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THE ROLE OF EXTENSION IN UNROOFING THE CYCLADIC BLUESCHIST BELT

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ABSTRACT

Peak metamorphic pressure conditions of 15 kbar indicate that the Cycladic blueschist unit emerged from a depth of ca. 50 km. The HP rocks are delimited from above by low-angle faults which cut-out crust and hence operated with a normal sense of motion. These normal faults facilitated the exhumation of the HP rocks by removing and dispersing the overburden laterally. A ca. 30 km thick section was removed from above the blueschist unit in the Oligocene but extensional structures of this age are not known. Oligocene - Miocene ductile stretching, probably enhanced by elevated temperatures, occurred in Naxos and Paros, whereas contemporaneous low-angle normal faulting attenuated the crust in the western part of the Cyclades (Tinos). Continuous extension is documented by low-angle normal faults which cut through foot-wall Miocene granites and which show a prolonged deformation history.

The blueschist unit overthrusted a lower pressure para-autochthon when a significant portion of the overburden was removed. Therefore, the extensional unroofing of the Cycladic blueschist unit occurred during plate convergence.

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INTRODUCTION

Published petrological and geochronological data show that rocks exposed in the Cycladic islands were metamorphosed at HP-LT metamorphic conditions in the Eocene (Okrusch & Brocker 1990; Schliestedt et al. 1987 and references there). Mineral equlibria and thermobarometry show that P-T conditions reached 15 kbar and 500°C (in Syfnos, Syros and Tinos; Fig. 1). The pressure estimates indicate that the high-pressure rocks were buried at a depth of ca. 50 km. Therefore, the exposure of these rocks on the earth's surface requires the removal of a very thick overburden.

A greenschist-facies overprint affected the HP rocks during decompression, and caused the transformation of the HP minerals into lower-pressure assemblages. Mineral equilibria show that the transformation occurred at pressures of 5-7 kbar (Jansen & Schuiling 1977; Matthews & Schliestedt 1984; Buick & Holland 1989) and radiometric dating yield ca. 20 Ma on retrograde mineral assemblages (Altherr et al. 1979; 1982). This indicates that the HP rocks exhumed to a depth of 15-20 km in the Early Miocene and that a 20-30 km thick portion of the original overburden has been removed from above the Cycladic blueschist unit during the Oligocene. Granitic plutons intruded the blueschist unit during the Miocene (Altherr et al. 1982), at a depth of ca. 5 km.

Erosion and whole-crust uplifting may result in the exposure of HP metamorphic rocks. However, the absence of thick clastic sequences which may store the eroded overburden, and the rapid exhumation rate (more than 1.0 mm/y) which is inferred from the P-T-t data, suggest that erosion did not play an important role in the exhumation of the Cycladic blueschist unit.

Post-Eocene deformation affected the Cycladic massif and is best demonstrated by the emplacement of an allochthonous Upper-unit (Marmara nappe; Bonneau 1984) which consists of L-P metamorphic rocks, various sedimentary sequences and ophiolite remnants (Durr et al. 1978). The emplacement of the Upper unit over the blueschist unit was considered to be a result of thrust faulting and large-scale nappe translation (Altherr and Seidle, 1977;Papanikolaou, 1980; Bonneau 1984). However, thrust faulting cannot exhume HP metamorphic rocks because it is rooted at their base; it leads to thickening and burial rather than to the unroofing and thinning which are required in order to exhume deeply buried rocks. Additional work in the Cyclades led Lister et al. (1984) and other workers (Avigad and Garfunkel, 1989, 1991; Gautier

et al. 1990; Faure et al. 1991; Buick, 1991; Lee and Lister, 1992) to propose that extensional deformation played an important role in the exhumation of the high-pressure rocks.

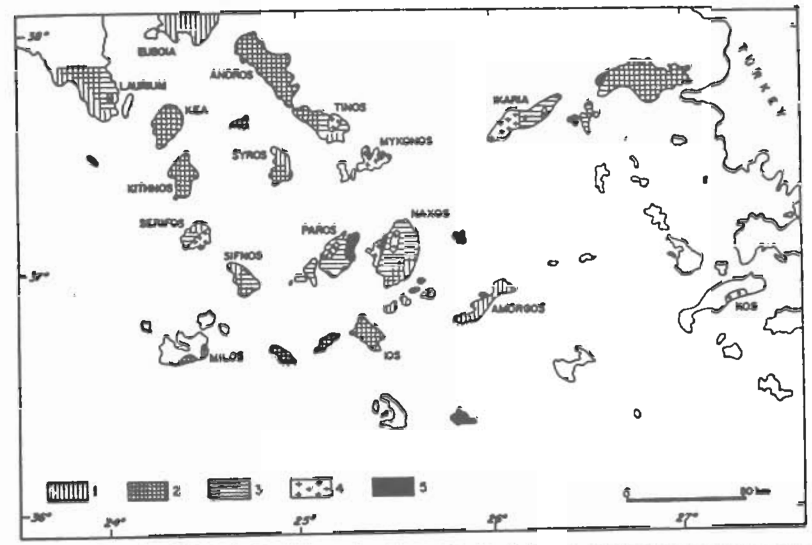

Fig. 1. Metamorphic rocks of the Attic-Cycladic complex. Lower (Basal) unit, 1–4. 1 = Eocene high-pressure metamorphic rocks; 2 = Eocene high-pressure metamorphic rocks overprinted by the Oligocene/Miocene low/medium-pressure metamorphism; 3 = Oligocene/Miocene low/medium-pressure metamorphic rocks; 4 = Oligocene/Miocene granitoids; 5 = undifferentiated rocks of the upper tectonic unit. Geology is generalized after Altherr et al. (1979, 1982)

UNROOFING BY EXTENSION

The area of the Cyclades is dissected by high-angle normal faults but these are related to the Late Miocene extension and fragmentation of the Aegean crust, and hence did not contribute much to the exhumation of the HP rocks. An older generation of normal faults exists in Mykonos, Naxos and Paros (Fig. 1). These are low-angle normal faults which cut through Miocene (ca. 10 Ma) granites (Fig. 2). The structures in the granites show a prolonged deformation history during the decompression and cooling of the footwall (Lister et al. 1984; Gautier et al. 1990; Faure et al. 1991; Avigad and Garfunkel, 1991; Lee and Lister, 1992): mylonitization is overprinted by cataclasis and brecciation at shallower depth. The hanging walls are dominated by sedimentary clastic sequences and show brittle deformation. These low-angle normal faults probably unroofed ca. 5-10 km (depending on the depth of the intrusion) from above the granites, subsequently to the

Middle Miocene. Evidence for the extensional tectonics which operated earlier, in the Early Miocene, include synsedimentary normal faults in Lower Miocene molasse sequences preserved on Paros (Papanikolaou 1978), ductile deformation in Naxos (Lister et al., 1984; Buick 1991) and low-angle normal faulting in Tinos (Avigad and Garfunkel 1989; 1991).

On Naxos, the Eocene HP metamorphic assemblages were almost completely obliterated during decompression; they were overprinted by Barrovian metamorphic assemblages at pressures of ca. 5-7 kbar at 650°C (Jansen & Schuiling 1976; Buick & Holland 1989), in the Oligocene-Miocene (Altherr et al. 1982). The investigation of the microstructures revealed that the Barrovian assemblages were deformed ductile during and subsequently to their crystallization (Buick 1991). The ductile deformation took place during the decompression of the HP rocks, i.e. during the reduction of the thickness of the overburden which overlain these rocks in the Eocene. Therefore, the fabric is interpreted to be a result of stretching and is taken to indicate the kinematic direction of the extensional deformation. This gains support also from the fact that the isograds on Naxos are condensed so that the present distribution of isotherms reflects abnormally high- temperature gradient.

On Tinos, as well as on Syros and Sifnos, ductile deformation during the transformation to greenschist facies is practically absent. Unlike Naxos and Paros, the rocks in this part of the Cyclades remained rigid during their motion to the earth's surface. The deformation which unroofed the Cycladic blueschists was probably concentrated along widely-spaced faults and shear-zones which penetrated to a depth of more than 20 km. One of these shear zones was probably located on Naxos, where elevated temperatures enhanced ductile deformation.

On Tinos, the tectonic contact between the Upper unit and the underlying blueschist unit is exposed over several tens of kilometers. The contact is undulated and the Upper unit is preserved in the synforms. The Upper unit contains LP metamorphic and ultrabasic rocks with no evidence of a HP metamorphism. Moreover, K-Ar ages revealed that the greenschist- to amphibolite-facies metamorphism in this unit is of Upper Cretaceous (70 Ma) age (Patzak 1988). This shows that in the Eocene, when the blueschist unit suffered HP metamorphism, the Upper unit resided at shallow crustal levels. At the contact between the Upper unit and the

blueschist unit a rock sequence, perhaps several tens of km thick, is missing. Therefore, the low-angle fault contact in Tinos operated with a normal sense of motion. The timing of the juxtaposition of the Upper unit above the blueschist unit is well constrained: a 18 Ma granite pierced the low-angle normal fault in NE Tinos (Livada bay; Fig. 3), and caused contact metamorphism in both units. The rocks of the Upper unit were not affected by the greenschist-facies metamorphism which overprinted the underlying blueschists in the Oligocene - Miocene (Brocker, 1990), and hence the juxtaposition in Tinos is dated at around 20 Ma.

Normal faults older than the 20 Ma old contact on Tinos are not known in the Cyclades and extensional structures of Oligocene age, during which period a large portion of the exhumation of the Cycladic blueschist unit has been completed, are not known. It is likely that Oligocene juxtapositions cannot be recognized because rock sequences on both sides of the contact would be pervasively overprinted by the greenschist-facies overprint and would became indistinguishable.

THE SCALE OF THE OLIGOCENE-MIOCENE EXTENSION

The exposure of HP metamorphic rocks requires large scale vertical movements and at least 50 km is implied by the exposure of eclogite-facies rocks on Sifnos, Syros and Tinos. The investigations on Tinos show that lithological layering in the hanging-wall (Upper unit) is shallowly dipping and roughly parallel to the contact with the underlying blueschist unit. As a consequence, the low-angle normal fault in Tinos cannot be considered as a high-angle normal fault rotated during extension; it was formed shallow dipping. This has important implications concerning the scale of the lateral displacement which is required to exhume the HP rocks (Avigad & Garfunkel, 1991). The lateral displacement (d) as a function of the structural separation (s) and the original dip (Θ) of the fault plan is given by:

$$d=s/\tan\Theta$$

with a shallower fault plan, a larger amount of lateral displacement is required to expose a given crustal level.
To exhume the eclogite facies rocks in Tinos we assume a structural separation of 30-50 km, and a low-angle fault plan dipping 15°. This yields a lateral displacement of 120-180 km.

Fig. 2. Small granitic intrusions (arrows) in the Upper unit (Livada bay, Tinos) indicate that the juxtaposition of the Upper unit above the blueschist unit occurred prior to the intrusion of the 18 Ma old granite (photo kindly provided by M. Engi).

Fig. 3. A low-angle normal fault juxtaposes Early-Miocene clastic sediments above a Miocene granite in Mykons island (Panormos bay).

THERMAL EVOLUTION

The thermal evolution of the Cycladic blueschist unit is deduced from the P-T-t paths which were constructed for rocks exposed on several islands. The extensional unroofing of this unit resulted with different P-T paths in different parts of the Cyclades (Fig. 4). The Cycladic blueschist unit is divided by the NNE-SSW trending island chain including Sifnos, Syros and Tinos: rocks occurring to the east of this chain were heated during their decompression, whereas rocks comprising this chain or exposed west of it, were isothermally decompressed. Particularly interesting is the fact that rocks which were heated during decompression were metamorphosed at lower peak P-T conditions than rocks which decompressed isothermally. This contrasts with thermal modeling of whole-crust uplifting and erosion which predict maximum heating at the base of the uplifted section (England & Richardson 1977), and is consistent with the fact that erosion did not play an important role in the unroofing of the blueschists.

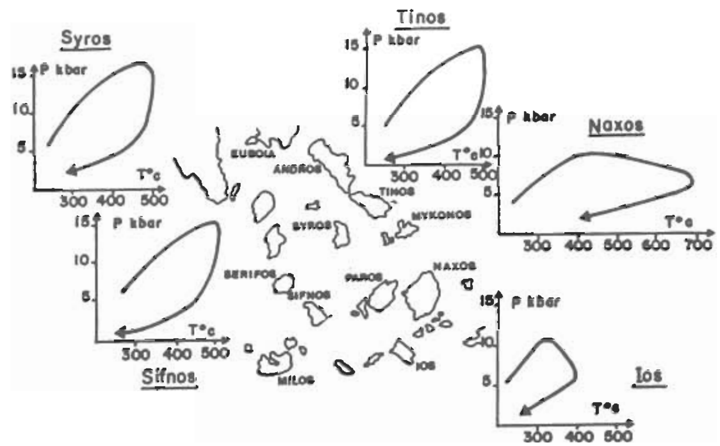

Fig. 4. P-T loops in the Cycladic blueschist unit. Isothermal decompression affected rocks exposed in the west, whereas rocks exposed in the east reached maximum temperatures during decompression (data sources in the text).

Isothermal decompression and cooling (as observed on Sifnos and Tinos) may result from continuous underthrusting of a cold material at the base of the orogenic wedge, below the HP rocks. This can cause refrigeration and would inhibit thermal relaxation (Rubie 1984). Nevertheless, thermal modeling of continental extension (Rupple et al. 1988) and extensional denudation of orogenic belts (Thompson & England 1984) show that rocks unroofed by extension either cool or decompressed isothermally, as observed in the Cyclades. This is consistent with the observations in the western part of the Cycladic massif but does not explain the heating observed in the east, such as in Naxos, Paros and Ios.

THRUSTING AT THE BASE OF THE BLUESCHIST UNIT

A lower basal unit is exposed below the Cycladic blueschist unit (Katsikatsos et al. 1986) in Evia, Tinos and Samos and a crucial question concerns the presence and the intensity of the HP metamorphism in these windows.

The investigations in Tinos show that the basal unit below the eclogite - facies rocks of the Cycladic blueschist unit does not contain eclogite-facies rocks. Instead, we find phyllitic layers and a carbonate sequence (mainly dolomites) which contains fossils (Melidonis, 1980; Avigad & Garfunkel 1989). This led us to the conclusion that the basal unit was not metamorphosed in eclogite-facies conditions. The fact that the basal unit was metamorphosed at lower pressures than the blueschist unit indicates that it was overthrusted by the blueschist unit subsequently to the removal of a large part of the overburden from above the later. The overburden from above the blueschist unit has been removed by normal faulting, and therefore, overthrusting of the blueschist unit onto the basal unit post-dated an important extensional deformation. This indicates that the extensional unroofing of the overburden from above the blueschist unit was accompanied by thrust faulting at the base of this unit. Therefore, the extensional unroofing of the HP rocks does not imply a transition to a wholesale lithospheric extension but is related to the orogenic process.

CONCLUSION

The Cycladic blueschist unit was metamorphosed at a depth of several tens of kilometers in the Eocene. P-T-t data suggests that a 30 km thick section was removed from above the blueschist unit in the Oligocene. The rest of the thickness of the

overburden was removed subsequent to a greenschist-facies overprint which affected the blueschist unit in the Oligocene-Miocene. The absence of thick clastic sequences and the inferred rapid exhumation rates suggest that whole-crust uplift and erosion did not play an important role in the exhumation of the HP rocks. The structural investigations reveal that brittle and ductile extension may have unroofed the overburden from above the blueschists. Evidence of extension are found starting in the Early Miocene. In Tinos, a low-angle normal fault cut-out large crustal sections between the blueschist unit and the overlying Upper unit and has been pierced by a granite and rendered inactive at 18 Ma. In Naxos and Paros a ductile stretching deformation affected the Oligocene-Miocene Barrovian assemblages and caused ductile thinning of the rock pile. Concurrent, shallow level extensional deformation is recorded by synsedimentary normal faults in Early Miocene molasse in Paros. Preliminary kinematic analyses of the low-angle normal fault in Tinos suggests that the exhumation of the HP rocks required a large amount of lateral displacement. A younger generation of low-angle normal faults cuts through Miocene granites in Naxos and Mykonos but involves a moderate amount of structural separation, in the order of ca. 5 km. All these were later cut by the Late Miocene block faulting of the Aegean region.

A basal unit is exposed below the Cycladic blueschist unit and does not show HP mineral assemblages. This implies that the blueschist unit overthrust a lower pressure, para-autochthon subsequent to the removal of large portions of the overburden. The time of the overthrusting is not well constrained so that we may conservatively conclude that at least the initial period of the extensional exhumation is related to the orogenic process. Finally, it is remarkable that extensional structures of Oligocene age, in which period a 30 km of the overburden were unroofed from above the blueschist unit, are not known. Fig. 5 shows a schematic and a prliminary model for the evolution of the Cycladic massif.

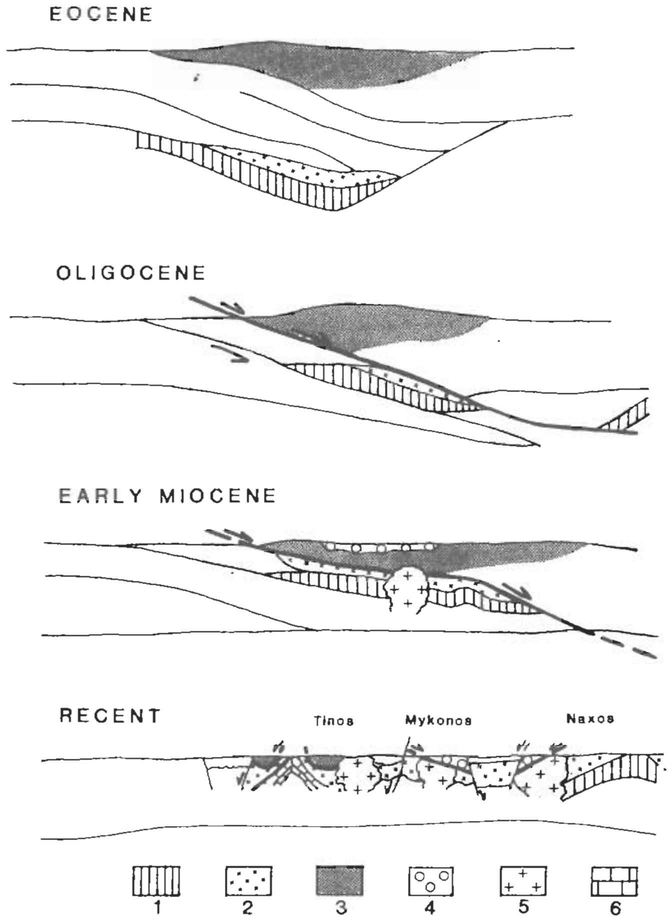

Fig. 5. A schematic model showing the evolution of the Cycladic massif from Eocene to Recent. Legend: 1) metamorphosed basement of the Cycladic blueschist unit; 2) Cycladic blueschist unit (cover); 3) Upper unit; 4) clastic sediments; 5) granite; 6) L-P basal unit.

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