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PALEOBIOGEOGRAPHICAL RECONSTRUCTION OF THE KATHARO PLAIN.

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Abstract: An updated interpretation of facies analysis and sedimentary processes is presented, on the basis of existing and reinvestigated paleontological, additional sedimentological, and structural data. The tectonic and sedimentary history of the broad area of the Ierapetra region is critically reviewed. The geology, geomorphology and tectonics of the Katharo Plain are investigated, in order to reconstruct the tectonic evolution and depositional history of the Polje during the Pleistocene. Furthermore, it focuses on the guidelines of the ongoing paleobiogeographical field research and study of the Katharo Plain. The paleobiogeographical setting is a crucial input to the paleoecological reconstruction of the large mammal fauna and the habitats of the Katharo Plain during the Upper Pleistocene.

Key Words: *Katharo Basin, geological setting, hippos, paleobiogeography*

Introduction

The island of Crete is situated along the southernmost bend of the east Mediterranean Hellenic Arc, which lies between a volcanic arc in the north and the Ionian Trench (subduction zone) in the south (Mckenzie, 1978; Le Pichon & Angelier, 1979). The Neogene basins on Crete are thus situated in an outer arc setting (Fig. 1). Their fills record alternating periods of compressional and extensional tectonics (Meulenkamp et al., 1988; Postma et al., 1993).

The systematic study of the Neogene basins of Crete allowed the representation and recognition of the co-sedimentary active faults. As far as the palaeogeography of Crete is concerned, during the Middle and Late Miocene, Crete was connected to Asia Minor. In the Pliocene the island broke up into small islands, while in the Pleistocene Crete attained its present shape. The changing paleogeography, therefore, had major consequences on the evolution and dispersal of mammals.

The Katharo plain is a basin-shaped, level depression of 4 km length and 1 km width in the Dhikti mountains, which forms the eastern part of middle Crete. Only part of the bottom of the valley is still covered by Pleistocene sediments.

Psariaros (1961), and Theodoropoulos & Papapetrou-Zamani (1973) studied the region, and concluded that the basin should be considered a polje.

The Katharo basin contains a basin-fill, which consists of maximally 20 m of Pleistocene clays, clayey sands and angular gravels. Into these sediments plenty of *Hippopotamus* bones have been found.

The present work aims to establish a high-resolution tectonic and sedimentary reconstruction of the Katharo Basin incorporating new paleobiogeographical data. At first, the tectonosedimentary evolution of the broaden area of the Ierapetra region will be documented and reviewed.

Geological setting

The Ierapetra region is located in eastern Crete and occupies the area of the Ierapetra and Merabellou districts of the Prefecture of Lasithi. 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 limestones (Fortuin, 1977, 1978). They are underlain by the pre-Neogene rocks, which form the complex structure of an autochthonous basement of Permian-Oligocene age (Plattenkalk Series), overlain by the Phyllite-Quartzite Series (LP-HT), Tripolitza Limestone Series (dark micritic limestone of the Gavrovo Tripolitza Zone) and Eocene flysch, the Pindos-Ethia Series (deep water limestones, chert and shales), Asteroussia Series, (system of ophiolites and limestones, locally intruded by granitic to granodioritic dykes and sills), and the Ultra mafic (UM) Series (including flysch with mafic volcanics-diabase, pillow lavas, spilites; ultra mafic rocks, peridotites mainly serpentinized, metabasalts and andesite), (Baumann et al., 1976, Bonnneau, 1984).

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. This resulted in the formation of small sedimentary basins, in which the complex interaction between the faults resulted in the frequent change of land-sea distribution (Drooger & 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 during the Messinian salinity crisis and its consequences had a strong impact upon sedimentation.

The Ierapetra Basin developed as a large, N-S oriented transverse graben structure in upper Middle Miocene in eastern Crete. Its present day morphology is a central NE-SW oriented depression. The pattern of basin fill is strongly controlled by tectonics, which changed the basin relief and sediment flux.

Detailed structural, stratigraphical and sedimentological data showed that sedimentation in the Late Miocene was controlled by two stages of compression separated by a stage of extension (Postma et al., 1993). The compressional stages culminated around the Middle/Upper Miocene boundary and around the Miocene/Pliocene boundary respectively.

The tectonic history of the Ierapetra Basin has been reconstructed in a recent paper (Postma et al., 1993). A high-resolution tectonic and sedimentary reconstruction of Neogene extensional basins on eastern Crete has been carried out by Ten Veen (1998).

During the culmination of compression at the Middle/Upper Miocene boundary, folding and reverse faulting due to steepening of the drainage basin relief directly controlled sediment transport and basin-fill patterns. The relief steepening increased the slope instability and caused rapid infill of available accommodation space with numerous landslides, mass-flow deposits, and fault-scarp-derived breccias deposited in rapidly prograding alluvial fan and fan-delta environments.

During the following extensional stage in Tortonian times, slope instability features are rare. Their absence is related to a reduction of the drainage basin relief due to progressive northward rotation of fault-blocks. The resultant half-graben fills are strongly tabular, with alternating intervals of fine- and coarse-grained clastic sediments indicating periods of deepening and progradation. The texture of the half-graben sediments is more mature and grains are better rounded compared with the clastic sediments deposited during the peak of the previous compression. Biostratigraphical data show that the activity of the extensional tectonics and related sedimentary wedge coincides with an early Tortonian global 3rd order sea level rise TB3.1 of an estimated duration of 1 Myr as postulated by Haq et al., 1988.

During the compressional stage at the end of the Miocene, progressive steepening of the basin relief controls sedimentation again. This is shown by basin-subsidence analysis and structural data, and is recorded in the basin fill by numerous synsedimentary subaqueous slide and mass-flow deposits. In contrast with the former compressional stage, the supply of terrigenous material is very limited, which may be related to an increasingly dry climate in Messinian times.

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 (Angelier, 1976; 1977).

Tectonosedimentary history of the Ierapetra region

The occurrence of Neogene deposits in the Ierapetra region was first mentioned by Bonarelli (1901), Chalikiopoulos (1904), Christodoulou (1963) and Symeonidis (1965) and was first studied by Dermitzakis (1969) and later on by Fortuin (1977), Dermitzakis & Theodoridis (1978) and Dermitzakis (1980). More recently, sedimentological aspects of the basin fill were studied in detail by Drinia (1989, 1990), Monogiou (1989), Drinia et al. (1989), Postma & Drinia (1993), Postma et al. (1993), Drinia & Dermitzakis (1996/97).

The stratigraphy of the Ierapetra region, presented in Table 1 and Fig. 4, is largely based on earlier work of Fortuin (1977, 1978), supplemented with data from Fortuin & Peters (1984), Postma & Drinia (1993) and Postma et al. (1993). For the Middle to Late Miocene period seven stratigraphic intervals can be recognized, in accordance with the work of Fortuin (1977). The tectonosedimentary evolution these intervals is given below (Fig. 2, 3):

Early-Middle Miocene

The Late Serravallian sediments were laid down in elongated depressions, which resulted from pre-depositional compressional tectonics, although syndepositional effects cannot be excluded completely. Folds have a dominant orientation of approximately N100E, but their orientation varies along strike between N130E and N100E (Ten Veen, 1998).

During that period the deposition of the Mithi and Males Formations, which contain mainly sediments of alluvial origin, took place.

The Mithi Formation probably represents immature, clastic alluvial-fan sequences with clast composition, mainly igneous rock-fragments stemming form the Ultra-Mafic series.

In contrast with the Mithi Formation, the younger Males Formation comprises mature alluvial sediments of quite different composition, with components derived mainly from the Pindos Series (Fortuin, 1977). According to Peters (1985), the characteristic white limestone pebbles found in Males Formation may have been derived from the Pindic Kalimini unit from the neighboring island of Karpathos (Aubouin et al., 1976).

Palaeocurrent measurements indicate a consistent pattern of westerly palaeocurrent directions in the Males Formation. This pattern suggests that the rivers were confined in approximately E-W running valleys paralleling the southern margin of the Aegean landmass (Fortuin, 1977). The origin of the river valleys may be related to the onset of large-scale folding of the crystalline basement (Plattenkalk Series) during N-S compression, which started probably after the termination of the HP-LT metamorphism about 16 My ago.

The Males Formation becomes gradually marine upwards (Parathiri Member) towards the end of the middle Miocene. Deposition occurred in estuarine, coastal and deltaic environments. Stratigraphically higher a gradual deepening of the depositional environment becomes apparent by the change from brackish into open-marine fauna. The transgression is contemporaneous with a period of compression, which resulted in rapid uplift, folding and steepening of relief along and south of the Kritsa Fault Zone. After the onset of the marine transgression, a gradual change in composition occurred through the arrival of immature dark-blue, micritic limestone breccia of the Tripolitza Series. The deposits of the Males Formation, including those of the Parathiri Member, are widely covered by the Breccia Series, a series of slides, slumps and debris-flow deposits containing exotic large Tripolitza blocks and Mithi, Males and brecciated Tripolitza limestone material. The Breccia Series are deposited in alluvial cones and fans, which had their apex against the Kritsa Fault Zone. Their thickness decreases basinwards (towards the south).

In conclusion, the entire nappe-pile underwent progressive deformation in the late Middle Miocene times during the Males River period as a result of folding of the underlying clystalline basement (Plattenkalk Series).

In the north part of the basin (Kritsa Valley and Gulf of Merabellou) sheared relics of immature, clastic alluvial fan sequences (Mithi Formation sensu Fortuin (1977)), are found covered by a thin sequence of brackish-water limestone beds. Massive blocks and finer detritus derived from the underlying basement are found in the Kritsa Valley, indicating that the sediments of the Mithi Formation have been eroded.

Middle/Late Miocene Transition

The period around the Middle-Late Miocene transition is marked by the break up of the southern Aegean landmass and the basin bordering it to the south.

After the compressional phase, the Ierapetra region became dominated by NNE-SSW extension in early Tortonian times. A reconstruction of the early to middle Tortonian basins show a laterally highly variable facies distribution, which resulted from the interaction of changes in sea-level, sediment supply and paleorelief, which were all governed by fault-block tilting.

During the early Tortonian, the sea slowly invaded Crete through a complex horst and graben morphology, resulting in the deposition of a thick sequence of interfingering fluviatile, brackish and marine strata. Subsidence during this period has been recognized all over Crete (Drooger & Meulenkamp, 1973). Fortuin (1978) and Postma et al., (1993) demonstrated that deposition and facies trends in the early Tortonian basin are controlled by activity along major fault zones.

During that period a sediment wedge is created containing a lower part (Stratified Prina Series) with coarsening upward units representing progradational, shallow-marine deltas and a marly to sandy upper part, which is called the Kalamavka Formation. These two Formations constitute the basal part of the Upper Miocene basin fill (Fortuin, 1977, 1978, Fortuin & Peters, 1984). Deformation of the wedge is complex, with syn- and post- depositional faults. Upward in the succession, the units become composite (coarsening-upward subunits), thicker and finer grained. The composite structure, the thickening and the fining trend is related to progressive increase in accommodation space inherent in fault growth.

In the earliest Tortonian, during the deposition of the Kalamavka Formation, faulting along N130E or N100E normal faults can be confirmed for the Ierapetra Basin (Ten Veen, 1998). The fault activity in the Ierapetra region, gave birth to differential vertical motions of fault blocks. Both N130E and N100E faults were active together in an orthorhombic symmetry.

The facies analysis, description and interpretation, allowed Monogiou (1989), Drinia (1989, 1990) and Drinia & Dermitzakis (1996/97) the reconstruction of the depositional environment of the sedimentary sequences of the Stratified Prina Series and the Kalamavka Formation. According to them, the proposed model for the Stratified Prina Series represents a shallow marine, wave-dominated, mouth bar type of delta with flood-generated debris flow lobes, mainly deposited in a more offshore direction.

Rapid deepening from the photic zone (evidenced by intercalated coral and stromatolite beds) up to a depth of 900 m started at the top of the Stratified Prina Series. The deepening continued over some tens of metres of marly sediments of the base of the Kalamavka Formation and may be related to structural collapse of the fault block. The deep-water deposits of the Kalamavka Formation which are marly and sandy basinwards and marly to gravelly towards the footwall, resemble those described from deep-water fan-delta systems (Prior & Bornhold, 1988, 1990, Postma, 1990).

In the middle to late Tortonian, sedimentation did not keep up with subsidence and marine conditions became more open, as illustrated by contemporaneous deep marine deposits in many Cretan basins (Peters, 1985; Meulenkamp, 1985).

A new basin-fill period is heralded by the gradual change from dominant calcareous clastic sediments (eroded from the Tripolitza and Plattenkalk Series in the north) into brownish, predominantly siliciclastic sands derived from the west. The apparent change in basin configuration is recorded in the sedimentary development of the Makrilia Formation.

Foraminiferal assemblages of the Makrilia Formation are rich in benthic and planktonic fauna and have plankton/benthos ratios between 64 and 94%. These suggest, in combination with the benthic assemblages, upper to middle bathyal (between 500 and 1000 m) palaeobathymetry.

Absence of Makrilia deposit in the north is related to a N075E fault (Ten Veen, 1998). The deep marine character of the deposits together with a western origin of the turbidites requires marine (slope) environments westward. We therefore infer that the distribution controlled by N075E faults is post-depositional.

Late Miocene

Meulenkamp et al., (1979) postulated that the late Tortonian/early Messinian period on Crete was typified by apparently uninterrupted submergence. Sedimentation changed from predominantly clastic in the Tortonian to carbonates during the transition period from Tortonian to Messinian.

In some parts of Crete, tilting and erosion of the older parts of the Neogene sequence took place during a period of tectonic instability, which caused the changes in basin configuration and sedimentation in the Tortonian-Messinian time-interval boundary. Evaporites formed in various parts of Crete (Fortuin, 1977, 78, Meulenkamp et al., 1979) and formed in response to the Messinian Salinity Crisis.

Calcareous (bioclastic) and marly sediments characterize sediments belonging to this period with abundant sponge needles. The basal part of the sequence still contains terrigenous clastic sediments, similar to the Makrilia Formation, although mixed with some bioclastic material. Upward in the sequence, a gradual change from predominantly lithoclastic to bioclastic is evident. These sediments are grouped in the Ammoudhares Formation, which is estimated to be 100 m thick. Evaporites (gypsum and white limestones) deposited in the Late Messinian belong to the Mirtos Formation. The description of the sedimentary facies of this part of the basin fill will show that sedimentation during that period is increasingly controlled by important relief-steepening along the south coast and by aridification of the climate.

From Crete there is a Miocene balanced mainland fauna known. This means that Crete was connected with the mainland in the Miocene whereas in the Pliocene it was mostly submerged. The Late Miocene mammals, which are found, are all of pre-Messinian age. No fossil mammals have been found to date in deposits of Messinian age. It must have been a tectonically active period, together with the Salinity Crisis.

Pliocene

Sediments belonging to the earliest Pliocene are mostly incorporated to the «marl breccias» (sensu Fortuin, 1977) together with Messinian gypsum and conglomerates. According to Peters (1985) the marl breccias resulted from the spasmodic subsidence along the pre-existing but still active E-W and N-S trending fault systems. As a rule in eastern Crete, late Messinian to earliest Pliocene sediments are not present.

From the Early Pliocene, Meulenkamp et al., (1994) reported marly limestones of the Trubi type reflecting the effect of the Pliocene flooding which terminated the Mediterranean Messinian salinity crisis. At the end of the Early Pliocene, Crete was probably subject to an overall regression which caused the emergence of almost the entire island in the course of the Pliocene (Meulenkamp & Hilgen, 1986).

The Cretan uplift is coupled with tilting towards the north and northeast and is separated by a short, early Late Pliocene episode of subsidence (Meulenkamp et al., 1994). The northward tilting of the island was accompanied by folding and thrusting which caused the uplift of the pre-Neogene massifs (Meulenkamp et al., 1988).

During the late Middle Pliocene (3.4 million years ago) the Pliocene transgression took place, which resulted in the submerging of most of the land area.

Based on studies of O_{16}/O_{18} isotopes on foraminifera from several localities in the Mediterranean including Crete, Zachariasse & Spaak (1983) came to the conclusion that the warm and stable Pliocene climate was succeeded by a very cold interval about 3.3 x to 3.2 million years ago. The climatic alterations caused considerable glacial/eustatic changes in sea level. In this way, during the Late Pliocene, we can observe successive alterations in sea level, which combined with the tectonics, formed Crete's modern morphology and that of the Hellenic Arc in general. This led to a redistribution of basins and morphological alterations, with changing periods of strong subaerial and marine erosion accompanied by changes in sea level.

Crete must have attained its present form at the end of the Pliocene.

No Pliocene mammals are known, indicating a submergence of the area which started in the middle Miocene, continuing into the Pliocene (Dermitzakis, 1989).

Pleistocene

For the mid-Pleistocene to Recent, Angelier et al. (1982) found the southern Hellenic Arc to be dominated by radial extension and motions along north-south strike-slip faults.

Fortuin (1978) mentioned that in the latest Pliocene to Quaternary time span largest displacements were along the old E-W faults (N100E) and faults such as the NNE-SSW faults bordering the Ierapetra depression. The results from the reconstruction analysis show that these faults were initiated in the course of the early Tortonian; data from literature suggest that they were still active during the Pliocene to Recent.

In the northern parts of the Ierapetra Region, subhorizontal to weakly N-dipping shear planes are present, along which deposits of the Breccia Series and pre-Neogene rocks are overlying deformed clastic sediments of the Mithi and the Males Formations. The shear planes dip north probably due to the well-documented northward tilt of the island during the Quaternary (Fortuin, 1977; Flemming, 1978; Angelier, 1979). Thus the initial dip of the faults may have been subhorizontal. The amount of displacement, the superposition of the elements and small scale deformation structures varies considerably along the different shear planes.

During the Pleistocene period, Crete obtained its present shape. Renewed fragmentation and strong differential movements were the most dominant tectonic features controlling the Quaternary landscape evolution (Drooger & Meulenkamp, 1973, Meulenkamp, 1985). Many displacements along the Cretan fault systems occur even today, which result in the continuing accentuation of the topographic relief.

In Crete, the faunal evolution is somewhat more complex and most of the Pleistocene mammals (deer, dwarf elephants, dwarf hippos and mice) are endemic (Dermitzakis & Sondaar, 1985). The degree of endemism differs in the different localities and groups.

The Katharo basin

1. Tectonosedimentary Evolution.

The Katharo Basin constitutes the northwestern edge of the Ierapetra Region and is located in the southeastern side of the Dhikti Mountains. The various lineament analyses carried out in the area (Ten Veen, 1998) led to the identification of a fault group of N130E, which has been observed south of the Dhikti Mnt. Along these faults, the earliest Tortonian extensional deformation occurred. During that time the present Dhikti Mnt were probably not yet formed. Drainage was towards the hanging wall basin, implying that footwall uplift and fault-block tilting, which would have led to an oppositely trending drainage, did not occur.

The South Dhikti Fault Zone, the Parathiri Fault Zone and the North Lasithi Fault Zone delimit a tectonic window comprising rocks of the lowermost basement units. Quaternary fan breccias are juxtaposed against the pronounced fault of the S. Dhikti Fault Zone suggesting that these faults were at least active until subrecent times.

The evolution of the Katharo plain was largely controlled by the combination of

N130E and N100E normal faults which were active together in an orthorhombic symmetry, during Middle/Late Miocene transition.

The northeastern side of Katharo basin is characterised by the presence of debris flow breccias, slides, slumps and exotic blocks, which are attributed to the lower part of the Breccia Series and overlie the Males Formation with an angular unconformity.

The deposition of the Breccia Series around the Middle/Late Miocene transition reflects the effects of the culmination of transpressional (Fortuin & Peters, 1984) or compressional tectonics. Reverse faulting, thrusting and mass-displacement of exotic blocks express this culmination. The thickest sediment pile of the Breccia Series is entangled between the Fault south of the Dhikti Mnt and a fold zone in the central part of the area. Ten Veen (1998) suggests that the thickest pile of the breccia deposits, present in the central part of the area resulted from preservation due to activity along various fault groups. The general southward decrease in thickness is in agreement with the interpretation of the Breccia Series as alluvial fans and cones which had their apex to the north (Postma et al., 1993).

In a stratigraphically higher level well-bedded congomerates with a white limestone matrix are presented. Locally intercalated fine sediments may include brackish water faunas including abundant *Terebralia bidentata* and *Ostrea* shells. In particular, in the SW side of the hill of Katharo in the region of Kaminaki a rich fauna of Mollusks, Madreporaria, Bryozoans etc. has been found (Bezes et al., 1983). These sediments have characteristics suggesting rapid accumulation of debris in coastal plains, either as sheetfloods or in ephemeral channels. They are attributed to the Stratified Prina Series and have an early Tortonian age. These formational units constitute the highest elevated Neogene strata of Crete.

The lithology of the Breccia Series in Katharo valley mainly consists of exotic blocks and associated debris. Most of the elements belonging to this category are Mesozoic limestones of the Tripolitza Series. In addition, marbles and other rock types from the UM-unit have been found. Aggregates of limestone blocks, tectonic breccias and debris-cones are common. Elements derived from the UM-unit are confined to the base of the complex. These exotics are only exposed at localities where also the Mithi and Males Formations (sensu Fortuin, 1978) are incorporated. The largest blocks are at least 200 m in diameter and several tens of meters thick. The presence of allochthonous sediments of the Mithi Formation is restricted to the lower level of the complex. Due to their relatively soft character they act as a matrix between the exotic competent bodies.

At the eastern margin of the Katharo valley, folded pre-Neogene flysch is truncated by a chaotic gliding mass of Tripolitza limestones, breccias and Males sediments, showing imbrication. The minimum displacement is at least 500m. The spatial relationships between the different lithologies in the gliding mass is well illustrated in a nearby section (Pirgos section), where various pre-Neogene rocks occur as laterally discontinuous blocks, separated by small strike-slip faults with subhorizontal slickensides. Folded and sheared Males lithologies, some limestone blocks and minor quantities of flysch overlie the pre-Neogene exotics. The top of the section consists of massive breccias. The contact at the base of the breccias is not exposed but in the absence of a stratigraphic transition, is interpreted as an important gliding plane.

The position of the UM-unit in the Katharo valley proves the existence of early WNW-ESE trending graben structures became (partially) filled with Neogene sediments (Peters, 1982). The Breccia Series and the Stratified Prina Series, as exemplified by the spatial distribution of pre-Neogene subsequently covered the normal faults and Neogene rocks at the southeastern end of the Katharo valley.

The N-S development of the Stratified Prina Series can be studied along a line from the Katharo valley to the village of Anatoli. In the north the complex almost directly overlies the UM-unit, whereas 8 km to the south it lies above some 500 m of Neogene sediments. Observations along the north side of the Katharo valley indicate that in this area Tripolitza limestones and flysch are thrusted on rocks of the UM-unit and its thin Neogene cover, including the lower parts of the Breccia Series. The estimated minimum displacement along the thrust is several hundred meters.

Due to fault activity in the northwestern part of the area, sediments of the Kalamavka Formation are only characterized by minor thickness indicating that faulting postdates the deposition of the Kalamavka Formation. However corals and stromatolites characteristic of the transitional zone between the Stratified Prina Series and Kalamavka Formation have been found.

Indeed, in Kaminaki region, at a height of approximately 1200 m, SW of the Katharo hill, a coral fauna was found during the hydrogeological recognition and hydrolithological mapping by I.G.M.R (Knithakis et al., 1986).

The studied corals: *Tarbellastrea siciliae, Palaeoplesiastrea columnaeformis* and *Thegioastraea reasendai* are hermatypical, show a temperature of about 20° C (subtropical climate) and a depth of about 50 m (Marcopoulou-Diakantoni & Knithakis, 1978).

The coral and stromatolite beds on top of the Stratified Prina Series indicate still shallow water depths.

Burrowed lacustrine limestones have been intercalated in the upper part of the alluvial series, south west of Kritsa along the Kritsa-Avdeliakos road. Palaeosols of «mottled» brown clayey to fine sandy composition with reed roots and lignites are present

The Katharo basin contains a basin fill, which consists of maximally 20 m of Pleistocene clays, clayey sands and angular gravels.

The gravels are mainly consisting of sandstone fragments: moreover vein quartz and red chert occur. Less numerous are limestone and steatite pebbles. Occasionally reworked Miocene shells are found.

The sands consist of rounded grains of micaceous shales in the coarser fractions: chert grains. steatite grains. diabase grains. some muscovite flakes occur also. Angular quartz grains are common in the coarser fractions and abundant in the finer.

The sediments contained no limestone grains with the exception of some limestone pebbles in the gravels and of the strata with fossils. In the latter. whitish concretions occur abundantly. Thus. solution of carbonates after the deposition of the sediments has occurred. Decalcification may account for the vagueness of the lamination of the Katharo sediments. This process. moreover. has probably destroyed most of the fossils originally present in the sediments.

Pollen analysis revealed the presence of some badly corroded grains of *Pinus*. *Quercus*. Liguliflorae and Gramineae. *Pinus* is not present in the Katharo nowadays.

Lowermost unstratified gray sandy clays with gravel are found. which contain carcareous concretions and *Hippopotamus* bones. These are covered by the same sediments. brick red and totally decalcified. Next is a well-stratified level of sand and gravel with gully fills in the older sediments. Topmost there is a layer of beige laminated stony clay.

These deposits can be explained as that a deposit in a lacustrine environment. where relatively little sands was available. Extensive biological homogenization and loss of structure owing to decalcification may account for the absence of stratification. The scarcity of sand is due to the nature of the source rocks that consist largely of flysch shale and slate with intercalated beds of sandstone and quartzite. Whereas the former disintegrated into clay. the latter mainly part into pebbles. These weathering products slowly filled the Katharo depression. At certain time sedimentation stopped and red-coloring took place.

Renewed flooding brought new gravel deposits in which red material was resedimented. Finally. during the drying out of the basin variegated clays were laid down. The basin is currently being reworked by modern stream action.

2. Large Mammal Turnover and Paleobiogeography.

The existence of mammal fossils in Crete is known since the 18th century (Pocock. 1745. in de Vos. 1996). The first mammal fossils were described at the beginning of the 20th century (Bate. 1905. Simonelli. 1908). Today. numerous mammal fossil sites have been established on the island. For a comprehensive list of Pleistocene mammal fossil sites in Crete see Lax. 1996. The Pleistocene mammalian fauna in Crete is considered endemic and unbalanced (Sondaar. 1971:

papers in Reese. 1996). Like in many Mediterranean islands and elsewhere. such unbalanced endemic fauna contains large herbivores of the Order Artiodactyla (Cervidae. Hippopotamidae). Proboscidea (Elephantidae). Rodentia (Muridae). Insectivora (Soricidae). birds and reptiles. Carnivores are lacking. with the exception of otter and possibly mustelids (see papers in Reese. 1996). Adaptation. evolution and biogeography are unique in island faunas (MacArthur et al.. 1967). Characteristic changes include dwarfism in large herbivores. gigantism in small mammals. different life activities (diurnal) and changes in behavior. such as flightlessness.

Dermitzakis et al.. (1987) and de Vos (1996) studied the biostratigraphy of the Pleistocene mammal sites in Crete. The biozonation is based on the murid rodent *Kritimys* and *Mus* (phylogeny by Mayhew. 1977: 1996). The *Kritimys* zone. Early to Middle Pleistocene. is divided into the *K. kiridus* (older) and *K. catreus* (younger) subzones. and the *Mus* zone. Middle to Upper Pleistocene. is divided into the *M. bateae* (older) and *M. minotaurus* (younger) subzones. In the *Kritimys* zone a pigmy elephant (*Elephas criticus*) and a pigmy hippo (*Hippopotamus creutzburgi*) are present. along with *Kritimys*. The hippo first appearance in Crete is in the Seitia I site of Early Pleistocene age (Spaan. 1996). It belongs to the *K. kiridus* sub-zone. The cervids appear at the *Mus* zone. specifically in the *M. minotaurus* subzone (de Vos. 1996). along with large elephantids. (*E. antiquus* and *E. creutzburgi*. Mol. et al.. 1996). In terms of age. the *Kritimys* zone is considered Lower Pleistocene and the Mus zone Upper Middle Pleistocene. More specifically. *K. kiridus* spans the Late Ruscinian to Late Villanyan. and *K. catreus* the Late Villanyan to Early Biharian (Mayhew. 1977: 1996).

In the Pleistocene of Crete. cervids are represented more than any other mammal. in terms of species diversity as well as in number of sites (Caloi. et al.. 1996). They are followed by hippos (Spaan. 1996: Caloi. et al.. 1996) and elephantids (Mol. et al.. 1996). Elephants are represented by two forms of different size. *Elephas criticus* is the smaller and the older. It is present in the upper part of the *K. kiridus* subzone (de Vos. 1996). Two larger species *E. creutzburgi* and *E. cf. antiquus* (Mol. et al.. 1996: Boekschoten et al.. 1966: Sondaar. 1971: Kuss. 1973: but see also Symeonidis et al.. 1982: Theodorou. 1986). are present in the *Mus* zone (de Vos. 1996). De Vos (1979) distinguished at least 8 taxa of cervids in the Pleistocene of Crete. Capasso Barbato (1989) recognized only 5 species. They belong to *Candiacervus* and *Cervus* (Capasso Barbato. 1990:1992a.b). All cervids span the *Mus* zone (de Vos. 1996).

Katharo site in eastern Crete. at the east slopes of mount Dhikti. has produced so far a sizable hippo fossil bone assemblage (Spaan. 1996: Caloi. et al.. 1996: Pavlakis et al.. in press). 3 specimens of Elephantidae. a small size molar and two pieces of tusk (large size. Pavlakis et al.. in press). and a very large distal fragment of humerus of Testudo (Brinkerink. 1996). *Hippo* fossils have been found so far in 7 more sites in Crete (Spann. 1996:100. where also a history of the hippo fossil collections in Crete can be found). The temporal range is from the earliest *K. kiridus* subzone of Early Pleistocene age in the Seitia I site. where a hippo rib has been found (Mayhew. 1977). up to Stavros cave and Kato Zakros sites. at the upper part of *K. catreus* subzone. of Early Middle Pleistocene age (de Vos. 1996). The size of the rib from Seitia I fits that of the Katharo sample (Spaan. 1996). The entire sample belongs to *Hippopotamus creutzburgi* (Boekschoten et al.. 1966). The younger sites produce hippo samples of smaller size (Kuss. 1975. Capasso Barbato et al.. 1982). This indicates that within the pigmy hippos of the Pleistocene of Crete. there was a trend towards size reduction approaching the Middle Pleistocene. The various AAR and ESR dating efforts produced an age range of 846 to 378 +/- 20% Ky BP(Lax. 1996). The new excavations in 1988. yielded cranial and postcranial hippo material from the locality Anaskama. within the plain of Katharo. An ESR date is being determined for this locality (Pavlakis et al.. in press).

Hippopotamus remains in Crete. were first described by Owen (1845) and de Blainville (1847). while Bate (1905) started the first systematic excavation of hippopotamus remains in the Katharo basin. According to Spratt (1865). the first information on hippos from Katharo was in reference to *Hippopotamus minor*.

The major recent studies of the Pleistocene hippos from Crete include Boeckschoten et al.. (1966). Kuss (1975). and Capasso Barbato et al.. (1982). In 1966. Boekschoten & Sondaar collected new material. studied the Bate (1905) collection from Katharo and some material from Karoumpes IV. and named the species *Hippopotamus creutzburgi. Hippopotamus creutzburgi* is the typical large mammal of the *Kritimys* biozone. Boeckschoten et al. (1966) study. showed that the size of *H. creutzburgi* was considerably smaller than *H. amphibious* and larger than *H. minor* from Cyprus. Until then. it was thought that the dwarf mammals on islands were the result of degeneration working on a small and isolated population (Vaufrey. 1929). However. the study of the morphology of the Cretan hippo by Boekschoten & Sondaar (1966). showed that these animals present a high degree of adaptation to the insular environment. which is characterized. among others. by a small number of species and a lack of predators. Since then. other paleontologists have continued to collect material in Katharo (Kuss. 1970. 1975: Capasso Barbato et al.. 1982. Verhuel. 1991).

Kuss (1975) studied the material from Kato Zakros and Stavros cave. He found morphological and size differences from the Katharo hippo. mainly smaller teeth. and established two subspecies: *H. c.creutzburgi* and a younger *H. c. parvus* in the upper *Kritimys carteus* faunal sub-zone. The material that Capasso Barbato studied from Katharo. for the purposes of this work. falls within the total morphological range of Boeckschoten et al., (1966) and Kuss (1975) hippo samples. Spaan (1996) in a review of the Cretan Pleistocene hippo sample, concludes that the subspecies *H. c. parvus*, which was based on the fact that the dental remains from the Kato Zakros were smaller than those from Katharo and Karoumpes, is not a sufficient taxonomic criterion, and larger samples from both sites are needed in order to validate taxonomically this subspecies (Spaan, 1996:104). The new hippo material collected by the 1998 and early 1999 fieldseasons in Katharo by Dermitzakis and Pavlakis (Pavlakis, et al., in press), will test the taxonomic validity of the two proposed subspecies, and will help determine the taxonomic status of the hippopotamid fossil sample particularly from Katharo. Caloi et al., (1996) examined hippo material housed in Rome and reconstructed the animal as being more lightly built than the massive animal Boeckschoten and Sondaar had reconstructed. According to Spaan (1996), the hippo fossil bone sample permits only the determination of the limb bones length and the intermembral index. These show that the humerus is longer than in *H. amphibious*, but the relative length of the front leg is shorter than in the two extant hippos. The same is true for the hind limb. This body anatomy is typical of medium heavy weight animal. Spaan's (1996) locomotor analysis of *H. creutzburgi* indicates that several articulations allowed relatively large movability in the sagittal plane i.e. in the fore and aft move.

The morphology of *H. creutzburgi* differs from that of *H. amphibious*. The recent hippo is mediportal with no cursorial adaptations. The skeleton is constructed to carry its large weight. The proximal bones of the appendicular skeleton are located vertically and the whole limb is short, typical for heavy animals. The foot has been adapted to walking on soft substrate. There is a pad under the digits, that spreads the weight over a large area, since the digits were separate. The pad acts as a shock-absorber as well. *H. creutzburgi* is different. The shoulder and pelvic joints have greater stability against transverse movements, while the for and aft movements was greater. According to Spaan (1996), the femur and tibia are less vertically arranged than in *H. amphibius*. He concludes that *H. creutzburgi* has more of an unguligrade stance. The 3rd phalanx is short and located high from the ground. The distal interphalangeal articulation is elevated. The weight of the animal was carried by the digits having a more vertical position than in the modern hippo.

In summary, *H. creutzburgi* presents a reduction of the graviportal structure and a tendency to greater anteroposterior limb mobility. In addition it had slender limbs and could move quickly on uneven grounds. *Hippopotamus creutzburgi* was undoubtedly a form with good motor capability, relatively agile, and capable of moving on rocky and more or less sloped ground. Boekschoten & Sondaar (1966) supposed that *Hippopotamus creutzburgi* took advantage of these abilities for seasonal migration from coastal areas to the higher altitudes of the central area of Katharo, where climatic conditions in the winter would have been incompatible to the permanent dwelling of hippos. The Katharo basin, under ideal climatic conditions, must have constituted a territory congenial to the life of hippos, considering the presence of water and presumably, of vegetation, but the possibility that the herds moved to surrounding areas in unfavourable periods cannot be overruled. The feeding habits of *Hippopotamus creutzburgi* must have been intermediate between those of typical grazer and a typical browser: its diet must have included leaves, sprouts or fruits, in addition to grasses, to meet possible seasonal variations.

Besides the large hippo fossil bone sample and the few specimens of *Elephas*, in Katharo has been found a distal humerus fragment of a tortoise. Its size is very large (Brinkerink, 1996). The elephantid material from Katharo is under study (Pavlakis et al., in press). Mol et al., (1996) classify the Pleistocene elephantids from other sites than Katharo in Crete to a pigmy *Elephas criticus* and a large *E. cf. antiquus*. The former belongs to the *Kritimys* faunal zone of early Pleistocene, and the latter to *Mus* zone.

Crete attained its present shape during the Pleistocene (Sondaar et al., 1996). Dermitzakis et al., (1978) distinguished four ways trough which animals from the mainland could have reached the island: 1) through a corridor to the mainland, 2) through a filter like a narrow land bridge with (ecological) obstacles that not all kinds of animals could have passed, 3) a sweepstake, chance event, such as rafting, and 4) a pendel route, like a narrow sea straight crossed by some animals.

The Pleistocene fauna of Crete is characterized as endemic, impoverished and unbalance (Sondaar et al., 1996). They suggest that sweepstake is the most possible route of colonization, since Crete was an isolated island from the earliest Pleistocene times. The site of Seitia I, estimated as Lower Pleistocene, produced only *Hippopotamus* and *Kritimys*. These two animals and *Elephas* were the first mainland mammals to adapt to the Pleistocene island environment by adopting dwarf size. *Hip. creutzburgi* and *Elephas creticus*, are the only large mammals of the *Kritimys* biozone. Deer is not present yet in Crete. The *Kritimys* fauna became extinct in the Middle Pleistocene. At this time period a radical faunal turn over took place in Crete (Kuss, 1970; de Vos, 1984; Dermitzakis et al., 1987). In the *Mus* biozone, deer appear and are the most common large mammals. In addition, the *Elephas* had about the mainland size (ca. 150 ñ 21 Ky). *Hippopotamus* might have made it to the Middle Pleistocene if the 12.000 C14 age in Katharo is correct, but with yet undetermined morphological changes. The *Mus* biozone fauna, therefore, is not endemic. It does not show adaptations to island environments. It is more like those in the mainland.

The extinction of the Early Pleistocene endemic fauna may be due to a combination of factors (Spaan, 1996), such as: 1) sea level eustatic fluctuation. When the sea level raises, the island size is reduced, mammal competition for space and resources is increased while the resources decrease. When the sea level is lowered, the island size increases, the connection to the mainland is facilitated for any of the four colonization ways of Dermitzakis et al., (1978). This results in recolonization of the island by new species from the mainland; and 2) by fluctuations in climatic factors, which cause changes in the vegetation cover, in the amount of humidity and may cause extinction of too specialized animals.

Around 800 Ky BP the sea level was lowered (Mol, et al., 1996). Crete became periodically more accessible to animals that were good swimmers, like elephants and hippos. These two animals could have reached the island from the mainland, either through the east or through the north, and most possibly through a sweepstake event. The large elephants could have had the ability to go back and forth to the mainland, thus maintaining genetic continuity with the mainland population. This should have prevented the island populations to became isolated and achieve endemism. Something the first immigration wave of the Early Pleistocene achieved very quickly through effective faunal isolation in Crete.

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STRAT. INTERVALS	DESCRIPTION	AGE
Mitros Formation	Allochthonous gypsum bodies associated with marl breccias of reworked Messinian and Early Pliocene components, overlain by homogenous and laminated, fossiliferous marls. Upwards, intercalations of coarse sand occur in the marls.	Early Pliocene N19 biozone: G. margaritae G. punticulata
Ammoudhares Formation	Alternating sandy, bioclastic limestones and yellow-grey homogeneous and laminated marls. Local intercalations of coarse clastics are interpreted as proximal turbidites or channel fills. The entire formation underwent slumping and sliding, so that most of the sections are incomplete. Distinction is made between a lower unit with sandy turbidites and gravelly debris flow deposits, a middle unit with thinly bedded horizontally laminated sand passing upwards into alternations of laminated and homogeneous marls, and a top unit consisting of whitish homogeneous chalky marls.	Late Tortonia/Early Messinian Lower & Middle unit: G. Menardii form 5 Upper unit: FO G. conomiozea
Makrilia Formation	Succession of fossiliferous, blush-grey marls with in the middle part a variable amount of intercalated brownish sands (turbidites) which originated from west.	Early Tortonia/Late Tortonian Base: FAD dextral N. acostaensis. Middle: sinistral N. acostaensis. Top: G. menardii form 4
Kalamavka Formation incl. SP Series	A succession of up to 600 m with a gravelly lower part (SP Series) and a sandy and marly upper part. The coarse grained lower part shows a N to S change from stream-dominated alluvial fans to wave dominated deltas. More southwards, channelised boulder conglomerates embedded in the marls are associated with major submarine sliding. the marly deposits of the Kalamavka Formation were deposited in a pro-delta to delta front environment.	Early Tortonian Base: upper N15 biozone (G. menardii form 3) Top: early N16 biozone (C. parvulus and primitive dextral N. acostaensis)
Breccia Series	A series of slides, slumps and debris flow deposits containing exotic large Tripolitza blocks and Mithi, Males and brecciated Tripolitza material.	Early Tortonian
Males Formation incl. Parathiri Member	Mature alluvial sediments (conglomerates and sandstones) of different composition. Towards the top of the Males Formation, shallow marine, sandy to gravelly deposits of the parathiri Member onlap over Males flood plain/coastal sediments. The deepening is alos evidenced by the change from brackish to open-marine fauna.	Parathiri Mb. = late Serravallian-early Tortonian (N. acostaensis lower dextral)
Mithi Formation	Oligomict and monomict conglomerates and breccias with components derived from nearby exposed rocks of the highest pre-Neogene units.	<Aquitanian Middle Miocene

Table 1: Statigraphy of the Ierapetra Region after Fortuin (1978) and Postma et al., (1993). References used for dating of the stratigraphic intervals: Kopp & Richter (19983), Jacobshagen (1986), Zachariasse (1975), Fortuin (1977), Postma et al., 1993.

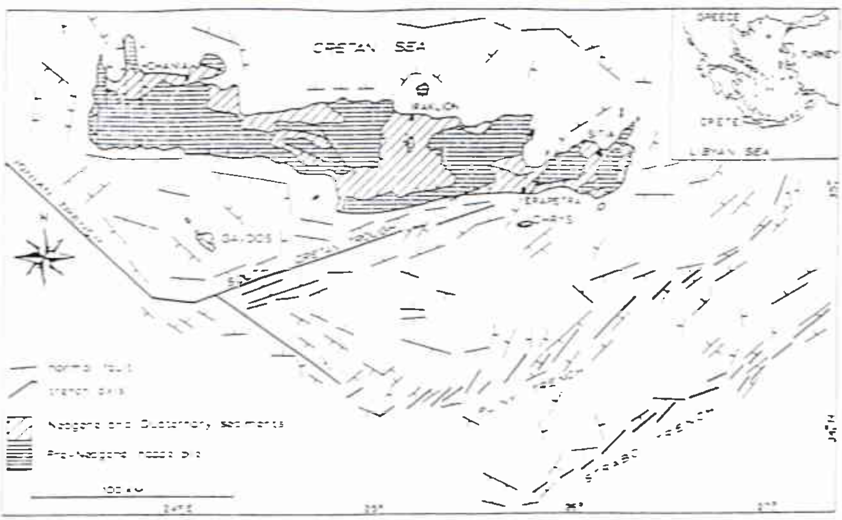

Fig. 1. Geological sketch map of the south Hellenic Arc and location of the Ierapetra region. The offshore fault pattern has been compiled after Angelier et al., (1982) and Mascle et al., (1982).

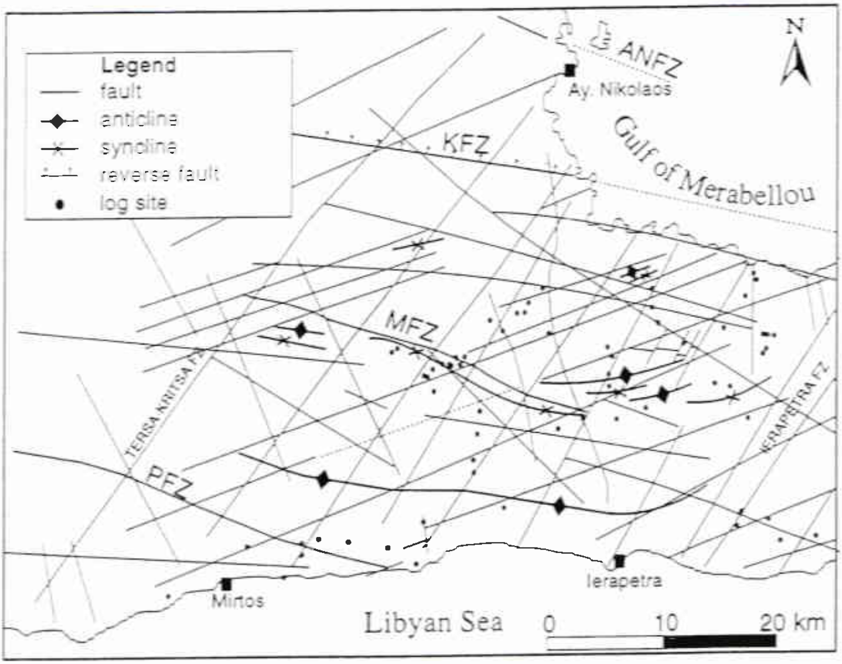

Fig. 2. Fault block configuration of the Ierapetra Region. Important structural features are specifically mentioned. ANFZ: Ayios Nikolaos Fault Zone; KFZ: Kritsa Fault Zone; MFZ: Makrilia Fault Zone; PFZ: Parathiri Fault Zone (after Postma et al., 1993 and Ten Veen, 1998).

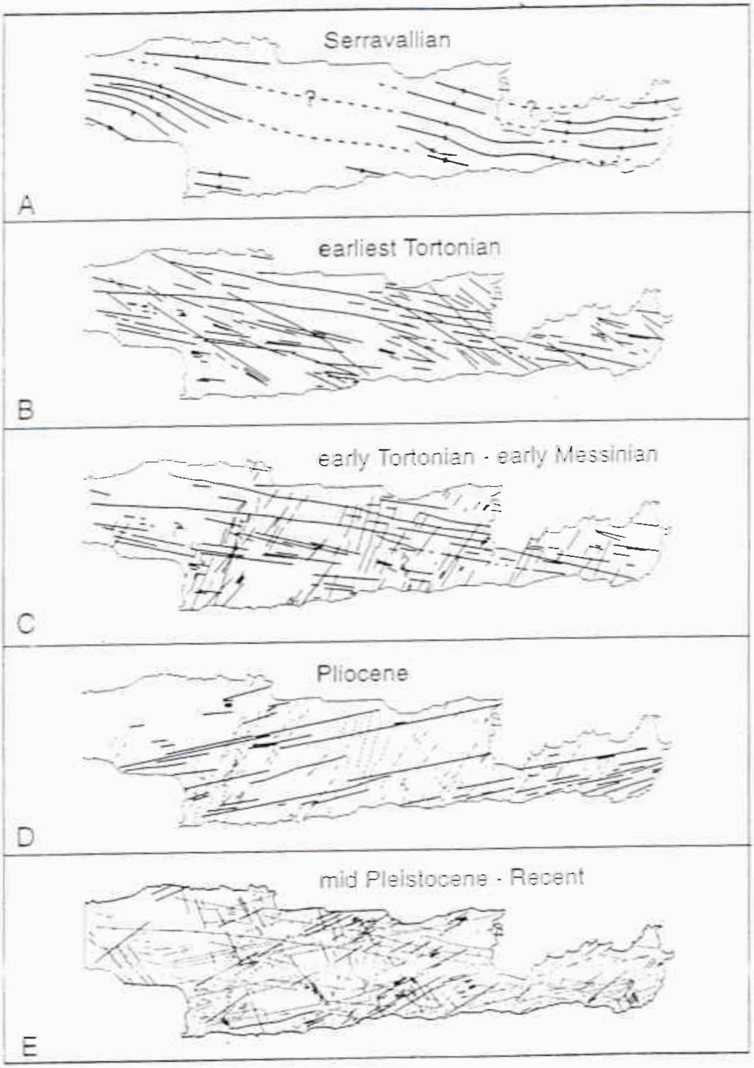

Fig. 3. Middle Miocene to Recent tectonostratigraphy for central and eastern Crete based on Baumann et al., (1976), Wachendorf et al., (1975), Meulenkamp et al., (1988), Postma et al., (1993), Ten Veen (1998).

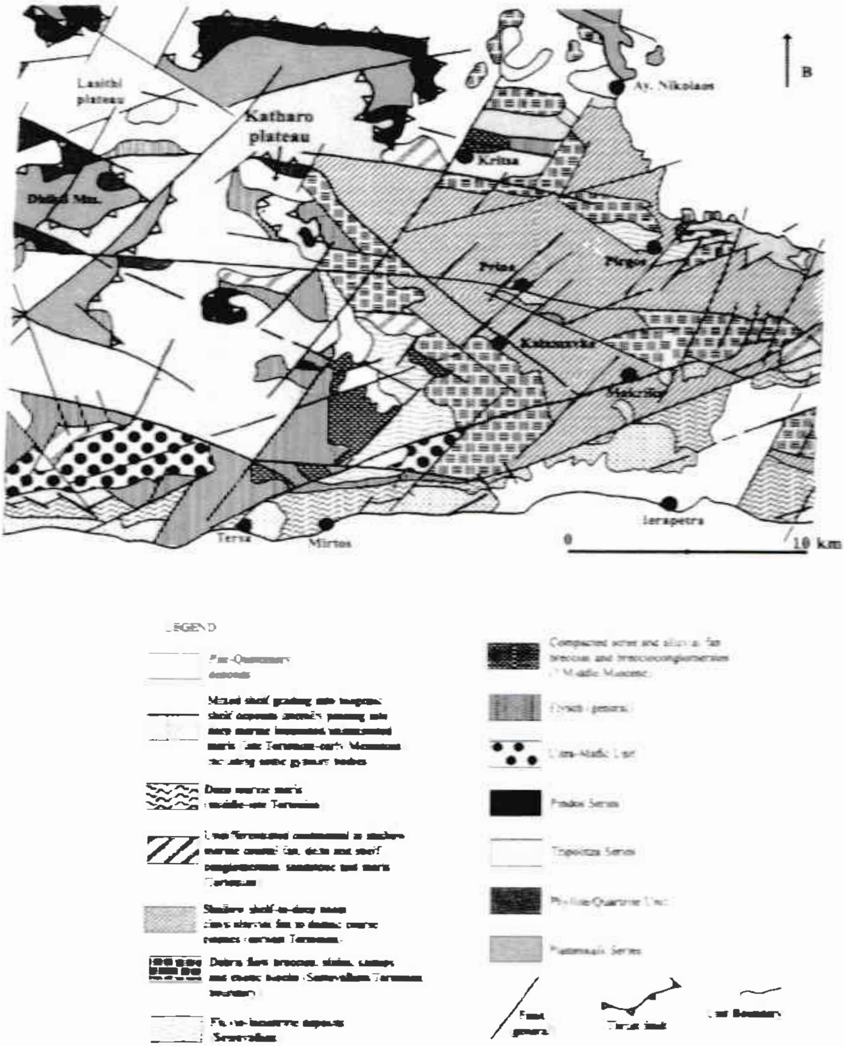

Fig. 4. Geological map of the study area based on Fortuin (1977, 1978), Postma et al., (1993), Ten Veen (1998).