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HIGH-PRESSURE/LOW-TEMPERATURE METAMORPHISM IN THE EXTERNAL HELLENIDES(CRETE, PELOPONNESE)

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ABSTRACT

High-P/low-T metamorphic rocks are found as coherent sheets at the base of the nappe piles of Crete and the Peloponnese. P-T estimates for the Plattenkalk Series in the lowermost tectonic position are near 10 kbar and 350°C in Central Crete and even higher in the Peloponnese. The overlying Phyllite-Quartzite Unit also shows a gradation in P-T conditions of metamorphism from E-Crete (320±40°C, 8±3 kbar) via W-Crete (400±40°C, > 10 kbar) to the Peloponnese (450±30°C, 17±4 kbar). Lower-grade high-pressure metamorphism is indicated for the Rawdoucha and Tyros Beds in the top of the Phyllite-Quartzite Unit. The existence of a high-P/low-T metamorphic belt in the external Hellenides places constraints on geodynamic models of this region.

INTRODUCTION

High-pressure/low-temperature metamorphic rocks are typical constituents of the mountain chains in the Eastern Mediterranean. They are regarded as indicators of fossil suture zones and are thus of special interest for the geodynamic interpretation of this region. A large terrain of high-P/low-T metamorphic rocks is exposed in the island of Crete and in the Peloponnese.

TECTONIC SETTING

Both the island of Crete and the Peloponnese are situated in the external part of the Hellenides, the Greek segment of the Alpine-Himalayan mountain belt. The geologic architecture of Crete and the Peloponnese is characterized by nappe tectonics comprising metamorphic and nonmetamorphic units. The rocks in the lower part of the nappe piles underwent high-P/low-T metamorphism. They are separated from the higher, nonmetamorphic units by post-metamorphic thrust faults.

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HIGH-P/LOW-T METAMORPHIC UNITS

The high-P/low-T metamorphic rocks occur as coherent, bedded sheets of different tectonic units. The Plattenkalk Series in the lowermost position is regarded as the relative autochthone (i.e. the lowermost tectonic unit exposed, its substratum being unknown). The overlying Phyllite-Quartzite Unit is the first (lowermost) definitively allochthonous element within the nappe piles of Crete and of the Peloponnese. High-P metamorphism is also indicated for the Rawdoucha and Tyros Beds in the top of the Phyllite-Quartzite Unit.

The Plattenkalk Series largely consists of recrystallized calcareous sediments. The stratigraphy begins with the Late Carboniferous/Early Permian (KÖNIG & KUSS 1980) and ends with the Eocene (FYTROLAKIS 1972, BONNEAU 1973) or Early/Late Oligocene (BIZON & THIEBAULT 1974). There are observations indicating the presence of pre-Alpine metamorphic rocks at the base of the Plattenkalk Series in Central Crete (SEIDEL et al. 1982).
In the period between Oligocene and Late Miocene (onset of postorogenic sedimentation), the Plattenkalk Series was metamorphosed. The scarcity of rocks of suitable composition makes the estimate of metamorphic P-T conditions difficult. However, in outcrops west of Iraklion/Central Crete, the discovery of magnesiocarpholite coexisting with pyrophyllite, diaspore, chloritoid, and sudoite in metabauxites as well as the finding of lawsonite-sudoite-bearing marbles in the same section (SEIDEL 1978, 1983, THEYE 1988) prove the high-P/low-T type of metamorphism. The P-T conditions of metamorphism estimated for the Plattenkalk Series of Central Crete are near 10 kbar and 350°C according to the stability of lawsonite, magnesiocarpholite, and pyrophyllite+diaspore (THEYE et al. 1992).
Further indications for high-P/low-T metamorphism of the Plattenkalk Series were recently discovered in the Peloponnese. In the Taygetos, mica-rich layers intercalated with chert-bearing marbles contain the paragenesis sodium pyroxene, phengite, dolomite, calcite, and quartz (specimen kindly provided by Prof. Dr. G. Kowalczyk; cf. Dittmar & Kowalczky, in prep.). The pyroxene is an aegirine with about 15 mol% jadeite component, phengite contains 3.60 ± 0.01 Si per formula unit. Applying the phengite barometer of MASSONNE & SCHREYER (1987), a minimum pressure of about 15 kbar (at 450°C) is estimated for the Plattenkalk Series of the Taygetos.
Although petrological data are still sparse for the Plattenkalk Series of Crete and the Peloponnese, the results given above point to an increase in P-T conditions of metamorphism from E to W.

In W-Crete the Tripali Unit (CREUTZBURG & SEIDEL 1975) is wedged between the Plattenkalk Series and the overlying Phyllite-Quartzite Unit. The Tripali Unit largely consists of recrystallized dolomites in which shallow-marin fossils (KOPP & OTT 1977) have been found. Paleogeographically, it may be regarded as a more proximal equivalent of the Late Triassic-Liassic part of the Plattenkalk Series (HALL et al. 1984, KRAHL et al. 1988). The lithology of the Tripali Unit is unsuitable for an evaluation of the metamorphic conditions. For the present, a high-P/low-T type of metamorphism is assumed.

High-P/low-T metamorphism is an essential criterion for distinguishing the Phyllite-Quartzite Unit[1]. Diagnostic minerals like blue amphiboles, sodium pyroxenes, lawsonite, aragonite, and Fe-Mg-carpholite are common in this unit. K-Ar data indicate a late Oligocene/early Miocene age of metamorphism which is contemporaneous with the metamorphic overprint of the Plattenkalk Series (SEIDEL et al. 1982). Contrary to the units above and below, no fossils younger than Triassic are known from the Phyllite-Quartzite Unit.
The Phyllite-Quartzite Unit consists mainly of phyllites and quartzites, with minor intercalations of metaconglomerates, marbles, anhydrite/gypsum lenses, and metavolcanics. The lithofacies of the sedimentary protoliths indicates a shallow-marine environment. In Crete, the range of sedimentation from Late Carboniferous to Late Triassic is well documented by microfossils (KRAHL et al. 1983, 1986, 1988). For the Phyllite-Quartzite Unit of the Peloponnese, a paleontological evidence is still expected. In E-Crete, slices of Hercynian metamorphites are intermingled with the Permo-Triassic constituent of the Phyllite-Quartzite Unit (SEIDEL et al. 1982). These Hercynian metamorphites were also affected by the Alpine high-P/low-T metamorphism.
Detailed studies of the metamorphic petrology of the Phyllite-Quartzite Unit (SEIDEL 1978, THEYE 1988, THEYE & SEIDEL 1991, THEYE et al. 1992) clearly demonstrate an increase of metamorphic P-T conditions from E to W. For example, metavolcanics in E-Crete contain magnesio-riebeckite and aegirine-augite, whereas glaucophane and omphacite are found in equivalent rocks of W-Crete. In metapelites of E-Crete, pyrophyllite+chlorite is a frequent assemblage. Passing to Central Crete, it is replaced by parageneses with chloritoid. A futher increase of metamorphic grade can be observed in the Peloponnese and the island of Kythira south of it. Here, garnet, sodic pyroxene, and the paragenesis chloritoid+glaucophane occur in metasediments. In respect to their chemical composition, the chloritoid-glaucophane-bearing metasediments correspond with the widespread chloritoid-chlorite-paragonite schists of Central and Western Crete.
The P-T conditions of metamorphism, estimated for the Phyllite-Quartzite Unit in Eastern Crete (E of Ierapetra), Central Crete (Ag. Nikolaos to Rethymnon), Western Crete and the Peloponnese, are (cf. THEYE & SEIDEL 1991):

Eastern Crete	320 ± 40 °C, 8 ± 3 kbar
Central Crete	350 ± 40 °C, > 8 kbar
Western Crete	400 ± 40 °C, > 10 kbar
Peloponnese	450 ± 30 °C, 17 ± 4 kbar

These estimates are based on experimentally determined stability fields, phengite barometry and mineral equilibrium curves calculated with published thermochemical data.
Within the individual outcrop areas, the P-T conditions are fairly constant. Only Central Crete can be further subdivided according to illite crystallinity. In its eastern part, white K-micas are still illites with broad basal reflections, whereas, in the

[1] The terms "(Phyllites) Lower Nappe" or "Principal Crystalline System" (THIEBAULT & TRIBOULET 1984), "Parnon Phyllites" (BASSIAS & TRIBOULET 1985) and "Arna Unit" (PAPANIKOLAOU & SKARPELIS 1986) are synonyms of the "Phyllite-Quartzite Unit" as defined by SEIDEL et al. (1982).

western part, peak sharpness indicates epimetamorphic conditions (SEIDEL 1978).

Locally, a Permo-Triassic sequence of sedimentary and volcanic rocks is sandwiched between the Phyllite-Quartzite Unit and the overlying limestones of the Tripolitza Series. This sequence resembles the Phyllite-Quartzite Unit in lithology, but is clearly lower in metamorphic grade. These Rawdoucha Beds in Crete (SANNEMANN & SEIDEL 1976) and Tyros Beds in the Peloponnese (KTENAS 1924, THIEBAULT & TRIBOULET 1984) were regarded as the anchimetamorphic sedimentary base of the Tripolitza Limestone, although there is no unequivocal prove of sedimentary continuity. Recent investigations, however, revealed that, at least partly, this sequence is high-P/low-T metamorphic. In Crete, the outcrop of Rawdoucha Beds near Asi Gonia (KOPP & OTT 1977) comprises pyrophyllite-chlorite schists with abundant carpholite-bearing segregations. The grade of metamorphism of these rocks conforms to the high-P/low-T metamorphic Phyllite-Quartzite Unit in Eastern Crete. Other occurrences of Rawdoucha Beds (Rawdoucha, Selia, Lasithi) show coal rank/illite crystallinity correlations that indicate low-grade high-P metamorphism (FELDHOFF et al. 1991, this volume). In line with these results, two occurences of the high-P indicator lawsonite in the Tyros Beds of the Peloponnese were reported (PE-PIPER 1983, BALTATZIS & KATAGAS 1984). High celadonite contents of phengites (3.3 - 3.5 Si p.f.u.) in metavolcanics of the Tyros Beds in the northern Peloponnese (MEYER 1983; BALTATZIS & KATAGAS 1984) give further evidence of high-P/low-T metamorphism.
In summary, at least parts of the Rawdoucha and Tyros Beds represent slices of low-grade high-pressure metamorphic rocks that consequently can not be the sedimentary base of the nonmetamorphic Tripolitza Limestone.

Essential features of the Phyllite-Quartzite Unit and the Rawdoucha and Tyros Beds are:
1. Permo-Triassic age of the protoliths, shallow-marine lithofacies, calc-alkaline volcanics.
2. High-P/low-T metamorphism.
3. Uplift of the Phyllite-Quartzite Unit along a cold geotherm as indicated by the preservation of aragonite in marbles of Western Crete.
4. Discontinuous increase of metamorphic grade from E to W in the Phyllite-Quartzite Unit (see above) as well as in the Rawdoucha Beds (FELDHOFF et al. 1991, this volume).
5. Discontinuous decrease of metamorphic grade from the base (Phyllite-Quartzite Unit) to the top (Rawdoucha and Tyros Beds).
6. Volumes of the different sequences decrease from the base to the top: the Phyllite-Quartzite Unit forms extensive regional terrains, the Rawdoucha and Tyros Beds occur as small slices.
7. Exhumation of the metamorphic sequences as regionally coherent segments.

OVERLYING UNITS

In Crete as well as in the Peloponnese the high-P/low-T metamorphic Phyllite-Quartzite Unit is overridden by the shallow-marine platform limestones of the Tripolitza Series which ranges

in age from Late Triassic to Late Eocene. The rocks of this nappe show no signs of metamorphic overprint. The same holds true for the following nappe of the Pindos Series, a sequence of basinal sediments of Late Triassic to Paleocene/Eocene age.
In Crete, a composite nappe with Jurassic ophiolites and slices of various metamorphic, igneous and sedimentary rocks forms the uppermost allochthonous unit. Besides small remnants (Angelona), this nappe is absent in the external Hellenides of the Peloponnese.

DISCUSSION

The P-T conditions estimated for the metamorphic units at the base of the nappe piles of Crete and the Peloponnese imply that surface-derived rocks were buried to depths up to about fifty kilometres and thereafter were exhumed as regionally coherent segments. The tectonic thickness of the overlying nonmetamophic units (at the most 3000 m) is not adequate to explain the high-P/low-T metamorphism. Moreover, simple uplift of whole-crustal blocks and synchronous erosion would result in continuous metamorphic sections (e.g. ENGLAND & RICHARDSON 1977). In the external Hellenides, however, tectonic contacts separate sequences that were buried to various depths. Because these contacts omit crustal sections, they operated as (low-angle) normal faults (PLATT 1986, AVIGAD & GARFUNKEL 1991). As discussed by PLATT (1986), in an accretional wedge, normal faults can account for the exhumation of deeply buried rocks by dispersion of the overburden. In the external Hellenides, relics of the omitted crustal section may be represented by intermediate-P slices of the Rawdoucha and Tyros Beds. The accretional wedge and related deep burial may correspond with subduction beneath the central Aegean.
Deep burial of rocks by accretion or underplating implies significant lateral shortening which may be in the range of some hundred kilometres. This fact makes palinspastic restoration difficult if not impossible. Nevertheless, it is generally agreed that the nappes represent different paleogeographic zones which, before nappe stacking, were arranged one behind the other. Accordingly, the following arrangement results from external to internal: Plattenkalk Series - (Tripali Unit) - Phyllite-Quartzite Unit inclusive Rawdoucha/Tyros Beds - Tripolitza Series - Pindos Series. The two units in the upper part of the nappe piles can be easily correlated with the well-known isopic Pindos and Tripolitza zones of the Greek mainland, and the Plattenkalk Series fits fairly well the Ionian zone of W-Greece in its sedimentary age and lithology. The paleogeographic position of the Phyllite-Quartzite Unit is still disputed (see KOPP & RICHTER 1983). Many geologists regard this unit as the former basement of the structurally overlying Tripolitza nappe (e.g. BONNEAU 1984). Others ascribe it to a separate isopic zone between the Plattenkalk zone and the Tripolitza zone (e.g. KOPP & OTT 1977). Both views pose serious problems: the missing high-P/low-T metamorphism in the Tripolitza Series on the one side, the absence of post-Triassic sediments in the Phyllite-Quartzite Unit on the other side. If one of these concepts is correct, how to restore the Phyllite-Quartzite Unit to its original paleogeographic position after burial with high-P/low-T metamorphism and following exhumation, and before the final stacking of nappes? But a geodynamic interpretation in terms

of the model proposed by PLATT (1986) also bears problems, because exhumation by dispersion of the overburden should result in tectonic contacts between variable units. In the external Hellenides, however, always the same and monotonous stacking sequence occurs over a distance of 600 kilometres along the strike of the orogenic belt.

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