Exhumation of the Meliata high-pressure rocks (Western Carpathians): Petrological and structural records in blueschists

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***Abstract**:: The Meliata unit, situated in the SE part of the Western Carpathians, represents an accretionary complex assembled during the closure of the Triassic-Jurassic Meliata oceanic basin. Blueschists, ophiolites and very low-grade metamorphosed sedimentary rocks are imbricated in a tectonic zone between the Gemericum and the Silica nappe. Petrological and microstructural analyses indicate a single progressive deformation coincident with prograde metamorphism at blueschist facies conditions. The foliation is defined by preferred orientation of mica, blue amphibole and rarely also by Na-pyroxene. The exhumation path is documented by ductite deformation, formed at blueschist-greenschist facies boundary and at greenschist facies conditions. The E-W directed thrust faults which are parallel to the foliation seem to be responsible for exhumation of the blueschists. Later stages of deformation in phyllites are documented by shear bands that crosscut the blueschist facies foliation. Low-temperature Cretaceous nappe tectonics resulted in brittle deformation and used mostly the older tectonic systems that formed at blueschist-greenschist facies conditions.*

***Key words**: Blueschists, microstructures, exhumation path, Meliata unit, Western Carpathians.*

Introduction

Petrological and structural data from several well-known convergence zones showed that oceanic and continental crust subducted to a depth of a few tens to hundreds of kilometers has been rapidly exhumed (Chopin, 1984; Smith, 1984; Schreyer, 1995; Chemenda et al., 1995, Reinecke, 1998). Besides surface erosion and possibly gravitational collapse of overthickened crust, the principle mechanism for exhumation of high-pressure rocks is assumed to be the uplift of upper plate by underplating (England and Molnar, 1990; Platt, 1993). Most studies have been concentrated on large scale examples of long lived subduction zones (Platt, 1987; England and Molnar, 1990; Jacobson et al., 1996). In areas with slice and nappe tectonics or in accretionary complexes, where the exhumed high-pressure rocks are mixed with low-grade or unmetamorphosed rocks (Ernst, 1990; Clift, 1996; Goodge, 1995), information is limited to reconstruct the exhumation path of high-pressure rocks. This is the case for the Meliata unit, where slices and tectonic blocks of high-pressure rocks, mostly imbricated with unmetamorphosed to very low-grade metamorphosed rocks (Lešo and Varga, 1980), are overthrusted by other nappes. The Meliata unit consists of blueschists, ophiolites and very low-grade metamorphosed sedimentary rocks. Detailed metamorphic petrology, including some geochronological analyses, on different group rocks were provided by Faryad (1995a; 1995b) and Faryad and Henjes-Kunst (1997). The process by which the high-pressure rocks returned to the surface is important for understanding of kinematics and dynamics in this part of the Western Carpathians. This work aims to constrain the exhumation history of blueschists by discussing and interpretation of recent tectonic, metamorphic and geochronological data. Fundamental information is provided by the PT path and by structural records acquired by the rocks on their return to the surface.

Geological framework

The Meliata unit consists of very low-grade oceanic and continental rocks and blueschists, reflecting a subduction and formation of an accretionary complex along the EW-striking and south-dipping thrust zone between the Gemericum and the Silica nappe in the southern part of the Western Carpathians (Fig. 1). Based on a to paleogeographical reconstructions (Mahel', 1986; Dercourt et al., 1990; Kozur and Mock, 1995; Mello, 1993) and tectonic and petrological characteristics (Reichwalder, 1973; Arkai, 1983; Neubauer et al., 1992; Faryad and Henjes-Kunst, 1997), this unit formed during closure of the Triassic Meliata oceanic basin which separated the Slovak part of the Apulian promontory from the Tisza-Bihor unit or from the Bükk unit.

The Gemericum, that is overthrust on the Veporicum, consists of Early Palaeozoic sequences overlain by Late Palaeozoic and Mesozoic rocks. Apart from some amphibolite facies slices and blocks (the so-called Gneiss-amphibolite Complex), occurring along the northern and eastern boundaries of the Gemericum, the Early Palaeozoic rocks were metamorphosed mostly at greenschist facies conditions. Conversely, the Late Palaeozoic rocks underwent only low- to very low-grade metamorphic conditions, so that the greenschist facies metamorphism appears to be of pre-Late Palaeozoic age.

The Silica Nappe is composed mainly of Triassic platform carbonates, but some Late Permian evaporites are also a part of this nappe. Recently, Mello (1993) and Vozárová and Vozár (1992) distinguished a Turna nappe which underlies the Silica nappe. In addition to Triassic rocks with evaporites, the Turna nappe contains

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Permian and Upper Carboniferous clastic sediments. Both the Silica and Turna nappes are correlated with similar rock in the Bükk mountain in Hungary (Kozur and Mock, 1995; Mello, 1993; Vozárová - Vozár, 1992).

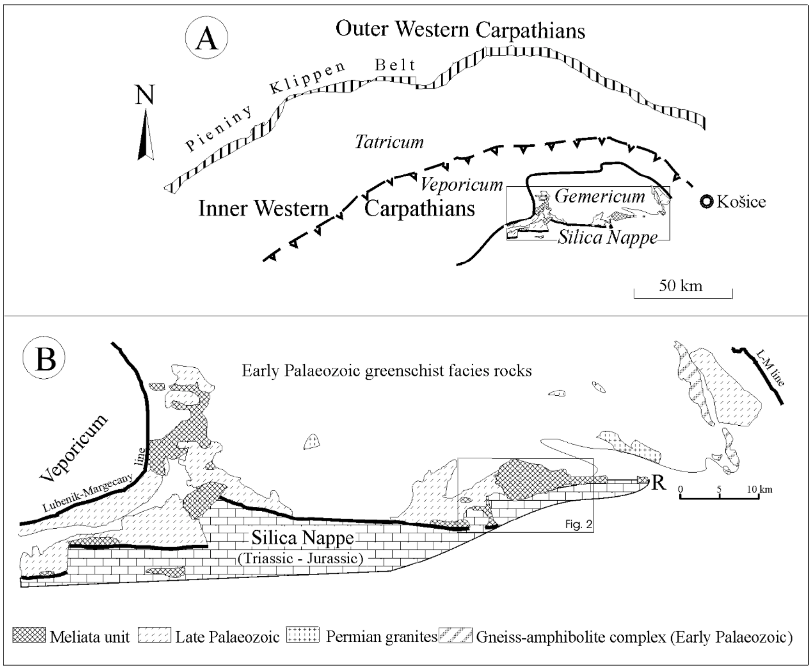


Fig. 1. Geological setting of the Meliata blueschists in a framework of the Western Carpathian geotectonics.

The name of Meliata was formerly used for a group of rocks, representing oceanic sediments, described from the Meliata village (Čekaltová, 1954). Latter was this name adapted to a tectonic unit containing pelagic sediments, ophiolites and high-pressure rocks (Mock, 1978; Kozur and Mock, 1995; Maheľ, 1986; Reich-walder, 1979). The Meliata unit form only slices and blocks outcropping beneath the Silica and Turna nappes. In the Western part, they overthrust the Early Palaeozoic of the Gemericum to the north. The geological situation and strati-graphical relations of the Meliata unit are complicated because of its imbrication with the adjacent tectonic units.

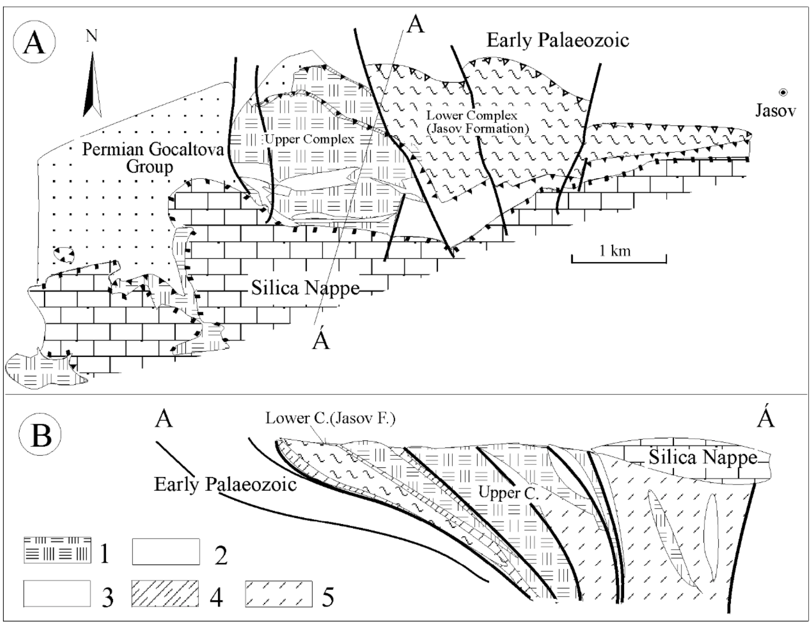


Fig. 2. Position of the upper (glaucophane-bearing) and lower (glaucophane-free) complexes (A) with idealized cross-section (B): 1-marbles, 2-metabasites, 3-phyllites, 4-black phyllites and rauhwackes, 5- very low-grade metamorphic of the Meliata unit (undifferentiated).

In addition to isolated slices of high-pressure rocks which are mostly exposed in the eastern and western sector of the Meliata unit (Fig. 1B and Fig. 2), the blueschist fscies rocks form small blocks within low-grade clastic sedi-ments, even within carbonate-evaporite sequences (Faryad, 1988; Dianiška, 1984). The oceanic rocks are represented by deep sea pelagic sediments, radiolarian limestones, turbidites and ophiolites. Black shales mostly occur in the lower part of the slices. Several serpentinite bodies occur along this tectonic zone in the southern part of the Gemericum. The presence of large amounts of ultramafic rocks at depth exceeding 2.5 km is indicated by geophysical data (Plančár et al., 1977). The serpentinite bodies are usually lens shaped and occur in a schistose carbonate sequence under the Silica nappe (Hovorka et al., 1985).

Lithology of the Meliata rocks

BLUESCHIST FACIES ROCKS

Regarding lithology and metamorphic history, the Meliata blueschists are classified into four groups. The most common rocks are marbles with intercalated metabasalts and phyllites (group I) which record P-T conditions of 9-12 kbar at 350-450 ^oC (Faryad, 1995b). Geochemically, the metabasalts have composition between MORB and arc basalts. Textural relations, mineral composition and geochronological data indicate a single-stage prograde metamorphism. Middle Jurassic ages (152-155 Ma) were obtained forthe high-pressure metamorphism by Maluski et al. (1993), Dallmayer et al. (1993) and Faryad and Henjes-Kunst (1997).

Table 1. Blueschist facies mineral assemblages from the Meliata unit rocks.

lithology	metabasite			phyllite		micaschist
mineral/group	I	II	IV	I	III	II
quartz	----------	----------	----------	----------	---------	----------
phengite	----------	----------	----------	----------	---------	----------
albite	----------	----------	----------	-----	--	-----
chlorite	----------	----------	---------	-------	------	---
epidote	----------	---------	----			
Na-amphibole	----------	----------	----------	----		
Na-pyroxene	----			--		
garnet	----			---		
titanite	----------	--	--			
chloritoid		---		----	------	----

The metabasites and micaschists of group II differ from group I rocks by the lack of marbles, and by chemical composition of the metabasites, which is similar to that of within-plate basalts. The micaschists contain relic Palaeozoic micas for which minimum cooling ages of ca. 375-380 Ma are inferred from their Ar-Ar spectra (Faryad and Henjes-Kunst, 1997). Metamorphic P-T conditions similar to those of group I rocks are inferred for the blueschist-overprint on these rocks.

Group III phyllites and phengite quartzite (known as lower complex, Reichwalder, 1973, Faryad, 1995b) are exposed in the eastern part of the Meliata unit (Fig. 2). They are separated from the upper complex (group I blueschist) by thrust faults that are mostly characterized by the presence of breccia, rauhwackes and mylonitized black phyllites. In contrast to the upper complex (group I), they are not associated with marbles and metabasalts. Sedimentary textures, mainly high amounts of quartz pebbles in metaconglomerates, suggest that the protoliths were shallow-water clastic sediments formed on continental margin. Petrological and geochronological data indicate a complex metamorphic evolution for group III rocks. At least a two-stage metamorphic history of Late Triassic (219 Ma) greenschist and Lower- to Middle Jurassic high-pressure metamorphism (172 Ma) can be assumed based on white mica composition and ^{40}Ar-^{39}Ar age spectra (Faryad and Henjes-Kunst, 1997). Furthermore, a very late overprint probably related to low-temperature deformation processes with maximum ages of ca. 80-90 Ma is supposed.

Group IV rocks correspond to earlier amphibolite facies basement rocks, overprinted by blueschist facies metamorphism. Although there are no geochronological data supporting a Paleozoic age of the earlier amphibolite facies metamorphism, a correlation with the Gneiss-Amphibolite Complex of the Gemericum can be envisaged from lithology and amphibolite facies mineralogy (Faryad, 1988).

VERY LOW-GRADE METAMORPHOSED ROCKS

The very low-grade rocks which envelope the blueschis are characterized by deep sea, mostly terrigeneous sediments and by ultramafites. Sedimentary rocks from the Meliata type locality are radiolarian limestones, cherts and different kinds of shales. Biostratigraphical results gave a Late Triassic to Early Jurassic age for their sedimentation (Mock, 1978; Kozur and Mock, 1995; Mello, 1993). In some localities they are associated with blueschist facies white marbles. Although the typical phase assemblages in the very low-grade sedimentary rocks which may involve quartz, white mica, chlorite, siderite or calcite are not diagnostic of metamorphic conditions, they are comparable with low-T facies. Considering average illite crystallinity (Kübler index) and b_o = 9.01-9.02 A^o), temperature of 250-300 ^oC and low/medium pressure are assumed (Arkai and Kovács, 1986). Such mineral assemblages were reported also from the melange matrix (Vozárová and Vozár, 1992). Some clastic metasediments, underlain by blueschists in the eastern part of the Meliata unit contain phengite with maximum contents of 3.26 a./f.u. which may indicate moderate pressures of 3-5 kbar at 300 ^oC (Velde, 1972; Massonne and Schreyer, 1987).

The ultramafic rocks are represented by lizardite-chryzotile serpentintes that derived from dunite and harzburgite (Hovorka et al., 1985). Apart from lizardite and chrysotile they contain relic olivine, orthopyroxene and spinel. Some ultramafic rocks from the eastern sector are classified as pyroxenite of websterite composition. Several boreholes from the Western sector indicated the presence of olistostromes of serpentinites and coarse-grained breccia (Vozárová and Vozár, 1992). These rocks additionally contain laminated pelites and sandstones. Basaltic rocks contain relic pyroxene and pseudomorphs of albite/epidote after plagioclase.

Structures in the blueschist facies rocks

PHYLLITES

Primary structures discernible in phyllites is bedding (S_o). Foliation (S_1) is mostly parallel to bedding and generally strikes approximately EW and dips with an angle of 20-50^o towards the S (Fig. 3). The orientation of the foliation varies between different outcrops, but the spread usually overlaps. The foliation is defined mostly by preferred orientation of phengite, but in some samples also by glaucophane (Fig.4a) and pyroxene. Stretching lineation is developed on S_1 planes and indicates N-NNE direction of shear sense (Fig 3). Some phyllites are characterized by isoclinal folds that fold S_1 fabric (Faryad et al., 1997).

Based on textural relations at least two types of chloritoid can be distinguished in the phyllites: 1) Chloritoid crystals enclosed by glaucophane were found in group II micaschists and group I phyllites (Fig.4b). 2) Most chloritoid crystals from glaucophane-free phyllites form lath-shaped porphyroblasts or rosettes. They have partly overgrown the S_1 foliation (Fig. 4c) and probably formed during the final stage of D_1 deformation.

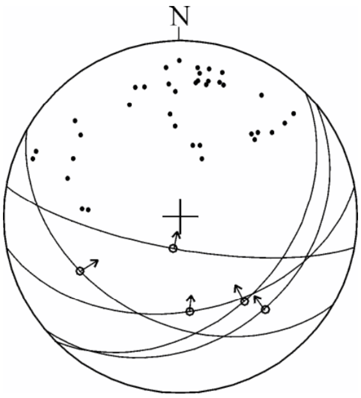
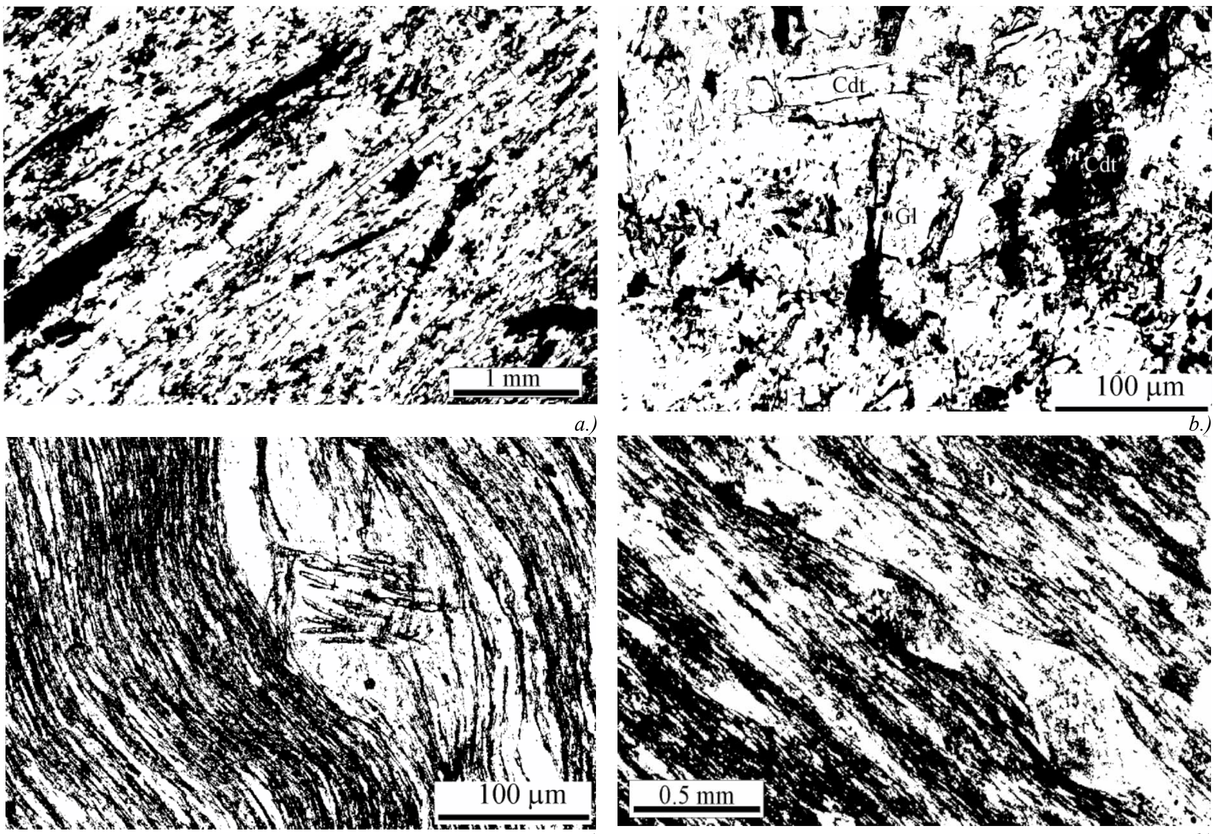


Fig.3. Stereographic projection of S_1 poles (doted) and stretching lineations (arrows) on S_1 foliation (great circles). Summary of structural data from the eastern sector of the Meliata unit (Faryad et al., 1997).

Phyllites are mostly retrogressed to greenschist facies assemblages. Glaucophane is almost completely replaced by chlorite and albite. Mylonitized black phyllites which usually occur along thrust faults, separating lower and upper complex, contain σ-type mantled porphyroclasts of glaucophane pseudomorphs (Fig.4d). The strain shadows adjacent to porphyroclasts consist of quartz and mica. Later stages of deformation in phyllites become apparent from cleavage S_2 and shear bands. In some calcite-rich phyllites boudinaged albite porphyroblasts indicate extensional deformation in relation to main foliation in the rocks.



a.) b.) c.) d.)

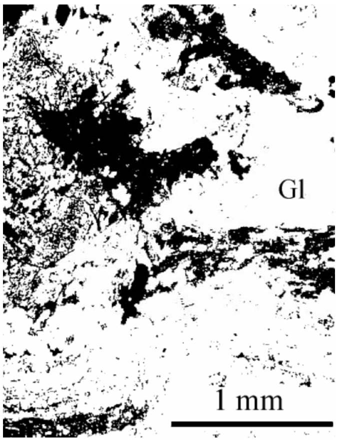
Fig. 4. Some examples of blueschist to greenschist facies metamorphic fabrics from the Meliata HP/LT phyllites, a) strongly foliated phyllite with blueschist facies foliation, defined by blue amphibole, phengite and quartz, b) partially resorbed chloritoid inclusions in glaucophane, c) chloritoid crystals, enclosing foliation, are partly rotated. S_1 fabric is folded by F_2 folds. S_2 axial-planar cleavage contains phengite, quartz, d) phyllitic foliation, wrapping around porphyroclast of albite + white + chlorite mica (pseudomorph after glaucophane). Strain shadows consists of quartz and white mica.

The SW plunging mineral lineation defined by phengite in conglomerates is parallel to the stretching lineation defined by elongate quartz pebbles. Pressure solution was the dominant deformation mechanism in these rocks. The aspect ratios of flattened clastic quartz grains indicate, similar to that shown by Schwarz and Stöckhert (1996) from HP/LT quartz phyllites in Crete, a positive correlation with mica content. The late stage of dynamic recrystallization in conglomerates is characterized by boudinage and by bounds of new quartz grains cross cutting prolonged pebbles in metaconglomerates.

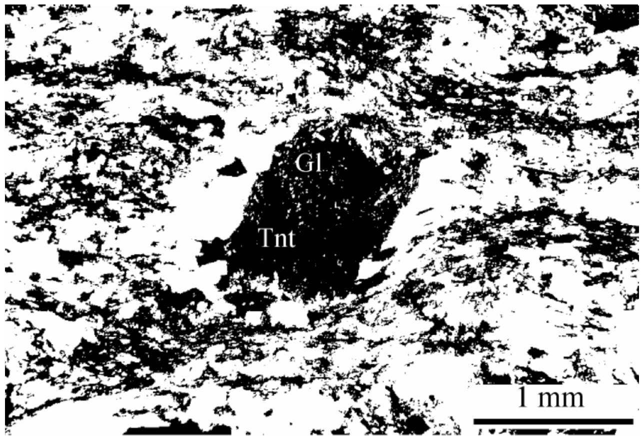
METABASITES

Metabasites are usually massive without obvious foliation. Diopsidic augite from some metabasites is the only relic igneous phase which is rimmed or partly replaced by aegirine. In addition to aegirine, glaucophane rims and also tabular actinolite probably formed by replacement of igneous hornblende. Actinolite and actinolitic hornblende pre-date the blueschist facies metamorphism and are rimmed by glaucophane. Some metabasalts that indicate no sign of deformation contain chlorite veins of various directions. The veins are partly cross cut by glaucophane and pyroxene and can be dated to represent pre-blueschist facies metamorphism. A second type of veins, filled by albite and glaucophane, occurs in weakly foliated metabasite. They are usually sub-parallel to the foliation and exhibit low aspect ratios.

In some coarse-grained metabasites, the foliation flows around glaucophane with strain shadows filled with quartz, phengite and rarely with fine-grained glaucophane (Fig.5a,b). This indicates formation of porphyroblastic glaucophane before deformation. Garnet and glaucophane are partly replaced by biotite.



a.)



b.)

Fig. 5. Microfabrics from the Meliata blueschist facies metabasites. a) blue amphibole porphyroblast, containing numerous inclusions of Fe-Ti phases, is surounded by fine-grained matrix of epidote, albite, blue amphibole. Inclusion-free blue amphibole occurs in the strain shadows of porphyroblast and follows the schistosity, b) porphyroclast of blue amphibole with strain shadows filled by quartz and white mica.

MARBLES

Pure white marbles are usually unfoliated. Compositional banding of white mica, quartz, albite and glaucophane can be found at the contact of marbles with phyllites and metabasites. No aragonite was found in marbles. Several kinds of twins can be observed in calcite from the same sample: i) thin straight twins (<5 μm) are slightly lens shaped. In strongly foliated marbles with subgrains in calcite, the twins are deformed. ii) thick twins (15-20 μm) and iii) twins in twins are common, but mostly they occur in calcite rounded by thin twinned calcite. Grain-boundary migration post-dating thick twinning is also present. Some marbles contain mantled σ- or δ-type primary lapilli of basaltic composition which are mantled in carbonate matrix.

Metamorphic conditions and P-T paths

Zoned blue amphibole, garnet, chloritoid, pyroxene, some phengite, titanite and epidote in metabasites indicate a progressive increase of pressure and temperature from the greenschist-blueschist boundary to blueschist facies. Metamorphic pressures and temperatures (7-9 kbar and 350-380 ^{o}C, Fig. 6) are constrained by mineral equilibrium reactions in Act_1-bearing metabasite for assemblage Act+Gl+Ab+Cpx+Grt+Chl and in glaucophane-free phyllites containing Ph, Ctd, Pg, Chl (Faryad, 1995b). Maximum P-T conditions of to 12 kbar at 460 ^{o}C are estimated for blueschist facies metamorphism in Act_1-free metabasites. Thermodynamic calculations, used for core and rim compositions of garnet, blue amphibole and chlorite, indicate relatively steep prograde P-T path of this high-pressure metamorphism.

A retrograde stage of blueschist facies metamorphism is recorded by the appearance of actinolite (Act_2) rimming blue amphibole and by formation of Act_2 + Ab symplectites after glaucophane. Consistent with textural relations, biotite and Act_2 represent post P-climax and retrograde phases and were formed at 9-10 kbar and 400 ^{o}C (Faryad, 1995b). Preservation of blueschist facies assemblages in most metabasite samples suggests a rapid uplift of the Meliata blueschists.

Reconstruction of the exhumation path

Inclusions of actinolite (Act_1) or chloritoid (Ctd_1) in glaucophane may be considered as pre-blueschist facies phases which are compatible with greenschist- or greenschist-blueschist facies boundary conditions. Deformation under blueschist facies conditions at 12 kbar and 460 ^oC is characterized by the foliation defined by glaucophane and pyroxene in phyllites (Fig. 6) and by foliated glaucophane-epidote-albite matrix surrounding glaucophane porphyroblasts in metabasites. The exhumation path is only partly recorded by mineralogical and structural changes of rocks. Deformation was heterogeneous and during their exhumation most part of marbles and metabasites have remained essentially passive without undergoing any discernible modification.

The appearance of actinolite (Act_2) and biotite at the expense of glaucophane and garnet probably the result of prsessure decrease and introduction of a hydrous fluid. Regarding the P-T grid and thermodynamic calculation P-T conditions of 9-10 kbar and ca. 400 ^oC are estimated for this stage of retrogression (Faryad, 1995). Further decrease of metamorphic conditions resulted in transformation of blueschist to greenschist facies mineral assemblages (chlorite, albite, quartz, mica). Deformation at greenschist facies conditions is characterized by the presence of quartz, white mica and chlorite in strain shadows of glaucophane porphyroblasts which replaced by chlorite and albite. Structural relations of chloritoid in glaucophane-free phyllites indicate that syntectonic chloritoid porphyroblasts and rosettes that overgrown the foliation S_1 are rotated and surrounded by white mica and quartz. This suggests that S_1 system was used during exhumation of the blueschists. In contrast to some black phyllites where SW-NE striking penetrative cleavage of greenschist facies conditions completely transposed the S_1 foliation, most phyllites are characterized by tighter or discrete cleavage. Beside cleavage the late stage deformation is represented by boudinage which can be well observed in metaconglomerates and some albite-rich carbonatic rocks.

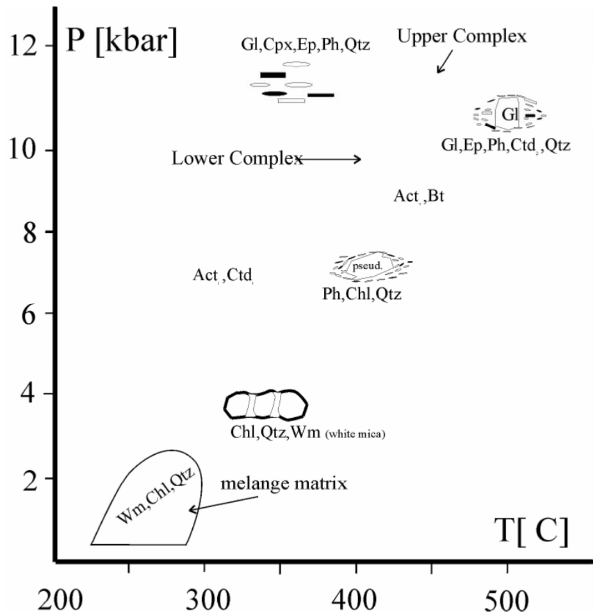


Fig. 6. Schematic P-T diagram for Upper and Lower Complex rocks (Faryad, 1995b) showing relationships between deformation and mineral crystallization. Inferred P-T conditions of melange matrix is also shown. Act_1-actinolite rimmed by glaucophane, Cdt_1-chloritoid inclusion in glaucophane.

Tectonic significance

Regarding lithology, metamorphic characteristic and geological position of individual rocks, the Meliata unit represents an accretionary complex that is characterized by a structurally complex melange, in which rocks with different P-T histories are tectonically mixed. Due to converging plate-margin processes blueschists were associated with ophiolites and sedimentary rocks of oceanic and continental ridge affinities.

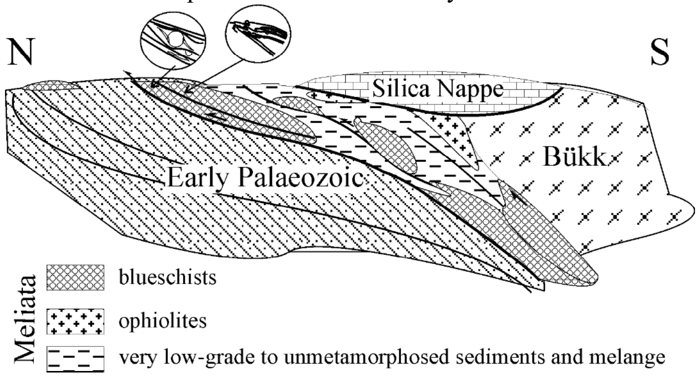


Fig. 7. Simplified cross section, indicating northvergent faults and shear zones, formed during exhumation of the Meliata unit blueschists.

The blueschists exhibit a single progressive deformation concomittant with prograde metamorphism. The observed structures reflect a strong strain partitioning under blueschist and blueschist-greenschist facies boundary conditions. This partitioning allowed the preservation of weakly or even undeformed rock bodies of km scales. The blueschist shear zones bound the lens-shaped weakly deformed bodies. P-T conditions of metamorphism and direction of ductile faults which bound the rock slices allow to constrain the exhumation mo-del of the blueschists. Although later deformation processes partly transposed the earlier structural systems, the E-W striking and southwards dipping faults which were formed synchronously with retrograde metamorphism are responsible for exhumation of the blueschists (Fig. 7). Microstructural relations and metamorphic minerals suggest that the thrust faults occurred in highly compressional regime under blueschist facies and blueschist-greenschist facies boundary conditions. The emplacement of high-pressure metamorphic rocks was probably a result from partial subduction of the continental margin which, because of its high flexural rigidity, produces a rapid change in the trajectory of the descending slab (Hynes et al., 1996). High-pressure metamorphosed terains emplaced by such mechanism would be bounded by thrust and normal faults which accommodate large displacement of up to several tens of kilometers (Chemenda et al., 1995).

As noted earlier, metamorphic mineral assemblages in the very low-grade sediments and ultramafic rocks have not been investigated. However, the typical phases in sediments and the advanced stage of serpentinization of ultramafic rocks are comparable with low-T facies metamorphism (T<300 ^{o}C, Fig. 6). Considering phengite composition with Si content of 3.26 a./f.u. from some very low-grade metasediments underlain by the blueschists in the eastern part of the Meliata unit, moderate pressures are inferred for very low-grade rocks.

The Middle Jurassic age obtained for metabasites and phyllites in the upper complex (Faryad and Henjes-Kunst, 1997) is related to the blueschist facies metamorphism. There are no data to constrain the age of melange formation. The Late Cretaceous, low-temperature overprint in the lower complex rocks is probably related to the nappe tectonic in the Western Carpathians for which a Cretaceous age is assumed (Kantor, 1960; Maluski et al., 1993; Dallmayer et al., 1993). During the Cretaceous thrusting the thrust faults between the lens-shaped blueschist bodies are reactivated as mylonitic shear planes with moderate amount of displacement. Overthrusting of the Silica nappe on the Meliata rocks probably also occurred during this time. Since these tectonic movements resulted mostly in brittle deformation, the extensional fabrics synchronous with appearance of mica, chlorite and quartz relate to exhumation processes.

Acknowledgments

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