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THE PHYLLITE-QUARTZITE UNIT (PQ): STRUCTURAL EVOLUTION AND FLUID INCLUSION TRAILS-CONSTRAINTS ON THE METAMORPHIC HISTORY

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ABSTRACT

In the Tertiary the Phyllite-Quartzite (PQ) Unit on Crete experienced high pressure/low temperature metamorphism. During uplift and cooling of rocks, progressive deformation caused formation of various structural elements. The oldest episode of the progressive deformation is characterized by plastic deformation mechanisms of HP-minerals such as carpholite and chloritoid. This deformation produced a flat dipping foliation, striking E-W, N-S trending intrafolial fold axes and N-S and E-W stretching lineations. Continuing deformation caused N-S and E-W trending fold axes, often with an axial plane cleavage. Related to the continuing uplift, at higher crustal levels the deformation generated a flat dipping fracture cleavage, striking roughly N-S, kinkbands, deformation lamellae and transgranular fluid trails, decorated by fluid inclusions in quartz aggregates. The transgranular fluid trails and the deformation lamellae strike in N-S direction. The investigated fluid inclusions along the deformation lamellae and along the transgranular trails contain a brine, whose composition corresponds approximately to the systems H_2O-$NaCl$-$CaCl_2$ and H_2O-$NaCl$-$MgCl_2$/$FeCl_2$ (density= 0.8 $g*cm^{-3}$, based on microthermometric analysis). The temperature of trapping of these inclusions is between 130°C and 250°C. During the development of these deformational processes, the dominant deformation mechanism was pressure solution of quartz .

All features were mainly caused by E-W extensional tectonics. Deformation took place in the flattening field with an elongation between 40% to 60%. The latest, Quarternary deformation took place at a shallow crustal level and caused normal faults and joints, striking N-S and E-W.

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INTRODUCTION

Structural evolution and the PT-history of metamorphic terrains, exposed at the earth surface, help to understand, how rocks are buried to great depth and how they are brought back to the surface (e.g., Snoke & Frost, 1990). Preserved macro- and microstructures provide also information about the processes that operated at depth (e.g., Zwart et al., 1987; Knipe, 1989). The present paper is concerned with structural and microstructural studies that were confined to the Phyllite-Quartzite Unit in south Central Crete (area of Kerames village and Drimiskianos) (fig.1). The PQ Unit in this area is composed of metapsammite, metapelites, metabreccia, marbles and cross cutting quartz-calcite and quartzitic veins. The main object of this paper is to unravel the deformational history of the PQ Unit.

Principal units of Crete

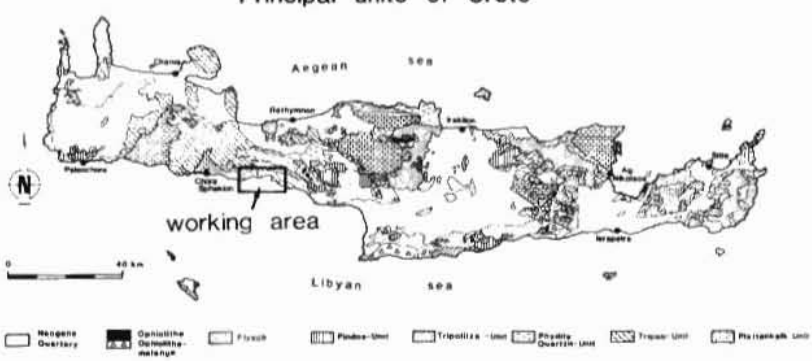

Fig.1: Our study was confined to the Phyllite-Quartzite Unit in south Central Crete, area of Kerames village and Drimiskianos. The map is taken from Creutzburg & Seidel (1977)

GEOLOGICAL SETTING

The island of Crete is located in the external part of the Hellenides, which represent the greek part of the Alpine mountain chain in the Eastern Mediterranean. The framework of Crete is dominated by thrust tectonics, which initiated stacking and emplacement of a nappe pile consisting of pre-Néogene rocks. In Crete, the lowermost tectonic position is represented by the *Plattenkalk Series* consisting mainly of calcareous metasediments, whose age range from the Late Carboniferous/Early Permian (König & Kuss, 1980) to the Eocene (Fytrolakis, 1972; Bonneau, 1973) or Early/Late Oligocene (Bizon & Thiébault, 1974). The Plattenkalk Series experienced a high-P/low-T metamorphism of post-Oligocene age (Epting et al., 1972a) with peak conditions near 350°C, 10 kbar (Theye, 1988).

The Plattenkalk Series is structurally overlain by the *Phyllite - Quartzite Unit* which comprises mainly clastic rocks, carbonatic/dolomitic rocks and gypsum with intercalated volcanites and pyroclastics (Wachendorf et al., 1974). The lithofacies of the sedimentary protoliths indicates a shallow marine environment (Theye et al. 1992). In Crete, sedimentation took place between Upper Carboniferous and Upper Trias (Krahl et al. 1983). In Eastern Crete, slices of Variscan age high-grade metamorphic rocks are tectonically included in the *PQ Unit*. During Late Oligocene/Early Miocene (Seidel et al., 1982), the rocks of the PQ Unit were affected by a high- P/low-T type of metamorphism. Estimations of the P-T conditions of metamorphism for Crete by Theye & Seidel (1991) show an increase of P and T from E-Crete to W-Crete. The given values are 300°C ± 50°C, 8 ± 3 kbar for E-Crete, 350°C ± 50°C, 9 ± 3 kbar for Central Crete and 400°C ± 50°C, 10 ± 3 kbar for Western Crete (Theye & Seidel, 1991).

These HP/LT metamorphic units are overlain by the *Tripolitza* and the *Pindos Series* preserving carbonatic and flysch sediments and show no signs of metamorphic imprint. The uppermost units consist of the *Asteroussia Nappe*, which underwent Cretaceous HT-metamorphism (70 Mill. y., Seidel et al., 1976), the *Arvi-Nappe* - consisting of Jurassic metamorphic rocks (Seidel et al., 1977a) - and *ophiolites*.

STRUCTURAL EVOLUTION OF THE PQ UNIT

The PQ underwent progressive deformation. The oldest episode of deformation affected the peak pressure minerals carpholite and chloritoid and indicates deformation after P-T peak conditions of 8(±3) kbar and 350 (±50)°C (Theye & Seidel, 1991). Carpholite and chloritoid are often elongated parallel to the trace of a flat dipping foliation, which strike E-W, and which is orientated at low angle to the

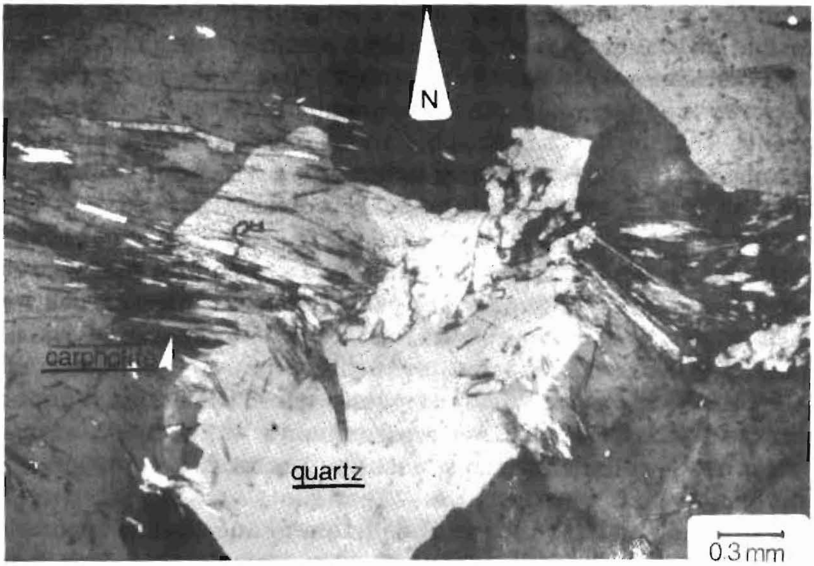

Fig.2: Carpholite orientated parallel to the stretching lineation in E-W direction

Fig.3: "Chocolate table" structures of quartz veins indicate deformation in the flattening field

trending stretching lineation, defined by preferred orientation of carpholite (fig.2) and chloritoid, was observed. Quartz-calcite segregations crystallized parallel to the foliation surfaces. They are considered as "channel-ways of fluids" (Theye, 1988) and often contain ferro-carpholite. The crystallization of carpholite should follow the reaction 4pyrophyllite + chlorite + $2H_2O$ = 5carpholite + 9quartz after Theye (1988). These veins and the more competent metapsammite layers have been stretched to form "boudinages" and "chocolate table" structures and suggest deformation in the flattening field (fig.3). "Micafishes", which indicate top to E-shearing, and asymmetric pressure shadows show the non-coaxial character of this deformation. Quartz fibres, that crystallized in the pressure shadows around pyrite (Ramsay & Huber, 1983) show also deformation in the flattening regime with extension of about 60% in E-W direction and about 40% in N-S direction. Continuing deformation in the flattening field produced folds, with fold axes trending approximately N-S and E-W. The enveloping surfaces show varying dip directions. Frequently an axial plane cleavage striking NE-SW, was formed. In more competent layers, folds of class 1B and 1C are dominant. The less competent layers show folds of class 3 (Ramsay & Huber, 1987). Fig.4 show the penetrative foliation, striking to the E-W, in metapelites of the PQ Unit near Kerames. The generated fold axes trend as well in N-S as in E-W direction.

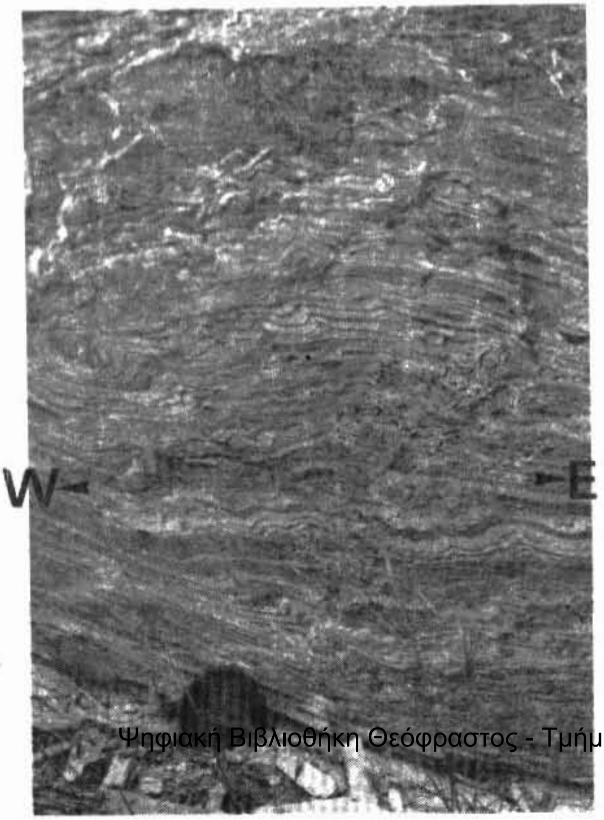

Fig.4: Metapelites of the PQ Unit near Kerames. The sedimentary layering is characterized by the different colored layers. The foliation surface is orientated subparallel to the sedimentary layering and strike E-W. The fold axes trend as well to the N-S as to the E-W.

The c-axes patterns of quartz and recrystallized grains show girdles around the N-S orientated fold axes and the stretching lineation, which trends parallel to these axes (after Price, 1985). Subsequent deformation resulted in a new generation of open folds, whose axes strike to the NE-SW and in refolding of former fold axes.

During continuing retrograde metamorphism and cooling, the deformation generated fracture cleavages in metapelites and macroscopic kinkbands in all metasediments. Microscopic kinkbands appeared in quartz, white mica, chlorite and calcite. Quartz aggregates show transgranular fluid inclusion trails and deformation lamellae decorated with fluid inclusions. Quartz grains with c-axes orientated at high angle to the foliation, show predominant basal deformation lamellae, initiated by <a>-gliding (after Ave Lallement & Carter, 1971). In naturally deformed rocks, basal deformation lamellae are produced at temperatures of about 275°C and strain rates of 10^{-12} to 10^{-14} sec. (Voll, 1976). The orientation of the transgranular fluid trails in quartz aggregates allows to determine the orientation of the stress direction σ_3 during this deformational episode: The transgranular fractures are subvertical and trend N-S, and σ_3 dips gently to the E.

The main deformation mechanism during the progressive deformation was pressure solution of quartz (after Nicolas, 1984). This was accompanied and followed by dislocation glide and recrystallization of quartz.

At a later stage of the deformation history, mainly N-S and E-W trending normal faults and joints with extensional geometry developed as result of brittle deformation. They are supposed to be initiated by the subduction of oceanic crust under the Hellenic arc and are associated with Neogene block tilting to the N (Pirazzoli et al., 1982).

FLUID INCLUSIONS TRAILS

The investigated fluid inclusions in quartz aggregates were formed along transgranular fractures and deformation lamellae. Microthermometric analysis give eutectic temperatures between -52.7°C and -31.3°C. These temperatures correspond to the freezing point depression of water for NaCl, KCl, $CaCl_2$ and $MgCl_2$ solutions (after Linke, 1958, 1965). The eutectic composition give salt concentrations between 0% and 23%. The homogenization temperatures of the fluid inclusions vary between 130°C and 250°C and are characteristic for a fluid density between 1.0 $g*cm^{-3}$ to 0.8 $g*cm^{-3}$ (after Crawford, 1981). The homogenization temperature corresponds to the temperature of trapping of the fluid inclusions by the quartz crystals (after Roedder, 1984). Corresponding to this, the fluid trails are interpreted as to have been formed at temperatures between 130°C and 250°C. The fluid inclusions of these trails contain a brine, whose composition corresponds nearly to the systems H_2O-NaCl-$CaCl_2$ and H_2O-NaCl-$MgCl_2$/$FeCl_2$ (after Roedder et al., 1972).

The transgranular fluid trails in quartz aggregates strike N-S. This indicates, related to the proofed deformation in the flattening field and top to E-shearing, a regional stress distribution probably governed by E-W extension.

CONCLUSION

In summary, during uplift and cooling, the rocks of the PQ Unit in south Central Crete experienced a progressive deformation in a stress field mainly governed by E-W extension. The first episodes of deformation affected the peak pressure indicating minerals, carpholite and chloritoid, and suggest consequently retrograde P-T conditions. Continuing stress under retrograde metamorphism caused deformation of the metasediments in the plastic/brittle transition zone of quartz at temperatures of about 200°C, as was revealed from the homogenization temperature of the fluid inclusions. All these produced mainly N-S and E-W orientated structures. The geometry of the deformation during this uplift part is probably linked to E-W extension under flattening conditions: σ_1 is subnormal to the foliation surface and σ_3 dips gently to the E. Uplifted to the surface, the rocks became brittle and the deformation generated N-S and E-W striking normal faults and joints, probably related to the Neogene block rotation of the Cretan island. Geothermal gradients calculated from the fluid isochores, the homogenization temperatures and the petrological data of Theye and Seidel (1991) are between 10°C/km at P-T peak conditions and about 35°C/km near the surface.

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