the sequence, the HCS sandstone beds become amalgamated by the erosion of the interbedded mudstones. According to LECKIE & WALKER (1982), the amalgamation suggests slightly shallower water where more frequent storms were able to generate and to rework the bottom, preventing the preservation of fair weather mudstones.

The isolated pebbles which are occasionally found floating in the sandy beds may indicate that the storm currents were very erosive at some stages, deriving the clasts of the nearshore region through bed erosion and transporting them basinwards.

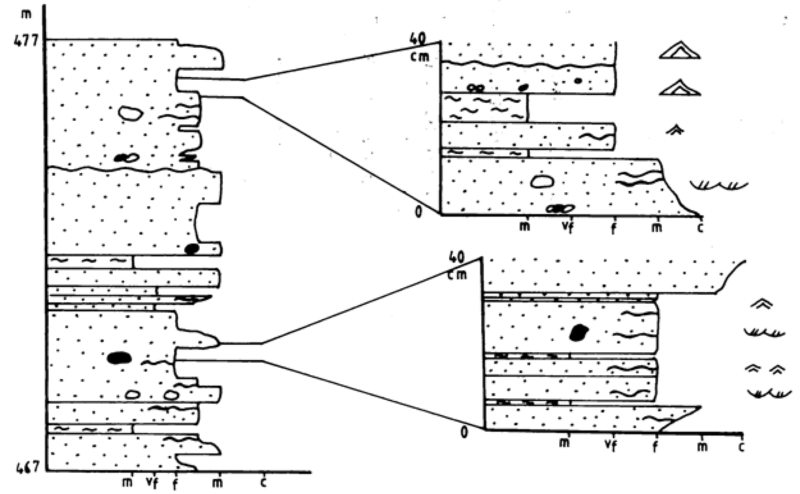


Fig. 12: Selected vertical log through Facies 4.

A

B

C

Fig. 13: (A) Medium to coarse-grained sandstone beds, generally amalgamated with crudely-developed internal tractive structures. (B) Load structures in Facies 4. (C) Outsized pebbles in a sandy bed of Facies 4.

FACIES 5

Description

Facies 5 (Fig. 14, Fig. 15a, Fig. 15b, Fig. 15c) consists of matrix- to clast-supported, cobble to boulder conglomerates. Usually, these conglomerate beds are stacked one at the top of the other, to form composite conglomerate units up to 10 m thick. Individual conglomerate bodies show flat bases and convex-upward tops, surrounded by sandstones (lobe-shaped) (Fig. 15a).

The gravel size-distribution ranges from bimodal to polymodal. Clasts are subrounded to subangular and are poorly cemented (Fig. 15b). The matrix is marly to sandy and is more abundant in beds belonging to the lower part of the conglomerate units. Irregular patches of muddy matrix which are locally associated with surrounding slumping also occur (Fig. 15c).

The base of the conglomerate body consists of marls with boulders (clasts of Tripolitza limestone, laminated sandstone and conglomeratic clasts) floating in it. Marls are also disturbed by important load structures. Gastropod shells and burrows are indicative of a marine environment.

At the top, there is a wavy, parallel-laminated, wave ripple cross-laminated, sandy bed with intercalated very thin gravel layers.

Interpretation

The conglomerates of Facies 5 are thought to represent mass flow deposits, emplaced as cohesionless or cohesive debris flows (NEMEC *et al.*, 1980; NEMEC & STEEL, 1984). These mass flow deposits may have originated either from slope instabillity or flood-generated currents. The first possibility is rather unlikely as indications for a steep slope have nowhere been found. Flood-gererated river currents may have been responsible for the cobble and boulder transport basinwards.

The top of many conglomeratic beds records brief reworking which is an indication for deposition above storm-wave base.

To summarize, the vertical sequence of the Kalamavka Formation (Fig. 5) in its type section comprises bioturbated, mud-dominated shelf deposits (Facies 1) which pass transitionally upward into shoreface deposits (Facies 4). Furthermore, an overall crude coarsening-upward trend can be inferred for the Kalamavka Formation based on a predominantly marly lower part and a predominantly sandy upper part. In addition, smaller scale «cycles» (up to 10 m thick), stacked one at the top of the other, can be distinguished which comprise sequences of a marly base and a sandy top. Proceeding upwards in the section, the thickness of the marls decreases and the thickness and the grain size of the sandstome increases.

4.4. Lateral changes in the Kalamavka Formation (type section)

Generally, the Kalamavka deposits show lateral consistency (a feature of a wave dominated environment), yet some variations in the facies distribution exist in the areas adjacent to the type locality. The Kalamavka sediments of the study locality have been examined along their strike (NW-SE) and normal to this direction in order to determine any lateral variability.

Facies 5

LOC 7

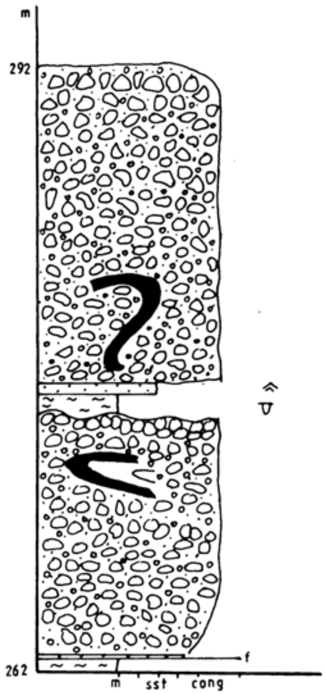


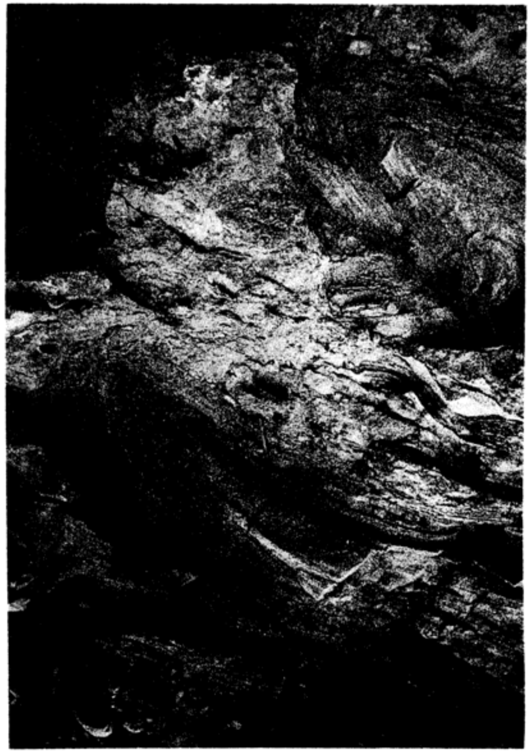
Fig. 14: Selected vertical log through Facies 5.

B

Fig. 15: (A) Matrix -to clast- supported conglomerate body of Facies 5. (B) Subrounded to angular clasts, poorly cemented. (C) Irregular muddy patches, associated with local slumping of the muddy sea floor.

A

C



The deposits SE of the village Kalamavka are characterized by a predominantly uniform lithology which obscures any possible cyclic pattern of the sediments and apparently accounts for a thickness reduction of the calcareous sandstone sequences and an increase in the thickness ofthe marl intercalations.

NW of the village, the opposite situation prevails; the thick-bedded calcareous sandstone deposits are more pronounced, comprising a major part of the Kalamavka sediments.

Taking into consideration the above observations, it is inferred that along the strike, there is a proximal-distal facies transition: the greatest thicknesses of the sandstone beds of the Kalamavka basin are more proximal to the major E-W thrust fault (sources area), whereas the thinner deposits, south of Kalamavka, have distal properties.

5. DISCUSSION

5.1. Depositional model and implications

According to FORTUIN (1977), the Kalamavka Formation was deposited in a submarine fan environment. This interpretation was mainly supported by the depositional depth of the Kalamavka sediments (more than 100 m) and by the sedimentary structures of the thin-bedded sandstones which resemble those of turbidites.

The depositional depth of the Kalamavka Formation probably did not exceed the 200 m suggested by benthonic foraminiferal fauna (FORTUIN, 1977) and ichnofacies. Besides, the observed sedimentary structures suggest deposition in rather shallow water, at least above wave base and on this basis, a submarine fan origin as suggested by FORTUIN (1977), can be ruled out.

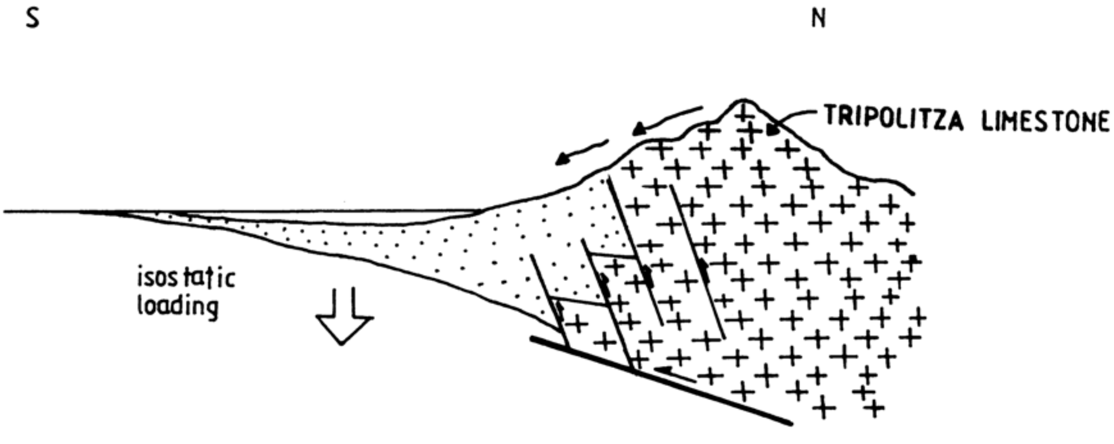
Furthermore, this paper shows that the Kalamavka Formation sediments are usually characterized by thythmical, turbidite-like deposits. However, they differ from real turbidites by the presence of low-angle cross laminations (hummocky-cross-stratification) and wave ripples resulting from storm wave oscillation effects. These structures are found mostly in the proximal part of the sequence (in Facies 4), and not in the distal part (Facies 2 and 3), where a predominance of bioturbated, even laminated thin sandstone beds (storm-layers) occur.

In other words, the rhythmical deposition of the sediments of the Kalamavka Formation is attributed to the repeated storm-wave action (this mechanism has been largely discussed by SCHUMACHER & TRIPP, 1979; CACCHIONE & DRAKE, 1982; MORTON, 1981; NELSON, 1982; SWIFT, FIGUEIREDO *et al.*, 1983).

To conclude, storm-related density flows seem to have been produced on a shallow gradient slope, (there are no indications of sedimentation on a steep slope), and provided a mechanism for delivering sediment offshore (HAMBLIN & WALKER, 1979). This sediment was deposited under the influence of strong oscillatory flows (i.e. above storm wave base but below fair weather base).

5.2. Tectonic and sedimentary controls

The development of the Kalamavka Formation was closely related to the onset of the break-up stage of the Aegean region in the Late Serravallian-Early Tortonian times. During that period, the Ierapetra region was probably affected by compressional tectonics, which resulted in thrust faulting (formation of the E-W oriented main



Flig 16: Diagrammatical portrayal of the developement of the depositional basin of the Kalamavka Formation in the Late Serravallian-Early Tortonian times. Faults are schematic, wavy arrows indicate transport of eroded debris.

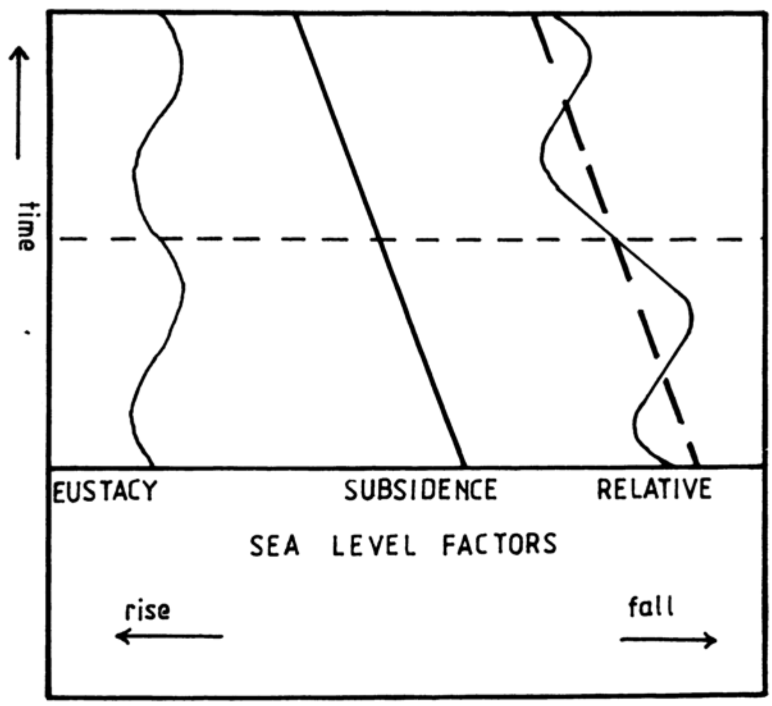


Fig. 17: Schematic diagram showing the relative sea-level curve as a function of the overall tectonic subsidence due to isostatic loading and low amplitude of absolute (eustatic) sea-level fluctuations (after Nummedal and Swift. 1987).

fault, POSTMA, pers. comm.) and associated folding in the study area (FORTUIN & PETERS, 1984; Fig. 3). Due to thrusting, the northern part of the region was uplifted and denudated whereas the area in front of the thrust was gradually subsiding (probably as a result of isostatic loading), (Fig. 16).

The deposition of the Kalamavka Formation was largely controlled by this tectonic setting. During the Late Serravallian-Early Tortonian, thrust plate loading with attendant flexural subsidence, plus eustatic sea-level changes of low amplitude resulted in relative sea level rise along the Ierapetra basin.

The subsidence which led to the preservation of the sheet-like sandstone deposits of the Kalamavka Formation combined with an assumed low-amplitude eustatic signal caused the relative sea-level curve to consist of periods of slow relative sea-level rise (or unsignificant fall) separated by periods of rapid rise (Fig. 17). This variation in the rate of relative sea-level rise without associated periods of significant sea-level fall can be attributed to the fact that the eustatic fall may fail to lower sea level significantly and it merely suffices to slow the relative rise. The vertical stacking of the sandstone bodies and the lack of major unconformities between them support this idea.

In other words, during the overall transgression, high-frequency oscillations of the shoreline during the retreat caused intermittent progradation, shoreface retreat and the formation of multiple sand bodies separated by a series of non-erosive surfaces.

The above described processes, which may account for the Kalamavka Formation, would predict an overall fining-upward trend of the Formation. However, an overall (crude) coarsening-upward trend has been observed. This coarsening-upward trend must be attributed to shoreline progradation. Shoreline progradation in a relative sea-level rise regime might then mean that the local sediment supply was high enough to cause progradation.

The local sediment supply can be mainly controlled by the climate. Periods of heavy rainfalls can be inferred by the presence of the flood-generated debris flow lobes into the sequence. During heavy rainfalls, an excess of sediment supply is transported by the flooded rivers basinwards. In this case the sedimentation rate exceeds the rate of the relative sea-level rise resulting in the (crude) coarsening-upward trend of the Kalamavka Formation.

6. CONCLUSIONS

A generalized depositional model for the Kalamavka Formation is illustrated in Fig. 18. The tectonic setting facies and the interpreted sedimentary pattern of the Kalamavka Formation lead to the following conclusions:

(i) The sedimentary succession of the Kalamavka Formation was deposited in front of an E-W oriented thrust fault which separated a northern uplifted part from a southern subsiding sedimentary basin.

(ii) The Kalamavka Formation deposits consist of fine-grained sediments, derived mainly from the uplifted Tripolitza limestone and partly from the resedimented conglomerates of the Prina Complex.

(iii) The presence of low-angle laminations (hummocky-cross-stratification) and wave ripples found mostly in the proximal part of the sequence and of bioturbated, even laminated thin sandstone beds found in the distal part, indicates deposition of these fine-grained sediments in a storm-dominated (wind-and wave-driven) shelf environment. After deposition, the whole succession was intensely reworked by waves which led to the formation of wave rippled structures.

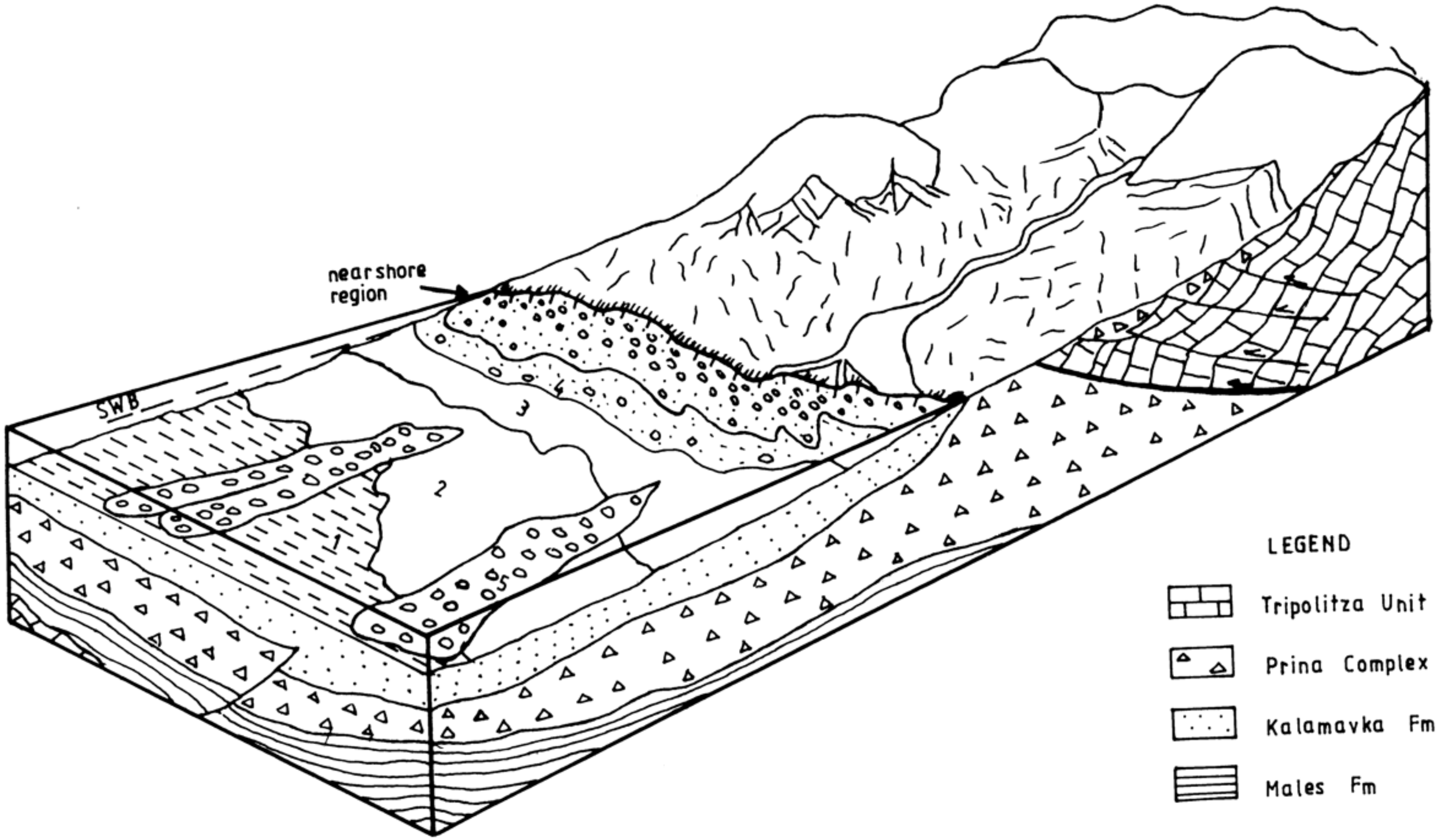


Fig. 18: Schematic representation of sediment facies distribution of the Kalamavka shelf depositional environment. Numbers 1 to 5 refer to facies associations described in text.

(iv) The sedimentation of the Kalamavka Formation has been influenced by contemporaneous tectonism with gradual subsidence of the basin floor and superimposed eustatic sea level changes. The observed vertical stacking of the sandstone bodies can be attributed to gradual subsidence due to eustatic sea-level fluctuations of low amplitude.

(v) The Kalamavka sedimentary succession itself constitutes a (crude) coarsening-upward sequence with offshore facies grading upwards into lower shoreface sandstones. This coarsening-upward trend is thought to indicate progradation of the coast line which can be attributed to the excess of local sediment supply maybe due to favourable climatic conditions.

(vi) Finally, foraminiferal data as well as ichnofacies indicate that the depositional depth of the Kalamavka Formation did not exceed the 200 m, that is the deposition of the Kalamavka sediments took place in a shallow marine (shelf) environment.

ΠΕΡΙΛΗΨΗ

Από την μελέτη της σχετικής βιβλιογραφίας για το Νεογενές της περιοχής του Αιγαίου, έγινε γνωστό ότι η τεκτονο-ιζηματολογική εξέλιξη του Νεογενούς της Κρήτης επηρεάστηκε σε μεγάλο βαθμό από την προς βορράν υποβύθιση της Αφρικανικής πλάκας κάτω από την λιθόσφαιρα του Αιγαίου. Το Ανώτερο Σερραβάλλιο χαρακτηρίζεται από την έναρξη του «σπασίματος» της πλάκας του Αιγαίου. Την ίδια περίοδο, μια φάση συμπίεσης κυριάρχησε στην περιοχή της Ιεράπετρας (Αν. Κρήτη), η οποία χαρακτηρίστηκε από την απόθεση «ανώριμων» ανθρακικών κλαστικών ιζημάτων (Prina Complex) και ρυθμικών εναλλαγών ασβεστιτικής μάργας με ψαμμίτη (Kalamavka Formation).

Η εργασία υπαίθρου που έγινε στον σχηματισμό της Καλαμαύκας, είχε σαν σκοπό την μελέτη αυτής της ρυθμικής ακολουθίας καί την ερμηνεία της διαδικασίας απόθεσής της.

Ο σχηματισμός της Καλαμαύκας αποτελείται στη βάση τοθ, κυρίως, από βιοαναδευμένες αποθέσεις ιλύος, οι οποίες περνάνε σταδιακά προς τα πάνω σε αποθέσεις χονδρόκοκκου ψαμμίτη. Στο κατώτερο και μέσο τμήμα της ακολουθίας, υπάρχουν λοβοί debris flow. Η ακολουθία αυτή, πιστεύεται ότι αποτέθηκε υπό την επίδραση θαλασσίων ρευμάτων που δημιουργήθηκαν κατά την διάρκεια ανέμων.

Η ιζηματογένεση του σχηματισμού της Καλαμαύκας φαίνεται να επηρεάστηκε από σύγχρονες τεκτονικές κινήσεις, καθώς επίσης από την διαφορική βύθιση του πυθμένα της λεκάνης απόθεσης και από ευστατικές αλλαγές της στάθμης της θάλασσας.

Παλαιοντολογικά δεδομένα, καθώς επίσης και ιχνοστοιχεία, δείξανε ότι ο σχηματισμός της Καλαμαύκας αποτέθηκε σε ένα περιβάλλον θαλάσσιας κρηπίδας.

ABSTRACT

The Neogene tectono-sedimentary evolution of Crete has been largely controlled by the northward subduction of the African plate beneath the Aegean lithosphere. The Late Serravallian is characterized by the onset of the break-up stage of the Aegean Landmass. During the same timespan, a compressional phase prevailed in the Ierapetra region (E. Crete) which was punctuated by the deposition of immature carbonate clastics (Prina Complex) and the rhythmical alternations of calcareous mudstone and sandstone (Kalamavka Formation).

A field study of the Kalamavka Formation was undertaken to investigate this rhythmically deposited sedimentary succession and to interpret the depositional system and the depositional sequence. The results can be summarized as follows:

The Kalamavka Formation constitutes a coarsening-upward sequence which is composed of mainly bioturbated, mud-dominated shelf deposits which pass transitionally upward into lower shoreface deposits. In the lower and middle part of the sequence, debris flow lobes are found. This sequence is thought to have been deposited from storm induced «ebb» surges.

The sedimentation of the Kalamavka Formation seems to have been influenced by contemporaneous tectomism with differential subsidence of the basin floor and superimposed eustatic sea level changes.

Faunal data and ichnofacies also suggest that the Kalamavka Formation was deposited in a shallow marine environment (shelf). The combination of storm-induced currents, gradual basin subsidence and sea level fluctuations can explain the facies associations and their evolution in time.

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