# New evidences of the low-P/high-T pre-alpine metamorphism and medium-P alpine overprint of the pelagonian zone documented in metapelites and orthogneisses from the Voras Massif, Macedonia, Northern Greece

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## ABSTRACT

Pelitic rocks of the pre-Alpine "gneiss series" from the Voras Massif record a polymetamorphic history of three metamorphic events; a first HT event indicated by migmatitization phenomena, a subsequent LP-HT event (andalusite-sillimanite series) at 2.5-3 Kbar and 610-640$^o$C, and a third medium-P event at ~11 Kbar and ~550$^o$C. The LP-HT metamorphism is associated with intrusion of Variscan granitoid plutons in a magmatic arc setting. The medium-P metamorphism records an Alpine event (probably Early Cretaceous) indicated by kyanite, chloritoid, garnet and staurolite formation replacing andalusite and cordierite. The Variscan granitoids and the overlying lithologies of the "schist series" are affected only by the medium-P metamorphism. Granitoids are transformed into phengite orthogneisses having the mineral assemblage phen (Si=3.35-3.47 a.p.f.u.)±Bt-Ab-Kfs-Qtz±Czo±Grt and high-alumina pelites into garnet-chloritoid schists with the mineral assemblage Grt-Ctd-Chl-Ms-Qtz-Rt±Ilm.

The "schist series" which underlies the Late Triassic-Early Jurassic marbles and overlies lithologies of the "gneiss series" and metagranitoids represents protoliths of the Permo-Triassic volcanosedimentary series deposited at the eastern margin of the Pelagonian continental block.

## INTRODUCTION

The Pelagonian Zone is composed of several tectonic units. The two lowermost units, namely the neritic carbonate unit, now exposed in the form of tectonic windows (Olympos-Ossa, Rizomata, Krania) and the blueschist unit (Ambelakia) are characterized by Tertiary metamorphism and deformation. By contrast the overlying Pelagonian nappe (Kilias and Mountrakis, 1989) displays a more complex tectonometamorphic evolution during pre-Alpine and Alpine times. It comprises pre-Alpine metamorphic and igneous rocks, clastic and volcanic rocks of Permo-Triassic age, platform carbonates of Triassic-Jurassic age, ophiolites obducted in the Late Jurassic-Early Cretaceous, transgressive limestones of Cretaceous age and flysch of Paleocene age.

Granites, orthogneisses and metapelites predominate amongst the pre-Alpine lithologies. Various dating techniques applied to the granites and orthogneisses invariably yielded Carboniferous to Early Permian crystallization ages (e.g. U-Pb and Pb-Pb on zircon, Mountrakis, 1983; Yarwood and Aftalion, 1976; Reischmann et al., 2001; Rb-Sr on muscovite and biotite, Katerinopoulos et al., 1992). Petrological investigation on metapelites from Vernon Massif. eastern Orthrys and northern Euboea (Mposkos et al., 2001, 2003) showed that the Pelagonian pre-Alpine metamorphic rocks suffered low-pressure/high-temperature (LP-HT) metamorphism (andalusite-sillimanite series)

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and migmatitization. Subsequent metamorphic events during Alpine times and particularly that of epidote-amphibolite facies by Early Cretaceous (Barton, 1976; Yarwood and Dixon, 1977; Mposkos and Perraki, 2001; Most et al., 2001) erased, almost completely, the pre-Alpine assemblages and textures, making it difficult to discriminate pre-Alpine from Alpine protoliths in most areas of the Pelagonian nappe.

In the northern part of Greek Macedonia the Pelagonian nappe is represented by the Vernon and Voras crystalline Massifs (Fig. 1). In Vernon Massif, which extends to the west of the Voras Massif the pre-Alpine LP-HT metamorphic event, is well documented in metapelitic rocks. In the western part of the Massif andalusite-cordierite gneisses and schists constrain P-T conditions at $\sim$2.5 Kbar, 600-610$^o$ C, whereas in the northeastern part of it migmatitic sillimanite-biotite gneisses and garnet-sillimanite-biotite gneisses constrain P-T conditions to >4.5 Kbar/640$^o$C. Alpine overprinting is characterized by P-T metamorphic conditions of 6 Kbar and < 350$^o$ C in the western part and $\sim$ 9 Kbar/500-570$^o$C in the northeastern part of the Massif respectively (Mposkos et al., 2001).

In this paper we present field observations and new petrological data from metapelites and orthogneises, from the Voras Massif, indicating, that the Voras Massif underwent a similar pre-Alpine and Alpine tectonometamorphic evolution like that of the Vernon one.

## 1.1 FIELD OBSERVATION

According to Kilias and Mountrakis (1989), the Voras crystalline Massif forms a huge antiform structure with one side sinking to WSW and the other one to ENE. It comprises pre-Alpine basement rocks and tectonically overlying dolomitic and calcitic marbles having a Triassic-Jurassic sedimentation age. The pre-Alpine basement consists of biotite-orthogneisses in the core overlaid by muscovite gneisses, two mica gneisses and amphibolites. The uppermost series of the pre-Alpine basement (?) comprises garnetiferous mica schists. In the pre-Alpine basement rocks, Kilias and Mountrakis (1989) recognized a pre-Alpine amphibolite facies metamorphism and Alpine overprint of greenschist facies.

During our field observations on a SW-NE section between Agios Athanasios and Skopia area (the Ski center of the Voras mountain), along a 17 km road, we observed that in the pre-Alpine "gneiss series" which overlies the biotite orthogneisses, occur pelitic and quartzofeldspathic migmatites (Fig. 2) overprinted by subsequent penetrative deformation and recrystallization. In less deformed domains, pegmatites, which are also deformed, crosscut the foliation of the migmatites. High-alumina pelitic gneisses that escaped penetrative deformation (as for example at the location 40$^o$ 52' 07'' N - 21$^o$ 46' 58'' E), preserve relics of a LP-HT metamorphism documented by the mineral assemblage andalusite + sillimanite + biotite + plagioclase $\pm$ muscovite + K-feldspar $\pm$ cordierite + quartz + ilmenite. They are overprinted by a medium pressure metamorphism as indicate neoformation of kyanite, garnet, chloritoid, muscovite and chlorite replacing minerals of the LP-HT event.

At the place located at 40$^o$, 53', 43'' N - 21$^o$, 48', 26'' E, a series of garnet and chloritoid bearing metapelites having the mineral assemblage Grt$\pm$Ctd-Chl-Ms-Qtz$\pm$Rt$\pm$Ilm (abbreviations after Bucher and Frey, 1994) overlie leucocratic orthogneisses. They have a thickness of more that 200 metres and occur extensively in Voras Massif, especially in the Skopia area. Migmatitic textures, crosscutting pegmatites or minerals which could indicate a previous LP-HT metamorphic event like that observed in the underlying gneisses are not observed. These observations suggest that the garnet-chloritoid bearing metapelites represent a metasedimentary series, originated from Alpine protoliths.

## 1.2 PETROGRAPHY AND MINERAL CHEMISTRY

*A: Chlorite-chloritoid schists, garnet-chlorite schists and garnet-chlorite-chloritoid schists.*

The chlorite-chloritoid schists, garnet-chlorite schists and garnet-chlorite-chloritoid schists are represented by the mineral assemblage: chlorite $\pm$ garnet – white K-mica $\pm$ chloritoid – quartz $\pm$ rutile $\pm$ ilmenite. Dependent on the bulk rock composition garnet and chloritoid can be major or minor mineralogical components, or they can be absent from the rock.

Two major deformation phases led to the formation of two foliations (S1, S2). The second one dominates macroscopically. The first foliation is imprinted by parallel development of muscovite and
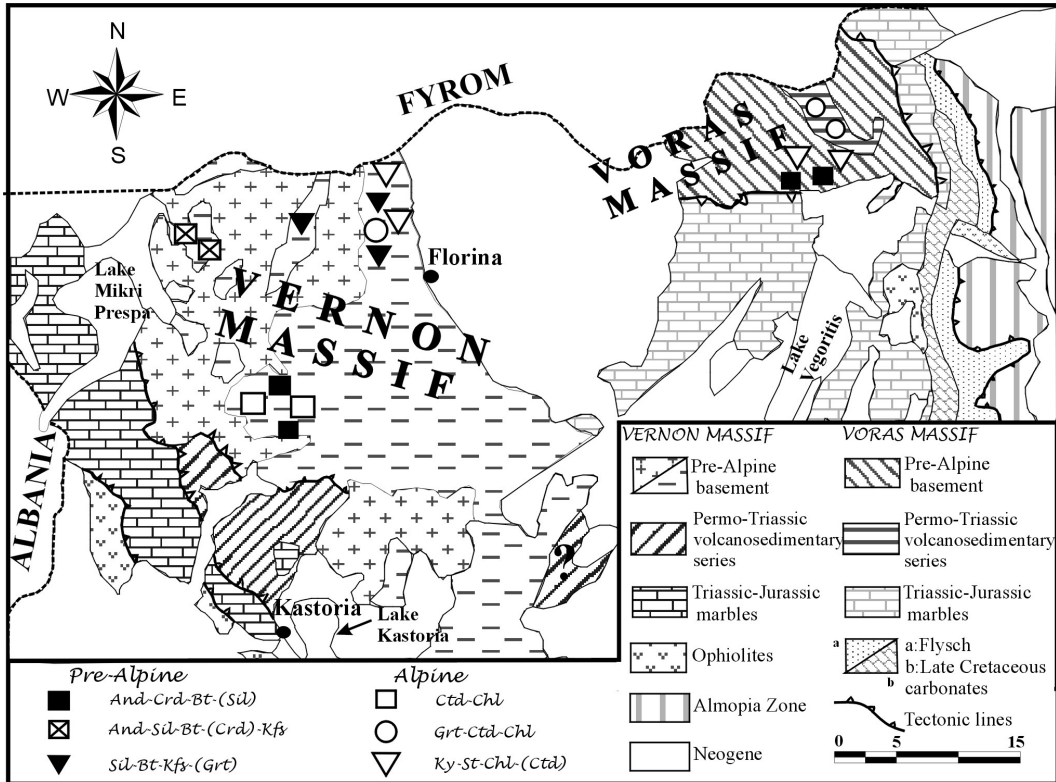
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Fig. 1: Simplified geological map of the Voras and Vernon Massifs (after Kilias and Mountrakis, 1989, and Avgerinas et al. 2003, modified).



Fig. 2: Migmatitic gneiss intensely deformed in a post migmatitic stage. "Gneiss series". Location of outcrop 40° 52' 07'' N, 21° 46' 58'' E.

chlorite flakes and chloritoid laths (S1), while the second one (D2) folds isoclinally S1. A third deformation phase is characterized by crenulation cleavage, especially in bands rich in white-K mica. In quartz rich bands (alternating with mica-rich bands) quartz grains are isometric and polygonal indicating that a static recrystallization followed the deformation.

Garnet appears as porphyroblasts, containing inclusions of quartz, rutile, ilmenite and chloritoid. Chloritoid inclusions in garnet show corroded edges indicating garnet growth at the expense of chloritoid according to the prograde reaction $Ctd+Chl+Qtz \rightarrow Grt+W$. Garnet is almandine rich having the composition $Alm_{0.61-0.77}Grs_{0.1-0.2}Prp_{0.05-0.1}Sps_{0.03-0.14}$ It usually shows compositional zoning with increasing FeO and MgO and decreasing CaO and MnO from the core to the rim (Table 1).

Chloritoid is a common phase in the most studied samples, and usually contains inclusions of rutile. It is commonly included in garnet and ilmenite. Chloritoid is iron rich with Mg# [Mg/(Mg+Fe)] ranging from 0.15 to 0.18. The highest values are observed in the matrix chloritoid and the lowest ones in chloritoid inclusions in garnet (Table 1), an observation which is in accordance to the above mentioned chloritoid consuming and garnet forming bivariant reaction.

White K-mica is phengite and less phengitic muscovite (Table 1). The presence of phengite and less phengitic muscovite, indicated by the wide range of Si values from 3.13 to 3.37 atoms per formula unit (a.p.f.u.), records the metamorphic evolution of the metapelites, from higher to lower pressure conditions. Phengites document a high-pressure stage, while the less phengitic muscovites are formed during decompression.

The titaniferous phases are ilmenite or rutile and ilmenite in garnet bearing rocks and only rutile in those where garnet is absent. Ilmenite contains inclusions of chloritoid and rutile, while chloritoid contains only rutile inclusions. Rutile and ilmenite occur also as inclusions in garnet. If both phases are included in the same garnet, rutile is commonly included in the core and ilmenite in the outer part of the garnet. The described textural relations indicate that ilmenite coexist with garnet and is formed according to the reaction $Chl+Rt \rightarrow Grt+Ilm+W$.

Table 1: Representative mineral compositions from metapelites of the "schist series" and orthogneisses, (Voras massif)

| | Garnet - Chloritoid - Schist | | | | | | | | Orthogneiss | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Garnet | | Chloritoid | | | Chlorite | White K-Mica | | Phengite | | Biotite |
| | core | rim | i-Grt_c | i-Grt_r | matrix | matrix | | | 1 | 2 | |
| $SiO_2$ | 37.31 | 37.49 | 24.81 | 24.77 | 25.09 | 24.60 | 47.70 | 50.90 | 49.68 | 51.50 | 38.03 |
| $TiO_2$ | 0.22 | - | - | - | - | - | 0.33 | 0.25 | 0.26 | 0.15 | 1.24 |
| $Al_2O_3$ | 20.70 | 20.97 | 39.90 | 39.93 | 40.07 | 22.79 | 34.61 | 28.93 | 26.75 | 24.91 | 15.54 |
| $FeO_t$ | 27.32 | 34.63 | 24.05 | 23.99 | 23.84 | 27.28 | 1.75 | 2.54 | 4.20 | 4.39 | 18.54 |
| MnO | 6.31 | 1.26 | 0.42 | 0.20 | - | - | - | - | - | - | 0.59 |
| MgO | 1.17 | 2.48 | 2.44 | 2.67 | 2.97 | 12.78 | 1.02 | 2.62 | 3.28 | 3.13 | 10.78 |
| CaO | 6.91 | 3.79 | - | - | - | - | - | - | - | - | 0.23 |
| $Na_2O$ | - | - | - | - | - | - | 1.53 | 0.72 | 0.26 | 0.15 | 0.20 |
| $K_2O$ | - | - | - | - | - | - | 9.33 | 9.80 | 11.26 | 11.37 | 9.12 |
| Total | 99.94 | 100.62 | 91.62 | 91.56 | 91.97 | 87.45 | 96.27 | 95.06 | 95.69 | 95.6 | 94.27 |
| Cations/O | | | (12) | | | (14) | | (11) | | | |
| Si | 3.01 | 3.00 | 2.06 | 2.06 | 2.07 | 2.62 | 3.13 | 3.35 | 3.35 | 3.47 | 2.91 |
| Ti | 0.01 | - | - | - | - | - | 0.02 | 0.01 | 0.01 | 0.01 | 0.07 |
| Al | 1.97 | 1.98 | 3.91 | 3.91 | 3.90 | 2.86 | 2.68 | 2.27 | 2.13 | 1.98 | 1.40 |
| Fe | 1.84 | 2.32 | 1.67 | 1.67 | 1.65 | 2.43 | 0.10 | 0.14 | 0.24 | 0.25 | 1.19 |
| Mn | 0.43 | 0.09 | 0.03 | 0.01 | - | - | - | - | - | - | 0.04 |
| Mg | 0.14 | 0.30 | 0.30 | 0.33 | 0.36 | 2.03 | 0.10 | 0.26 | 0.33 | 0.32 | 1.23 |
| Ca | 0.60 | 0.32 | - | - | - | - | - | - | - | - | 0.02 |
| Na | - | - | - | - | - | - | 0.19 | 0.09 | 0.03 | 0.02 | 0.03 |
| K | - | - | - | - | - | - | 0.78 | 0.83 | 0.97 | 0.98 | 0.89 |
| Mg# | 0.07 | 0.11 | 0.15 | 0.165 | 0.18 | 0.46 | 0.50 | 0.65 | | | |

Mg# [Mg/(Mg+Fe)], i-Grt_c = inclusion in garnet core, i-Grt_r = inclusion in garnet rim.

*B: Orthogneisses*

In the Voras Massif orthogneisses are the dominant rock types. Depending on the grade of deformation, they occur either as plate gneisses, or as augen gneisses. They are mainly composed of phengite-biotite-albite-microcline-quartz ± clinozoisite. Garnet, titanite and apatite are present as subordinate phases.

Orthogneisses have the appropriate mineral assemblage to apply the phengite geobarometer (Massonne and Schreyer, 1987). In phengites the Si values range from 3.35-3.47 a.p.f.u. Such Si values are common in phengites from orthogneisses from high-pressure metamorphic terranes. Large phengite flakes have a homogeneous composition from the core to the rim, indicating that they have preserved their high pressure composition during exhumation. Representative compositions of phengite are presented in Table 1. Biotite coexisting with phengite has a homogeneous composition with Mg# value ranging from 0.51-0.52.

*C: Andalusite - Sillimanite - (cordierite) gneisses and migmatitic - (cordierite) gneisses.*

The field observations show that the pre-Alpine granitoids intruded migmatitic metapelites and quartzofeldspathic gneisses, contributing to the LP-HT metamorphism in the surrounding rocks. Relics of this pre-Alpine metamorphic event are preserved in those parts of the "gneiss series" that escaped penetrative deformation during subsequent Alpine deformations and fluid access was limited. These rocks preserve still minerals and textures of the LP-HT metamorphism.

*a: Andalusite - sillimanite - (cordierite) gneisses*: The pre-Alpine mineral assemblage of these rocks is: Andalusite + sillimanite (+cordierite) + biotite ± muscovite + K-feldspar + plagioclase + quartz + ilmenite. Andalusite usually forms idiomorphic to xenomorphic porphyroblasts, and is rich in ilmenite quartz and biotite inclusions (Fig. 3a). Andalusite and associated biotite show corroded edges (Fig. 3b) and are replaced by cordierite and K-feldspar indicating the prograde reaction And+Bt+Qtz $\rightarrow$ Crd+Kfs+W. Fibrolitic sillimanite is commonly associated with biotite and K-feldspar. Sillimanite fibres are, like the biotite flakes, oriented parallel to the foliation (Fig. 3c) and seem to be formed at the expense of previous muscovite according to the reaction Ms(ss)+Ab(ss)+Qtz $\rightarrow$ Sil+Kfs(ss)+W. Since muscovite still occurs in sillimanite and K-feldspar bearing samples, its presence indicates that P-T conditions did not exceed those limited by the reaction Ms+Qtz $\rightarrow$ Sill+Kfs+W. Sillimanite, if present, overgrows andalusite and in part replaces it (Fig. 3d). Relics of cordierite are very rare. In most studied samples it is totally replaced by sericitic muscovite, chlorite and frequently by chloritoid and staurolite. Also, K-feldspar is completely replaced by sericitic muscovite. The Mg# value in biotite ranges between 0.50 and 0.53. During Alpine overprint it is replaced by muscovite and ilmenite. Pre-Alpine plagioclase is oligoclase with An-content ranging between 13-17%.

A medium pressure Alpine overprint is indicated by kyanite, garnet, chloritoid and staurolite growth replacing pre-Alpine phases. Kyanite occurs in form of thin prismatic, unoriented aggregates that replace pseudomorphically andalusite (Fig. 4a). Chloritoid, also occurs in thin columnar-aggregates in "Garben style" bundles (Fig. 4b), or radiated around garnet, and in association with staurolite pseudomorphically replacing "cordierite" (Fig. 4c). Mg# values in chloritoid range from 0.20 to 0.25 (Table 2) and are higher than those of chloritoid from the garnet-chloritoid-chlorite schists (0.15-0.19), indicating a higher grade of metamorphism which is also supported by the coexistence of staurolite with chloritoid in the overprinted andalusite-sillimanite gneisses. Garnet forms aggregates of idiomorphic crystals containing ilmenite, chloritoid and quartz inclusions. It is usually associated with chloritoid, sericitic muscovite and more rarely chlorite. Garnet is formed replacing pre-Alpine biotite and possibly cordierite, as indicate textural relations, according to the pressure dependent reaction Bt+Crd+Qtz $\rightarrow$ Grt+Ms+W. Since garnet includes chloritoid it is also possible that garnet thas been formed at the expense of chloritoid according to the prograde water releasing reaction Ctd+Chl+Qtz $\rightarrow$ Grt+W. Garnet is almandine-rich with a composition: $Alm_{0.65-0.77}Grs_{0.06-0.15}Prp_{0.06-0.11}Sps_{0.06-0.12}$. Zoned garnets show a typical growth zoning with increasing Fe, Mg and decreasing Mn and Ca from the core to the rim (Table 2). The Mg# values range from 0.09-0.10 in the core to 0.10-0.12 in the rim and are slightly higher in comparison to the corresponding Mg# values of the garnet from the garnet-chloritoid-chlorite schists. Staurolite forms aggregates of very small laths in association with muscovite and chlorite (Fig.4d) and chloritoid and quartz, replac-

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ing pseudomorphically cordierite (Fig. 4c). The Mg# values in staurolite range between 0.20-0.22. Alpine overprinting led to partial replacement of biotite by chlorite and muscovite, and to almost
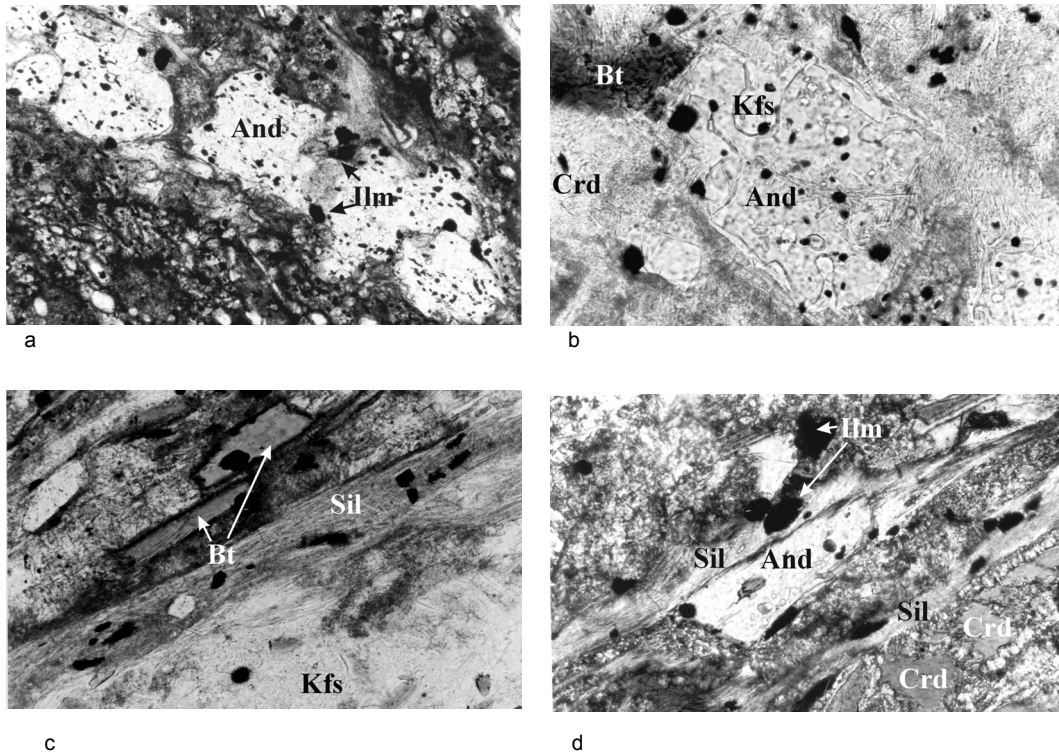


Fig. 3: Andalusite-Sillimanite - (cordierite)- gneisses: Pre-Alpine assemblages:
a: Andalusite porphyroblasts containing inclusions of ilmenite is oriented parallel to the schistosity of the rock. Microphotograph: length 2.5mm: one polar only.
b: Andalusite, with corroded edges is replaced by K-feldspar. And=andalusite, Kfs=K-feldspar, Bi=biotite, Crd=cordierite (altered to sericitic muscovite and chlorite). Microphotograph: length 1mm: one polar only.
c: Fibrolitic sillimanite associated with biotite and K-feldspar: K-feldspar is completely replaced by sericitic muscovite. Note the parallel orientation of the sillimanite fibres and biotite flakes to the foliation of the rock. Microphotograph: length 1.5mm: crossed polars.
d: Fibrolitic sillimanite associated with biotite, cordierite and K-feldspar overgrows andalusite. The K-feldspar is completely replaced by sericitic muscovite. Microphotograph: length 1mm: crossed polars.

completely replacement of K-feldspar by sericitic muscovite and of cordierite by chloritoid, staurolite and chlorite, making thus difficult to recognize the last two minerals of the pre-Alpine assemblage. Alpine muscovite has a higher Si value (3.22) compared, to the pre-Alpine one (3.07-3.08). The presence of paragonite in association with the more phengitic muscovite indicates that during Alpine overprint the retrograde reaction Ab+Sil+W $\rightarrow$ Pg+Qtz occurred.

*b: Migmatitic - (cordierite) gneisses*: Alpine overprinting accompanied by penetrative deformation erased almost completely the pre-Alpine mineral assemblages and textures in the migmatitic gneisses. Porphyroclasts of lensoidal aggregates composed of K-feldspar, plagioclase, quartz, and red-brown biotite represent relic minerals of the pre-Alpine migmatite. The Alpine overprint assemblage consists of garnet + chloritoid + chlorite + muscovite + quartz. Garnet coexists in textural relation with chlorite and muscovite. Chloritoid forms aggregates replacing pseudomorphically previous cordierite.
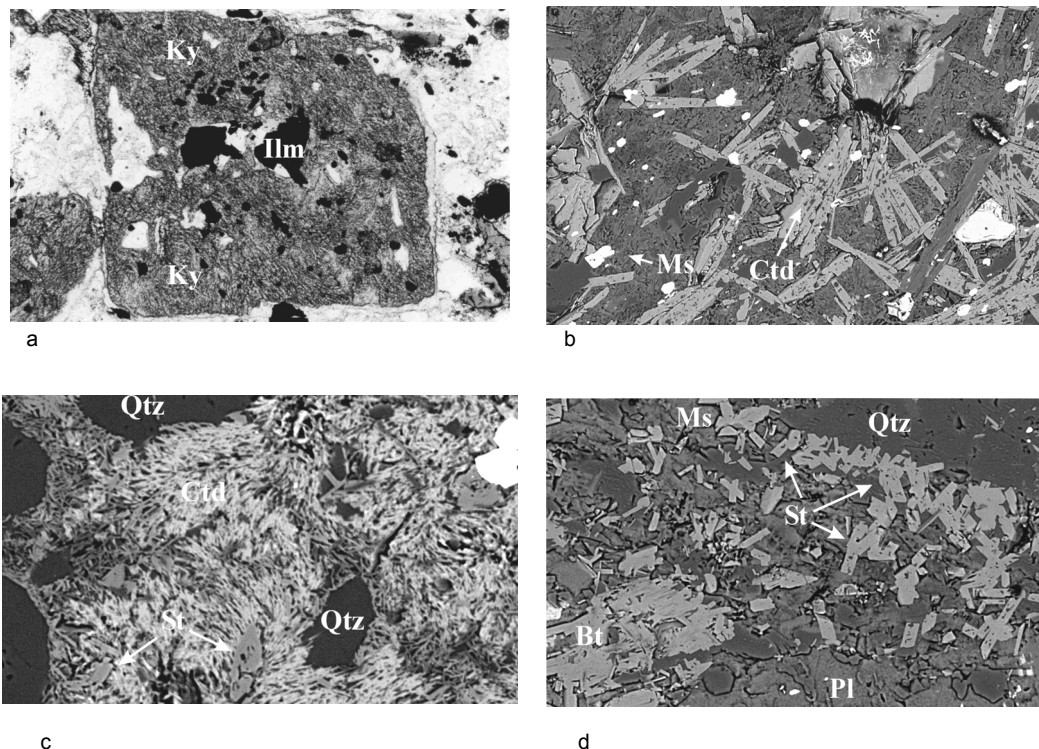
Fig. 4: Andalusite-sillimanite-(cordierite)-gneisses: Alpine overprint.

a: Thin prismatic kyanite aggregates (Ky) replace pseudomorphically idiomorphic andalusite crystal. Black grains are ilmenite inclusions in former andalusite. Microphotograph: length 1.5mm: one polar only.

b: Chloritoid aggregates (Ctd) in "Garben style" bundles. SEM-photograph: length 1mm. (Ms=muscovite)

c: SEM-photograph showing aggregates of staurolite (St), chloritoid and quartz, replacing pseudomorphically cordierite: SEM.

d: Aggregates of staurolite laths associated with Alpine muscovite. SEM-photograph: length 0.7mm. (Bt=pre-Alpine biotite, Pl=pre-Alpine plagioclase)

## 1.3   P-T CONDITIONS OF METAMORPHISM
### a: Pre-Alpine metamorphism

Pelitic rocks are sensitive to pressure and temperature changes and form minerals that are easy to identify and may be used as indices of metamorphic grade.

Migmatitic textures in rocks of the "gneiss series" are evidence of a HT metamorphism, exceeding the minimum P-T conditions indicated by wet melting of granite (Fig. 5, curve 1). The mineral assemblage andalusite-sillimanite-cordierite-biotite-muscovite-K-feldspar-plagioclase-quartz in pelitic rocks of the "gneiss series" is evidence of a LP-HT metamorphic event. The replacement of andalusite and biotite by cordierite and K-feldspar, shown in Fig. 3b, indicates a prograde path of metamorphism with increasing temperature, at temperatures exceeding those indicated by the reaction curve $And+Bi+Qtz \rightarrow Crd+Kf+W$ (Fig. 5, curve 2). The prograde path is also indicated by partial replacement of andalusite by sillimanite. The high temperature limit lies within, the sillimanite stability field between curves 3 ($Ms+Qtz \rightarrow Sil+Kfs+W$) and 4 ($Ms_{ss}+Ab_{ss}+Qtz \rightarrow Sil+Kfs_{ss}+W$) in Figure 5 because of the assemblage $Sil+Kfs+Pl+Ms+Qtz$. This in conjunction with the presence of cordierite and the absence of pre-Alpine garnet (curve 5 in Fig. 5) constrains the peak P-T metamorphic conditions between 2.5 and 3 Kbar and 610-640$^{o}$C. These P-T conditions are lower than those defining the beginning of granite wet melting. Therefore the migmatitization observed in the gneisses is not related to this metamorphic event, but to a previous one at pressures higher than 3 Kbar.

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Table 2: Representative compositions of pre-Alpine and Alpine overprint minerals from high alumina metapelites of the "gneiss series" (Voras Massif).

| | pre-Alpine | | | Alpine | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Biotite | Musco-vite | Plagio-clase | Garnet | | Chlori-toid | Strauro-lite | Chlorite | Musco-vite | Parago-nite |
| | | | | core | rim | | | | | |
| SiO$_2$ | 35.26 | 46.39 | 64.14 | 37.88 | 36.65 | 25.21 | 31.24 | 26.06 | 48.62 | 47.46 |
| TiO$_2$ | 1.40 | 0.34 | - | - | - | - | - | - | 0.43 | - |
| Al$_2$O$_3$ | 20.27 | 36.47 | 22.61 | 21.33 | 20.69 | 40.03 | 53.07 | 21.96 | 32.10 | 40.56 |
| FeO$_t$ | 18.31 | 0.88 | 0.20 | 29.27 | 33.59 | 22.24 | 13.01 | 23.42 | 1.80 | 0.22 |
| MnO | - | - | - | 5.35 | 2.81 | - | - | - | - | - |
| MgO | 10.54 | 0.55 | - | 1.57 | 2.65 | 3.64 | 1.88 | 15.57 | 1.96 | - |
| CaO | - | - | 3.78 | 5.15 | 2.03 | - | - | - | - | 0.50 |
| Na$_2$O | 0.36 | 0.87 | 10.19 | - | - | - | - | - | 0.94 | 7.02 |
| K$_2$O | 8.90 | 9.83 | - | - | - | - | - | - | 9.83 | 0.80 |
| Total | 95.04 | 95.33 | 100.92 | 100.55 | 98.42 | 91.12 | 99.20 | 87.01 | 95.68 | 96.56 |
| Cations/O | (11) | | (8) | (12) | | (23) | | (14) | (11) | |
| Si | 2.67 | 3.07 | 2.81 | 3.02 | 3.00 | 2.08 | 4.23 | 2.73 | 3.22 | 2.99 |
| Ti | 0.08 | 0.02 | - | - | - | - | - | - | 0.02 | - |
| Al | 1.81 | 2.84 | 1.17 | 2.01 | 2.00 | 3.90 | 8.46 | 2.71 | 2.50 | 3.01 |
| Fe | 1.16 | 0.05 | 0.01 | 1.95 | 2.30 | 1.54 | 1.47 | 2.05 | 0.10 | 0.01 |
| Mn | - | - | - | 0.36 | 0.19 | - | - | - | - | - |
| Mg | 1.19 | 0.05 | - | 0.19 | 0.32 | 0.45 | 0.38 | 2.43 | 0.19 | - |
| Ca | - | - | 0.18 | 0.44 | 0.18 | - | - | - | - | 0.03 |
| Na | 0.05 | 0.11 | 0.87 | - | - | - | - | - | 0.12 | 0.86 |
| K | 0.86 | 0.83 | - | - | - | - | - | - | 0.83 | 0.06 |
| Mg# | 0.51 | | | 0.09 | 0.12 | 0.23 | 0.21 | 0.54 | | |
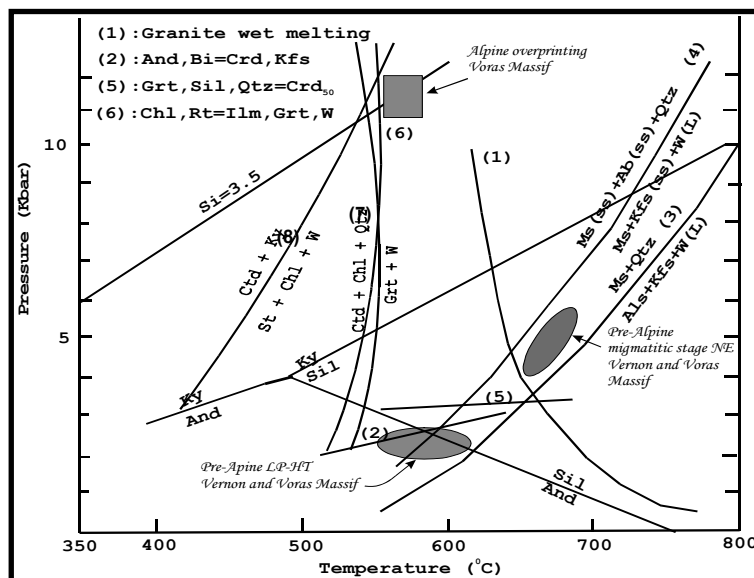


Fig. 5: P-T diagram with reaction curves in a pelitic system, taken from Spear (1995). Isopleth Si=3.5 is from Massonne and Schreyer (1987). Reaction curves 2 and 5 are taken from Mposkos et al., 2001; reaction curves 6, 7 and 8 are calculated with the TWEEQU software (Berman, 1991) using analyzed mineral composition.

*b: Alpine metamorphism*

The Alpine metamorphism is recorded in the garnet-chloritoid bearing metapelites of the "schists series" and the orthogneisses as a single metamorphic event, and as overprinting one in the migmatitic metapelites of the "gneiss series".

P-T conditions are estimated applying the phengite geobarometer in orthogneisses, and thermodynamic calculations on the mineral assemblages of the high-alumina metapelites for pressure and temperature estimations respectively. The reaction curves Ctd+Chl+Qt $\rightarrow$ Grt+W, Ctd+Ky (+Qtz) $\rightarrow$ St+Chl+W and Chl+Rt $\rightarrow$ Grt+Ilm+W shown in Fig. 5, are calculated with the TWEEQU program (Berman, 1991) using real mineral compositions. The mineral paragenesis garnet-chloritoid-chlorite, which is common in the high-alumina metapelites of the "schist series" and the underlying "gneiss series" limits the metamorphic conditions close to the curve 7. The coexistence of chloritoid with staurolite, kyanite and chlorite in the metapelites of the "gneiss series" limits the metamorphic condition in the "gneiss series" close to the curve 8. The intersection of curves 6, 7 and 8 with the phengite isopleth Si=3.5, constrains the peak P-T conditions at ~ 11 Kbar and $550^{\circ}$ C.

## 2. DISCUSSION AND CONCLUSIONS

The present study has shown that pelitic protoliths of the migmatitic "gneiss series" from the Voras Massif record a polymetamorphic history of three metamorphic events i.e. a first HT event indicated by migmatitization, a subsequent LP-HT event (andalusite-sillimanite series) at 2.5-3 Kbar and $610-640^{\circ}$ C, and a third medium pressure metamorphic event indicated by kyanite, chloritoid, garnet and staurolite formation at the expense of andalusite and cordierite. Migmatitization in pelitic gneisses containing garnet and prismatic sillimanite and quartz-feldspar gneisses are widespread in the basement of the Pelagonian nappe indicating a pre-Alpine HT regional metamorphism at P >4.5 Kbar and T~$640^{\circ}$C (Mposkos et al., 2001, 2003). The LP-HT metamorphic event which affected the migmatitic gneisses is associated with heat transport from deeper to shallower levels within the crust due to intrusion of Carboniferous granitoid plutons (Avgerinas et al., 2001) in a magmatic arc setting. A similar metamorphic event is recorded in migmatitic metapelites from the Vernon Massive (Mposkos et al., 2001) and is genetically connected also with the intrusion of Carboniferous granitoids. The medium pressure metamorphism is recorded in the Carboniferous granitoids and in garnet-chloritoid schists of the overlying "schist series" as a single metamorphic event. Therefore it must be post-Carboniferous in age. An Alpine tectonometamorphic event, deduced from Cretaceous K-Ar muscovite and biotite cooling ages is recorded by Most at al., (2001) in Voras Massif and in the part of the Pelagonian nappe that extends to the north of Voras Massif within FYROM.

According to Kilias and Mountrakis (1989) and Avgerinas et al. (2001), the "schist series" which underlies the Late Triassic-Early Jurassic marbles and overlies the "gneiss series" represents pre-Alpine lithologies having a common regional tectonometamorphic evolution with those of the "gneiss series". In the geological section Agios Athanasios Skopia area (Voras ski center) the "schist series" overlies leucocratic orthogneisses (visible on the road at the location $40^{\circ}$ 53' 43'' N, $21^{\circ}$ 48' 26'' E) and has a thickness >200 m. This series underwent only one metamorphic event i.e. that of the medium pressure, at P-T conditions ~11 Kbar - $550^{\circ}$ C indicating that the protoliths of the "schist series" must be post-Carboniferous and pre-Late Triassic in age. The "schist series" in the Voras Massif represents probably the Permo-Triassic volcanosedimentary series, which is well-known in the western Pelagonian margin (Mountrakis et al., 1983).

Pelitic metasediments, indicating Alpine metamorphism at similar P-T conditions to those of the "schist series" from the Voras Massif, occur also in South Vermion mountain (area of Kastania - Nea Santa), an area which represents a southern part of the Pelagonian nappe to that of the Voras. In this area the metapelites occur between underlying orthogneisses and migmatites and overlying Triassic-Jurassic marbles; like the "schist series" of the Voras Massif. They are also interpreted to represent metamorphic rocks of the Permo-Triassic volcanosedimentary series (Mposkos and Perraki, 2001).

The presented petrological data and the field observations indicate that Permo-Triassic clastic sedimentation took place not only on the western margin of the Pelagonian continental block but also on the eastern one. The Early-Cretaceous metamorphism recorded in the eastern part of

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Pelagonian zone (Yarwood and Dixon, 1977; Barton, 1976; Mposkos and Perraki, 2001; Most et al., 2001), was more intense and reached P-T conditions of the epidote-amphibolite facies, in contrast to the western part of it, where the P-T conditions reached the lower greenschist facies (Kilias and Mountrakis, 1989).

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