ABSTRACT CODE: SG21_270

Δελτίο της Ελληνικής Γεωλογικής Εταιρίας τομ. XXXVI, 2004
Πρακτικά 10ου Διεθνούς Συνεδρίου, Θεσ/νίκη Απρίλιος 2004

Bulletin of the Geological Society of Greece vol. XXXVI, 2004
Proceedings of the 10th International Congress, Thessaloniki, April 2004

PATTERNS AND CONDITIONS OF DEFORMATION IN THE PLATTENKALK NAPPE, CRETE, GREECE: A PRELIMINARY STUDY

Fassoulas C.[1], Rahl J.M.[2], Ague J.[2], and Henderson K.[2]

[1] *Natural History Museum of Crete, University of Crete, Irakleio, 71409, Crete, Greece, fassoulas@nhmc.uoc.gr,*

[2] *Department of Geology and Geophysics, Yale University, P.O. Box 208109, New Haven, Connecticut 06520-8109, USA, jeffrey.rahl@yale.edu, jay.ague@yale.edu, Katryn.henderson@yale.edu*

ABSTRACT

We present preliminary results from an ongoing study of deformation and fluid flow within the meta-carbonates of the Plattenkalk nappe exposed in central and western Crete, Greece. Deformation was controlled by lithological properties and is mainly expressed as large to meso-scale folds and localized thrusts. Folds along several profiles are mainly asymmetric flexural-slip folds with south to southeast vergence, sub-horizontal east-west trending fold axes, and variable fold opening angles. The large folds commonly invert the stratigraphic section. Variable recrystallization near cracks and bedding contacts within the carbonate rocks suggests that localization of fluids into channelways left much of the rock sequence “dry” during metamorphism. The style of the late Tertiary deformation and general tectonic setting for the Plattenkalk nappe suggests that accretion and deformation are “thin-skinned”.

1 INTRODUCTION

The island of Crete is the southernmost extension of the Hellenide mountain chain that formed during late Tertiary convergence between the European and African plates. Structurally, the island is composed of at least 7 distinct allochthonous units stacked during the Oligocene (Bonneau 1984, Papanikolaou 1988, Fassoulas 1999; Fig. 1). Several of these units, collectively referred to as the lower nappes, record a late Oligocene high-pressure, low-temperature (HP-LT) metamorphism associated with nappe-stacking and underplating of sediments (Seidel et al. 1982, Theye et al. 1992, Jolivet et al. 1996; Fig. 1). Peak metamorphic conditions of 0.9-1.0 GPa and 350-400 °C were achieved at about 24 Ma (Jolivet et al. 1996, Theye & Seidel 1991). This history contrasts with that of the upper nappes, which have resided in the upper 6-10 km of the upper crust for the past 40 Ma (Thomson et al. 1998a). The large metamorphic break between the upper and lower nappes suggests that normal faults have excised the middle crust and played a significant role in the exhumation of the HP-LT rocks (Fassoulas et al. 1994, Jolivet et al. 1996, Stöckhert et al. 1999, Thomson et al. 1998b). Detailed thermochronologic work suggests that extensional exhumation began by about 20 Ma, soon after peak metamorphism (Thomson et al. 1998b).

Deformation associated with subduction, underplating, and subsequent exhumation is observable in several of the lower nappes. The structurally shallowest high-pressure nappe is the Phyllite-Quartzite (PQ) unit, a Late Carboniferous to Late Triassic package of sedimentary rocks composed mostly of quartz-rich siliciclastic sediments, with minor limestone, gypsum, and volcanic rocks (Krahl et al. 1983). The PQ underwent significant deformation, as indicated by meso-scale folds (wavelength10-20m), a pervasive subhorizontal foliation, and brittle shear zones.

The deepest and most extensive tectonostratigraphic unit is the Plattenkalk nappe (PK), a 5 km thick package (Bonneau 1976) of Permian to Oligocene metacarbonate rocks. The PK has been interpreted to represent the sedimentary cover of a continental platform (known as Apulia or Adria) that was overridden by the more internal Hellenide nappes of mainland Greece during Tertiary con-

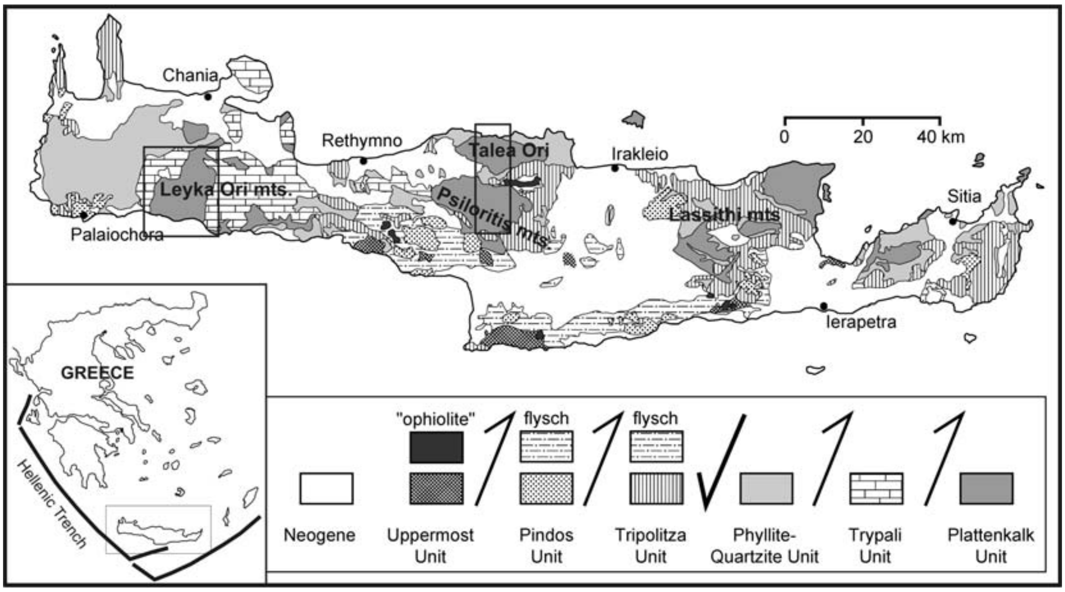

Figure 1. General geological map of Crete and nappe relations (slightly modified from Creutzburg et al. 1977, Seidel et al. 1982, Thomson et al., 1998b). Areas for the detailed maps of Figs. 2a and 4a denoted by boxes.

vergence. Bonneau (1984) correlated the PK with the carbonates of the Ionian Zone of western mainland Greece. Although its base is not observed on Crete, the presence of an active subduction zone suggests that the PK is an allochthonous unit. This interpretation is consistent with observations from the east in Rhodes, where the PK (Lindos nappe) is found thrust above a more outboard carbonate platform associated with the "pre-Apulian domain" from mainland Greece (Bonneau 1984).

The PK is commonly overturned in large recumbent folds found in some areas. Nonetheless, the unit maintains a coherent, well-defined internal stratigraphy that allowed, for example, abundant Permian fossils to remain completely undeformed (Epting et al. 1972). The PK rocks generally lack the penetrative structures of the PQ but often contain localized shear zones near the nappe contacts (Fassoulas et al. 1994). At a micro-scale the bulk of the nappe appears undeformed, although meso- to mega-scale folding is common in many areas. In some areas large-scale, asymmetric folding yielded overturned series as in the Talea Ori Mountains in central Crete (Bonneau 1976). Other studies (Hall & Audley-Charles 1983, Papanikolaou 1988) suggest that intense, meso-scale, isoclinal folding may explain the overturned outcrops.

The geologic relations suggest that the PK was buried more deeply than the PQ, but deformation patterns and the metamorphic history of the PK have been relatively little studied. For example, several important questions regarding the tectonic evolution of the PK remain to be addressed. (1) What were the tectonic conditions during the period of underplating and exhumation of the rocks and how was deformation internally localized to preserve undeformed Permian fossils? (2) What were the peak metamorphic conditions experienced by the nappe? (3) How was the metamorphism related to the tectonic activity?

To better understand these questions we are studying deformation patterns, crystallization processes, and the regional tectonic setting along specific profiles in the PK rocks in several characteristic outcrops of Crete. To date we have mapped in detail the folding pattern and collected samples that preserve valuable information regarding the metamorphism and deformation. This contribution reports the preliminary findings of our study.

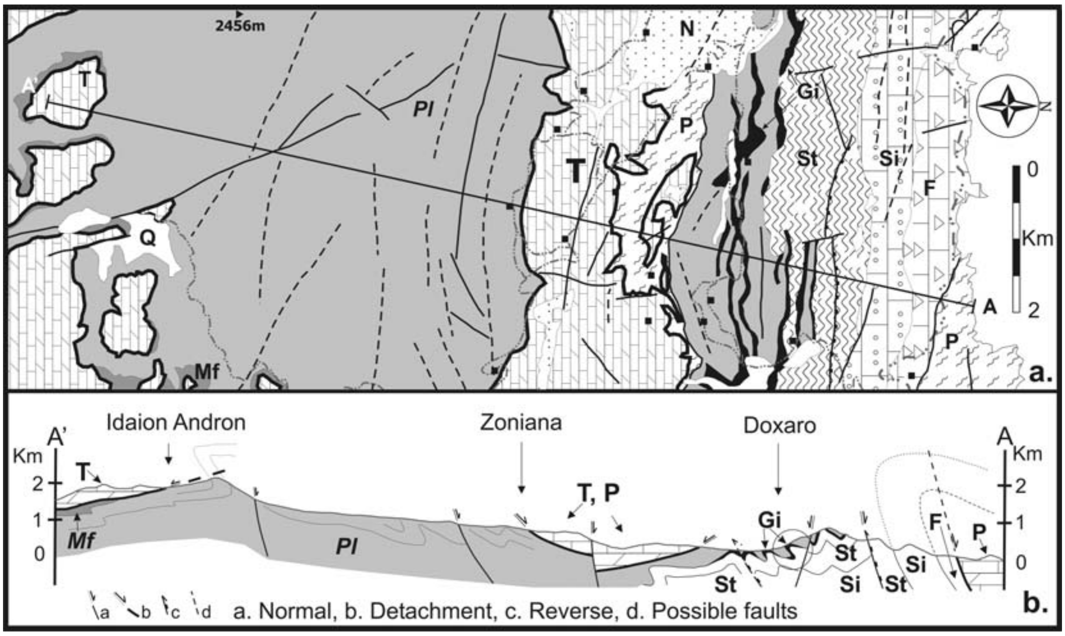

Figure 2. a. Geological map of Central Crete based on geological maps of IGME (1984, 2004) and Fassoulas (1999). b. Cross section of Psiloritis Mountains. showing folding of Plattenkalk nappe and main tectonic features (equal horizontal and vertical scales). Location of Fig. 3 denoted by circle. Symbols are: F, the *Fodele* beds; Si, *Sisses* beds; St, stromatolites; Gi, *Gigilos* beds; Pl, Platy marbles; Mt, meta-flysch; P, Phyllite-quartzite nappe; T, Tripolitza nappe; N, Neogene sediments; Q, Quaternary sediments; double-dotted line, the main roads.

2 GEOLOGICAL SETTING OF STUDY AREAS

2.1 The Plattenkalk group

The Plattenkalk Group is a 5 km thick carbonate sequence deposited over a period of about 300 m.y. (Epting et al. 1972, Bonneau 1984). Sedimentation of clastic marine, deposits and neritic carbonates began in the Late Permian, changing gradually into more pelagic sediments with silica intercalations by the Upper Jurassic. The oldest rocks, known as the *Fodele* beds, contain clastic sediments, dark dolomites and limestones of Late Permian age. Remarkably well-preserved corals, brachiopods and bryozoa are locally present within the dolomites (Epting at al. 1972). A series of clastic dolomites and limestones of Upper Permian to Scythian age (the *Sisses* beds) conformably overlie the *Fodele* rocks. Sedimentation ceased following deposition of the *Sisses* rocks until the Norian, when a typical stromatolite-rich dolomite and overlying calcite-rich limestone were deposited. The unconformity is now marked by karstic erosional surfaces and is occupied by a meta-bauxite horizon. Another late Norian unconformity marks the contact with the overlying shales, platy dolomite and brecciated limestones (the *Gigilos* beds).

A package of distinctive platy marbles (originally limestones) containing cherty nodules and horizons were deposited in Upper Jurassic times. The platy marbles comprise a succession of thin (ranging from several cm to a few dm) metamorphosed limestone beds and silica-rich intercalations; in central Crete the total thickness of these beds is about 2 km. Red radiolarites are found in the upper stratigraphic horizons and gradually pass into a thin (less than 50 m), late Oligocene, calcareous flysch.

Although the Plattenkalk nappe is exposed throughout Crete, particularly in the areas of high mountains, the entire stratigraphic section is preserved only in central Crete (Fig. 1). In all other areas just the upper stratigraphic horizons (including the distinctive platy marbles and meta-flysch) are found. Excellent exposures of the PK are also available in dozens of large gorges carved by recent river incision. Thus, this study focuses on two areas: (1) a north-south transect in central Crete

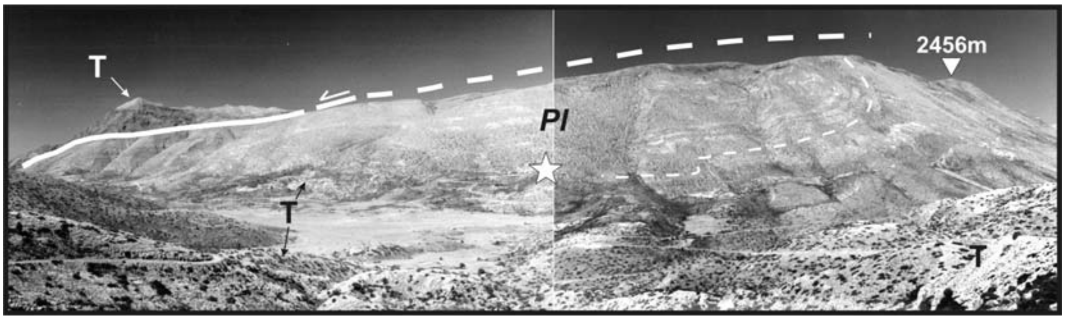

Photo 1. Panoramic view of Psiloritis Mountains looking west. Thick white line, south-dipping major detachment fault; thin-dashed white line, folded bedding; star, Idaion Andro cave over Nida Plateau. Symbols as in Fig. 2.

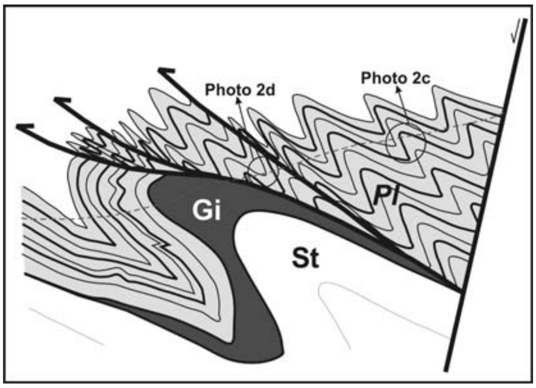

Figure 3. Deformation pattern in the Vossakos area, Talea Ori Mountains (see Fig. 2b). St, stromatolites; Gi, *Gigilos* beds; Pl, Platy marbles; thick lines, thrust faults; straight line, normal fault; dashed line, the topography.

from the Psiloritis Mountains to the northern coast (Fig. 1), where the entire stratigraphic section is exposed; and (2) a north-south section through the Samaria gorge in western Crete (Fig. 1), where recent river incision has created an accessible and continuous section through the upper horizons of the PK.

2.2 Geology in Central Crete

In central Crete, the PK crops out in the Psiloritis Mountains in the core of the island and in the Talea Ori Mountains along the northern coast (Figs 1, 2a). The intermediate Mylopotamos valley is a Neogene graben covered by a small appearance of the PQ nappe to the west and the upper nappes at the central and eastern parts.

We have constructed a detailed north-south cross section based on published geological maps (IGME 1984, 2004) and field observations, from the northern coast through the Psiloritis Mountains (Fig. 2b). The northern flanks of the Talea Ori Mountains expose an inverted series of the stromatolitic dolomite and the *Sisses* and *Fodele* beds (IGME 1984 2004, Epting et al. 1972, Bonneau 1984, Hall & Audley-Charles 1983). The inverted series overrides the normal-lying beds of the southern Talea Ori flanks in the hanging wall of a large thrust fault within the stromatolitic dolomite in the Talea Ori area. Landscape morphology and kinematic criteria suggest that this structure was likely reactivated latter as a normal fault. In this area, the *Gigilos* beds and the overlying platy marbles form large synclines and anticlines that dip below the main normal detachment fault near the villages of Damasta and Aimonas (Figs 2b, 3). Here, the detachment fault has a top-south sense of motion, with the upper plate rocks resting directly on the PK (Fassoulas et al. 1994).

The lithology of the PK in the Psiloritis Mountains is monotonous, primarily composed of the characteristic interbedded marbles and meta-cherts of the upper stratigraphic horizons. Qualitatively, the intensity of small-scale folds within the platy marble appears to increase near the area of the Nida Plateau and summit of the Psiloritis Mountains. Here, the marbles pass gradually to the meta-flysch. The lowermost unit of the upper nappes commonly caps the mountain tops in the area, separated from the lower PK nappe by a large detachment fault (Photo 1).

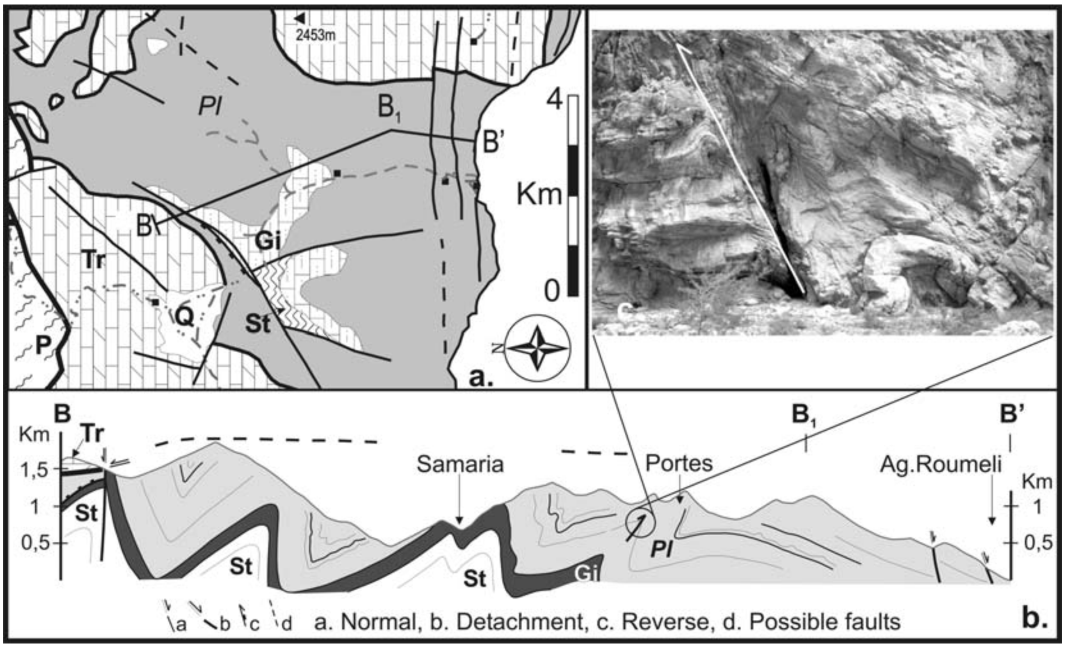

Figure 4. a. Geological map of Samaria area modified from Creutzburg et al. (1977) and Fytrolakis (1980). b. Cross section in Samaria area showing the folding of Plattenkalk nappe and major tectonic features (equal horizontal and vertical scales). c. Differential asymmetric folding in Samaria area inferred to be result of competence contrasts. Angular, isoclinal folding in thin-bedded marble; cylindrical, tight, folding in thick-bedded marble. Note thrust fault (white line) that developed during progressive deformation. Unlike the cross-section, the photo has north to the right. Symbols are: St, stromatolites; Gi, *Gigilos* beds; Pl, Platy marbles; P, Phyllite-quartzite nappe; Tr, Tripali nappe; Q, Quaternary sediments; double-dotted line, the main roads; gray-dashed line, Samaria stream.

2.3 Samaria area

The area around the Samaria Gorge is primarily composed of the PK and the overlying metacarbonate rocks of the Trypali nappe (Fig. 4). The rocks of the Trypali nappe crop out in the area north of the Omalos plateau and along the tops of the Leyka Ori Mountains just east of the Samaria gorge. A detachment fault (exposed east of Kallergi's refuge in the Omalos area) separates the two units. We have constructed a north-south cross-section through the region, based on published geological maps (Creutzburg et al. 1977, Fytrolakis 1980) and new field observations from the Samaria gorge.

The gorge itself is entirely developed within rocks of the PK. The stromatolitic dolomite is exposed in the area of the Gigilos summit and again along the northwestern side of the gorge, forming a large anticline. The thickest outcrop of the *Gigilos* beds in Crete occurs in this area. Platy dolomites and schist crop out at the northern, very steep side of Samaria gorge(Xiloskalo area), extending northward from the Gigilos summit to the northeastern Leyka Ori Mountains and southward to the Samaria village. The contact between *Gigilos* beds and the overlying platy marble appears to be a thrust fault with shear indicators indicating top eastwards shear (Fig. 5), that was later overprinted by a northeast-southwest trending normal fault (Fig. 4). These faults are exposed near the top of the trail that crosses the Samaria gorge.

The typical platy marbles of the PK nappe crop out throughout the southern part of the gorge and the surrounding mountains. In places the platy marbles and the underlying *Gigilos* beds are intensely folded into large anticlines and synclines; small reverse faults tended to form at the fold hinges (Fig. 4b,c).

3 DEFORMATION AND FOLDING OF THE PLATTENKALK

Deformation within the PK is apparent throughout Crete as meso- to macro-scale brittle fault zones and folds. Most faults are associated with the late Tertiary to Quaternary regional extension that occurred throughout the southern Aegean (Angelier et al. 1982). An older set of faults is mainly composed of small thrusts related to folding. Existing geological maps as well as field observations do not support the presence of large overthrusts or duplexes within the PK. Asymmetric S-C structures are present locally within the brittle shear zones; these can be used as a shear-sense indicator (Fassoulas et al. 1994). Throughout Crete, most rocks of the PK lack any penetrative foliation. However, both the schists within the *Gigilos* beds and the Oligocene meta-flysch at the top of the stratigraphic section display a spaced cleavage or schistosity. These fabrics are either parallel to lithological contacts or parallel to the axial plane of nearby folds.

Folds are the most prominent structure within the PK, and all study areas contain km-scale to meter-scale folds. However, the magnitude and style of deformation varies with the lithology of the deforming strata. The relatively massive lower stratigraphic horizons have been deformed into large (100m scale) wave-length folds, with displacement between beds much like a card-pack. These beds deformed in a more competent manner than the thinly-bedded *Gigilos*, platy marble, and meta-flysch beds that commonly preserve primary sedimentary structures. These weaker layers behaved in a more ductile and heterogeneous manner and deformed in both large and meso-scale folds.

Throughout Crete large (in some cases km-scale), isoclinal to tight, disharmonic folds deform the entire stratigraphic section. The stratigraphy is locally overturned in large synclines and anticlines, as in the area of Talea Ori or Samaria (Figs 2, 4). The fold axes trend east-west and axial planes dip gently northward (Fig. 5). Folding is generally asymmetric, with the length ratio of the shorter, upturned or inverted limbs to the subhorizontal limbs usually ranging from 1:1 to 1:5, and locally reaching 1:10 (Figs 2, 4; Photos 1, 2a). In a few areas reverse faults terminate the folding succession, such as at the northern slopes in the Talea Ori Mountains where a large inverted anticline overrides the normal stratigraphy on a high angle reverse fault (Fig. 2).

In all areas the fold axes generally trend east-west and axial planes dip northward (Fig. 5). Some differences exist between the two detailed study areas; the fold axes and axial planes of the Samaria area show a more southwestward-northeastward trend than those in the Psiloritis area. These differences may be due to late Neogene counterclockwise block rotations in western Crete that may have exceeded 20° in some places (Duermeijer et al. 2000).

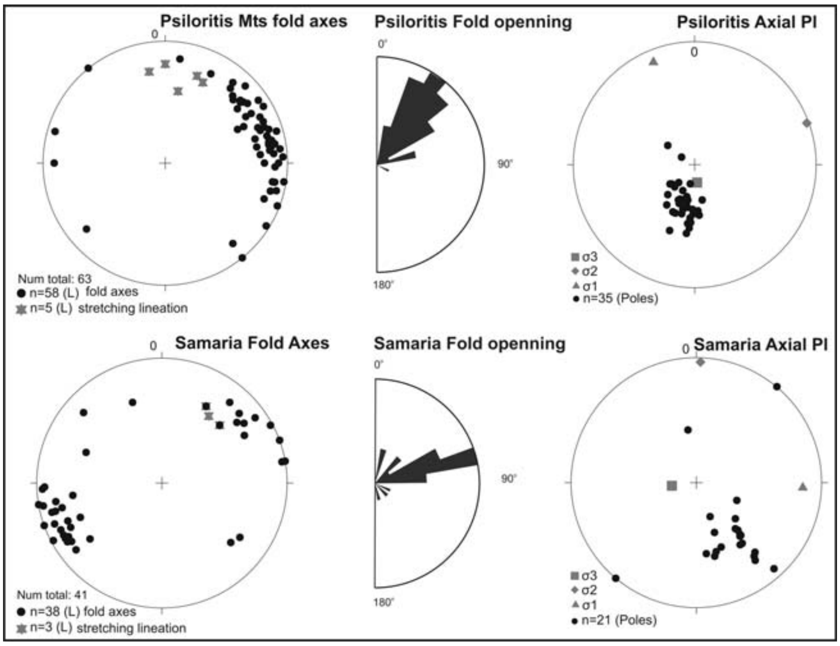

Figure 5. Lower hemisphere, equal area projections of fold axes and axial plane (poles) and fold opening diagrams in Psiloritis and Samaria areas.

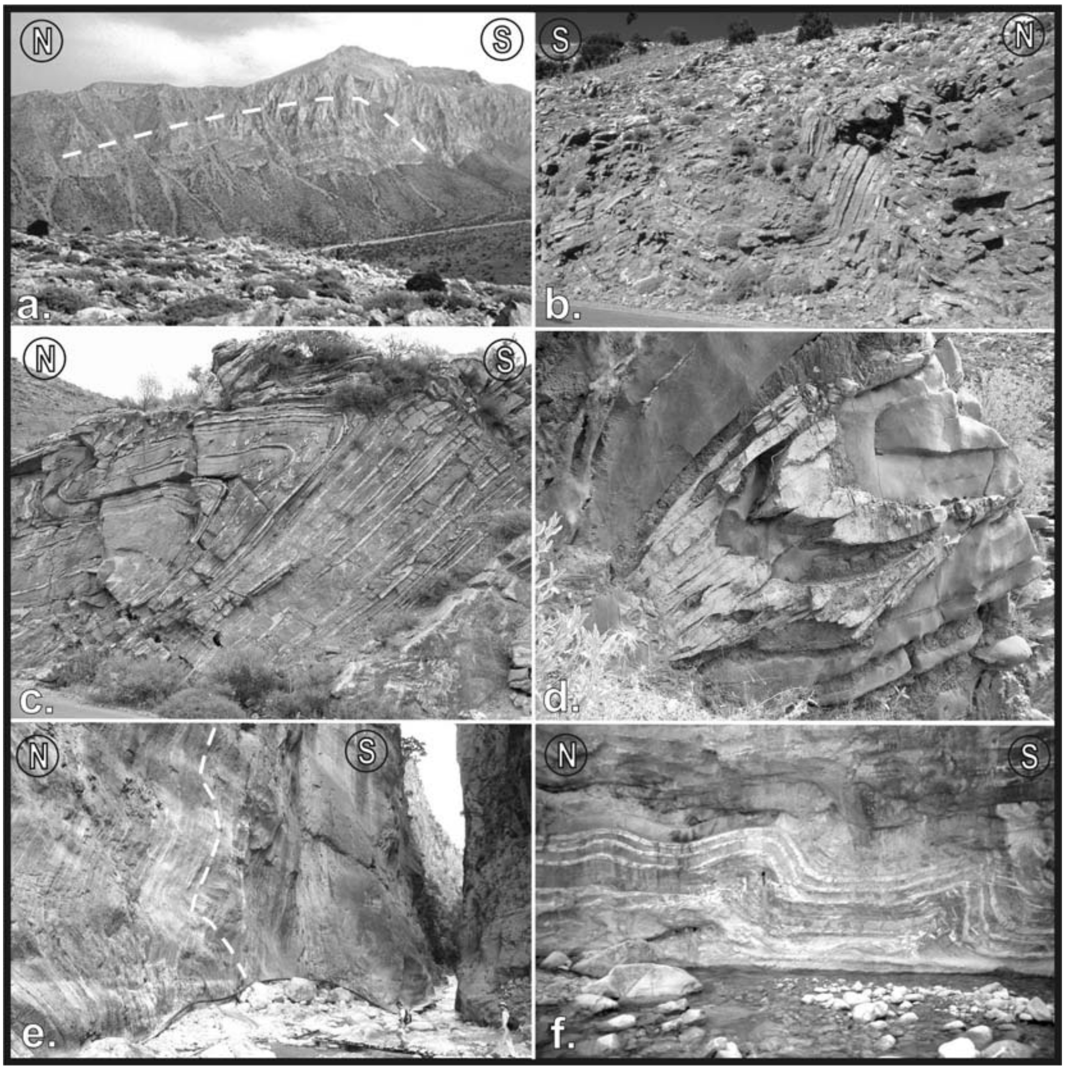

Photo 2. a. Large scale anticlinic structure (dashed line) at the face of Limnakaro fault, Lassithi mts (Fig. 1). b. Close, similar folding in Psiloritis Mountains (south of Anogia village), c. Recumbent, asymmetric fold in Vossakos area (see Fig. 3). Note thickening and buckle-folding at the inverted limb. d. Isoclinal folding and axial plane schistosity in Vossakos area (see Fig.3) illustrating a hinge zone thickened by flexural slip. e. Open angular folding at the inverted limb in Samaria gorge (Portes); axial plane approximately horizontal. f, Propagating deformation forming open-similar and asymmetric, drag folds in Samaria gorge. All pictures in platy marbles.

The nature of deformation also varies between the limbs of each asymmetric fold. The longer, subhorizontal limbs are characterized by one of two styles: 1) symmetrical and cylindrical, open to tight folds (Photo 2b), or 2) disharmonic and sometimes parasitic folds in layered sequences with strong competence contrasts (e.g., the *Gigilos* beds or the lower parts of the platy marbles). Unlike in the Psiloritis area, folds in the Samaria Gorge tend to be more open and angular, sometimes appearing as chevron-style folds. A shear cleavage between the platy marbles indicates top-south shear sense, similar to observations in the Psiloritis area.

The hinge zones indicate a markedly different style of deformation than the limbs. There, most folds are dominantly disharmonic, asymmetric, drag folds that become tighter down dip. The hinges commonly form narrow zones (10 to 30 meters wide) of tight to isoclinal, recumbent folds, as can be readily observed in the area of Vossakos in the Talea Ori Mountains (Figs 2b, 3). There the asymmetric folds tighten with increasing deformation, becoming recumbent (Photo 2c) and finally isoclinal (Photo 2d) near small reverse zones or faults having top-south shear sense. In areas with intense isoclinal folding, dilatational veins normal to the bedding and mullion structures are common, and a north-south plunging stretching and slickenside lineation is present on bedding planes (Fig. 5). Moreover, axial planar cleavage, shear folds and small-scale boudinage of competent siliceous layers are found within the hinge zones (Photo 2d). The hinge zones have been thickened relative to both limbs of the large-scale folds. On a larger scale, the siliciclastic *Gigilos* rocks occupy the core of the antiform that comprises the southern Talea Ori slopes (Figs 2b, 3). The style and pattern of deformation in this area is similar to the deformation of the Morcles nappe (Switzerland) that resulted from overthrusting during nappe stacking (Ramsey et al. 1983).

Second-order folds on the inverted or short limbs are generally open. In the Samaria area these folds are angular, are locally kink-like, and have near-horizontal or southwards dipping axial planes (Photo 2e, f). Buckle folds and asymmetric tight folds are found in inverted limbs (Photo 2e) with east-west trending fold axes.

Kinematic analysis of fold patterns is based on the asymmetry of folding, the inclination of the axial plane (Fig. 5), and on associated structures such as the crenulation or shear cleavages locally observed. Folds consistently verge either south (in the Psiloritis Mts) or southeastwards (in the Samaria area). In all cases the field relations are consistent with reverse fault kinematics. Where possible, fault plane, striae and shear-sense were measured and analysed using the P-T method (Turner, 1953). The compressional P axis trend is parallel with fold vergence and the fold c-axes, suggesting top-south transport (movement) of the rock mass.

The age of folding is bracketed to by the age of the youngest PK sediments (~29 Ma; Bizon et al. 1976) and by the fact that the folds are overprinted by brittle faults associated with the large-scale detachment faulting that juxtoposes the upper and lower units in Crete (e.g., Samaria gorge, Psiloritis mountains). Detachment faulting occurred in Late Miocene times (Thomson et al. 1998b) during the exhumation of the high-pressure rocks. The age of the folding is thus constrained to be late Oligocene/Early Miocene, contemporaneous with the high-pressure metamorphism of the lower nappes.

4 METAMORPHIC CONDITIONS

The lower nappes in Crete experienced HP-LT metamorphism in the Oligocene. Previous work on the PQ unit revealed increasing temperature and pressure conditions from eastern to western Crete (Theye & Seidel 1991), from about 300°C, 0.8 GPa in the east to 400°C, 1.0 GPa in the west. Argon dating of metamorphic white micas suggests peak conditions were reached between 24 and 20 Ma (Seidel et al. 1982, Jolivet et al. 1996).

Although the PK is thought to have undergone HP-LT metamorphism similar to the overlying PQ nappe, estimates of metamorphic conditions for the PK come from only one outcrop in Talea Ori. There, a meta-bauxite horizon containing the mineral paragenesis Fe-Mg carpholite, diaspore, and pyrohpyllite indicates high pressure metamorphic conditions (Seidel 1978). These are the only currently available data for the metamorphism of the nappe.

The sedimentary carbonate minerals of the PK rocks, however, appear to have coarsened and recrystallised during metamorphism, but the degree of recrystallization varies strongly from place to place and even within individual outcrops. In eastern (Elounda area) and central Crete (Talea Ori), recrystallization was commonly extensive (calcite crystals exceed 5 cm in length; these were probably originally aragonite). In other places such as the Psiloritis Mountains or Samaria gorge, the rocks are very fine-grained (mm or sub-mm grain size) and metamorphic recrystallization appears to have been much more limited. In the lower stratigraphic horizons, the recrystallization is found to have been very limited and can often be observed only at the micro-scale. Some recrystallized areas contain crystals characterized by elongate or nearly fibrous habits, suggesting that they were originally aragonite crystals that were retrograded to calcite during exhumation.

In outcrops where the degree of recrystallization is variable, sharp (although often irregular) contacts generally bound coarse- and fine-grained regions of rock (Photo 3a). In most cases in the platy marble, more coarsely recrystallized rock is localized around lithologic contacts, veins, and local thrust faults. In the Vossakos area (Talea Ori Mountains) recrystallization of platy marbles ap-

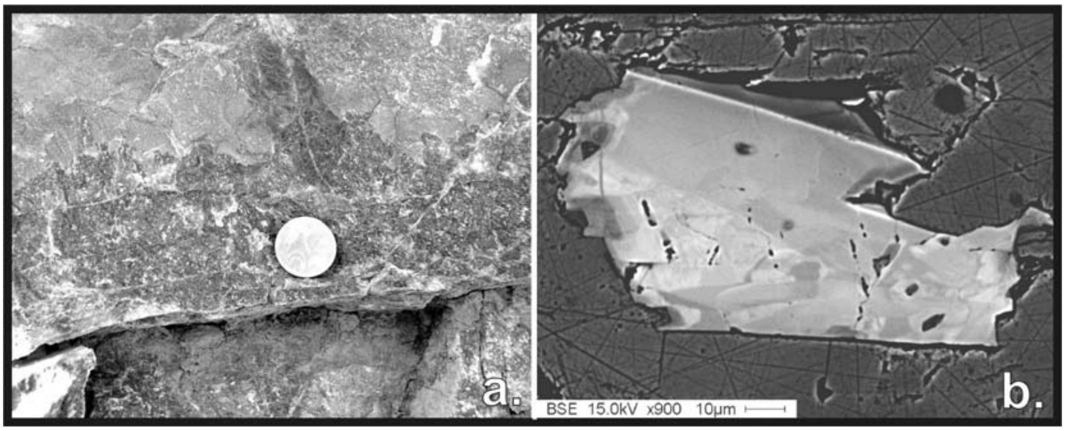

Photo 3. a. Sharp, irregular contact between coarse-grained (darker gray, under coin) and fine-grained rock in recrystallized platy marble, Psiloritis area. b. Backscattered-electron image of Ba-rich alkali feldspar from the Plattenkalk nappe. Variations in gray-scale represent chemical zonation.

pears best developed in areas of intense isoclinal folding and near thrusts. Alkali feldspar containing a significant celsian (barium) component can be found in some coarse-grained, recrystallized rocks (Photo 3b). We suggest that much of the recrystallization was mediated by fluid infiltration. A considerable proportion of the infiltration was channelized along contacts, in fractures and faults, and through fold hinges.

We have also applied the graphite thermometer (Beyssac et al. 2002) in the metacarbonate rocks to estimate temperature conditions during metamorphism. Preliminary results from several samples of the *Fodele* beds in central Crete indicate peak temperatures around 350^{o} C, consistent with the earlier data of Seidel (1978) and Theye & Seidel (1991) for the PQ unit. These preliminary estimates reveal no consistent trends in temperature within the PK, but much more detailed work is required to test for regional temperature variations.

5 CONCLUSIONS

The study of deformation patterns and metamorphic conditions in both central and western Crete indicates that intense asymmetric folding predominates. Small-scale structures and penetrative deformation are generally absent, except in zones of intense folding or faulting or in uncommon siliciclastic or flysch horizons. Some individual horizons underwent remarkably little internal deformation, allowing the preservation of fossils and sedimentary features.

Large-scale folds are both anticlines and synclines that locally overturn the stratigraphic sequence. In most cases flexural slip folding and internal thrusting are responsible for thickening of the hinges and overturned limbs (Figs 3, 6). Secondary asymmetric folds appear in upright limbs and at hinge zones, while more angular and open folds are found in the overturned limbs. Fold axes generally trend east-west, and vergence at all scales is consistent with top-south shearing. Small internal thrusts that cut the folding succession developed as a result of rock competency contrasts and progressive deformation. The paleostress analysis is consistent with fold geometry and kinematics indicating north-south compression, and southeastward shearing. Large overthrusts, duplexes or repetition of strata were not observed in the PK.

The style of deformation and general tectonic setting for the PK suggest that accretion and deformation are “thin-skinned” (Allmendinger 1999). Although a décollement is not visible in Crete, the unit is observed to be allochthonous to the east in Rhodes (Bonneau 1984). The PK represents the pre-Apulian sedimentary cover that was underplated below PQ rocks and the rest of the Hellenide nappes (similar to how the Adriatic platform is currently being underplated beneath the Appenines; Bally et al. 1986). We suggest that the décollement zone is the boundary of the PK with the Apulian basement, buried beneath the exposed PK in Crete. A thick-skinned model, on the other hand (Snyder et al. 1990, Allmendinger 1999), requires deformation of basement rocks, which is not observed in the case of the PK.

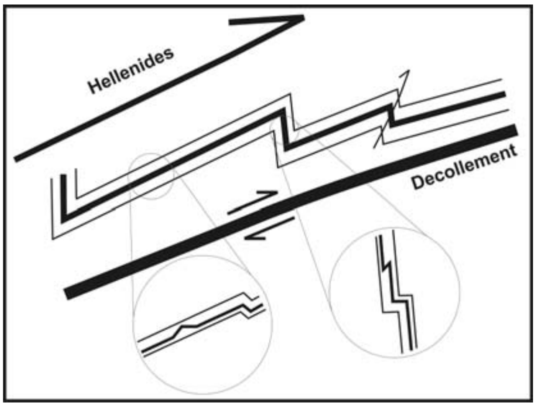

Figure 6. Model for the Plattenkalk folding development during the late Tertiary orogenic process.

Much of the transport of metamorphic fluids appears to have been channelized along lithologic contacts, fractures, faults, and fold hinges. Fluid infiltration may have mediated recrystallization of carbonate minerals to coarse (mm to cm-scale) grain sizes during metamorphism. The localization of fluids into channelways left much of the rock sequence "dry" during metamorphism, enabling deformation similar to a card-pack model and localizing deformation along faults/fracture zones, bedding plane contacts, and the hinge zones of folds. Existing work (Seidel et al. 1982) combined with preliminary thermometry data based on the graphitization of organic material suggest that HP-LT conditions were similar to those of the PQ nappe.

Ongoing study of metamorphic conditions and fluid infiltration will provide a better understanding of the tectonic regime and deformation of the Plattenkalk nappe, as well as the geological development of the external Hellenides.

AGKNOWLEDGEMENTS

This study presents preliminary results of the Natural History Museum of Crete (University of Crete) and Peabody Museum of Natural History (Yale University) collaboration on "Deformation and Fluid flow During Metamorphism and Mountain Building, Crete, Greece", funded by the Niarchos Foundation, New York. We thank Mark Brandon for discussions.

REFERENCES

Allmendinger R.W., 1999. Introduction to Structural Geology. *Cornell University*, New York. 280 pp.

Angelier, J., Lymberis, N., Le Pichon, X., Barrier, E. and Huchon, P., 1982. The tectonic development of the Hellenic arc and Sea of Crete: A synthesis. *Tectonophysics*, 86, 159-196.

Bally, A., Burbi, L., Cooper, C. and Ghelardoni, R., 1986. Balanced cross sections and seismic reflection profiles across the central Apennines. *Mem.Soc.Geol. It.*, 35, 275-310.

Beyssac, O., Goffé, B., Chopin, C. and Rouzaud, J.N., 2002. Raman spectra of carbonaceous material in metasediments : a new geothermometer. *J. Metamorphic Geol.*, 20, 859-871.

Bizon G., Bonneau, M., Leboulenger, P., Matesco, S. and Thiebault, F., 1976. Sur la signification et l' extension des 'massifs cristallins externes' en Peloponnese meridional et dans l'Arc Egeen. *Bull. Soc. Geol. Fr.,* 18, 337-345.

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., 1976. Esquisse structurale de la Crète alpine, Rapp. 5, Coll. Regions Egeennes, Orsey. *Bull. Geol. Soc. France,* 2, 155-157.

Creutzburg N., Drooger, C.W., Meulenkamp., J.E., Papastamatiou, J., Seidel, E. and Tataris, A., 1977. Geological map of Crete (1:200.000). *IGME*, Athens.

Duermeijer, C.E., Nyst, M., Meijer, P.T., Langereis, C.G. and Spakman, W., 2000. Neogene evolution of the Aegean arc: paleomagnetic and geodetic evidence for a rapid and young rotation phase. *Earth Planetary Science Letters*, 176, 509-525.

Epting, M., Kudrass, H. and Schafter, A., 1972. Stratigraphie et position des séries métamorphiques aux Talea ori. *Z. dt. Geol. Ges.,* 123, 365-370.

Fassoulas, C., 1999. The structural evolution of central Crete: Insight into the tectonic evolution of the south Aegean*. J. Geodynamics*, 27, 23-43.

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.

Fytrolakis, N., 1980. The geological structure of Crete. Problems, observations and conclusions. *Habil. thesis,* Nat. Techn. Univ. Athens, 143 pp.

Hall, R. and Audley-Charles, M.G., 1983. The structure and regional significance of the Talea Ori, Crete. *J. Struct.Geol.,* 5, N. 2, 167-179.

I.G.M.E., 1984. Geological Mapping of Greece (1:50000) Tymbakio sh. *Institute of Geological and Mining Exploration (IGME)*, Athens.

I.G.M.E., 2004. Geological Mapping of Greece (1:50000) Anogia sh. *Institute of Geological and Mining Exploration (IGME)*, Athens (in press).

Jolivet, L., Goffe, B.,Monie, P., Truffert-Luxey, C., Patriat, M. and Bonneau, M., 1996. Miocene detachment in Crete and exhumation P-T-t paths of high-pressure metamorphic rocks. *Tectonics,* 15,1129-1153.

Krahl, J., Kaufmann, G., Kozur., H., Richter, D., Forster, O. and Heinritzi, F., 1983. Neue Daten zur Biostratigraphie und zur tektonischen Lagerung der Phyllit-Gruppe und der Trypali-Gruppe auf der Insel Kreta (Griechenland). *Geol. Rundsch.,* 72, 1147-1166.

Papanikolaou D. 1988. Introduction to the geology of Crete (Field guide book). *IGCP Project No 276*. Chania.

Ramsay, J.G., Casey, M. and Kligfield, R., 1983. Role of shear in development of the Helvetic fold-thrust belt of Switzerland. *Geology*, 11, 439-442.

Seidel, E., 1978. Zur petrologie der phyllit-quarzit-serie Kretas. *Hab. Thesis*. Techn. Univ. Braunschweig, 145pp.

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.

Snyder, D. B., Ramos, V. A. and Allmendinger, R. W., 1990. Modes of thick-skinned deformation as observed in deep seismic reflection profiles in western Argentina. *Tectonics*, 9, 773-788.

Stöckhert, B., Wachmann, M., Küster M. and Bimmermann S., 1999. Low effective viscosity during high pressure metamorphism due to dissolution precipitation creep: the record of HP-LT metamorphic carbonates and siliciclastics rocks from Crete. *Tectonophysics*, 303, 299-319.

Theye,T. and Seidel, E., 1991. Petrology of low-grade high-pressure metapelites from the external Hellenides (Crete, Peloponnese). A case study with attention to sodic minerals. *Eur. J. Mineral*, 3, 343-366.

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.

Thomson, S., Stöckhert, B., Rauche, H. and Brix, M., 1998a. Apatite fission-track thermochronology of the uppermost tectonic unit of Crete Greece: implications for the post-Eocene tectonic evolution of the Hellenic subduction system. *Advances in Fission-Track thermochronology*. Kluwer Academic publishers, 187-205.

Thomson, S.N., Stöckhert, B. and Brix, M.R., 1998b. Thermochronology of the high-pressure metamorphic rocks of Crete, Greece: Implications for the speed of tectonic processes. *Geology*, 26, 259-262.

Turner, F.J., 1953. Nature and dynamic interpretation of deformation lamellae in calcite of three marbles. *Am. J. Sci*., 251, 276-298.