Δελτίο Ελληνικής Γεωλογικής Εταιρίας τομ. XXX/2, 67-81, 1994
Πρακτικά 7ου Επιστημονικού Συνεδρίου, Θεσσαλονίκη, Μάιος 1994

Bulletin of the Geological Society of Greece vol. XXX/2, 67-81, 1994
Proceedings of the 7th Congress, Thessaloniki, May 1994

NEW DATA ABOUT THE PRE-OLIGOCENE STRUCTURAL EVOLUTION OF CRETE (GREECE)

C. Fassoulas[*], A. Kilias[*] and D. Mountrakis[*]

ABSTRACT

In the area of central Crete the occurrence of the pre-Oligocene Alpine metamorphic rocks of the Ophiolitic, Asteroussia and Vatos nappe system (Vatos n. s.), as well as of the underlying unmetamorphosed Pindos and Gavrovo nappes, enables the study of the pre-Oligocene structural evolution of Crete and correlation with the previously studied post-Oligocene deformation events. Structural and kinematic analyses of these nappes, in central Crete, indicates that three Alpine events affected Crete, before the Oligocene. The first, synmetamorphic to a HT/LP metamorphism, DA event took place in the Late Cretaceous, under coaxial conditions, causing intense N-S subhorizontal, stretching and crustal thinning. Probably in the Palaeocene-Eocene, the synmetamorphic to a HP/LT metamorphism, D0 event caused westwards shearing of the Preveli group of the Vatos n. s.. In the Late Eocene/Early Oligocene, the $D0_1$ event overprinted the earlier DA and D0 events, causing westwards stacking and shearing in the Ophiolitic, Asteroussia and Vatos n. s. nappes, and internal westwards stacking in the Pindos nappe.

ΣΥΝΟΨΗ

Η εμφάνιση στην περιοχή της κεντρικής Κρήτης των προ-Ολιγοκαινικών Αλπικών μεταμορφωμένων πετρωμάτων των καλυμμάτων των Οφιολίθων, των Αστερουσίων και του συστήματος των καλυμμάτων του Βάτου (σ. κ. Βάτου), καθώς επίσης και των αμεταμόρφωτων καλυμμάτων της Πίνδου και του Γαβρόβου, επιτρέπουν την μελέτη της προ-Ολιγοκαινικής παραμόρφωσης της Κρήτης και τον συσχετισμό της με την μετα-Ολιγοκαινική τεκτονική της εξέλιξη. Η τεκτονική και κινηματική των ανώτερων αυτών τεκτονικών καλυμμάτων στην κεντρική Κρήτη, έδειξε ότι τρία κύρια τεκτονικά γεγονότα επηρέασαν τα καλύμματα αυτά μέχρι το Ολιγόκαινο. Το πρώτο DA γεγονός, συν-μεταμορφικό μιας HT/LP μεταμόρφωσης, έλαβε χώρα στο Ανω Κρητιδικό, σε συνθήκες συνολικά ομοαξονικής παραμόρφωσης, προκαλώντας έντονη έκταση στην διεύθυνση Βορρά-Νότου και λέπτυνση του φλοιού. Πιθανόν στο Παλαιόκαινο-Ηώκαινο, το συνμεταμορφικό μιας HP/LT μεταμόρφωσης, D0 γεγονός προκάλεσε μια προς τα δυτικά διάτμιση της ενότητας του Πρέβελι του σ. κ. του Βάτου. Στο Ανω Ηώκαινο/Κάτω Ολιγόκαινο, το D0 γεγονός επηρέασε τις παλιότερες DA και D0 δομές. Το γεγονός αυτό, προκάλεσε μια προς τα δυτικά διάτμηση και μετακίνηση των καλυμμάτων των Οφιολίθων, των Αστερουσίων και του σ. κ. Βάτου, ταυτόχρονα με μια εσωτερική λεπίωση του καλύμματος της Πίνδου.

---

[*] Aristotle University of Thessaloniki. Department of Geology and Physical Geography. 54006 Thessaloniki, Greece.

INTRODUCTION

The complicated nappe pile of Crete (BONNEAU et al. 1977, HALL et al. 1984) can be separated into the upper and lower nappes (KILIAS et al. 1992, FASSOYLAS et al. 1994; Fig. 1). Two Alpine metamorphic belts occur within the nappe pile. Unmetamorphosed Alpine sediments are sandwiched between the two metamorphic belts (Fig. 1).

The Plattenkalk series, the Tripali unit and the Phyllites-quartzite nappe constitute the lower nappes and the lower syn-to post-Oligocene metamorphic belt as well (SEIDEL et al. 1982, THEYE et al. 1992, KILIAS et al. 1992, FASSOULAS et al. 1994; Fig. 1).

The upper nappes include all the nappes lying above the lower metamorphic belt (Fig. 1), i.e. the unmetamorphosed Gavrovo and Pindos nappes, and the upper metamorphosed nappes of the Vatos nappe system, the Asteroussia and the Ophiolites. These upper metamorphosed nappes constitute the upper, pre-Oligocene, metamorphic belt (VICENTE 1970, SEIDEL & OKRUSCH 1976, SEIDEL et al. 1981; Fig. 1).

The syn- to post-Oligocene Alpine deformation of Crete is well established. During the Late Oligocene/Early Miocene, HP/LT metamorphism affected the Plattenkalk and the Phyllites-quartzite nappes, associated with southwards stacking of the nappe pile (CREUTZBURG & SEIDEL 1975, SEIDEL et al. 1982, BONNEAU 1984, HALL et all. 1984, KILIAS et al. 1992, FASSOULAS et al. 1994). Recent studies in the area of central Crete (KILIAS et al. 1992, FASSOULAS et al. 1993, 1994) revealed that a Miocene N-S trending extension affected Crete, causing extensional collapse of the nappe pile and exhumation of the Late Oligocene/Early Miocene HP/LT metamorphic rocks. Furthermore, a Late Miocene/Pliocene East-West orientated compression was recognised deforming the Alpine rocks and the Neogene sediments (FASSOULAS et al. 1993, 1994).

Data concerning the pre-Oligocene Alpine deformation of Crete are mainly given by BONNEAU (1984) and HALL et al. (1984). Both argue for a west directed emplacement of the upper metamorphosed nappes over the unmetamorphosed intermediate nappes. BONNEAU was mainly based, in his study, on the geometry and occurence of isoclinal folds, whereas HALL and hisparteners were mainly based on paleogeographic data.

In this paper we present new data about the pre-Oligocene structural evolution of Crete, based on the modern techniques of structural and strain analyses. We have studied the deformation and kinematics of the unmetamorphosed Gavrovo and Pindos nappes and the upper pre-Oligocene metamorphosed nappes (upper metamorphosed nappes), in the area of central Crete.

GEOLOGICAL SETTING

The main geological and metamorphic features of the studied in this paper upper nappes (Fig. 1, 2), are summarised bellow.

The *Gavrovo nappe* (Fig. 1, 2) is composed of a middle to upper Triassic, mainly carbonate sequence at the base, referred as "Ravdoucha beds" (WURM 1950, SANNEMANN & SEIDEL 1976, FYTROLAKIS 1978), a Triassic to Eocene carbonate sequence and an Upper Eocene-Oligocene flysch (CREUTZBURG & SEIDEL 1975). The nappe has been sligtly metamorphosed at the base only (SANNEMANN & SEIDEL 1976).

The *Pindos nappe* is exposed in the southern part of central and eastern Crete (Fig. 1, 2). It represents a pelagic sedimentary sequence with limestones, radiolarites and platty limestones of Triassic to Paleocene/

INTRODUCTION

The complicated nappe pile of Crete (BONNEAU et al. 1977, HALL et al. 1984) can be separated into the upper and lower nappes (KILIAS et al. 1992, FASSOYLAS et al. 1994; Fig. 1). Two Alpine metamorphic belts occur within the nappe pile. Unmetamorphosed Alpine sediments are sandwiched between the two metamorphic belts (Fig. 1).

The Plattenkalk series, the Tripali unit and the Phyllites-quartzite nappe constitute the lower nappes and the lower syn-to post-Oligocene metamorphic belt as well (SEIDEL et al. 1982, THEYE et al. 1992, KILIAS et al. 1992, FASSOULAS et al. 1994; Fig. 1).

The upper nappes include all the nappes lying above the lower metamorphic belt (Fig. 1), i.e. the unmetamorphosed Gavrovo and Pindos nappes, and the upper metamorphosed nappes of the Vatos nappe system, the Asteroussia and the Ophiolites. These upper metamorphosed nappes constitute the upper, pre-Oligocene, metamorphic belt (VICENTE 1970, SEIDEL & OKRUSCH 1976, SEIDEL et al. 1981; Fig. 1).

The syn- to post-Oligocene Alpine deformation of Crete is well established. During the Late Oligocene/Early Miocene, HP/LT metamorphism affected the Plattenkalk and the Phyllites-quartzite nappes, associated with southwards stacking of the nappe pile (CREUTZBURG & SEIDEL 1975, SEIDEL et al. 1982, BONNEAU 1984, HALL et all. 1984, KILIAS et al. 1992, FASSOULAS et al. 1994). Recent studies in the area of central Crete (KILIAS et al. 1992, FASSOULAS et al. 1993, 1994) revealed that a Miocene N-S trending extension affected Crete, causing extensional collapse of the nappe pile and exhumation of the Late Oligocene/Early Miocene HP/LT metamorphic rocks. Furthermore, a Late Miocene/Pliocene East-West orientated compression was recognised deforming the Alpine rocks and the Neogene sediments (FASSOULAS et al. 1993, 1994).

Data concerning the pre-Oligocene Alpine deformation of Crete are mainly given by BONNEAU (1984) and HALL et al. (1984). Both argue for a west directed emplacement of the upper metamorphosed nappes over the unmetamorphosed intermediate nappes. BONNEAU was mainly based, in his study, on the geometry and occurence of isoclinal folds, whereas HALL and his parteners were mainly based on paleogeographic data.

In this paper we present new data about the pre-Oligocene structural evolution of Crete, based on the modern techniques of structural and strain analyses. We have studied the deformation and kinematics of the unmetamorphosed Gavrovo and Pindos nappes and the upper pre-Oligocene metamorphosed nappes (upper metamorphosed nappes), in the area of central Crete.

GEOLOGICAL SETTING

The main geological and metamorphic features of the studied in this paper upper nappes (Fig. 1, 2), are summarised bellow.

The *Gavrovo nappe* (Fig. 1, 2) is composed of a middle to upper Triassic, mainly carbonate sequence at the base, referred as "Ravdoucha beds" (WURM 1950, SANNEMANN & SEIDEL 1976, FYTROLAKIS 1978), a Triassic to Eocene carbonate sequence and an Upper Eocene-Oligocene flysch (CREUTZBURG & SEIDEL 1975). The nappe has been sligtly metamorphosed at the base only (SANNEMANN & SEIDEL 1976).

The *Pindos nappe* is exposed in the southern part of central and eastern Crete (Fig. 1, 2). It represents a pelagic sedimentary sequence with limestones, radiolarites and platty limestones of Triassic to Paleocene/

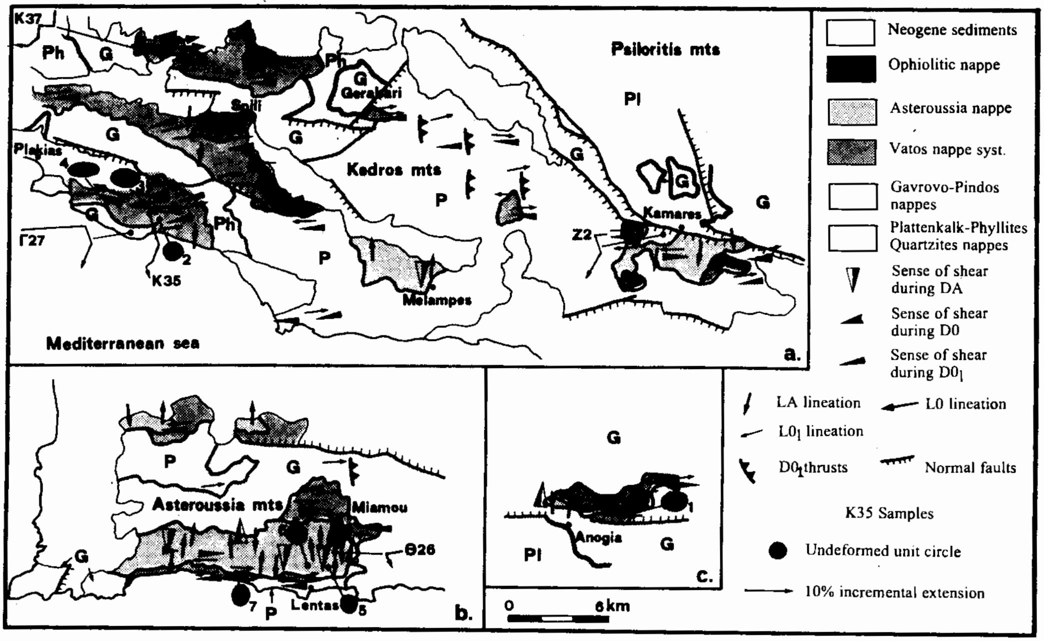


Fig. 2: Geological and tectonic maps in the areas of (a). Spili-Kamares, (b). Asteroussia, and (c). Anogia. Pk, Plattenkalk series; Ph, Phyllites-quartzite nappe; G, Gavrovo-Tripoli nappe; P, Pindos nappe. Each arrow represents 5-10 measurements. Ellipses represent the XY sections of the finite strain ellipsoid.

Σχ. 2: Γεωλογικοί και τεκτονικοί χάρτες των περιοχών (a). Σπηλίου-Καμάρων, (b). Αστερουσίων, και (c). Ανωγείων. P, Σειρά πλακωδών ασβεστολίθων, Ph, κάλυμμα Φυλλιτών-χαλαζιτών, G, κάλυμμα Γαβρόβου- Τρίπολης, P, κάλυμμα Πίνδου. Κάθε βέλος αντιπροσωπεύει ένα σύνολο 5-10 μετρήσεων, εκτός από τις D0 δομές. Οι ελλείψεις αντιπροσωπεύουν τις XY τομές του τελικού ελλειψοειδούς παραμόρφωσης.

exposed in the area of Lentas (Fig. 2, 5), where the Asteroussia nappe is resting directly above the Vatos group. Thus, we suggest that the Asteroussia group (of KRAHL et al. 1982) should possess the uppermost place in their tectonic subdivision (Fig. 1).

The *Asteroussia nappe* is mainly exposed in the area of the Asteroussia mts and also in the areas of Kamares, Melampes and Anogia (DAVI 1967, BONNEAU 1973, CREUTZBURG & SEIDEL 1975; Fig. 1, 2). It consists of crystalline rocks such as, gneisses, amphibolites, micaschists, quartzites, marbles and granitic intrusions of Late Cretaceous age (LIPPOLT & BARANYI 1976). The nappe was metamorphosed in Late Cretaceous (75-66 ma) under HT/LP (700°C and 4-5 Kb) metamorphic conditions (SEIDEL & OKRUSCH 1976, SEIDEL et al. 1981). The typical parageneses are hornblende + plagioclase + biotite + quartz, and cordierite + garnet + sillimanite + biotite + plagioclase + K-feldspar + quartz (samples AD2, AD12, AD27; Table 1). A retrograde paragenesis with actinolite + white mica + chlorite + epidote + calcite + quartz was also observed (Table 1).

The uppermost *Ophiolitic nappe* is exposed in the areas of Anogia, Spili and Asteroussia mts (Fig. 1, 2). It is composed of serpentinites, gabbros, basalts and peridotites obducted probably during the Late Jurassic (140 Ma) (THORBECKE 1973, SEIDEL et al. 1981).

The structural analysis of the pre-Oligocene metamorphosed rocks in the area of Crete was difficult because these always occur, due to younger

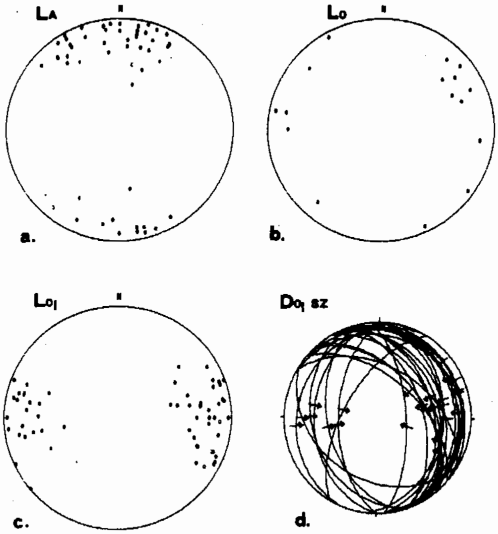


Fig. 3: Lower-hemisphere, equal area projections of main structures observed in the study areas. (a). LA stretching lineation, (b). LO lineation, (c). LO$_1$ lineation, and (d). DO$_1$ shear zones and the associated lineations.

Σχ. 3: Προβολή σε διάγραμμα Schmidt των κύριων δομών που μετρήθηκαν στις περιοχές μελέτης. (a). LA γράμμωση έκτασης, (b). LO γράμμωση έκτασης, (c). LO$_1$ γράμμωση, και (d). οι DO$_1$ ζώνες διάτμησης και οι γραμμώσεις ολίσθησης.

Table 1: Petrological analysis of samples from the upper metamorphic nappes.

Sample	**Nappe**	**Location**	**Paragenesis**
ME8	Spili group	West of Kerane	Hb+Plg+K-fds+Pyr, Act+Chl+Zoi+Ep+Qz
SE4	Spili group	North of Frati	Hb+Gr+Tit+Qz
SE15	Preveli group	Moni Preveli	Gl+Chl+Ep+Cc+Qz Chl+Act+Ep
RE3	Preveli group	NW of Spili	Gl+Chl+Wh. Mc, Act+Chl+Ab+Wh. Mc
AD2	Asteroussia n.	North of Lentas	Bi+Crd+Gr+Plg+K-fds+Qz, Chl+Act+Wh. Mc
AD12	Asteroussia n.	North of Lentas	Hb+Plg+Bi+K-fds, Act+Zoi+Qz
AD27	Asteroussia n.	North of Lentas	Bi+Crd+Plg+Qz, Chl+Ep

Hb, hornblende; Plg, plagioclase; K-fds, k-feldspars; Pyr, pyroxene; Act, actinolite, Chl, chlorite; Zoi, zoisite; Ep, epidote; Qz, quartz; Gr, granat; Tit, titanite; Gl, glaucophane; Cc, calcite; Wh. Mc, white mica; Ab, albite; Bi, biotite; Crd, cordierite.

deformations as isolated, intensely deformed and boudinaged bodies.

The post-Oligocene structural evolution of Crete has been recently studied in the area of central Crete, where almost all the nappes, except the Tripali unit, of the Cretan nappe pile are present (KILIAS et al. 1992, FASSOULAS et al. 1993, 1994). Two major events were observed, an Oligocene/ Early Miocene NNW-SSE trending D1 compression and a Miocene/Early Pliocene N-S trending D2 extension. A minor E-W trending D3 compression affected both the Alpine and the early Pliocene sediments, causing open folds and reverse faults.

STRUCTURAL ANALYSIS

The pre-Oligocene deformation was observed only in the upper nappes overprinted by the younger D1 and D2 events (KILIAS et al. 1992, FASSOULAS et al. 1994). Overprinting criteria, tectonometamorphic data, laboratory observations, as well as, the correlation of data between the individual locations, enabled the distinquishment of three pre-Oligocene events, the DA, D0 and $D0_1$. The main features of these events are listed bellow.

The DA event

The DA event was first observed in the Asteroussia nappe. Later field studies indicated that this event may has also affected the crystalline rocks of the Vatos n. s.

The main structures developed during this DA event are a N-S trending LA mineral stretching lineation (Fig. 2, 3a), and a gently northwards or southwards dipping SA foliation.

In the area of Asteroussia mts, a penetrative SA foliation dominates in the Asteroussia nappe, traced by the alignment of biotite, cordierite, andalusite, sillimanite, hornblende, calcite and quartz. The parallel development of hornblende, biotite and quartz on the SA planes define the LA stretching lineation. In the crystalline rocks at the Spili and Plakias areas, hornblende, symmetric pressure shadows arround pyrite and feldspar crystalls lie parallel to the LA lineation. Bending and rotation of the SA foliation around garnets in metapellitic rocks of the Asteroussia, show pre- to syn-tectonic development of the garnet crystals.

Early formed conjugate DA shear zones, dip gently towards North or South (Fig. 4). Kinematic indicators such as, S-C structures (LISTER & SNOKE 1984), assymetric mica fish (LISTER & SNOKE 1984) assymetric pressure shadows arround competent bodies (PASCHIER & SIMPSON 1986), quartz c-axis texture (LISTER & HOBBS 1980; Fig. 5), observed within the DA shear zones, indicate normal towards North or South sense of shear (Fig. 2, 4).

During progressive deformation, conjugate sets of extensional crenulation cleavages (PLATT & VISSERS 1980) dipping towards North or South, took place, affecting the earlier SA foliation. Extensional vein systems, filled with calcite, were also formed perpendicular to the SA foliation.

In the Asteroussia nappe, competent layers, deformed during DA, form large and small scale symmetric boudinage structures (Photo 1a, Fig. 4). Early isoclinal folds occur in places, trapped inside these boudinaged bodies.

Aplitic dykes, possibly formed simultaneously with the HT/LP metamorphism (SEIDEL et al. 1982), occur in the Asteroussia nappe cutting the SA foliation.

D0 event

The D0 event affected only the rocks of the Preveli group of the Vatos n. s. It is characterised by an E-W trending L0 mineral stretching lineation, a sub-horizontal to eastwards dipping, S0 foliation and by eastwards dipping D0 shear bands.

The parallel development of blue amphibole, chlorite, white mica and quartz (Photo 1b) trace the L0 stretching lineation (Fig. 2, 3b). As it can be seen in Fig. 3b, L0 trends from northeast-southwest to southeast-northwest, probably due to younger deformations.

The horizontal or eastwards dipping S0 foliation, formed by the parallel alignment of blue amphibole, K-feldspars, epidote, white mica and quartz associate the D0 shear bands.

The D0 shear bands occur as eastwards and locally westwards dipping, low-angle, ductile shear zones. Blue-amphibole crystals observed along the C-planes of the D0 shear zones are partly transposed and stretched (Photo 1b). The sense of shear indicated by S-C structures and ó-clasts is mainly towards the West (Fig.2).

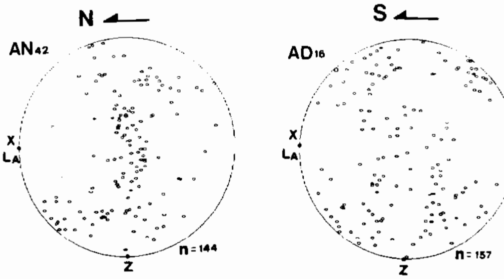


Fig. 4: Quartz c-axis textures from the Asteroussia nappe; lower hemisphere, equal area projections. X, Z, finite strain axes, n, number of measurements.

Σχ. 4: Προβολή σε διαγράμμα Schmidt c-αξόνων χαλαζία, από το κάλυμμα των Αστερουσίων. X, Z, άξονες του τελικού ελλειψοειδούς παραμόρφωσης, n, αριθμός μετρήσεων.

The $D0_1$-event

The DA structures in the area of Asteroussia mts and the D0 structures in the Plakias area are deformed by younger, mainly eastwards dipping, ductile to semiductile shear zones. Near the contact between the Asteroussia nappe and the Vatos group (Lentas area; Fig. 4), the SA foliation is totally transposed by a younger $D0_1$ event.

The $D0_1$ event was also observed at the base of the Ophiolitic nappe, in the Vatos n. s. and in the Pindos nappe. In the Gavrovo nappe, D0 structures were observed only in a few places in the lower carbonate rocks.

The most striking structure of this event are eastwards and in places westwards dipping, ductile to semi-ductile, $D0_1$ shear zones. The $D0_1$ shear zones dip with low- to middle-angles associated with an eastwards dipping $S0_1$ foliation and an eastwards plunging $L0_1$ stretching lineation (Fig. 3c,d).

$L0_1$ occurs in the Asteroussia and Vatos n. s. as a mineral stretching lineation, whereas, in the Pindos and Gavrovo nappes as a slickenside lineation (Fig. 2, 3c). Parallel alignment of chlorite, actinolite, calcite and quartz in the Vatos n. s., and of serpentinite, actinolite and calcite in the Ophiolitic bodies, trace the L0 lineation. Deformed calcitic pebbles in calcitic meta-conglomerates of the Preveli group expose their long axis parallel to the $L0_1$ stretching lineation.

$S0_1$ is defined in the Ophiolitic, Asteroussia and Vatos n. s. nappes by the parallel alignment of chlorite, epidote, white mica, calcite and quartz, while in the Pindos nappe by the shear planes.

In the Vatos n. s., isoclinal folds formed early on in the progressive deformation have their axial plane parallel to the $S0_1$ foliation and their b-axes parallel to the $L0_1$ lineation. In the area of Ag. Pavlos village angular, asymmetric, inclined folds deform the Palaeocene-Eocene platy

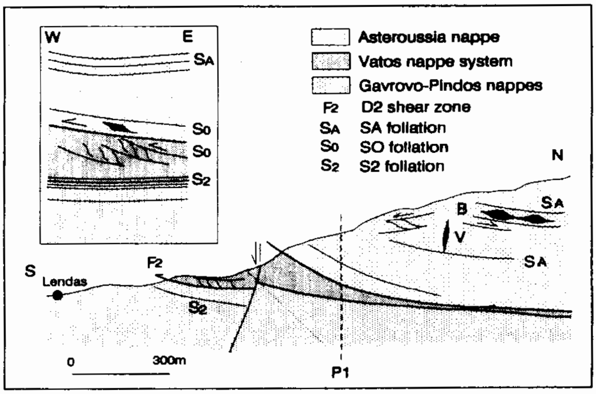


Fig. 5: Schematic N-S cross section in Lentas area (Fig. 2), illustrating the conjugate formation of the DA shear zones, the boudinaged bodies (B), and the extensional vein systems (V). The $D0_1$ shear zones, dominating in the nappe contact between Asteroussia and Vatos group, are also depicted in an E-W profile (P1).

Σχ. 5: Σχηματική Β-Ν τομή στην περιοχή του Λέντα (Σχ. 2), που δείχνει την συζυγή ανάπτυξη των DA ζωνών διάτμησης, τις boudinage-δομές (Β) και τις εφελκυστικές διακλάσεις (V), στο κάλυμμα Αστερουσίων. Επίσης απεικονίζονται σε μια τομή Α-Δ (P1), οι $D0_1$ ζώνες διάτμησης που κυριαρχούν στην επαφή των Αστερουσίων και της ενότητας του Βάτου.

limestones of the Pindos nappe (Photo 1c). The b-axes trend north-south, whereas the axial plane dips towards east, indicating a westwards vergence.

Kinematic indicators, such as S-C structures (Photo 1d), flat-ramp structures, and rotated boudins, observed in the $D0_1$ shear zones indicate a reverse, towards west and in places towards east, sense of shear. Thus, the $D0_1$ shear zones occur in the Asteroussia and Vatos n. s. as reverse, ductile to semiductile shear zones, while, in the Ophiolitic, Pindos and Gavrovo nappes as reverse faults or thrust zones.

These zones dominate in the contacts between the groups of the Vatos n. s. in the areas of Plakias and Spili, causing a tectonic mixture of the unmetamorphosed and metamorphosed groups. $D0_1$ shear zones occur also in the nappe contact between the Asteroussia nappe and the Vatos group in the area of Lentas (Fig. 4; Photo 1d), in contacts between the Pindos lithological units, and in the Pindos flysch (Fig. 2).

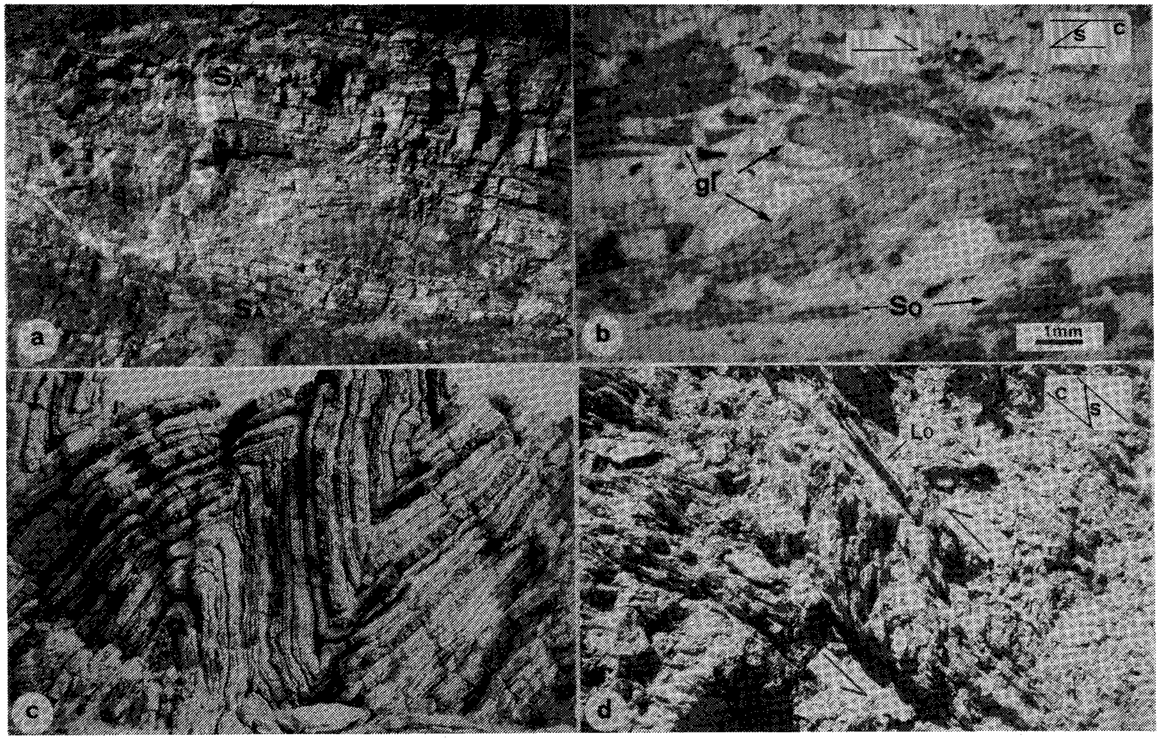
Semi-ductile normal shear zones, dipping eastwards or westwards were formed probably in a progressive stage of $D0_1$ event, as they cut in places the $S0_1$ foliation.

The $D0_1$ shear zones are in places deformed by the younger D1 structures that caused the southwards thrusting of the Vatos n. s. over the Pindos and Gavrovo nappes in the areas of Moni Preveli and NE of Spili (Fig. 2).

Strain analysis

Strain analysis of the pre-Oligocene deformation was carried out in the upper nappes by the study of the progressive deformation and the finite strain.

Extensional vein systems observed in five places in the upper nappes on the X-Y planes of the finite strain ellipsoid (X>Y>Z), were studied for the determination of the incremental extensions (RAMSEY & HUBER 1983). The results are depicted in Fig. 2 as straight lines with lengths analogous to



Phot. 1. **(a)**: Symmetric boudinage formation, during DA, of quartzites in the Asteroussia nappe. SA, SA foliation, North is at the right-side of picture, (b). Parallel to L0 development and stretching of blue amphiboles (gl). S-C structures indicate westwards sense of shear. S0, S0 foliation. (Sample SE15, XZ section) from the Preveli group, (c). Asymmetric, angular, $D0_1$ folds in the platy limestones of Pindos nappe, indicating westwards vergence. (d). East wards dipping $D0_1$ shear zones, at the contact between Asteroussia nappe and Vatos group in the area of Lentas (Fig. 2), indicate westwards sense of shear. $S0_1$, $S0_1$ foliation.

Φωτ. 1. **(a)**: Συμετρική boudinage ανάπτυξη κατά την διάρκεια του DA γεγονότος, στο κάλυμμα των Αστερουσίων. SA, SA σχιστότητα. Ο Βοράς είναι στα δεξιά της εικόνας, (b). Παράλληλη στην L0 ανάπτυξη και έκταση μπλέ αμφιβόλου (gl), από την ενότητα του Πρέβελη (δείγμα SE15, XZ τομή). S-C δομές δείχνουν κίνηση προς τα δυτικά. S0, S0 σχιστότητα, (c). Γωνιώδεις, ασύμμετρες $D0_1$ πτυχές στους πλακώδεις ασβεστόλιθους της Πίνδου, δείχνουν φορά προς τα δυτικά, (d). $D0_1$ ζώνες ολίσθησης, με βύθιση προς τα ανατολικά, που κυριαρχούν στην επαφή του καλύμματος των Αστερουσίων με την ενότητα του Βάτου, στην περιοχή του Λέντα (Σχ. 2). Κίνηση προς τα δυτικά. $S0_1$, $S0_1$ σχιστότητα.

the percentage of individual extensions. Two of them (Z2, Ã27) were analysed in a previous study (FASSOULAS et al. 1993).

Extension increments observed in the Vatos n. s. (samples K35 and K37 from the Spili group) indicate a first extension of about 3% in the N-S direction, a second increment trending E-W of aproximately 4% extension and two other increments in the N-S direction (Fig. 2). One sample from the Asteroussia nappe (sample Θ26) indicated a first extension increment in the E-W direction of about 4% and a later in the NNW-SSE direction of 1% extension. The other samples (Z2, Γ27), observed in the Pindos and in the Gavrovo nappes, indicated also a first increment of aproximately 5% extension in the E-W direction and two later increments in the NNW-SSE and N-S direction, of the same amount of extension.

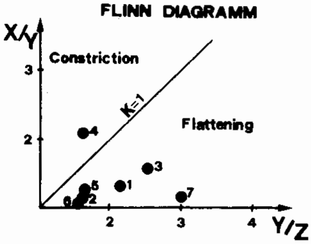


Fig. 6: Finite strain analysis results of the upper nappes plotted onto Flinn diagramm (FLINN, 1978), K=(Rxy-1)/(Ryz-1). Numbers refer to the ellipses of Fig. 2.

Σχ. 6: Προβολή των αποτελεσμάτων της ανάλυσης της τελικής παραμόρφωσης στα ανώτερα καλύμματα, σε διάγραμμα Flinn (FLINN 1978), K=(Rxy-1)/(Ryz-1). Οι αριθμοί αντιστοιχούν στις ελλείψεις του Σχ. 2.

The results of the progressive deformation measurements represent the later extension increments of the tectonic events which took place under semi-brittle to brittle conditions (RAMSEY & HUBER 1983).

The finite strain was measured in two principal perpendicular sections of the finite strain ellipsoid (XZ, YZ, X>Y>Z). X direction was regarded to be parallel to the stretching lineation (LA or $L0_1$) and XZ, YZ sections perpendicular to the foliation. The Fry (FRY 1979; CRESPI 1986) and the Rf/φ (DUNNET 1969) methods were applied in pure quartzites and conglomerates, deformed during DA, $D0_1$ events under ductile to semi-ductile conditions, of the Asteroussia and the Vatos nappes.

The majority of the derived strain ellipsoids lie in the field of apparent flattening (Fig. 6; FLINN 1978). The XY sections of these ellipsoids are plotted in Fig. 2.

DISCUSSION

Kinematic and strain analyses in the area of central Crete of the upper Alpine metamorphosed and the underlying unmetamorphosed nappes, indicated that three tectonic events affected these upper nappes before the Oligocene. All these events were overprinted by the syn- to post-Oligocene deformations (Table 2).

The earlier DA event affected only the Asteroussia nappe and probably the crystalline rocks of the Vatos n. s. The syn-SA development of hornblende, garnet, biotite, andalusite, sillimanite and cordierite in the Asteroussia nappe, indicate that DA was syn-metamorphic to the Late Cretaceous HT/LP metamorphism (SEIDEL & OKRUSCH 1976, SEIDEL et al. 1981), and thus DA should be of the same, Late Cretaceous, age.

The conjugate development and the opposing sense of shear of the normal DA shear zones, the symmetric and intense boudinage of competent layers, the symmetric pressure shadows arround rigid bodies, and the perpendicular to the SA development of extensional vein systems, prove that DA took place under bulk coaxial deformation conditions. The intense stretching, estimated in a subhorizontal direction and the vertical contraction of the

Table 2: The tectonic and metamorphic events which affected till Miocene the nappes of central Crete.

DEFORMATION / **NAPPES**	**DA**	**DO**	**DO_1**	**DO1'**	**D2**
	N-S	E-W	ENE-WSW	NNW-SSE	N-S
OPHIOLITES	?	-	+	+	+
ASTEROUSSIA	+ HT/LP	-	+	+	+
VATOS N.S.	? HT/LP	+ HP/LT	+ LP/LT	+	+
PINDOS	-	-	+	+	+
GAVROVO	-	-	?	+	+
PHYLLITES	-	-	-	+ HP/LT	+ LP/LT
PLATTENKALK	-	-	-	+ HP/LT	+ LP/LT

isograds, during the syn-DA, HT/LP metamorphism indicate a crustal thinning during the DA, as suggested by HALL (1987).

Kinematic analysis of the D0 structures, observed only in the Preveli group (Table 2) indicated a westwards rotational deformation. The microfabric analysis of these D0 structures evidence that D0 event is syn- to post-metamorphic to the HP/LT metamorphism. Hence, D0 event should be related to a westwards subduction process, that caused the HP/LT metamorphism.

The $D0_1$ event affected all the upper nappes, i.e. the Ophiolitic, the Asteroussia, the Vatos n. s., the Pindos and the lower stratigraphic units of the Gavrovo nappe. The westwards reverse $D0_1$ shear zones affected both the DA and D0 structures in the Asteroussia and Preveli group, respectively and caused the tectonic mixture of the unmetamorphosed and the metamorphosed rocks constituting the Vatos n. s., and the westwards stacking in the Pindos and Gavrovo nappes. Hence, $D0_1$ event took place, under regional compressional conditions, after the Late Cretaceous DA event and the peak of the HP/LT metamorphism.

In Oligocene/Early Miocene, $D0_1$ structures were overprinted by the younger D1 compression (Table 2), which caused southwards nappe stacking (KILIAS et al. 1992, FASSOULAS et al. 1994).

The finite strain ellipsoids resulted from the strain analyses of the DA and $D0_1$ events, lie in the apparent flattening field indicating a possible volume loss during the progressive deformation. Whereas, the study of progressive deformation in the upper nappes revealed three groups of extensional increments. The third, N-S trending group was atributed to the Oligocene/ Miocene tectonics (FASSOULAS et al. 1993). The second, E-W trending group should thus atributed to the $D0_1$ event and the former, N-S trending group to the DA deformation.

All the structural, kinematic and strain analysis results indicate that $D0_1$ should be younger than the Late Cretaceous DA deformation and older than the Oligocene/Early Miocene D1 deformation. As $D0_1$ event deforms also the Eocene flysch-like sediments of the Vatos group and the Eocene flysch of the Pindos nappe, its age should be of Late Eocene/Early Oligocene. Thus, the westwards stacking of the upper nappes (Pindos, Vatos n. s., Asteroussia and Ophiolites) and the tectonic mixture of the Vatos n. s., took place in Late Eocene/Early Oligocene, after the HT/LT metamorphism of the Asteroussia nappe and the HP/LT metamorphism of the Preveli group.

The synmetamorphic to the HP/LT metamorphism, DO event thus should be older than the Late Eocene/Early Oligocene $D0_1$ event. SEIDEL et al. (1977) and BONNEAU (1984) suggested that the HP metamorphism of the Vatos n. s. should be of Upper Jurassic in age, similar to the metamorphism of the "Kalypso unit" of Gavdos (VICENTE 1970). However, petrological and tectonic studies revealed that only a few, MT/HP metamorphic rocks of the Spili group (these near the Gerakari village) can be similar with the "Kalypso unit". Thus, the age of the HP/LT metamorphism of the Preveli group, and consequently of the D0 event, could be younger than Upper Jurassic. Probably the age of the HP/LT metamorphism of the Vatos n. s. should be analogous to the Eocene HP/LT metamorphism of the Cycladic area (ALTHERR et al. 1979, ANDRIESSEN et al. 1979), as both nappes possess similar tectonostratigraphic possitions in the nappe pilles and have similar petrology.

Hence, the westwards D0 shearing could have taken place in Paleocene-Eocene, simultaneously with the subduction of the Preveli group. The younger $D0_1$ event could be the evolutionary, collisional stage of this subduction process.

The differences in the geometry and the conditions of the tectonic events, affected the area of Crete from Late Cretaceous to Oligocene, can be interpreted by the independend rotation of the Apulia microcontinent (ZIJDERVELD et al. 1970, TAPPONNIER 1977, DERCOURT et al. 1986). From the Late Jurassic to Late Cretaceous/Paleocene (DERCOURT et al. 1986), Apulia was under an extensional regime, due to its relative, in respect to Africa, counter clockwise rotation. The DA deformation could thus be related to the regional extension of Apulia, indicating that the crystalline rocks of the Asteroussia and Vatos n.s. nappes may represent parts of the Apulia microcontinent, as also has been suggested by HALL (1987). From the Paleocene to Oligocene, Apulia acted as an African intenter and was collided with Europe along a sinistral strike slip zone (DERCOURT et al. 1986). This sinistral strike slip collision may have caused the westwards D0 shearing and $D0_1$ compression. In Oligocene (DERCOURT et al. 1986), the relative displacement between Apulia/Afrika and Europe changed into dextral causing the Oligocene/Early Miocene D1 compression.

CONCLUSIONS

Kinematic and structural analyses, in the area of central Crete, of the pre-Oligocene metamorphosed rocks of the upper nappes enables the distinguishment of three Alpine tectonic events, a Late Cretaceous DA, a probably Palaeocene-Eocene D0, and an Late Eocene/Early Oligocene $D0_1$ event.

The pre-Oligocene structural evolution in the area of Crete can be interpreted as follows:

During the Late Cretaceous, the pre-Alpine crystalline rocks of the Asteroussia nappe and the Vatos nappe system were affected by a regional N-S stretching event. This caused an intense crustal thinning and the development of the HT/LP metamorphism.

Probably in Palaeocene-Eocene, the westwards D0 shearing took place in the Preveli group of the Vatos n. s., simultaneously with the development of the HP/LT metamorphic conditions.

A younger E-W trending $D0_1$ compressional event caused, in Late Eocene/ Early Oligocene westwards shearing and stacking of the upper pre-Oligocene metamorphosed nappes (Ophiolites, Asteroussia and Vatos n. s.), tectonic mixure of the Vatos n. s., and internal stacking in the Pindos nappe.

In Oligocene/Early Miocene a NNW-SSE compression affected the nappe pile causing southwards nappe stacking and development of HP/LT metamorphic conditions in the lower nappes.

The structural evolution of Crete may be related to the independend, in respect to Europe and Afrika, rotation and behavior of the Apulia microcontinent.

ACKNOWLEDGMENTS

C. Fassoulas was financially supported by the Tect/1992 program of the National Grants Foundation of Greece (I.K.Y.).

REFERENCES

ALTHERR, R., SCHLIESTEDT, M., OKRUSCH, M., SEIDEL, E., KREUZER, H., HARRE, W., LENZ, H., WENDT, I. and WAGNER, G. (1979): Geochronology of high-pressure rocks on Sifnos (Greece, Cyclades). -*Contr. Miner. Petrol.*, 70, 245-255.

ANDRIESSEN, P.A., BOELRK, N.A., HERBEDA, E.H.,, PRIEM, H.M., VERDURMEN, E.A. and VERSHURE, R.H. (1979): Dating the metamorphic and granitic magmatism in the Alpine Orogen at Naxos (Cyclades, Greece). -*Contr. Miner. Petrol.*, 69, 215-225p.

BONNEAU, M. (1973): La nappe metamorphique de l'Asteroussia, lambeau d'affinites pelagoniennes charrie jusque sur la zone Tripolitza de la Crete moyenne (Grece). -*C.R. Ac. Sc. Paris*, 2303-6.

BONNEAU, M. (1984): Correlation of the Hellenides nappes in the south-east Aegean and their tectonic reconstruction. -*Geol. Soc. London, sp. publ.*, 17, 517-527.

BONNEAU, M. and FLEURY, J.-J. (1971): Precisions sur la serie d' Ethia (Crete, Grece): existence d' un premier flysch mesocretace. -*C.r. Seances Acad. Sci. Paris*, 272, 1840-1842.

BONNEAU, J., ANGELIER, J. and EPTING, M. (1977): Reunion extraordinaire de la Societe geologique de France en Crete. -*Bull. Soc. geol. Fr.*, 19, 87-102.

CRESPI, J.-M. (1986): Some quidelines for the practical application of Fry's method of strain analysis. -*J. Struct. Geol.*, 8, 799-808, 1986.

CREUTZBURG, N. and SEIDEL, E. (1975): Zum Stand der Geologie des praneogens auf Kreta. -*N. Jb. Geol. Palaont. Abh.*, 149, 363-383.

DAVIS, E.-N. (1967): Uber das Vorkommen granitischer Gesteine innerhalb des metamorphen Systems der Asterousia-Gebietes der Insel Kreta. -*Prac. Acad. Athens*, 42, 253-270.

DERCOURT, J., ZONENSHAIN, L.-P., RICOU, L.-E., KAZMIN, V.-G., LE PICHON, X., KNIPPER, A.-L., GRANDJACQUET, C., SBORTSHIKOV, I.-M., GEYSSANT, J., LEPVRIER, C., PECHERSKY, D.-H., BOULIN, J., SIBUET, J.-C., LAVOSTIN, L.-A., SOROKHTIN, O., WESTPHAL, M., BAZHENOV, M.-L., LAUER, J.-P., and BIJU-DUVAL, B., (1986): Geological evolution of the Tethys belt from the Atlantic to the Pamirs since the Lias. -*Tectonophysics*, 123, 241-315.

DUNNET, D. (1969): A technique of finite strain analysis using elliptical particles. -*Tectonophysics*, 7, 117-136.

FASSOULAS, C., KILIAS, A. and MOUNTRAKIS, D. (1994): Post-nappe stacking extension and exhumation of the HP/LT rocks in the island of Crete, Greece. -*Tectonics, 13*, 127-138.

FASSOULAS, C., KILIAS, A., MOUNTRAKIS, D. and MARKOPOULOS, T. (1993): Study of progressive deformation using extensional vein systems and paleostress analysis, in central Crete. -*Bull. Geol. Soc. Greece.*, (in press).

FLINN, D. (1978): Construction and computation of the three- dimensional progressive deformations. -*J. Geol. Soc., Lond.*, 135, 291-305.

FYTROLAKIS, N. (1978): Contribution to the geological study of Crete. -*Bull. Geol. Soc. Greece, XIII/2*, 101-115.

FRY, N. (1979): Randomly distributions and strain meassurements in rocks. -*Tectonophysics*, 60, 89-105.

HALL, R. (1987): Basement and cover rock history in the western Tethys: HT/ LP metamorphism associated with extensional rifting of Gondwana. -*In Audley-Charles, M. & Hallam, A. (eds), Gondwana and Tethys, Geol. Soc. London, spec. Publ.*, 37, 41-50p.

HALL, R., AUDLEY-CHARLES, M.-G. and CARTER, D.-J. (1984): The significance of Crete for the evolution of the eastern Mediterranean. -*Geol. soc. London, sp. publ.*, 17, 499-516.

KILIAS, A., FASSOULAS, CH. and MOYNTRAKIS, D. (1992): Tertiary extension of continental crust and uplift of Psiloritis "Metamorphic core complex", in the central part of the Hellenic arc (Crete, Greece). -*Bull. Geol. Soc. Greece*, (in press).

KRAHL, J., HERBART, H. and KATZENBERGER, S. (1982): Subdivision of the allocthonous Ophiolites-bearing formation upon the Pindos group, southwestern part of central Crete, Greece. -*In H.E.A.T., proc.*, vol. 1, 324-342., Athens.

LIPPOLT, HJ. and BARANYI, I. (1976): Oberkretazische Biotit- und Gesteinsalter aus Kreta. -*N. Jb. Geol. Palaontol., Mh.*, 1976, 405-414.

LISTER, G.-S. & HOBBS, B.-E. (1980): The simulation of fabric development during plastic deformation and its application to quartzite: the influence of deformation history. -*J. Struct. Geol.*, 2, 355-370.

LISTER, G.-S. and SNOKE, A.-W. (1984): S-C Mylonites. -*J. Struct. Geol.*, 6, 6,617-138.

PASCHIER, C.-W. and SIMPSON C. (1986): Porphyroclast systems as kinematic indicators. -*J. Struct. Geol.*, 8, 831-843.

PLATT, J.-P. & VISSERS, R.-L.-M. (1980): Extensional structure in anisotropic rocks. -*J. Struct. Geol.*, 2, 397-410.

RAMSAY, G.,J. and HUBER, I., M. (1983): The techniques of modern structural geology, vol. 1 & 2. -*Academic press Inc. XIII+307 S.*

SANNEMANN, W. and SEIDEL, E. (1976): Die Trias-Schichten von Rawducha/NW-Kreta. Ihre Stellung im Kretischen Deckenbau. -*N. Jb. Geol. Palaontol. Mh.*, 1976, 221-228.

SEIDEL, E. (1971): Die Pindos-Serie in West Kreta, auf der Insel Gavdos und im Kedros-Gebiet (Mittelkreta). -*N. Jb. Geol. Palaont. Abh.*, 137, 443-460.

SEIDEL, E. and OKRUSCH, M. (1976): Eo-Alpine metamorphism in the uppermost unit of the Cretan nappe system- petrology and geochronology. -*Contr. Miner. Petrol.*, 57, 259-275.

SEIDEL, E., KREUZER, H. and HARRE, W. (1982): A Late Oligocene/Early Miocene High Pressure Belt in the external Hellenides. -*Geol. Jb.*, E 23, 165-206.

SEIDEL, E., SCHLIESTEDT, M., KREUZER, H. and HARRE, W. (1977): Metamorphic rocks of Late Jurassic age as components of the ophiolitic melange on Gavdos and Crete (Greece). -*Geol. Jb.*, B 28, 3-21.

SEIDEL, E., OKRUSCH, M., KREUZER, H., RASCHKA, H. and HARRE, W. (1981): Eo-Alpine metamorphism in the uppermost unit of the Cretan nappe system, petrology and geochronology: Part 2. Synopsis of high temperature metamorphics and associated ophiolites. -*Contr. mineral. petrol.*, 76, 351-361.

TAPPONNIER, P., (1977): Evolution tectonique du system alpin en Mediterranee; poinconnement et ecrasement rigite-plastique. -*Bull. Soc. Geol. Fr.*, 7, 19, 437-460

THEYE, T., SEIDEL, E. and VIDAL, O. (1992): Carphollite, sudoite and chloritoid in low high-pressure metapelites from Crete and the Peloponneses, Greece. -*Eur. J. Mineral.*, 4, 487-507.

THORBECKE, G. (1973): Die Gesteine der Ophiolith-Decke von Anogia/Mittel kreta. -*Berichte Naturforsch. Gesell. Freiburg*, 63, 81-92

VICENTE, J. C. (1972): Etude geologique de l'lle de Gavdos (Grece), la plus meridionale de l' Europe. -*Bull. Geol. Soc. France*, (7), XII, 481-495.

ZIJDERVELD, J., HAZEU, G., NARDIN, M. and VAN DER VOO, R. (1970): Shear in the Tethys and the Permian paleomagnetism in the southern Alps, including new results. -*Tecotnophysics*, 10, 639-661.

WURM, A. (1950): Geologishe Beobachtungen im Asteroussis. -Gebirge auf der Insel Kreta. -*Bull. Geol. Soc. Greece, 2*, 80-87.