

LATE CENOZOIC HISTORY OF EASTERN CRETE AND IMPLICATIONS FOR THE GEOLOGY AND GEODYNAMICS OF THE SOUTHERN AEGEAN AREA¹

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ABSTRACT

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An interpretation is given of the structural setting and the sedimentary history of the Middle Miocene – Quaternary deposits in eastern Crete (Ierapetra region). The present tectonic structure, characterized by normal faults in W-E and NE-SW directions, is dominated by a central NE-SW graben, which seems to mark a dislocation in the curvature of the Aegean Arc. In Late Serravallian – Early Tortonian times deposition drastically changed from terrestrial to open marine, with turbidites, filling in a graben that extended over the southern half of the region. The sources of sediment supply then shifted from east to west and slices of sediments (in part of pre-Neogene age) slid from the uplifted blocks in the north to the central parts of the region, where a submarine valley was formed. A seismic reflection profile south of Crete may show analogous gravity sliding in the Neogene. From the Late Tortonian till the Pliocene carbonate sedimentation took place. A gradual shallowing followed, which ended with deposition of the well known Messinian facies. Unstable tectonic conditions controlled the sedimentation until the Early Pliocene, when quiet open marine sedimentation returned. In the early Late Pliocene tectonic uplift started to separate Crete as a horst from the surrounding seas. Although strong, this general uplift was periodically interrupted.

INTRODUCTION

Crete forms part of the Aegean Arc, an island arc that constitutes an elongated, horst-like structure, separated from the adjacent deep-sea troughs by normal faults, active during Pliocene – Quaternary times (ANGELIER, 1976). The Neogene deposits in the region of Ierapetra (eastern Crete) cover some 500 km². Much of these are situated between the Lasithi Mountains in the west and the Sitia Mountains in the east (Fig. 1). In this area Crete is at its narrowest.

In a recent study the author described the stratigraphy and sedimentary history of the region in detail (FORTUIN, 1977). The present paper goes into its structural setting, gives a modified version of the sedimentary history and discusses some interregional aspects. The sedimentary history is documented by Late Cenozoic sedimentary sequences of more than 1 km thickness. The Neogene strata are grouped into nine formal rock units, one of which is called a complex. Figure 2 schematically gives the lithostratigraphic frame and

correlations between the various parts of the region. Table I summarizes the main lithologic properties of the formations. The chronostratigraphic correlations are based on biostratigraphic investigations on the group of uniserial *Uvigerina* (benthonic Foraminifera) and on planktonic Foraminifera. Table II is an attempt at correlating the most important sedimentary and structural events of the Ierapetra region with those of the surrounding seas and with the chronostratigraphic scale.

Systematic studies on the Neogene of Crete have been made since about 1960. Amongst the many papers published, mainly in the field of palaeontology and stratigraphy, one in particular contributes to the general understanding of the geodynamics of the Cenozoic (DROOGER & MEULENKAMP, 1973). These authors recognized 7 depositional intervals, each one corresponding to a specific combination of sedimentary pattern, tectonic movements and palaeogeographic configuration. For the Ierapetra region 8 successive depositional episodes, or so-called 'phases' are distinguished.

The general depositional picture for Crete, as pointed out by DROOGER & MEULENKAMP (1973), is an initial period of terrestrial sedimentation of predominantly coarse clastics, followed by a transgression with deposition of fossiliferous, marine sands and marls. From the Late Tortonian until the

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Table I
Summary of the Neogene rock units in the Ierapetra region.

rock unit	max. exposed thickness	description
Pakhiammos Formation	30 m	Non-fossiliferous, terrigenous clastic deposits at the base (0-3 m), followed by up to 10 m of whitish cavernous algal limestones and marly limestones, which contain the Messinian marker species <i>Cyprideis pannonica agrentina</i> . Part of the limestones are broken up and incorporated in overlying marl breccia (10 m), which, in turn, passes into homogeneous and laminated marine marls; calcarenitic beds occur at the top. The formation is only found in the north coast areas.
Mirtos Formation	60 m	Displaced gypsum bodies (max. 25 m thick) in association with 8-12 m of marl breccia of reworked Messinian and Early Pliocene components, overlain by homogeneous and laminated, fossiliferous marls. Upwards, intercalations of irregularly bedded coarse sands occur in the marls. This unit is only exposed in the south coast areas where it represents the youngest Neogene.
Ammoudhares Formation	50-100 m	Alternating sandy, bioclastic limestones and yellow-grey homogeneous and laminated marls. Sponge spicules are abundant in the laminated marls. The amount of limestones increases upwards. Local intercalations of coarse clastics; either at the base of very proximal turbidites or as channel-fills. The formation is in most places strongly disturbed by postsedimentary slumping and sliding.
Makrilia Formation	450 m	Fossiliferous, bluish-grey marls with a variable amount of intercalated brownish, grades sands (turbidites).
Kalamavka Formation	350 m	Fossiliferous marls and dark-grey calcareous sandstones of variable thickness. At different levels conglomeratic channel-fills, pebbly mudstones and large olistoliths are found (Fig. 7). The strata tend to be grouped in rhythmically alternating marl and sandstone sequences.
Fothia Formation	375 m	Poorly rounded, polymict conglomerates, upward with an increasing number of sandy and marly intercalations. The formation only occurs east of the Ierapetra fault. Towards this fault zone allochthonous blocks and slabs (over 1 km large) of partly brecciated pre-Neogene become intercalated. The composition of the conglomerates is distinctly related to the rocks exposed to the north and east of the area of distribution. The uppermost marly strata may include <i>Crasostrea</i> and/or <i>Heterostegina</i>
Prina Complex	350 m	A complicated rock unit because much of the original lithostratigraphic succession is obscured by faulting and sliding. The complex is widely distributed; it covers most of the northern part of the Ierapetra region. Stratified breccias and breccioconglomerates with a variable number of finer grained, occasionally fossiliferous interbeds predominate in the NW part of the region. South of the Gulf of Merabellou, up to 300 m of marine boulder conglomerates with occasional intercalations of well-sorted calcareous sandstones constitute the bulk of this complex. The basal parts of the coarse clastic successions are closely associated with slabs and very large masses of dark, often brecciated pre-Neogene Tripolitza limestones. The majority of the clastics are derived from the pre-Neogene Tripolitza unit. Near Pirgos 25 m of fossiliferous marls form the top of this unit.
Males Formation	350 m	Alternations of conglomerates, sandstones and clayey marls. The conglomerate components are well rounded and sorted; most of them were derived from the pre-Neogene Pindos unit. Marly deposits predominate at the top (max. 100 m), forming the Parathiri Member. Part of these latter strata are fossiliferous and may contain large numbers of the gastropod <i>Terebralia bidentata</i> .
Mithi Formation	150 m	A conglomerate unit. The components are poorly rounded and were derived from underlying and nearby exposed rocks, which form the highest allochthonous pre-Neogene unit (ophiolites, granodiorites, gneisses, slates etc.).

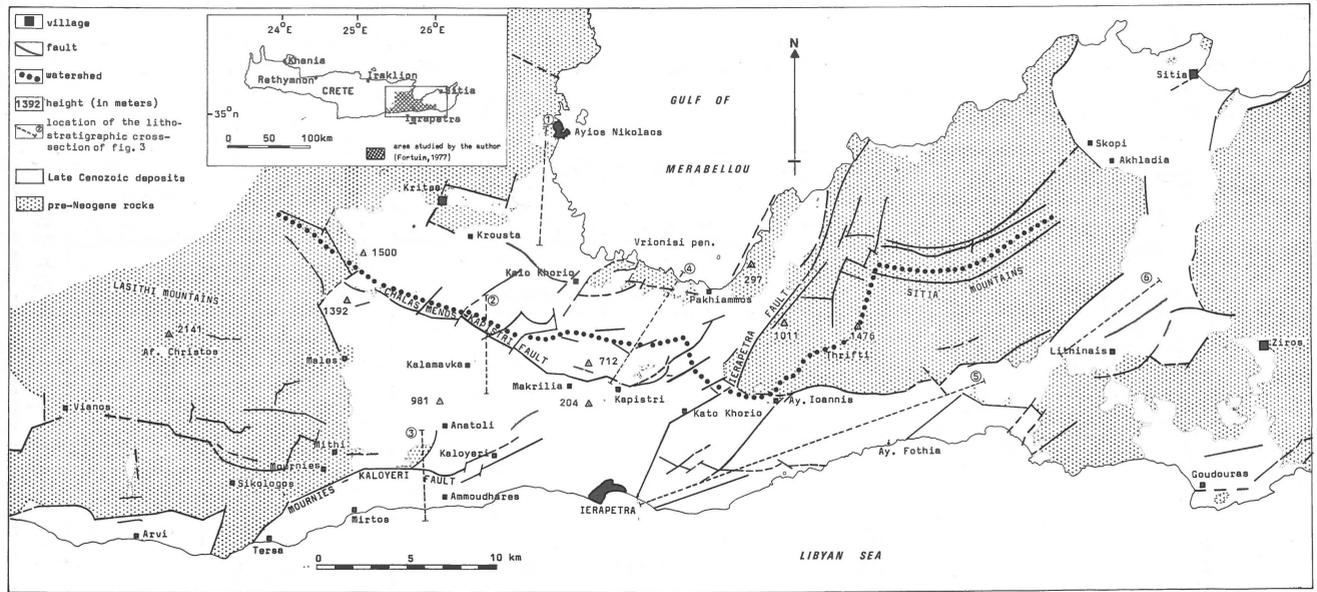


Fig. 1

Geologic sketch map, showing the distribution of the Late Cenozoic rocks in eastern Crete and the main faults. The data are compiled from the following sources: Ierapetra region (see inset for extent), FORTUIN (1977); Sitia region, GRADSTEIN (1973); pre-Neogene of the Lasithi Mountains, CREUTZBURG & PAPASTAMATIOU (1969); Sitia Mountains, WACHENDORF ET AL. (1975).

Late Messinian a supply of mainly bioclastics followed in marine to littoral facies. In the earliest Pliocene open marine conditions returned. The Upper Pliocene and younger sediments testify to a shallowing of the Cretan block and its final emergence.

The Neogene of the Ierapetra region differs from this general pattern by the early start of marine sedimentation and by the strong impact of crustal movements, which contributed to the widespread occurrence of gravity sliding of sediments from several stratigraphic intervals, and to the formation of rather uncommon facies types, such as submarine boulderbeds.

STRUCTURAL SETTING

The pre-Neogene rocks underlying the Cretan Upper Cenozoic deposits form a complex structure of an autochthonous basement of Permian – Oligocene age, overlain by four allochthonous units (BAUMANN ET AL., 1977). It is generally believed that this nappe pile developed during Oligocene – Early Miocene times. The Neogene thus takes a neo-autochthonous position in the alpidic stockwork of the Aegean Arc.

The geological map (see FORTUIN, 1977 and Fig. 1) illustrates the importance of block-faulting along roughly W-E and NE-SW lines. The faults are normal, reflecting crustal extension. They fit in the overall tectonic framework of Crete and its surrounding seas, where a close interrelation existed everywhere between sedimentation, tectonic and erosional

processes (DROOGER & MEULENKAMP, 1973; JONGSMA, 1977; JONGSMA ET AL., 1977). Although the W-E faults were already important in the Miocene, the present topography is the result of Late Pliocene – Quaternary fault movements.

A central NE-SW oriented graben-like depression ('la fosse d'Ierapetra': ANGELIER, 1976), forms the most striking recent tectonic and topographic feature of the Ierapetra region. As concluded from bathymetric maps its topographically accentuated eastern margin (Fig. 3) has a considerable submarine prolongation in both directions, thus forming one of the largest transverse faults of the South Aegean Arc. Its supposed submarine extension is indicated on a map by ANGELIER (1977). The sedimentary history of the Ierapetra region suggests that this graben structure was initiated in Late Serravallian times.

The many differential movements during the Late Cenozoic resulted in a complex interplay of faulting and facies changes. Each faultblock has its specific sedimentary history.

The intensity of faulting of the Neogene strata decreases from the central areas outward. In other words, the areas situated south of the large pre-Neogene uplifts of the Lasithi and Sitia Mountains (together with the adjacent Neogene, in the southern Iraklion province and the Sitia district respectively), are little disturbed. This feature may be connected with differences between the orientations of the longitudinal faults at both sides of the region: The faults of the Lasithi area tend to have WNW-ESE orientations, whereas the faults east of Ierapetra are oriented approximately WSW-ESE. This directional shift is also reflected by the orientation of the

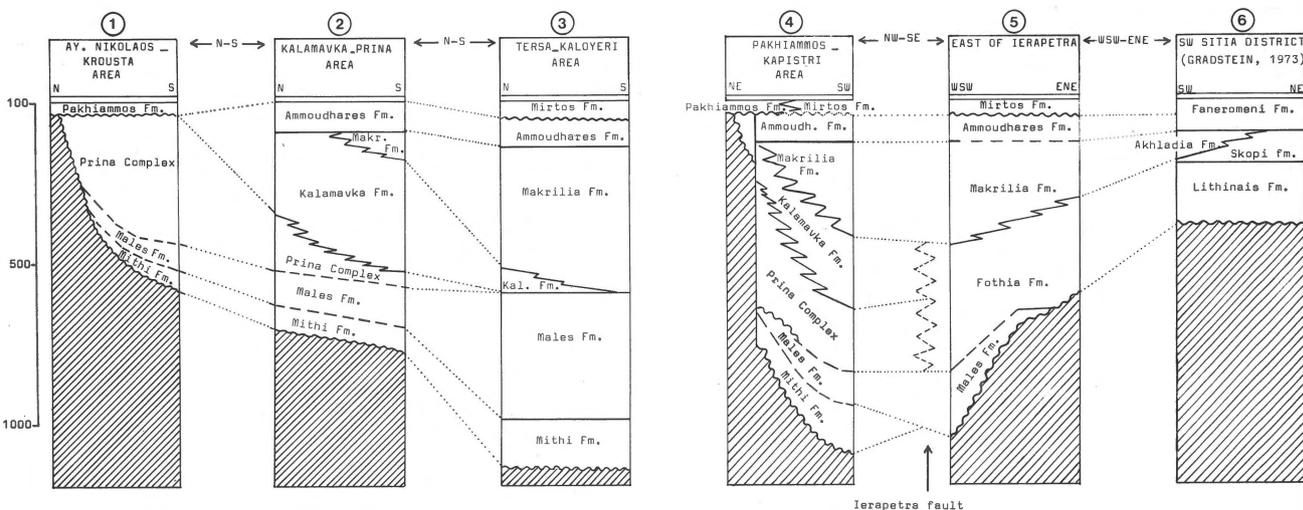


Fig. 2
Schematic lithostratigraphic cross-sections of the Neogene formations in various parts of the Ierapetra region. The formations east of Ierapetra are correlated with those from the SW Sitia district (according to GRADSTEIN, 1973). The numbers of the cross-sections refer to their position on the geologic map. Broken lines in the columns indicate sheared contacts; unconformable contacts are indicated with a wavy line.

—structure controlled— watershed (Fig. 1). The author is tempted to interpret the tectosedimentary setting of the central parts of the region as due to a stronger release of tectonic

stresses by a dislocation of the curvature of the island arc after general construction of W-E faults, the faults parallel to the strike of the arc.

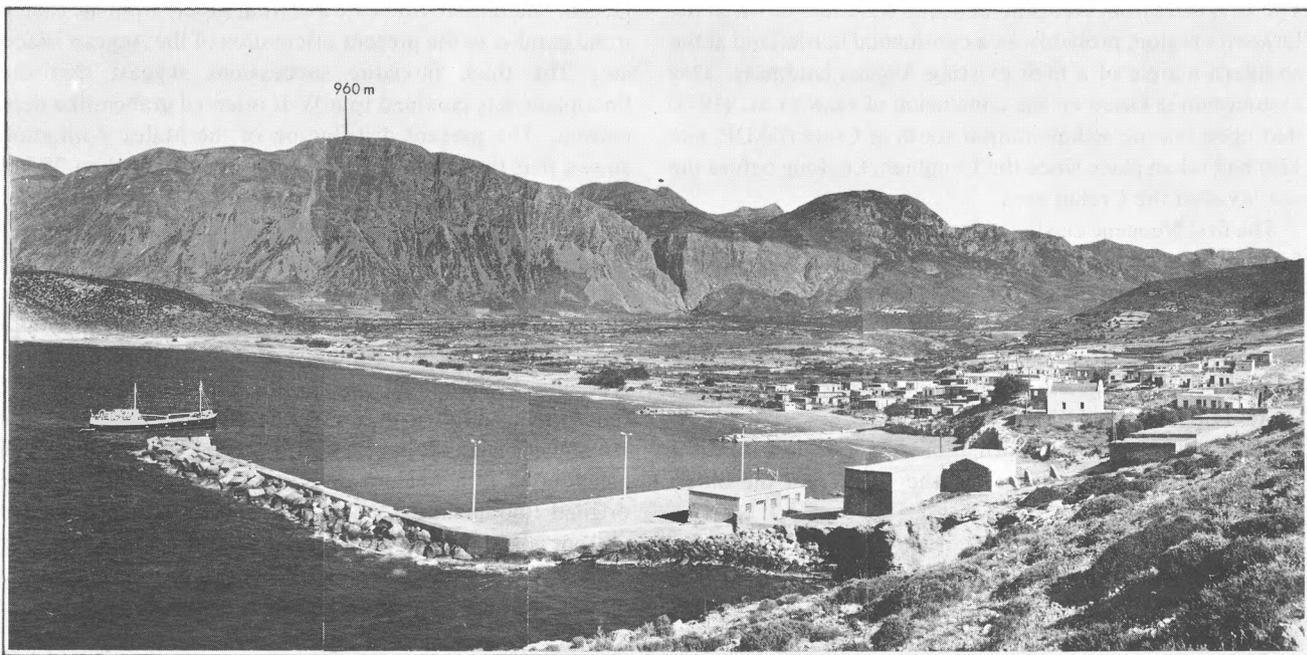


Fig. 3
View on the northern part of the Ierapetra depression, as seen from a cliff near the port of Pakhiammos. The pronounced scarp of the Ierapetra fault rises up to a maximum of 960 m. It is partly covered with fan breccias, visible left of the gorge, which is cut into pre-Neogene limestones. The floor of the depression is mainly formed by alluvial clastics. The sediments exposed in the cliff on the foreground are Early Pliocene marl breccias.

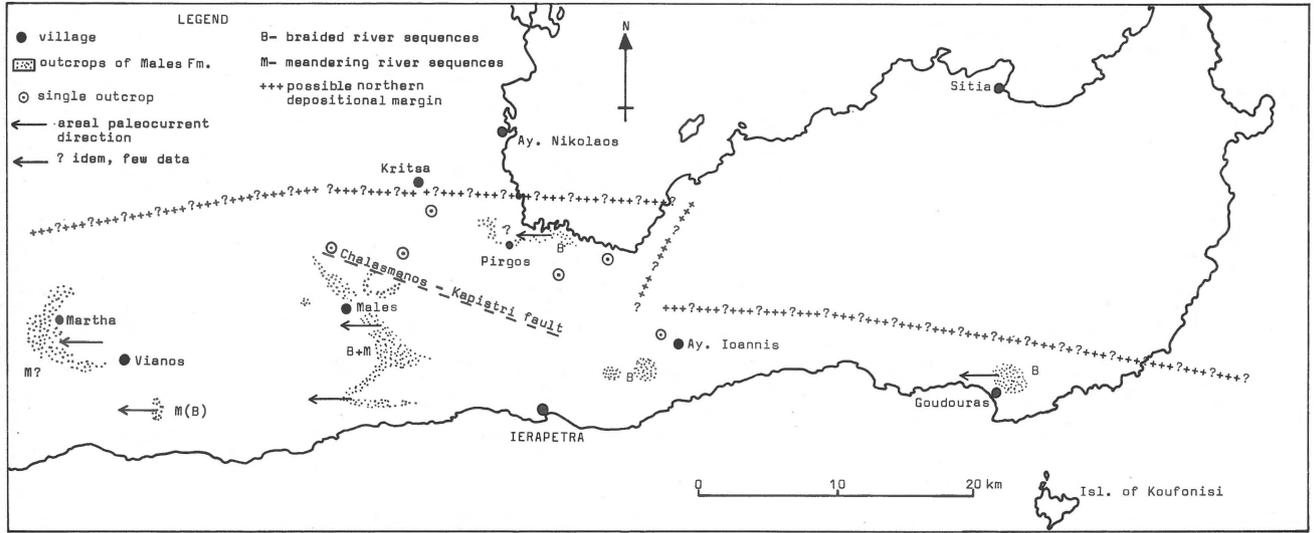


Fig. 4 Chief features of the palaeogeography of eastern Crete during phase 2.

SEDIMENTARY HISTORY

Phase 1 – an undated episode, somewhere in the Middle Miocene

Sediments involved: Mithi Formation

The first terrestrial Neogene deposits were laid down in the Ierapetra region, probably on a continental borderland at the southern margin of a then existing Aegean landmass. This assumption is based on the conclusion of RYAN ET AL. (1973) that open marine sedimentation south of Crete (DSDP, site 129) had taken place since the Langhian, i.e. long before the sea invaded the Cretan area.

The first Neogene clastics were deposited as conglomerate fans in front of an apparently rejuvenated relief. The lithology of the components and the stratigraphical contacts of the Mithi Formation with the underlying Neogene shows that it was deposited in front, and on top of the highest allochthonous unit, the 'volcano-sedimentary complex' of BAUMANN ET AL. (1977).

Sediments of the Mithi Formation do not occur east of the Ierapetra fault. We assume that they represent the oldest continental Neogene of Crete.

Phase 2 – finished in the Late Serravallian

Sediments involved: Males Formation

The deposition of continental strata continued during most of this phase. But the origin of the sediments rapidly shifted to much larger distances. The clastics obtained more mature textural properties and their lithological composition became

entirely different. The components were mainly derived from the Pindos Series. The formation was deposited in fluvial and lacustrine environments, except for the top part (Parahiri Member), where brackish – shallow marine conditions prevailed.

More than 350 m of fluvial conglomerates, sandstones and marly clays could accumulate in a subsiding area. Palaeocurrent features indicate a detrital supply from the east, a trend parallel to the present orientation of the Aegean island arc. The thick fluvial successions suggest that the floodplain was confined to a W-E oriented graben-like depression. The present distribution of the Males Formation shows that the floodplain extended over more than 75 km from east to west. The easternmost 300 m of sediments, present near Goudouras (Fig. 4) just outside the region studied, mainly consist of conglomerates and sandstones (MEULENKAMP, pers. comm.). In contrast, conglomerates are almost lacking in the equally thick deposits in the southern Iraklion Province (surroundings of Vianos-Martha). In the type area braiding and meandering channel sequences are found, many of them being of intermediate character. The streambeds will thus have gradually changed from braiding to meandering in a western direction. It is probable that the original floodplain extended farther eastward, outside the present island. It may have discharged the erosion products of the eastern parts of the Aegean landmass towards a coastal plain somewhere in the Iraklion Province (or even farther away).

At the end of this period the sea gradually invaded the area. Bluish marly clays were deposited with abundant *Terebralia bidentata*, a characteristic brackish water gastropod. Microfaunas from marine intercalations point to a Late Serravallian age. They represent the oldest marine strata on Crete.

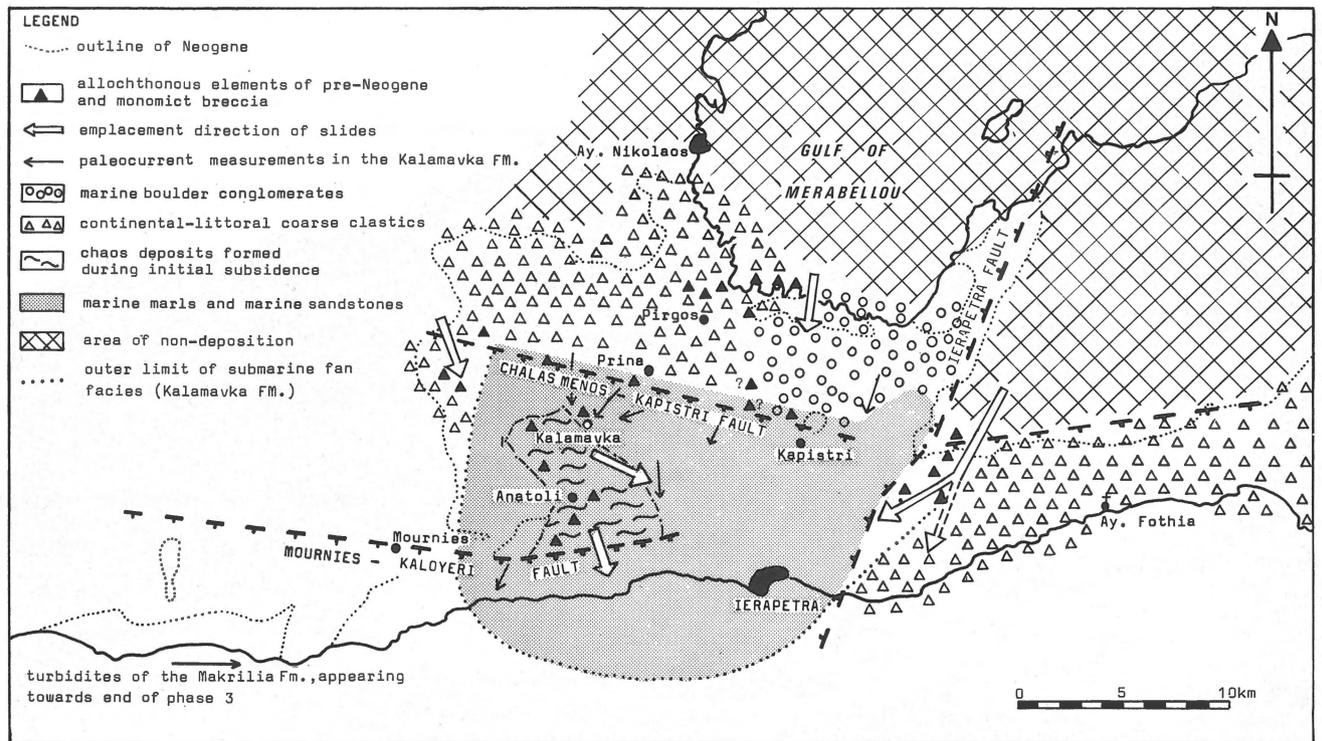


Fig. 5
Reconstruction of chief features of the palaeogeography of the Ierapetra region during phase 3.

Discussion – The Pindos Series, which supplied most of the clastics of the Males Formation, underly the highest nappe unit. This nappe provided the detritus for the sediments of the previous phase. This parallel order of sedimentation of monotypical component associations could point to base levelling of still undisturbed and flat lying nappes. This assumption agrees with similar conclusions by BONNEAU & GINSBURG (1974) for a region of western Crete.

Because the Males Formation is entirely broken-up north of the present Mt. Chalasmenos - Kapistri faultzone little can be said about the original stratigraphy in that area and the position of the northern limit of the floodplain system. The outcrops near Pirgos (see Fig. 4) suggest the presence of an originally very thick succession such as in the south. On the other hand intercalated very coarse grained beds including many components of non Pindos origin at the Vrionisi peninsula point to the proximity of the depositional margin. But east-west detrital transport also seems to have prevailed in the latter area, so that it is likely that the depositional margin had a similar orientation. It was perhaps located near Kritsa at the present northern limit of the Ierapetra region.

The successions of the Males Formation in the east, which are confined to the surroundings of Ay, Ioannis and Goudouras (Fig. 4), suggest that they were bounded to the north by pre-Neogene of the basin border. If the reconstruction in figure 4 is correct for the northern limit of the Males depositional area, a remarkable translation must have

taken place in the Ierapetra depression, which ought to be explained by later horizontal tectonic movements along the Ierapetra fault.

Phase 3 – Late Serravallian – Early Tortonian

Sediments involved: Fothia Formation (E of Ierapetra), Kalamavka Formation, Prina Complex, lowermost part of Makrilia Formation in south coast areas.

The tectonic movements of this phase completely changed the depositional pattern. Strong relief changes at the beginning connected Crete with the pre-existing open sea in the south. At the end a deep-water turbidite-basin was formed in the south in which the first strata of the Makrilia Formation were formed. These tectonic movements resulted in a complicated sedimentary pattern and in a total reversal of the palaeocurrent directions. Before this phase the rivers discharged their bedload in a westerly direction, whereas the turbidites deposited at the end of this phase came from the west. In between these times clastics in the central parts of the region were derived from northwesterly to northeasterly sources.

Evidently, we are dealing with a complex interplay of vertical movements along older fault lines in the pre-Neogene basement during this phase. A channelling of the erosion products from the north by subsidence via stepfaults along W-E elongated blocks to the south could have taken place,

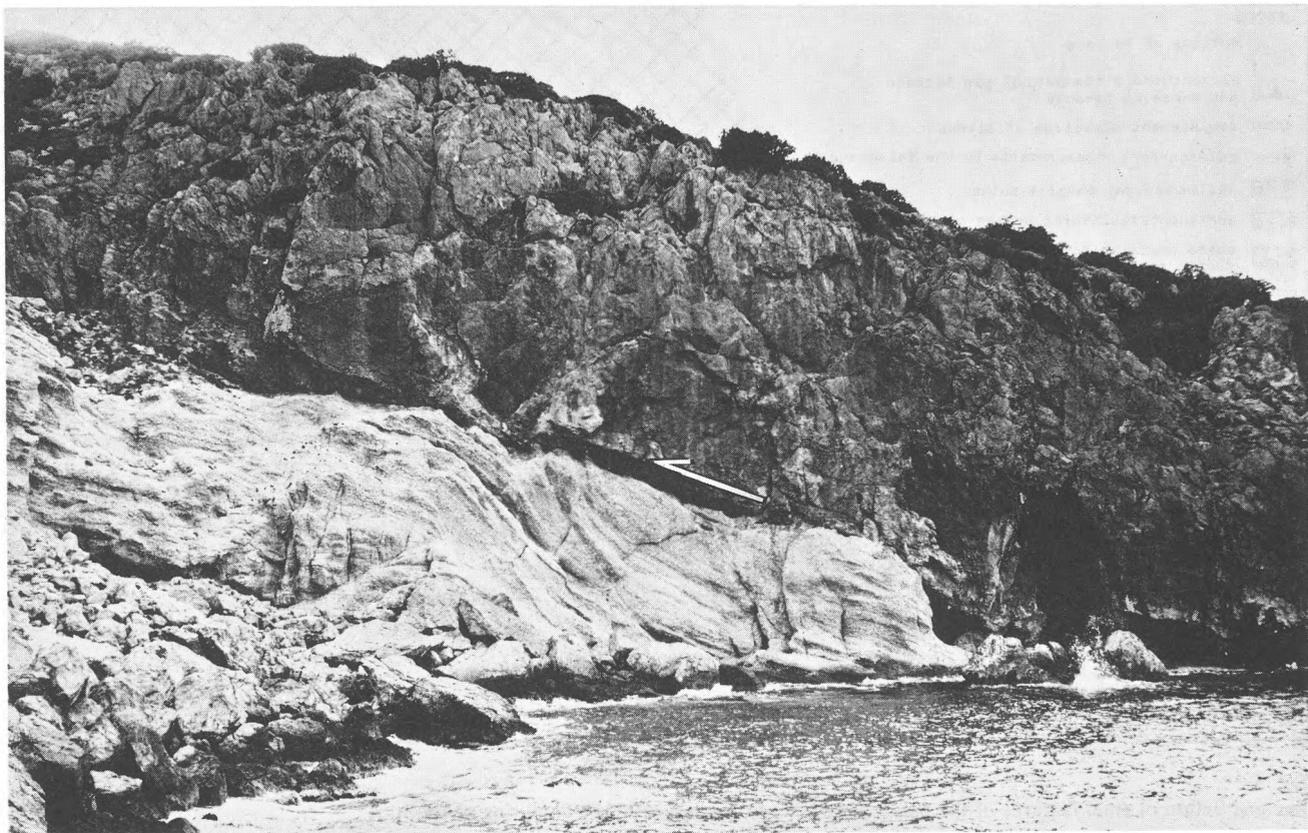


Fig. 6
Conglomerates of the Males Formation overlain by an allochthonous slab of Cretaceous Tripolitza limestone on the peninsula of Vronisi, Gulf of Merabellou. Slickensides exposed at both sides of this peninsula point to movement of the upper block from north to south (see arrow). The thrust plane is nearly parallel to the bedding of the conglomerates.

because of an additional about N-S trending grabenlike depression between the incipient Lasithi and Sitia Mountain blocks. The successive tectonic and sedimentary steps can be described as follows.

The northern areas became topographically accentuated, whilst a grabenlike depression formed in the central parts of the region which was open to the south where subsidence was strongest (see Fig. 5). The rising northern blocks were probably bounded by a WNW-ESE hingeline, corresponding to the present Chalasmenos – Kapistri fault zone. The northern blocks were tilted to the south, so that the Neogene cover was broken-up and/or eroded. Along the northern edges of these blocks brittle limestones of the Cretaceous Tripolitza Series became exposed. Detached elements of these limestones slid, eventually with a cover of monomict breccia, over and into parts of the youngest sedimentary cover towards the subsiding central and southern areas. The allochthonous elements measure from 1 m to perhaps more than 1 km in diameter and up to 200 m in thickness. The sliding was facilitated by pelitic intervals in the Males Formation, acting as lubricants. These movements culminated in the surroundings of Kalamavka and Anatoli (Fig. 5) in the formation of a

slide mass, perhaps up to 250 m thick, consisting of strongly sheared elements of the Males Formation, Tripolitza limestones and basal breccias of the Prina Complex. Orientations of slumpfolds near the eastern margin of this slide suggest movements to the SE.

Allochthonous elements present on some of the peninsulas in the Gulf of Merabellou came from the north (N10°-15°E directed slickensides), see Fig. 6. Evidence for mass slides E of the Ierapetra depression, directed also towards the central graben, is given by allochthonous, crushed or brecciated pre-Neogene limestones intercalated in terrestrial fanglomerates to fluviomarine fines of the Fothia Formation. These slides have their maximum development just east of the incipient graben margin. They are up to 250 m thick. Five km farther east they are no longer found in the Fothia Formation.

Breccias and breccioconglomerates were deposited in nearshore areas in the northwest and north of the Ierapetra region during and after transport of the allochthonous elements. They form part of the Prina Complex. The components were mostly derived from the Tripolitza Series. The deposits pinch out towards the depositional area of the Kalamavka Formation, which had its main development south

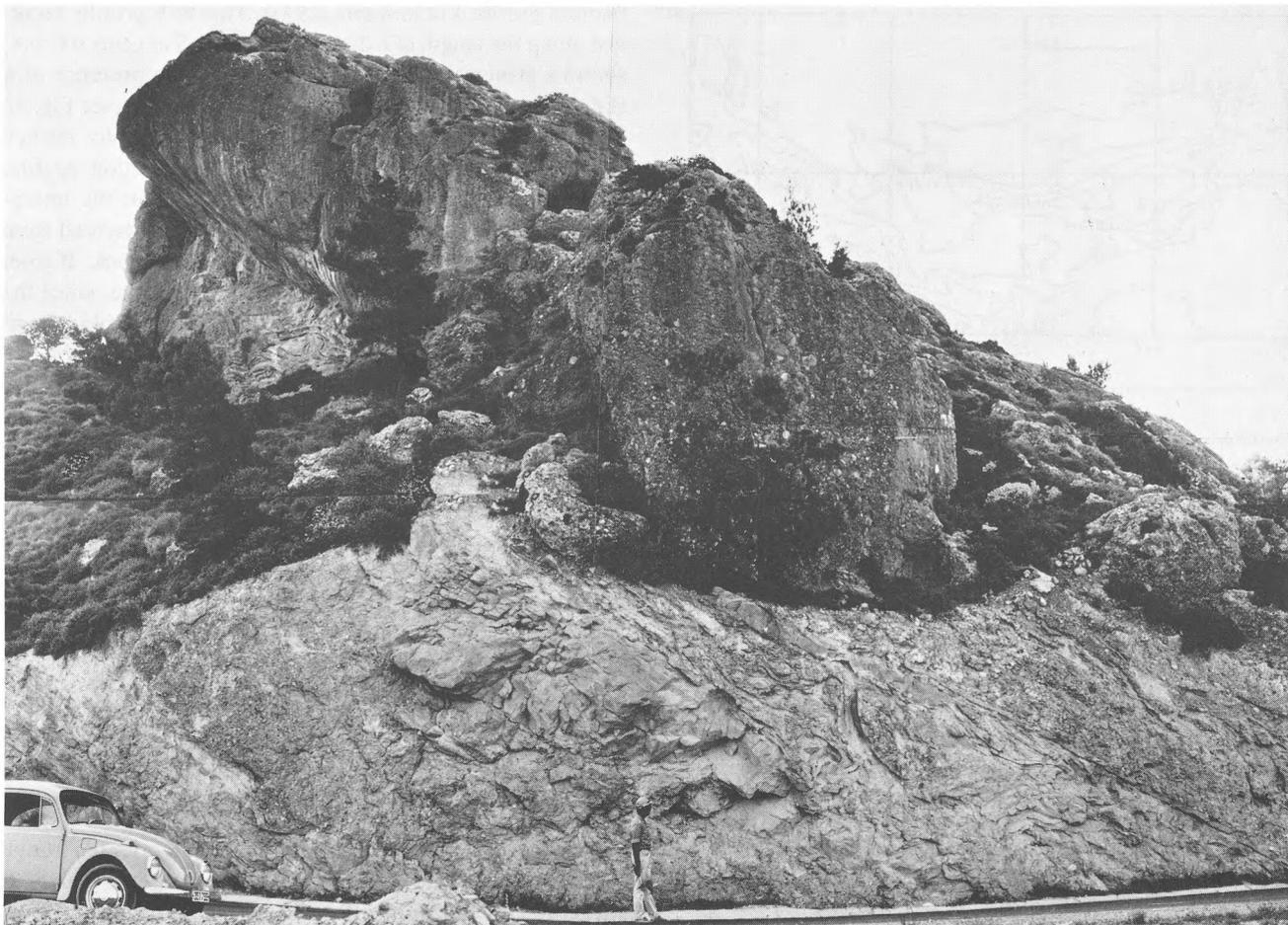


Fig. 7

Conglomerate olistolith intercalated in the Kalamavka Formation. Its lithology suggests that it was derived from the Prina Complex. The base (visible above the car) includes crumpled and contorted strata of the Kalamavka Formation, of which a large calcareous sandstone fragment (visible above the man on the road) has such lithological properties that it must have come from another, probably more proximal place, as this type of sediment is not found in the underlying strata. The dip is to ENE; photo taken in northern direction.

of the Chalasmenos – Kapistri fault zone. The Kalamavka facies is interpreted as the product of rapid filling-up of the submarine depression with fan deposits. The formation is well developed near Kalamavka (over 350 m thick). Its calcareous sandstone intervals pinch out to the south, in the downcurrent direction (most palaeocurrents came from the north or northeast). The most distal parts of this submarine fan facies are found in the south coast areas, S of the present Mournies – Kaloyeri fault and the Kalamavka Formation is not found W of Mournies and E of Ierapetra. The supposed facies boundary is indicated in figure 5. The Mournies – Kaloyeri fault-zone may have been another, less pronounced W-E hinge line, as suggested by distinct differences in thickness of the Kalamavka Formation NE and SW of it (300 versus 100 m).

Up to 300 m thick sandy cobble and boulder conglomerates of the Prina Complex occur in the area south of the Gulf of Merabellou. They are seen as the most proximal sediments of the submarine valley and must have accumulated close to

coastal escarpments. Deposition of these coarse clastics may have followed after renewal of differential movements during this phase in view of the fact that their base consists of strongly erosive boulder mudstones which may include reworked elements of older Neogene. Time and again clastics of the Prina Complex were redeposited as channel-fills, pebbly mudstones or slide blocks in the more distal parts of the depression, i.e. the Kalamavka Formation (Fig. 7).

East of Ierapetra, sedimentation of the Fothia Formation was initially controlled by rapid accumulation of coarse terrigenous clastics in a piedmont area along pronounced reliefs. The clastics of the Fothia Formation were derived mainly from the Phyllite-Quartzite Series, the first pre-Neogene allochthonous stockwork (BAUMANN ET AL., 1977). In a later stage the relief levelled-off to the north and most of the clastics were supplied by braided streams over a floodplain and transported in SW directions. Continued subsidence finally resulted in a gradual shift towards increasing marine sedimentation conditions.

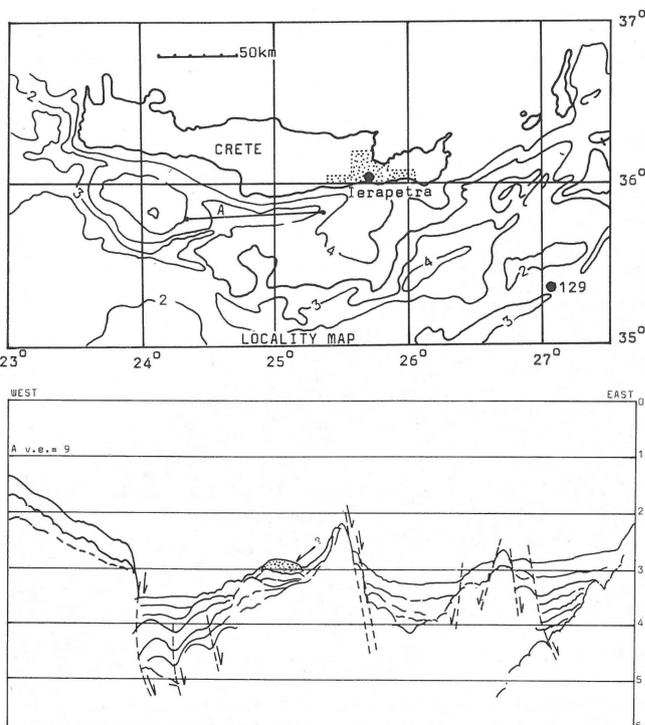


Fig. 8
Interpretation of seismic reflection profile A of JONGSMA (1977). The locality map gives the position of this profile in relation to the Ierapetra region and DSDP site 129. Added to the original profile are the interpreted faults and the indication of the possible slide mass in the Neogene (dotted sediments).

Towards the end of this phase the supply of coarse clastics from northern sources waned and marine marls were deposited, also in the northern areas. At about the same time the first turbidites of the Makrilia Formation appeared in the areas near the south coast.

Discussion – Although a general interpretation is given, problems exist with regard to several important details, e.g. the dimensions of the sediment slides (what distance did they cover?) and the questionable intra-Neogene position of some large culminations of pre-Neogene Tripolitza rocks in the area. For a discussion of these problems the reader is referred to FORTUIN (1977). Because indications for compressional tectonic movements have not been found, the unambiguous presence of allochthonous pre-Neogene can best be explained by gravity sliding over (and along with) marly strata during and after differential movements of tilting fault blocks. Tilting seems to have been an important factor. Where only differential vertical movements without tilt have taken place, such as in many other Cretan regions, mass movements were rare or absent. It is believed that gravity gliding of sediment successions may have played a more important part in the South Aegean Cenozoic history than so far assumed. Reference may be made to what can be seen in the seismic re-

flection profile A of JONGSMA (1977). This W-E profile, recorded along the length of a deep some 15 km S of central Crete, shows a structure which strongly suggests the presence of a slide mass of 250 m thick and 8 km W-E extension (see Fig. 8), associated with deformed underlying and frontally pushed successions. Inspection of the original reflection profile, kindly provided by Dr. Jongsma, suggests that the interpreted slide consists of well-stratified Neogene derived from the uplifted eastern margin of the tilted fault block. If true, this would imply a local doubling of the Neogene, since the reflections from the underlying sediments are strikingly similar. The dimensions of such a large slide mass fit the one intercalated in the Fothia Formation.

Dr. Jongsma, not prepared for the possibility of a large sediment slide, interpreted the folded lines to the west of this structure as strata folded by compressional tectonics. Growth faulting by crustal extension of the basement via a set of antithetic faults, as interpreted in figure 8, could also have been the cause here. Such basement faulting and tilting then, in turn, might easily have caused gravity sliding of the Neogene cover.

Phase 4 – Early-Middle Tortonian

Sediments involved: Makrilia Formation, Ammoudhares Formation at Prina.

During this episode part of a rather deep W-E oriented trough extended over the southern half of the Ierapetra region. It was gradually filled-up with sandy turbidites from sources in the west. The increasing westward trend of the proximal part of the turbidites in the upper half of the formation seems to express a progradational filling-up of the trough from the west. The interfingering turbidites of calcareous sandstone at the base of the Makrilia Formation (showing the lithology of the Kalamavka Formation) still came from NE sources. Their presence suggests that the turbidites supplying the Makrilia sands followed the longitudinal axis of the basin. The source area of these clastics has to be thought in the southern Iraklion province, where shallow marine sediments were deposited at the same time (Zachariasse, pers. comm.). Evidently subsidence had been stronger in the Ierapetra region than in the Iraklion province. Up to 450 m of marls and sandy turbidites were deposited.

While turbidite sedimentation was in progress in the south the northern areas were also gradually submerging. From the few marine deposits that are left from this episode, it may be concluded that sedimentation was slow. In these northern areas deposition of bioclastic limestones started towards the end of the Early Tortonian. We suppose that the northern boundary of the Makrilia turbidite basin followed the Chalasmenos – Kapistri trend, which zone may have formed the shelf break. This is suggested by a significant turbidite succession at Makrilia, just south of this fault zone, whilst turbidites are absent in a condensed succession of coeval marls

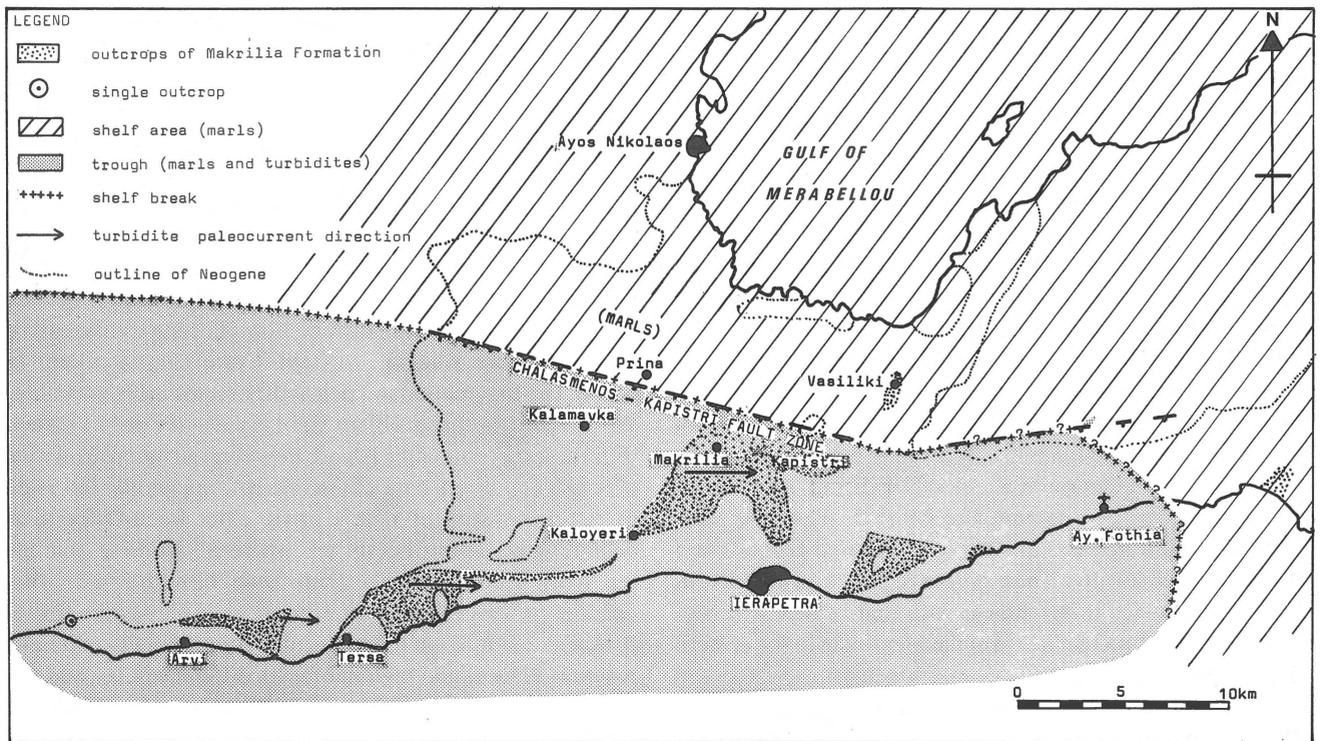


Fig. 9
Reconstruction of chief features of the palaeogeography of the Ierapetra region during phase 4.

at Vasiliki (Fig. 9). The rich open-marine microfaunas near Vasiliki indicate slow deposition on the deeper parts of a shelf.

Little is known about the Makrilia Formation between Ierapetra and the SW Sitia district, so that the eastward extension of the turbidite basin remains uncertain. However, it did not extend as far as the SW Sitia district, where some 100 m of shallow – open-marine sediments were laid down during this episode (as Skopi and Akhkladia Formations, see GRADSTEIN (1973 and Fig. 2).

Discussion – During phase 3 relief differences along the Ierapetra fault zone influenced the lithological picture (boundary between the Kalamavka Formation plus Prina Complex and the Fothia Formation). These differences had obviously disappeared towards the end of that phase. This may be concluded from the presence of a well developed series of Makrilia marls and turbidites E of the Ierapetra fault, overlying the Fothia Formation (see Fig. 2). But the interpretation of the Makrilia Formation in this eastern area is still somewhat problematic. No palaeocurrent measurements could be made, proving or disproving supply from the same western sources as elsewhere. Biostratigraphic data, moreover, suggest that deposition of the Makrilia Formation started, at least in part, contemporaneously with the deposition of the Kalamavka Formation.

Phase 5 – Middle/Late Tortonian - Messinian

Sediments involved: Ammoudhares Formation, basal part of Pakhiammos Formation.

Virtually all the successions of the Ammoudhares Formation in the south coast areas were crumbled by the effects of southwards directed slumping and sliding of rigid to semi-consolidated sediments along shear and gliding planes. The W-E extension of these deformations is about 50 km.

At the beginning of this phase distinct environmental changes took place, expressed by a transition to calcareous marls and bioclastic limestones. Most limestone bioclasts are from organisms that lived in shallow, warm waters. MEULENKAMP ET AL. (in press) relate this general Cretan shift from terrigenous-clastic to carbonate sedimentation to a major tectonic phase. Renewed deposition of proximal turbidites in the Ierapetra region indeed suggest that the weak submarine morphology that existed at the end of the previous phase soon became pronounced. Locally intercalated conglomeratic channel-fills and (rare) palaeocurrent measurements indicate that somewhere to the north pre-Neogene rocks emerged, bordered by carbonate shoals. Slumped strata and limestone olistoliths of intra-formational, shallow-water origin also support the idea of a rather steep palaeorelief.

After the Late Tortonian a general regression took place,

as in the other Cretan regions. Tectonics must have played a role. But also the Messinian salinity crisis may have influenced this development towards the shallowing of the sea. On other grounds, and in contrast to views expressed earlier MEULENKAMP & ZACHARIASSE (1973) and MEULENKAMP (in press) assume that tectonic instability continued during this time on Crete.

Also in the Ierapetra region a Messinian facies developed. Large slabs of displaced Messinian gypsum in Early Pliocene deposits prove that evaporites must have been deposited somewhere in the region. During the Messinian the northern, Merabellou part of the region was uplifted, eroded and levelled down. The boundary between the uplifted Merabellou block and the southern areas can be traced back between Kalo Khorio and Pakhiammos as a partly buried fault zone, which has an orientation of about WNW-ESE. This fault is indicated in lithologic column 4 of figure 2. When the Messinian sea again invaded this area, continental redbeds had been deposited locally. Their presence points to an arid climate, a conclusion in agreement with that of BENDA & SICKENBERG (1975) for the climate of the Messinian in the eastern Mediterranean.

It is assumed that differential vertical movements in the Late Messinian caused a southward tilting of some degrees of the sea floor in the southern Ierapetra region, thus favouring the initial conditions necessary to explain the submarine slumping and sliding of the Ammoudhares Formation.

Phase 6 – Early Pliocene

Sediments involved: Pakhiammos Formation (north coast), Mirtos Formation (south coast).

It is generally agreed that the Mio-Pliocene boundary in the Mediterranean coincides with a sudden and rapid transgression. In the Ierapetra region and in the adjoining SW Sitia district 10 – 15 m of marl breccias form the oldest Pliocene. They are overlain by marls deposited in an open marine environment. The lithology and components of the marl breccias, including Lower Pliocene marls, Messinian cavernous limestones, gypsum and few pebbles of pre-Neogene rocks, suggest that they originated in the Early Pliocene from submarine mass flows. Unconformable, erosive contacts with the underlying Messinian (and even with Tortonian marls in some outcrops in the SW Sitia district: GRADSTEIN, 1973), could point to last paroxysmal tectonic movements before quiet depositional conditions returned. The presence of similar Lower Pliocene marl breccias in other Cretan regions stresses the interregional significance of such movements.

The deposition of the younger marls, in a quiet open-marine environment continued up to the beginning of the Late Pliocene.

Discussion – The presence of Lower Pliocene marl in the

matrix of the marl breccias not only illustrates that these originated from an Early Pliocene tectosedimentary event, but also that their presence represents a time hiatus, separating lagoonal, shallow-marine strata from younger open-marine marls. One therefore cannot make a good distinction between the possibility of a rapid transgression by tectonic movements, leading to the formation of marl breccias or a catastrophic drowning of the Mediterranean deep and desiccated basins by the sudden reinstatement of the connection with the Atlantic Ocean, as for instance postulated by CITA (1976). In view of an undisturbed Mio-Pliocene transgressive sequence near Khania, western Crete (MEULENKAMP, in press), the first mentioned possibility seems more probable. With regard to this problem MEULENKAMP (in press) states: 'For the larger part of the island, however, an initial drowning of reliefs at the very base of the Pliocene apparently followed by a rejuvenation of reliefs along older fracture systems delimiting numerous horsts and grabens'. In these grabens the marl breccias would then have been formed. This opinion, however, cannot be entirely valid for eastern Crete. A rejuvenation of the older fracture zones there would have resulted in local and regional facies differences, as was the case during the earlier phases. And not as in the ubiquitous presence of marl breccias and overlying, uniform successions of *Pycnodonta* marls wherever the Pliocene is now found in eastern Crete. The uniform, interregional distribution of these sediments can be better explained by assuming a rather smooth submarine topography over large distances, i.e. subsidence of crustal blocks of much larger size than before.

Phase 7 – Late Pliocene

Sediments involved: upper parts of the Mirtos and Pakhiammos Formations

Approximately at the beginning of the Late Pliocene tectonic uplift affected the region. These movements, reflected by a sudden transition into littoral sedimentation conditions, caused a general emergence. Probably the interior part of the region emerged first, resulting in different environmental conditions between the north coast areas: calcareous deposits are found in the north and beach and nearshore sands and marls in the south coast areas. Differences between uniserial *Uvigerina* assemblages from below and above the erosive contact between the older open marine marls and these latter deposits suggest a break in the sedimentation

Discussion – According to MEULENKAMP (in press) the sedimentary expression of this tectonic uplift can be recognized all over Crete. These crustal movements may thus be seen as the first steps to the present configuration of Crete.

In several of the seismic reflection profiles north of Crete, as given by JONGSMA ET AL. (1977), a distinct, locally angular unconformity can be seen, which is correlated with a Middle

Pliocene tectonic event. This event probably corresponds with the beginning of this phase. Their profile 14, for instance, (located north of central Crete) shows an abrupt increase of less than 100 m of Late Pliocene – Quaternary on the Cretan margin block to some 400 m such deposits in a deep graben structure to the north. This is just contrary to that visible in the underlying Neogene of the Cretan margin block, where a transgressive thickening towards Crete is shown and illustrates the separation of Crete as a horst from the surrounding seas during this period.

Phase 8 – Latest Pliocene (?) – Quaternary

Sediments formed: bioclastic limestones, terrace deposits, talus and scree deposits etc., not formally subdivided into lithostratigraphic units.

Our observations support the views of ANGELIER ET AL. (1976) that strong differential movements recently took place in the Ierapetra region. The largest displacements were along the old W-E fault zones along NE-SW lines, such as the faults bordering the Ierapetra depression. Indications for strong differential vertical movements are for instance up to 25° S tilted terrace deposits E of Ierapetra and differently elevated Early Quaternary (?) bioclastic limestones in the Ierapetra depression. The latter deposits are elevated as high as 220 m nearby the Ierapetra fault, whilst those at some 2 km distance, in the centre of the depression are 75 m high. The Merabellou area underwent a tilt of up to 10° towards the Gulf of Merabellou.

It is assumed that the general trend of Late Pliocene – Quaternary uplift stagnated during some time in the latest Pliocene or early Pleistocene, since there are indications of levelling and (local?) submergence. In the first place, a relict of pre-Tyrrhenian marl (including *Globorotalia truncatulinoides* and *Hyalinea balthica*) was found in a coast cliff east of Ierapetra. The erosively overlying terrace deposits belong to the middle terrace level of ANGELIER & GIGOUT (1974), the age of which is somewhere between 2.5×10^5 and 1.14×10^5 yrs B.P. according to $^{230}\text{Th}/^{234}\text{U}$ age determinations given by ANGELIER ET AL. (1976), for the upper and lower terrace levels near Ierapetra, respectively. Secondly other marine, probably also pre-Tyrrhenian deposits occur. These are white algal and miliolid limestones, that could not be accurately dated by the author. Although they might be older than the uppermost marine platform (pF1) of ANGELIER ET AL. (1976), they may belong to this unit because an outcrop E of Ierapetra has been mapped by these authors as a pF1 terrace. The lithology and faunal composition of the limestones reflect deposition in warm, shallow waters beyond the reach of terrigenous clastic supply. Their presence so close to the Ierapetra fault strongly suggests that during their deposition a pronounced relief had not yet been formed. Finally, old planation surfaces occur in the Merabellou area. They were already mentioned by BONNEFONT (1965) and are elevated inland between 200 and

700 m. Nearby exposed bioclastic limestones (NW of Kalo Khorio) are elevated between 160 and 240 m. Their presence suggests an initial stage of levelling, followed by the installation of littoral carbonate platforms.

Pleistocene terraces are best developed in the Arvi area (see map in ANGELIER ET AL., 1976). The most prominent feature of Holocene sedimentation are the large debris fans that developed along the scarp of the Ierapetra fault (see Fig. 3).

Discussion – The NE tilt of the Merabellou area, which is very strong with regard to a generally very faint tilt of the Cretan north coast areas (ANGELIER ET AL., 1976) may account for bending of the Lasithi and Sitia massifs, as postulated in the chapter on the structural setting.

ANGELIER ET AL. (1976) calculated an absolute minimum of 5 cm/100 yrs for the average Late Quaternary uplift of the terraces in the Ierapetra region. Their calculation is based on a combination of radiometric age determinations and the amplitude of deformations of an old shore-level. If we depart from a possible age of 250,000 year of the shallow-marine bioclastic limestones, according to the age given by these authors for the highest pF1 terraces, and an elevation of 220 m of these limestones along the Ierapetra fault, an average uplift of about 1 m in 1,000 yr must be concluded. If we extrapolate this rate of uplift for the last 3 million years, which is roughly the time elapsed since the beginning of a general uplift of Crete in the early Late Pliocene, a total uplift of 3,000 m may have taken place. Although this calculation is provisional, it agrees very well with the vertical displacement rate of 1 mm/yr, calculated by RYAN ET AL. (1971) for the eastern Mediterranean and Aegean Sea and stresses the possibility that even the highest parts of Crete (max. 2,456 m) could have emerged as late as the beginning of the Late Pliocene.

The following, more interpretative calculation suggests an uplift with even twice as fast a rate: the limestones with an age of about 250,000 years were obviously deposited after a period of levelling in which no fault scarp as yet delimited that Ierapetra depression. Nowadays the eastern fault margin is elevated up to 1,000 m. If we take 500 m as an average uplift since then, an uplift of 2 m in 1,000 year is suggested.

SOME GEODYNAMIC CONSIDERATIONS

As pointed out in the chapter on the structural setting, increased bending of the Aegean Arc could be responsible for differences in the orientation of the longitudinal, about W-E striking faults at both sides of the Ierapetra depression. Before the possible geodynamic implications for Crete can seriously be taken into account more evidence is necessary from structural geology, but some support, at least, is given by ANGELIER (1977) who concludes a slight Pliocene – Quaternary expansion of the Hellenic Arc towards the eastern Mediterranean and a small correlative accentuation of the cur-

vature of the arc. Bending also fits into the geodynamic concept of BRUNN (1976) of the eastern Mediterranean, a general W-E constraint of the arc (RITSEMA, 1975) and a southward movement of the Aegean lithospheric plate (MCKENZIE, 1972). In this light the Ierapetra region might be seen as the site of a dislocation in the arc, where a large transverse graben structure developed in the late Middle Miocene. In theory, a further displacement by strike-slip faults is possible (a 'décrochement'). Although such faults seem absent or rare in the eastern Mediterranean, some faults in the Ierapetra region have an oblique slip, as could be concluded from the orientation of slickensides, which may dip as much as 30° in the strike of the fault. In combination with rapid facies changes and possible discrepancies, noted for phase 2 across the Ierapetra fault, the possibility of strike-slip movements cannot be entirely ruled out.

The correlation diagram of the most important sedimentary and structural events of the Ierapetra region with those of the surrounding seas and with the chronostratigraphic scale clearly shows that submergence took place earlier in the south, where probably deeper basins existed during the Miocene. After the installment of a turbidite basin in the southern part of the Ierapetra region in the Early Tortonian the rate of sedimentation gradually decreased. Disturbances of the sedimentary record at the Miocene-Pliocene boundary appear to be widespread and preceded open marine conditions. The Late Pliocene – recent general uplift of the region is reversed to the continued subsidence of the surrounding seas.

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