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ARTICLE *in* ZEITSCHRIFT DER DEUTSCHEN GESELLSCHAFT FÜR GEOWISSENSCHAFTEN · NOVEMBER 2003

Impact Factor: 0.57

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Z. dt. geol. Ges. **154**/1 p. 85–100, 8 figs. Stuttgart, November 2003

Tectonic structure and fabric development of the Plattenkalk unit around the Samaria gorge, Western Crete, Greece

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MANUTSOGLU, E., SOUJON, A. & JACOBSHAGEN, V. (2003): Tectonic structure and fabric development of the Plattenkalk unit around the Samaria gorge, Western Crete, Greece. [Tektonische Struktur und Gefüge-Entwicklung der Plattenkalk-Einheit im Bereich der Samaria-Schlucht, West-Kreta, Griechenland.] – Z. dt. geol. Ges. **154**: 85–100; Stuttgart.

Abstract: The Plattenkalk area around the Samaria gorge, western Crete, has been investigated by structural analysis and studies of microfabrics. The study area is dominated by a large-scale anticline striking to the NNE. All fracture systems observed correspond to that structure. In the northwestern limb of the anticline tectonic structures at meso- and micro-scales testify to movements top-to-the-ESE, while in the southeastern limb an opposite shear sense is documented. The morphologies and geometries of these structures clearly indicate flexural-slip folding. Within the Plattenkalk sequence bedding-parallel low-strain domains with no, or only weak, indications of shortening alternate with high-strain domains showing intense compressional deformation. Ductile deformation is restricted to discrete shear zones in the northwestern limb only, but from N to S meso- and micro-scale structures exhibit a conspicuous transition from ductile to brittle deformation. With respect to the calcite twin types observed, furthermore to the presence of cataclastic quartz fabrics and the absence of matrix coarsening in the majority of meta-cherts, metamorphism temperatures did nowhere exceed 300°C and have even decreased from N to S. All features of tectonic deformation and metamorphism have developed within the same tectonic phase, i.e. during the late Early Miocene.

The tectonic structures and fabrics probably originated autochthonously, within the foreland of an orogenic belt. Our observations fit in well with illite crystallinity measurements in all Plattenkalk areas of Crete (SOUJON & JACOBSHAGEN 2001) showing that on the whole island the temperatures of metamorphism have decreased from N to S. For the Plattenkalk of the southern Peloponnesus, an analogous trend had already been found by MANUTSOGLU (1990). All these features seem to reflect the mid-Tertiary subduction of the Plattenkalk platform beneath the Hellenic Arc.

Kurzfassung: Im Plattenkalk-Gebiet um die Samaria-Schlucht (West-Kreta) wurden die tektonischen Strukturen und Mikrogefüge im Detail untersucht. Das Arbeitsgebiet wird von einer großen, NNE-streichenden Antiklinale beherrscht, auf die alle beobachteten Bruch-Systeme bezogen sind. Im nordwestlichen Schenkel dieser Antiklinale weisen die mesoskopischen und mikroskopischen Strukturen durchweg auf Bewegungen „Hangendes gegen ESE“ hin, während im südöstlichen Schenkel ein entgegengesetzter Schersinn dokumentiert ist. Gestalt und Geometrie dieser Strukturen gehen eindeutig auf Biegegleitfaltung zurück. In den Plattenkalk-Abfolgen alternieren schichtparallel Deformationsbereiche, die nicht oder nur geringfügig verkürzt wurden (low-strain domains), mit Bereichen starker kompressiver Deformation (high-strain domains). Duktile Deformation ist auf diskrete Scherzonen im NW-Schenkel beschränkt, während die mesoskopischen und mikroskopischen Strukturen generell von N nach S deutlich Übergänge von duktiler zu spröder Verformung aufweisen. In den Mikrogefügen belegen die Typen der Calcit-Zwillinge sowie das Vorkommen kataklastischer Quarz-Gefüge und das Fehlen von Matrix-Vergröberung in der Mehrzahl der Meta-Cherts, daß die Temperaturen der Metamorphose nirgends etwa 300°C überschritten haben und sogar von N nach S

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0012-0189/03/0154-0085 $ 4.00

abgesunken sind. Demnach nahm die Versenkungstiefe im Untersuchungsgebiet während der Orogenese von N nach S ab. Alle tektonischen und metamorphen Gefüge wurden in derselben tektonischen Phase, vermutlich im unteren Miozän, geprägt. Sie sind wahrscheinlich autochthon, im Vorland eines Orogens, gebildet worden.

Unsere Ergebnisse passen gut zu den Resultaten umfangreicher Messungen der Illit-Kristallinitäten in allen Plattenkalk-Gebieten Kretas (Soujon & Jacobshagen 2001), die gezeigt haben, dass die IC-Werte auf Kreta generell von N nach S absinken, die Metamorphose-Temperaturen somit in dieser Richtung abgenommen haben. Einen analogen Trend – Abnahme der Versenkungstiefe von E nach W – hat bereits Manutsoglu (1990) auf dem südlichen Peloponnes nachgewiesen. Alle diese Befunde spiegeln offenbar die Subduktion der Plattenkalk-Plattform unter den Hellenischen Bogen wider.

Keywords: Plattenkalk, metamorphism, structural analysis, microfabrics

Greece, Crete

1. Introduction

Since late Jurassic times the Hellenide orogen has developed to the present fold-and-thrust belt, being the result of convergence of the African and Eurasian lithospheric plates in the Aegean region. The African plate exerted varying pressures on the whole belt with its irregular northern margins, while separate blocks and microplates were detached from that margin. Thus, a relatively rigid belt framework originated, with nappe piles partly crushed and squeezed. The pre-Neogene Hellenides were probably orientated approx. E-W, but since the beginning of the Miocene the northwestern part of the belt was bent clockwise to about 50° (Laj et al. 1982, Kondopoulou & Lauer 1984), whereas the southeastern part remained in its original position (Kissel et al. 1984). External parts of the Hellenides are represented by the Hellenic Arc, which extends from the Peloponnesus to Rhodes and is bordered to the SW and S by the Hellenic Trench. Since Papazachos & Comninakis (1971) had detected a Wadati-Benioff zone dipping beneath the Hellenic Arc, the Aegean arc-and-trench system is understood as a still-active subduction zone.

The island of Crete is part of the Hellenic Arc. Its geological framework consists largely of nappes with contrasting lithologies and facies that have been overthrust southwards during the Alpine orogeny (Jacobshagen 1986). Most of the nappes of continental Greece have been recognised on Crete as well, but with reduced thicknesses and more intensive shortening. They are stacked from bottom to top in the following order: Trypali nappe (locally), Phyllite nappe (according to the definition of Dornsiepen & Manutsoglu 1994), Tripolitza nappe, Pindos nappe, and, on top, some relics of a nappe tier with ophiolites, metamorphics, and late Cretaceous sediments. This nappe pile rests upon the Plattenkalk unit, which is interpreted as either autochthonous or parautochthonous.

The lowermost units of the Hellenic Arc up to the Phyllite nappe consist of rocks that have suffered HP-LT metamorphism in Oligocene to early Miocene times (Neohellenic phase, Jacobshagen 1986): The Plattenkalk unit consists mainly of marbles and metacherts, with siliciclastic rocks at the base and meta-pelites on the top. Its rocks have delivered fossils of Permian to early Tertiary age. To constrain the P-T conditions of Plattenkalk metamorphism is difficult, as metamorphic index minerals are rare. On Crete there are only two determinations up to now: In the Talea Ori Mts. of northern central Crete, magnesio-carpholite in metabauxites (Seidel 1978) and lawsonite in marbles (Theye 1988) suggest approx. 10 kb and 350°C, respectively. Theye et al. (1992) have extrapolated these values to the entire Plattenkalk unit of Crete. The Phyllite nappe consists mainly of rocks of the Phyllite Quartzite (P-Q) group, which is composed of metaclastics of late Paleozoic to Triassic age, with a few intercalated metavolcanics and marbles. In these rocks, P-T conditions could be determined in many places. They increased clearly from 8 ± 3 kb and 300 ± 50°C in eastern Crete to 9 ± 3 kb and 350 ± 50°C in central Crete and to 10 ± 3 kb and 400 ± 50°C in western Crete (Theye & Seidel 1991, Theye et al. 1992). That trend of increasing P-T values along strike then continues farther north to the Peloponnesus. A more detailed tectonometamorphic history of the PQ unit has been published for eastern Crete (Zulauf et al. 2001 and 2002).

As the metamorphic histories of the Plattenkalk and the PQ units show apparent similarities, many authors believe that both were metamorphosed in their present superposition, i.e. after the overthrust of the PQ unit. This seems doubtful, however. For in the southern Peloponnesus, the Plattenkalk unit shows considerable variations across strike (MANUTSOGLU 1990): In the Taygetos Mts., microfabrics and certain types of phyllosilicates suggest that metamorphism nowhere exceeded the very-low-grade range, but the metamorphic grade decreases from E to W towards the lower anchizone, parallel with a decrease of intensity of tectonic deformation.

Considering the structural development of Crete, indicators of direction and sense of shear in deformed rocks have been described from the Plattenkalk unit and the Phyllite nappe to show a top-to-the-S direction (e.g. BONNEAU 1984, GREILING 1979). Recent kinematic models of Aegean plate tectonics are mainly based on the occurrence of a N-S trending stretching within the Phyllite nappe in Crete, which is often associated with a top-to-the-N sense of shear. These structures have been interpreted as a result of Miocene crustal extension, which led to the formation of a large-scale major detachment fault dipping to the N. The latter has reactivated the existing thrust planes and was believed to have caused the rapid exhumation of the HP/LT-metamorphic rocks (e.g. FASSOULAS 1999, JOLIVET et al. 1996). There is, however, clear evidence for both top-to-the-S and top-to-the-N shearing at least in eastern Crete (ZULAUF et al. 2002), thus the geotectonic evolution seems to be more complicated than is suggested by the current models. Nevertheless, the southward directed nappe emplacement is generally accepted.

The present study aims to analyse the structural and metamorphic development of the Plattenkalk unit of Crete in an extended cross-section, which is exposed in the famous Samaria gorge in the southwestern part of the island. Our results are based on field data as well as on optical and SEPM microscopy.

2. The Plattenkalk of the Samaria gorge

The Samaria gorge is situated in the Lefka Ori National Park of southwestern Crete (Fig. 1). It extends 16 km in a N-S direction and exposes one of the largest and most important cross sections of the Plattenkalk on the island, although neither the lowermost units nor the top of the sequence are exposed. In addition, the Samaria gorge cuts through an external part of the Hellenic Arc on Crete. Our structural analyses and microfabric studies were based on a detailed stratigraphy of the Plattenkalk sequence, which will be outlined below.

2.1. Stratigraphy

The Plattenkalk group of Crete was deposited in a shallow-water regime on a carbonate platform (MANUTSOGLU et al. 1995, SOUJON et al. 1995). A lithostratigraphic subdivision for the whole island was presented by SOUJON et al. (1998), together with a revision of the stratigraphic nomenclature (Fig. 2). The new stratigraphic terms are also applied in this paper. In the Samaria gorge, the Plattenkalk sequence is exposed from the early Tertiary Kalavros formation down to the Rhaeto-Liassic Mavri formation. Deeper stratigraphic units do not crop out in the Samaria section. The whole sequence is in a non-overturned position (SOUJON et al. 1998). Here, we report on local peculiarities which were essential for our structural analysis.

Mt. Gigilos consists mainly of whitish to grey calcitic or dolomitic marbles, partly with stromatolites, which belong to the Mavri formation. The "Gigilos beds" (FYTROLAKIS 1980), about 500 m in thickness, overlie this sequence conformably, with well exposed contacts at Mt. Gigilos and about 1.5 km north of Samaria village. They correspond to member 4c of the Aloides formation. At the base and in the upper parts they consist mainly of multicoloured phyllites or calcschists. The latter are similar to those of the Kalavros formation. With the onset of clastic sedimentation lithistide sponges are present again. The middle part of the "Gigilos beds" consists of rhythmic sequences of pelites,

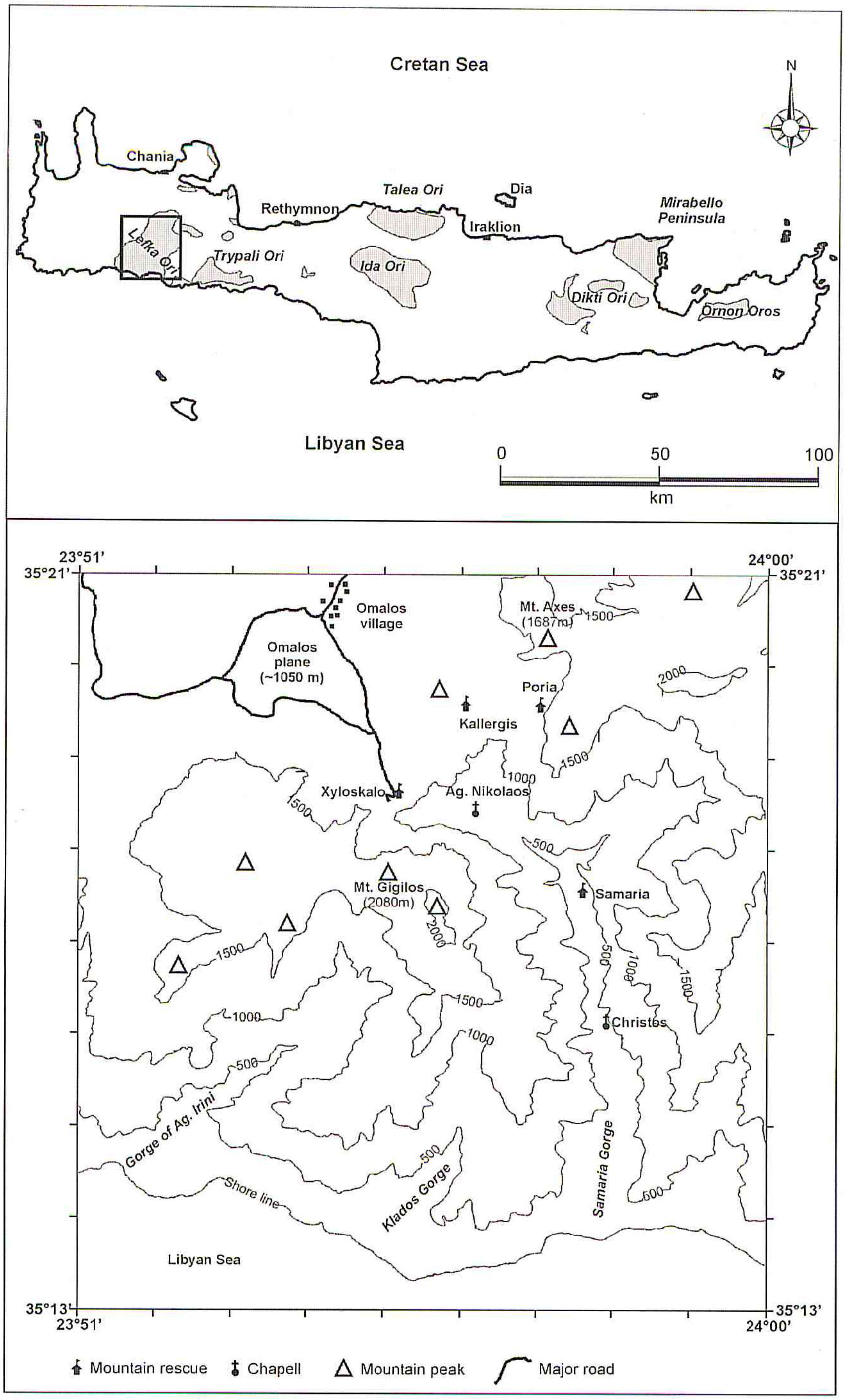


Fig. 1: Location of the study area around the Samaria gorge, SW Crete (square) and topographic map showing the localities mentioned in the text.

Abb. 1: Lage des Arbeitsgebiets um die Samaria-Schlucht (SW-Kreta) und topographische Karte mit den im Text erwähnten Lokalitäten.

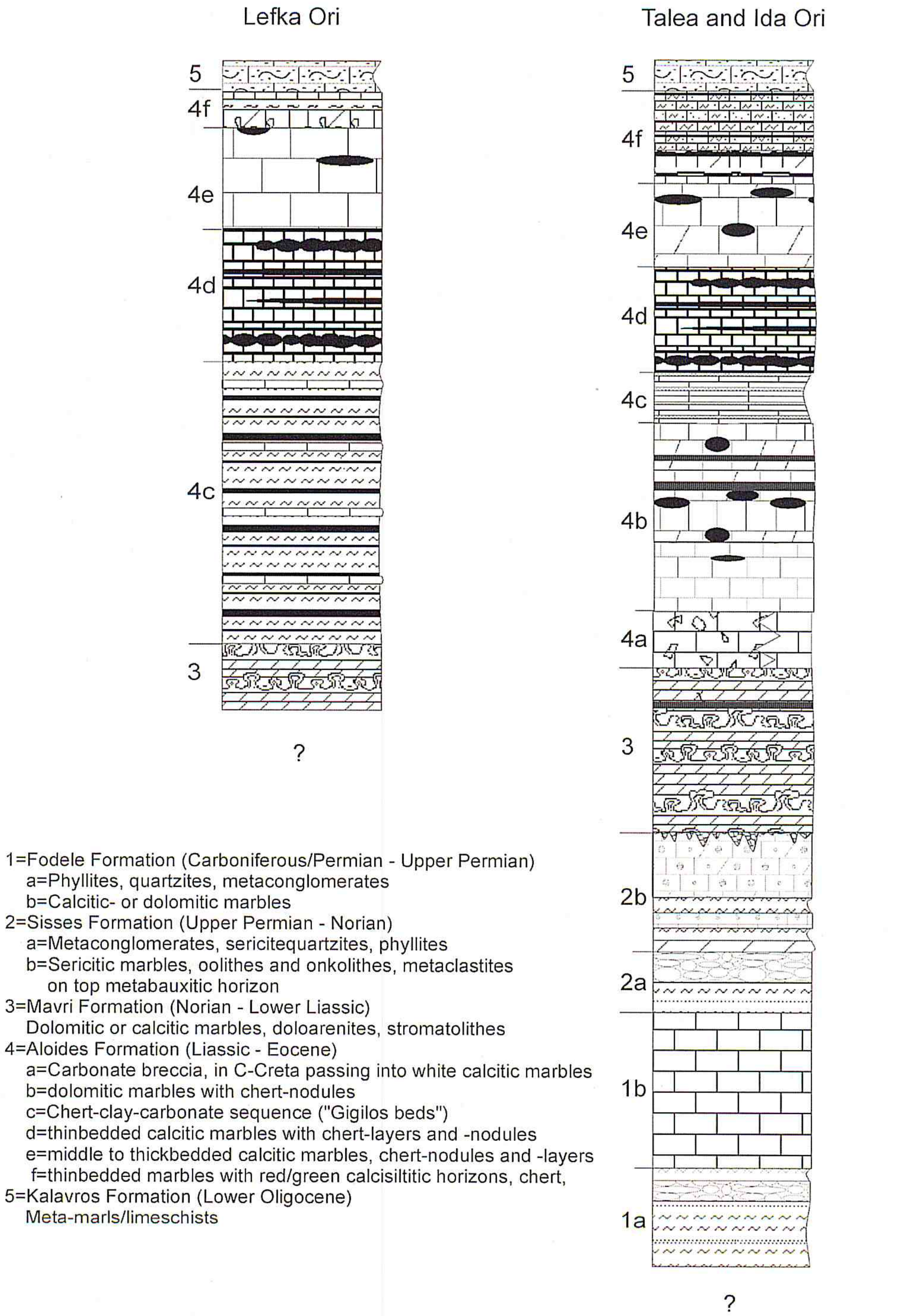


Fig. 2: Simplified stratigraphical columns of the Plattenkalk group of central and western Crete (not to scale).
Abb. 2: Vereinfachte stratigraphische Gliederung der Plattenkalk-Gruppe in Zentral- und West-Kreta (nicht maßstäblich).

metacherts, and marble layers. The transition from the "Gigilos beds" (4c) to member 4d of the Aloides formation is sharp and characterised by an interruption of the input of siliciclastic sediments. It is well exposed north of Poria at the western slopes of Mt. Axes (Figs. 1, 4), where an alternation of platy to thin-bedded marbles and layers or nodules of metachert have developed (i.e. typical "Plattenkalk"). Most of the silica phase resulted from lithistide silicosponges. That can easily be identified from the shape of individual sponges, but as well from spongocoels often filled with calcite (Manutsoglu et al. 1995, Soujon et al. 1995). At irregular intervals, thick marble layers with numerous round or irregular-shaped lithistides, are intercalated, pointing to cyclic sedimentary events. The carbonate sedimentation was interrupted several times by the input of fine-grained siliciclastic material, the latter forming separate horizons. The transition to member 4e of the formation is fluid and marked by a decrease of metachert layers until nearly total absence and by an increase of the thickness of the coarse-grained marble layers up to 3 m, corresponding to the other occurrences on Crete. This basal part of member 4e, about 150 m in thickness, passes into approx. 250 m of thin-bedded to platy marbles without metacherts.

The overlying sequence is characterized by an increase in metacherts and thin metapelite or calcschist intercalations as well as by the appearance of the characteristic green calcisiltites, representing member 4f. It starts with intercalations of only a few millimetres in thickness and ends up in a horizon of about 2 m. North of Poria, the exposed thickness of member 4f is about 80 m. The whole sequence is tectonically overlain by dark cellular dolomites of the Trypali nappe. The Kalavros formation is not exposed in the sections of the Samaria and Poria gorges.

3. Structural research

3.1. Large-scale structures

Our study area is dominated by a large NNE-SSW striking anticline with an axis dipping towards NNE, that could be identified by field mapping as well as by 3D-modelling of all geological data available (Manutsoglu et al. 1999). The amplitude of this anticline exceeds 1000 m. Its minimum half wavelength is about 6000 m. The geometries of the fracture systems, which were derived both from the analysis of LANDSAT TM images and from field observations, correspond to that anticlinal structure. In the surroundings of the big karstic depression of Omalos, most of the northwestern limb of the Samaria anticline is tectonically overlain by rocks of the Trypali nappe. The core of the anticline is built up of stromatolitic dolomite and calcite marbles of the Mavri formation. Towards the siliciclastic rocks of the "Gigilos beds" in the south, these Mavri marbles are limited by a sharp, brittle tectonic contact, which can be traced over several kilometers both in the field and on satellite imagery. The southeastern limb of the anticline is cut by the gorge of Samaria.

3.2. Mesoscopic structures

Meso-scale folds are widely distributed in the study area, but more frequent on the southeastern limb of the major anticline. The most frequent fold types are buckle folds, either z- or s-shaped, but nearly isoclinal folds also occur. Their fold axes strike to the NNE as well (Fig. 3). Field observations suggest the presence of low- and high-strain domains. Low-strain domains show no or but little evidence for shortening. Strain markers in marbles are lithistide sponges, which became more or less ellipsoidal in shape in high-strain domains, while their original spheroidal habitus has not been changed in low-strain domains. Regarding the two dominant rock types (marbles and metacherts), a distinction can be made with respect to their rheological properties and the strain paths in the two strain domains.

Duplexes and buckle folds are common in the Lefka Ori anticline and occur at all scales of observation (Figs. 4, 5, 6f). They can be found across the entire anticline, but are best exposed on the walls of the Samaria gorge in the southern limb and in the area around Poria in the northern limb.

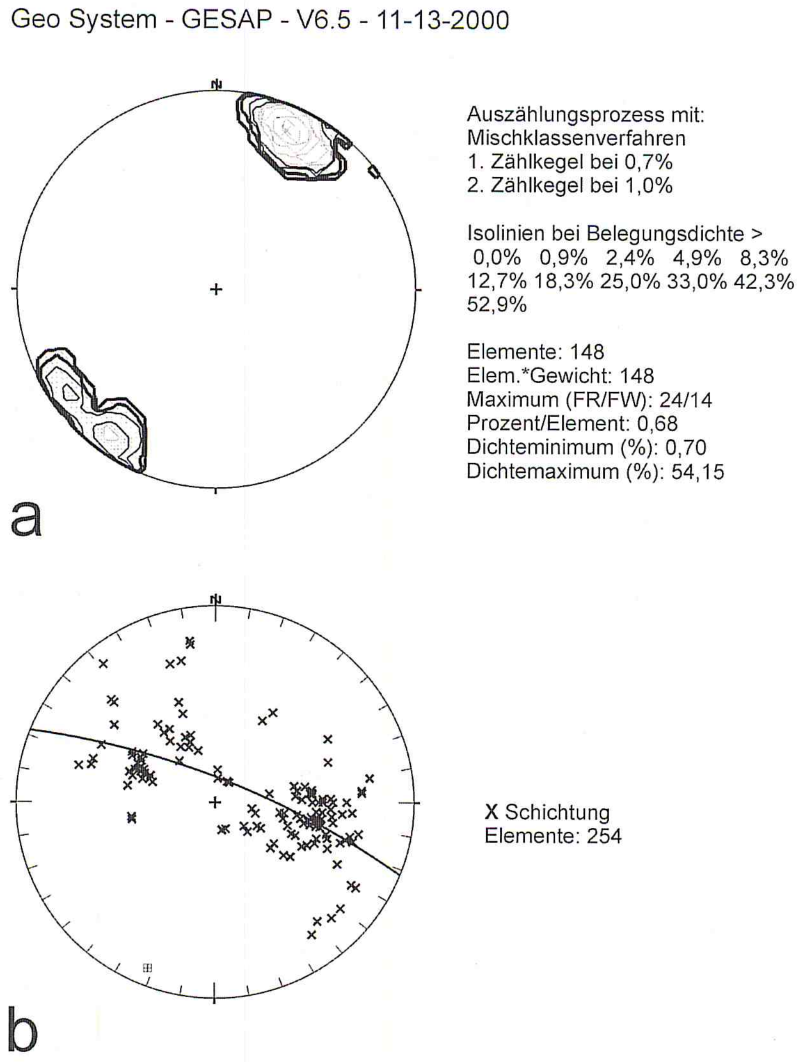


Fig. 3: Fold axes pattern of meso-scale folds (a) and pole diagram of bedding planes (b) of the Plattenkalk group. Measured at the northwestern and southeastern limbs of the Lefka Ori anticline.

Abb. 3: Achsenverteilung mesoskopischer Falten (a) und Pol-Diagramm von Schichtflächen (b) der Plattenkalk-Gruppe, gemessen auf dem nordwestlichen und dem südöstlichen Schenkel der Lefka Ori-Antiklinale.

North of Poria, at the western flank of Mt. Axes, a series of propagated z-shaped buckle folds is exposed in the northern limb of the Lefka Ori anticline (Fig. 4). These structures have developed in intermediate- to thick-bedded calcite marbles with scarce nodules and layers of metacherts, that overlie the "Gigilos beds" and are themselves overlain by alternations of thin-bedded calcite marbles and metachert layers, with a few siliciclastic intercalations. In that constellation, these thick beds reacted as the competent strata being surrounded by incompetent sequences. A wave train of buckle folds, which do not affect the surrounding units, was

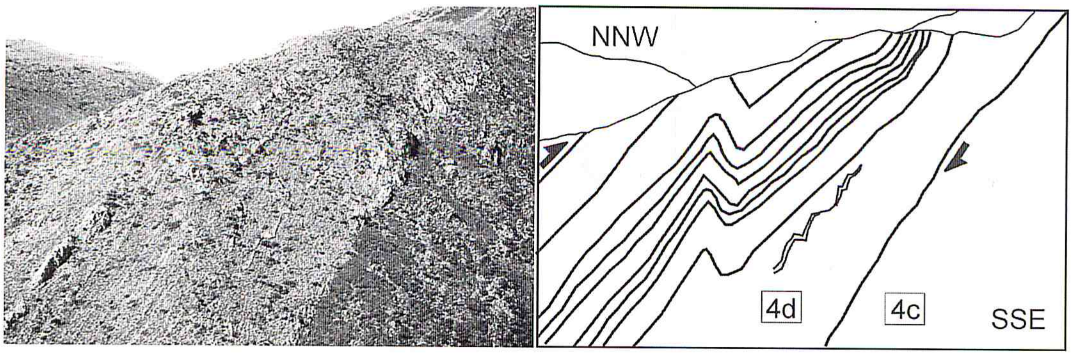


Fig. 4: Z-shaped buckle folds in member 4d of the Aloides formation, developed by flexural slip in the northern limb of the Lefka Ori anticline. Direction of movement "top-to-the-ESE". Notice the sharp boundary between member 4c and 4d. Western slope of Mt. Axes. Width of photo is about 100 m.

Abb. 4: Z-förmige Knickfalten im Schichtglied 4d der Aloides-Formation, gebildet durch Biegegleitung im Nordschenkel der Lefka Ori-Antiklinale. Bewegungssinn „Hangendes gegen ESE". Man beachte die scharfe Grenze zwischen den Schichtgliedern 4c und 4d. Westhang des Axes-Berges. Bildbreite ca. 100 m.

built within the thick-bedded sequence during southeasterly directed shear.

Duplex structures, up to 5 m thick and 20 m in length, have been observed at several places in the Samaria gorge (Fig. 5). They have smooth, nearly flat roofs and were formed within a shear zone with sharp planar boundaries. The shear sense is generally top-to-the-WNW, whereas it is top-to-the-ESE in the northern, steeper limb of the anticline. Regarding the whole anticline, the shear sense determined is compatible with flexural slip folding. Most of the shear planes are parallel to the bedding (Fig. 5). From S to N, the angles between floor- and roofthrusts and the linkthrusts increase progressively from about 20° to 70°.

4. Microfabrics

The types of microfabrics of the Plattenkalk group depend on strain magnitude and lithology.

4.1. Low-strain domains

4.1.1. Marbles

In the Mavri Formation dolomite marbles occur, with cryptocrystalline sparitic grains and coarse sparry dolomite crystals. The dolomite grains are not twinned. White, grey and/or blue coarse-grained (up to 5 mm in diameter) calcite marbles are typical protoliths with equal calcite grains and straight grain boundaries. All calcite grains are twinned. Most twins show moderately thick to thin straight lamellae with straight boundaries, types I and II by Burkhard (1993).

4.1.2. Metacherts

Two varieties of quartz can be distinguished within the bedded and nodular metacherts, microquartz and megaquartz after Flörke et al. (1991). Microquartz is fine-grained, up to 20 µm in size, and characterized by sutured grain boundaries and undulatory extinction (Fig. 6a). Refractive indices of 1.593-1.542 are close to megaquartz. Megaquartz is characterized by mosaics of equal-sized and -shaped crystals, from 20 to 300 µm in diameter (Fig. 6c).

Petrography and XRD data confirm that the metacherts are not exclusively composed of quartz, but small carbonate rhombohedra and illite are common as well. The rhombohedra within the nodular metacherts are obviously a product of chert diagenesis. They are abundant in all parts of the nodules and bedded metacherts and have random dispersion and orientation. An exception are calcite rhombohedra, which are situated along syngenetic veinlets.

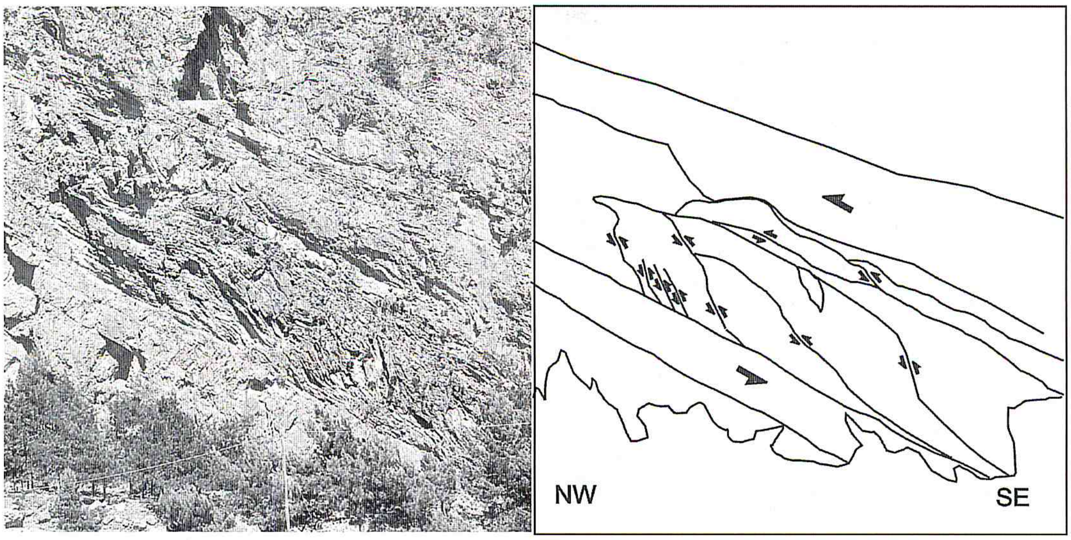


Fig. 5: Thrust duplexes in a thin-bedded marble layer. Member 4d of the Aloides formation. Sense of shear: top-to-the-WNW. Samaria gorge, approx. 1 km north of Christos. Width of photo is about 20 m.

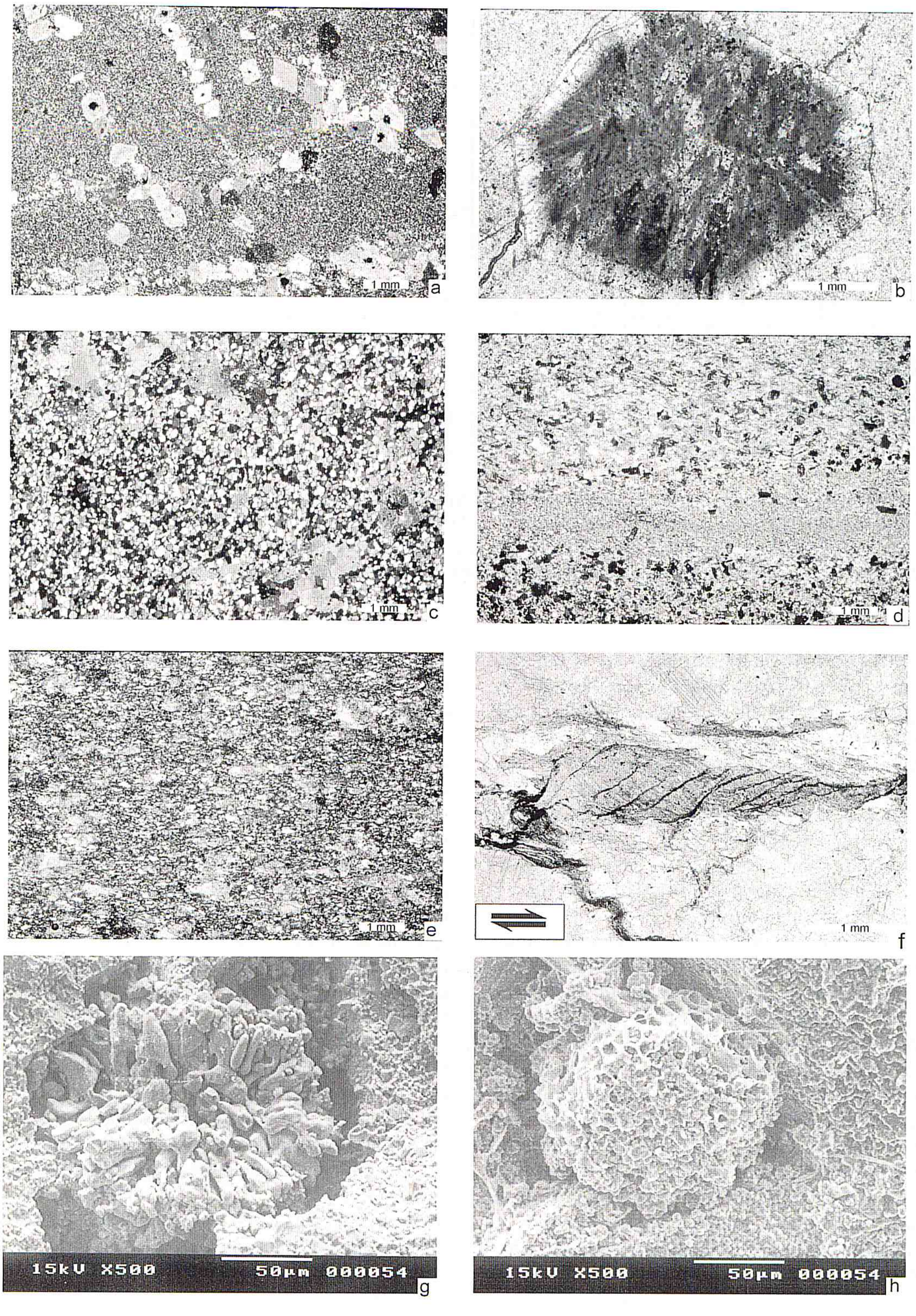
Abb. 5: Überschiebungsbedingte Duplex-Strukturen in dünnschichtigen Mergeln, Schichtglied 4d der Aloides-Formation. Schersinn: Hangendes gegen WNW. Samaria-Schlucht, ca. 1 km nördlich Christos. Bildbreite ca. 20 m.

The rhombohedra in metachert nodules do not exhibit twinning lamellae, despite the ubiquity of such lamellae in the surrounding rocks (Figs. 6a, 6b). The silica "matrix" protected them against the differential stress that was uniformly propagated through the packed calcite grains in limestone. The chert nodules, being more rigid than limestone, reacted by brittle fragmentation. As a result, the sets of veinlets in metachert nodules are always denser than in the surrounding marbles.

Carbonate rhombohedra in metachert nodules have previously been considered as dolomite by many authors, because only dolomite rhombohedra are ubiquitous in limestones and because well-shaped calcite rhombohedra are absent in marine limestones, except for dedolomitized rocks. But in nodular and bedded metacherts from the Plattenkalk group, calcite rhombohedra are found everywhere, sometimes accompanied by those of siderite and, occasionally, ankerite. Calcite monocrystals of globular shape have often continued to grow within the nodular metacherts and have then acquired rhombohedral shape. The rhombohedra originated in an early stage of chert formation, when the silicified substratum still had a high water content. A repeated alternation of the conditions that have favoured, on one hand, silica precipitation and, on the other, carbonate precipitation is required to produce the observed textures. Subsequent to the dehydration of silica nodules, the conditions favourable for the rhombohedra growth disappeared. This interpretation is confirmed by the fact that the rhombohedra are frequently associated with syngenetic veinlets (Fig. 6a), but no rhombohedra have been observed in association with epigenetic veinlets that are caused by differential stress (Mišík 1993).

Bedded metacherts contain dense accumulations of spherical structures. These microspheres have a regular size of 20-30 µm. Their internal structure is composed of radial fibres of cryptocrystalline quartz. The spherical structures resemble the diagenetic quartz microspheres described by Oehler (1975) and Gimenéz-Montsant et al. (1999). In size and shape, they are also similar to lepispheres (Figs. 6g, 6h).

The microspheres of our samples have a


1 mm
a
1 mm
b
1 mm
c
1 mm
d
1 mm
e
1 mm
f
15kV X500 50µm 000054
g
15kV X500 50µm 000054
h

characteristic internal structure and size, very similar to the spherical structures of sponge spicules. Therefore, the silica in the Plattenkalk metacherts is considered to have originated from sponge spicules, which were originally composed of metastable amorphous opal A (CALVERT 1971).

4.2. High-strain domains

4.2.1. Marbles

Several methods are available to determine the orientations of principal stress/strain axes. Twinning paleopiezometers are, however, to be regarded with some scepticism (BURKHARD 1993). Because the principal stress / strain axes in the study area can be examined at mesoscale structures, attention was paid only to the types and the distribution of twin lamellae.

Calcitic tectonites occur as moderately deformed calcite marbles or calcite mylonites. The majority of the moderately deformed calcite marbles are coarse grained with idiomorphous grains. Their size varies considerably, depending on the presence of additional mineral phases, especially of phyllosilicates. The grain boundaries are generally straight and meet in triple junctions, whereas sutured grain boundaries are not frequent. In calcite mylonites grain boundary migration recrystallisation was observed. The mylonites can be recognised from the abrupt decrease in grain size of calcite (Fig. 6d). The mylonite fabrics are essentially parallel to the thrust-related fabrics recorded in the protolith and in the deformed marbles of the area. The parallel orientation of these two fabrics indicates that the scarce shear zones have originated during thrusting.

Calcite twin types allow an approximate estimate of the deformation temperature

Fig. 6: Microfabrics of the Samaria Plattenkalk.
a, c, e # Nicols, b, d, f // Nicols.
Abb. 6: Mikrogefüge des Plattenkalks um die Samaria-Schlucht.
a, c, e # Nicols, b, d, f // Nicols.

a, b: Dolomite and calcite rhombohedra of different sizes in metacherts from low-strain domains. Note the absence of twinning. Aloides formation, southern Samaria gorge. Widths of views: a 9.6 mm; b 4.8 mm.
a, b: Dolomit- und Calzit-Rhomben verschiedener Größen in Metacherts aus low-strain-Domänen. Es sind keine Zwillinge zu beobachten. Aloides-Formation, südliche Samaria Schlucht. Abbildungsbreiten: a 9,6 mm; b 4,8 mm.
a, c, e: Stages of progressive recrystallisation of microquartz (a) to megaquartz (c) and the development of a continuous foliation defined by parallel crystals of quartz and carbonate in a high-strain domain (e), accompanied by the destruction of carbonate rhombohedra. Metacherts of the Aloides formation, Samaria gorge. Widths of views each 9.6 mm.
a, c, e: Stadien progressiver Rekristallisation von Mikroquarz (a) zu Megaquarz (c) und die Entwicklung einer durch parallele Quarz- und Calzit-Kristalle definierten kontinuierlichen Foliation in einer high-strain Domäne (e), begleitet durch die Zerstörung von Calzit-Rhomben. Metacherts der Aloides-Formation, Samaria Schlucht. Abbildungsbreiten jeweils 9,6 mm.
d: The abrupt decrease in grain sizes of calcite indicates ductile calcite mylonites within marbles of high-strain domains. Aloides formation, Samaria gorge. Width of view 9.6 mm.
d: Die plötzliche Korngrößenabnahme indiziert duktile Calzit-Mylonite in Marmoren aus high-strain-Domänen. Aloides-Formation, Samaria-Schlucht. Abbildungsbreite 9,6 mm.
f: Micro-duplexes of mica and chlorite in impure calcitic marble. The direction of movement is top-to-the-WSW. Aloides formation, Mt. Axes. Width of view 4.8 mm.
f: Mikro-Duplexstruktur von Hellglimmer und Chlorit in unreinem Marmor. Bewegungssinn: Hangendes gegen WSW. Aloides-Formation, Berg Axes. Abbildungsbreite 4,8 mm.
g, h: REM images of nearly undeformed microspheres in metachert nodules from low-strain domains, Aloides formation, southern Samaria gorge. Widths of views each 240 μm.
g, h: REM-Aufnahmen von nahezu undeformierten Mikrosphären in Metachert Knollen aus low-strain-Domänen. Aloides-Formation, südliche Samaria-Schlucht. Abbildungsbreiten jeweils 240 μm.

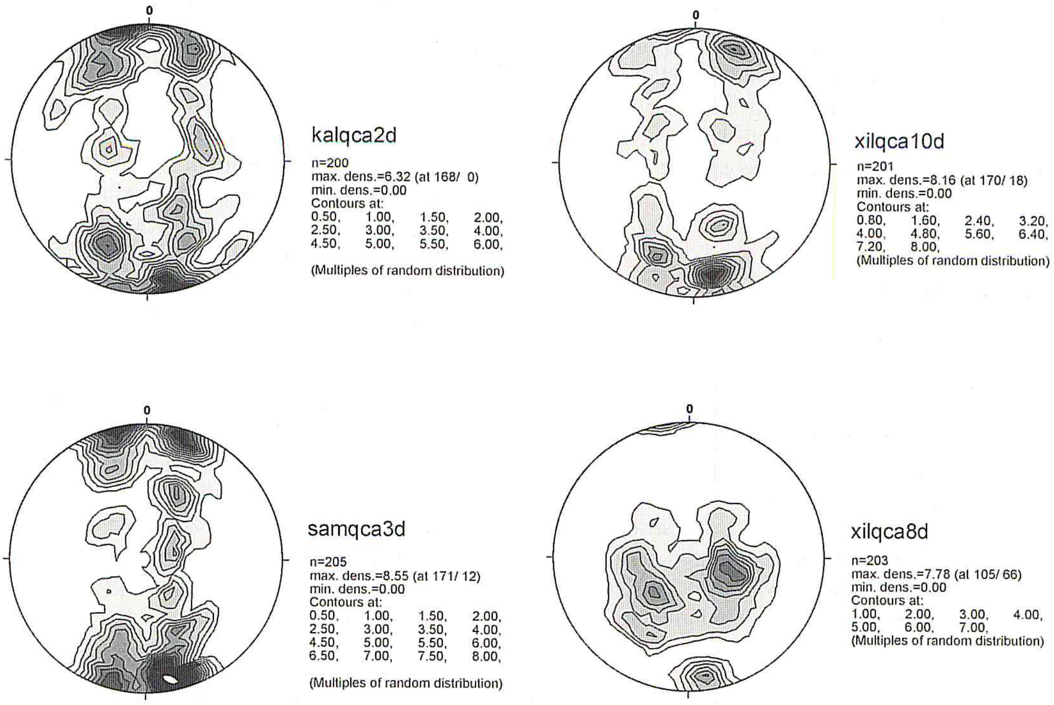


Fig. 7: Quartz-c-axis patterns of metacherts from the Aloides formation showing small circles around X.
Abb. 7: Quarz-C-Achsen-Diagramme von Metacherts der Aloides-Formation mit deutlicher Kleinkreisregelung um X.

(Burkhard 1993). The development of thick twins (type II) corresponds to a temperature of about 150°C. Curved twins and twins-in-twins (type III) are frequently observed within the anchimetamorphic (very low-grade) rocks (200-300°C). The origin of these fabrics can be related to enhanced crystal plastic deformation, which is temperature-dependent. Recrystallized twins with migrated twin boundaries (type IV) have frequently generated at temperatures above 250°C and are very sensitive indicators of syntectonic dynamic recrystallisation.

Within the Plattenkalk unit of the study area, type III twins predominate. Type II twins occur as well. Migrated twin boundaries have, however, not been observed. Therefore a temperature range of ca. 150 to ca. 300°C is indicated by the calcite twins.

4.2.2. Metacherts

Quartz-c-axes

The orientations of quartz-c-axes of ten oriented samples from metacherts were measured by means of U-stage microscopy. The samples were cut vertically to the axes of meso-scale folds and the raw data were rotated 90° around the Z-axis and then plotted using the software StereoNett 2.02 by J. Duyster, Bochum.

Six samples gave a random orientation, but the remaining four show small circles around X (Fig. 7), indicating axial symmetric elongation and rare cross girdles, which are typical for plane strain. The large opening angles of the small circles indicate that deformation took place at shallow structural levels, close to the ductile-brittle transition. This corresponds well to the microfabrics of the Plattenkalk of the Taygetos Mts., Peloponnesus (Manutsoglu 1990).

Quartz-crystallinity index (CI)

20 selected metachert-samples have been analysed by X-ray diffraction in order to determine their crystallinity index (CI sensu MURATA & NORMAN 1976) as a parameter for the ripening status of the SiO_2 phase. All samples were taken from metachert layers of the 4e member of the Aloides group. 10 samples are from outcrops south of Samaria village (southeastern limb of the anticline), and the other 10 were taken at Xyloskalo, at the entrance to the Samaria gorge (northwestern limb of the anticline). From all samples thin sections have been prepared to compare the results of the CI analysis with petrological data. The decarbonated metachert samples were analysed using a Philips PW 1710 diffractometer (40 kV, 35 mA, monochromator, CuKa, Ni-filter). A quartzite from the Phyllite nappe was used as a calibration standard (CI = 10).

Our CI-values (Fig. 8) vary between 5 and 8.4. The lowest value was derived from a sample near Christos (SS2), the highest came from a sample of Xyloskalo (XS3). RICHTER et al. (1994) have reported values varying between 6.1 and 9.6 for samples from the Plattenkalk group of Crete, without specifying the sample localities. For the samples of the Lefka Ori they have received the values 9.0 and 9.1. The CI-values vary significantly along the Samaria gorge, but there is a conspicuous decrease from north to south.

With increasing P/T conditions, crystal growth and recrystallisation along with an improved quartz crystallinity and a decrease of water content of the SiO_2 phases occurred during chert ripening. Unfortunately, the recrystallisation of the cherts of the Plattenkalk group of the Lefka Ori was not totally completed everywhere. These observations correspond to those of RICHTER et al. (1994).

In the Plattenkalk group of the study area predominant micro-structural features are the occurrence of both grain-size types, a) microquartz in the majority of the cherts from the southern limb of the anticline and b) coarse recrystallised grains mainly in the northern limb. That indicates that in the study area the northern parts of the Plattenkalk area were deformed under higher temperature conditions than the southern parts, during a progressive regional metamorphism.

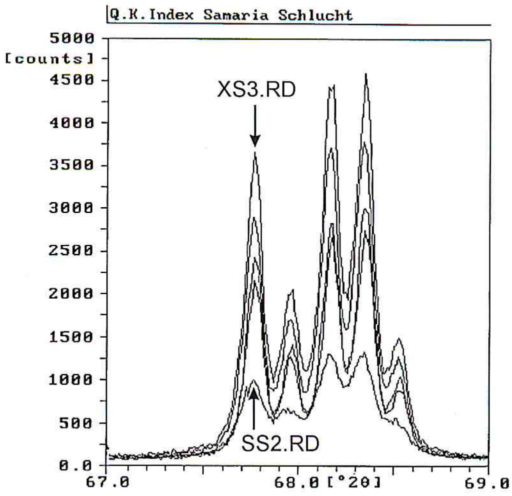


Fig. 8: XRD profiles showing the variations of the quartz-crystallinity index. See text for discussion.
Abb. 8: Röntgendiffraktometrische Profile zeigen die Variationsbreite des Quarz-Kristallinitätsindexes. Diskussion im Text.

5. Summary

The study area around the Samaria gorge, western Crete, is built up by rocks of the Plattenkalk group, reaching from the Rhaeto-Liassic Mavri formation up to the top of the Aloides formation (Eocene). In structural terms, it is dominated by a large-scale anticline striking SSW-NNE, with its axis dipping to the NNE. In its northern limb shear zones and chevron folds occur with a top-to-the-ESE sense of shear. In the southern limb, some of the nearly vertical shear zones in the external areas of the limb change to a flat position, showing a top-to-the-WNW sense of shear everywhere. The morphologies and the geometries of structures in meso- and micro-scales, e.g. duplexes and buckle folds, point clearly to flexural-slip folding mechanisms.

No pervasive ductile deformation has affected the Plattenkalk unit around the Samaria gorge, but the lithological sequence can be sub-

divided into bedding-parallel low- and high-strain domains. Low-strain domains exhibit little or no evidence of compressional shortening, whereas high-strain domains have suffered intense shortening (Figs. 6a, 6c, 6e).

Ductile deformation is restricted to discrete shear zones, which occur only in the northern limb of the anticline and have affected both marbles and metacherts.

From the calcite twin types observed, the presence of cataclastic quartz fabrics, and the absence of matrix-coarsening in the majority of the metacherts, we conclude that the temperatures of metamorphism nowhere exceeded about 300°C, and, moreover, decreased from N to S. Four deformation mechanisms predominate: flexural-slip folding, mechanical twinning, and microfracturing, connected with pressure solution.

In the study area, deformation and metamorphism have developed within the same tectonic phase. It is generally agreed that this happened during the early Miocene (Neohellenic phase according to JACOBSHAGEN 1986).

6. Conclusions

The tectonic structures and fabrics of the Plattenkalk group around the Samaria gorge point to deformation in the foreland of an orogenic belt. A possible detachment of the Plattenkalk unit from its basement might have occurred subsequently. The deformational structures of the northern part of the Samaria section have originated in a deeper structural level of the crust than in its southern part.

We are aware of possible uncertainties regarding the estimation of the metamorphic temperatures by the methods used in this work. Our aim was not to specify absolute temperatures, but to examine whether it is possible to identify certain trends in temperature distribution. So, the temperatures of metamorphism of the Samaria Plattenkalk were about 50-100°C lower than had been assumed by previous authors (SEIDEL et al. 1982), who had extrapolated the values from the Talea Ori, central Crete, over the whole island. Even within the limited Samaria section temperatures have decreased from N to S. This corresponds well with the results of illite crystallinity investigations by SOUJON & JACOBSHAGEN (2001). By analysing 170 samples from all Plattenkalk areas of western, central, and eastern Crete, these authors documented a clear distribution pattern of IC values, that remain approximately constant in E-W direction, but increase from S to N everywhere on the island. Thus, the temperatures of Plattenkalk metamorphism must generally have increased in that direction.

As mentioned before, MANUTSOGLU (1990) had already pointed to analogous relations in the Taygetos Mts., southern Peloponnesus. From the study of microfabrics and clay-mineralogical analyses he showed that the depths of Plattenkalk deformation and metamorphism have increased there from W to E. This trend continues even farther to the E, to the Parnon Mts., central Peloponnesus, where BASSIAS (1988) derived P-T conditions of 450-480°C and 3.5-5 kb from both mineral parageneses and thermobarometric calibration of zoned amphiboles.

Thus it seems likely to suppose that the increase of the temperatures of Plattenkalk metamorphism towards the internal parts is a general phenomenon of the Hellenic Arc. It may be explained by the assumption that the depths of subduction and subsequent deformation of the Plattenkalk platform, once having been a part of the Adria microplate, have increased from the external rim of the arc towards its interior. Further investigations may show whether this hypothesis is valid.

7. Acknowledgements

This study has been substantially supported by financial funding of the German Research Foundation (DFG), which is gratefully acknowledged. Furthermore, the authors feel very endebted to Dr. U.F. DORNSIEPEN for fruitful discussions and express their gratitude to Dr. D. MATARANGAS (IGME Athens) and to the colleagues of IGME Rethymnon for effective logistic support of their investigations. Special thanks are due to Prof. G. ZULAUF (Erlangen) for his detailed and helpful review of the manuscript and to A. BECK (Berlin) for language support.

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Manuscript received: 12.08.2002
Revised draft: 01.02.2003
Accepted for printing: 02.02.2003