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CRUSTAL EXTENSION AND PARTIAL MELTING POSSIBLY RELATED TO THE OPENING OF A MARGINAL BASIN. THE PELITIC MIGMATITES OF PIYI AND KARATHODORO, MACEDONIA, GREECE

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ABSTRACT

Two continental slivers within the confines of exposed parts of the Late Jurassic Guevgueli magmatic complex, which is thought to have been created at a marginal basin setting, bear evidence of ductile extension of a previously folded and metamorphosed terrane accompanied by high temperature decompression and partial melting reactions. Also affected by the extension were early basic dykes which intruded at relatively deep levels, whereas later basic dykes intruded at apparently shallower levels in a brittle regime and at high angles to the previously imposed ductile extensional fabric, suggesting a stability of the extensional stress field during exhumation. Similarities in the direction of intrusion and in geochemistry suggest that these dykes are parts of the Guevgueli magmatic complex. The two continental slivers are interpreted as fragments of the continental crust which floored the Guevgueli marginal basin prior to its rifting.

ΣΥΝΟΨΗ

Σε δύο ηπειρωτικά τεμάχη που βρίσκονται μεταξύ των εμφανίσεων του Υστερο Ιουρασικού μαγματικού συμπλέγματος της Γευγελής - το οποίο πιστεύεται ότι σχηματίστηκε σε περιθωριακή λεκάνη - βρέθηκαν ενδείξεις γενικευμένης έκτασης υπό πλαστικές συνθήκες ενός ήδη πτυχωμένου και μεταμορφωμένου υποβάθρου. Η έκταση αυτή συνοδεύτηκε από αντιδράσεις υψηλής θερμοκρασίας και μερικής τήξης με παράλληλη ελάττωση της πίεσης. Βασικές φλέβες που διείσδυσαν νωρίς και σε σχετικά μεγαλύτερα βάθη επηρεάσθηκαν επίσης από την πλαστική έκταση και την HT-LP μεταμόρφωση, ενώ μεταγενέστερες αμεταμόρφωτες φλέβες που διείσδυσαν σε μικρότερα βάθη υπό ένα εύθραυστο καθεστώς και σχεδόν κάθετα στις ήδη αποτυπωμένες εκτατικές υφές υποδεικνύουν σταθερότητα του εκτατικού πεδίου κατά την τεκτονική εκταφή. Ομοιότητες στη διεύθυνση διείσδυσης και τη γεωχημεία υποδεικνύουν επίσης ότι αυτές οι βασικές φλέβες αποτελούν μέλη του μαγματικού συμπλέγματος της Γευγελής. Τα δύο, λοιπόν, ηπειρωτικά τεμάχη θεωρούνται ως διασωθέντα τμήματα ενός συνεχόμενου, πριν τη διαμπερή του ρήξη ηπειρωτικού φλοιού στο χώρο της τότε διανοιγόμενης περιθωριακής λεκάνης της Γευγελής.

INTRODUCTION

The Vardar-Axios zone in the internal Hellenides (fig. 1) is composed of

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Mesozoic and Tertiary sedimentary formations, some acid and intermediate igneous intrusions of mainly Jurassic age and a number of subautochthonous ophiolite bodies of Late Jurassic age, the latter grouped together under the name "Innermost Hellenic Ophiolite Belt" (IMHOB), (Mercier,1968; Kockel et al,1971; Kockel and Mollat,1977; Vergely,1984; Gauthier,1984; Jung and Mussallam,1985; Bebien et al,1986,1987; Dimitriadis and Asvesta,1993).

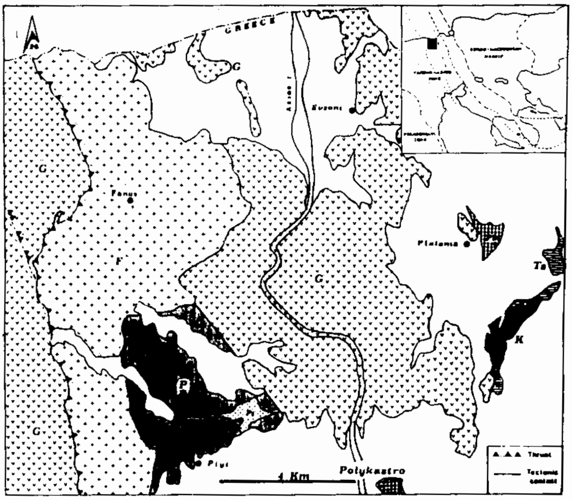


Fig. 1: Sketch map (based on Mercier 1968, Bebien 1982, I.G.M.E. 1982, 1993 and our own data) of the area north of Polykastro, where the Karathodoro and Piyi continental blocks crop out. K: Karathodoro block, P: Piyi block (Pt: tonalites), G: Guevgueli basic complex, F: Fanos granite, Pl: Platania granite, Ts: Triassic limestones, Unornament: post Upper Jurassic formations.

Dimitriadis and Asvesta (1993) suggested that pre-Late Jurassic (Permo-Triassic to Mid Jurassic) rift and passive margin sedimentary formations were deposited on top of an attenuated westward extention of the Serbomacedonian massif. This Serbomacedonian basement attenuation preceded the opening of a pre-Mid Jurassic oceanic basin, which was subsequently eliminated during Mid to Late Jurassic by an eastward oblique subduction below its former eastern passive margin. A volcanic arc (supposed to be the source of the Khromni volcanics and volcaniclastics in Paikon) formed above this subduction, as well as a series of pull-apart basins behind the arc, where the IMHOB ophiolites were created (see also: Bebien et al,1980,1986,1987; De Wet,1989). During the JE1 Kimmeridgian-Tithonian compressional event (Mercier,1968; Bebien,1982; Vergely, 1984) which followed immediately thereafter, rifted parts of the attenuated basement were probably infolded or detached and thrusted together with their sedimentary cover and ophiolite fragments onto the eastern parts of the Paikon zone.

In the eastern part of the Vardar-Axios zone fragments of basement looking deformed and metamorphosed rocks have been grouped by Kockel (1986) in what was named by him the "Stip-Axios zone". The fragmented Stip-Axios zone might actually represent parts of the suggested westward extension of the Serbomacedonian massif. We will examine here two fragments of this zone, the Karathodoro gneissic block near Polykastro and the migmatitic block of Piyi (Mercier,1968), both within the confines of exposed parts of the Guevgueli magmatic complex, which is the largest component of the IMHOB (fig. 1). Lithologicaly similar formations continue beyond the Greek frontiers in the north, in what is known as the Hudova-Bogdanci-Stoiakovo gneissic massif (Erdmannsdoerffer,1923; Mercier,1968).

If the Karathodoro and Piyi continental blocks were parts of a continuous metamorphic basement which finally rifted opening a marginal basin where the Guevgueli complex was created, then they must bear structural and metamorphic evidence of their participation in these events. The aim of this paper is to show that such evidence does exist.

Pelitic lithologies are predominant in both the Karathodoro and the Piyi blocks. Psammitic rocks, amphibolites and basic, intermediate and acid intrusions, are subordinate. Since changing P and T conditions are better recorded in pelitic rocks, our study is mainly concerned with such rock types.

FIELD RELATIONS AND STRUCTURAL FEATURES

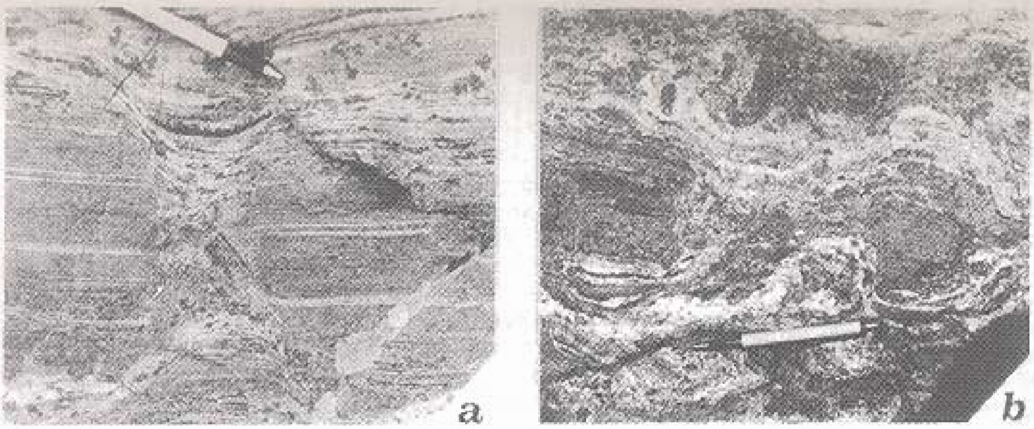
Contacts between the Karathodoro block and members of the Guevgueli basic complex are barely visible, but are infered to be tectonic or tectonized (Mercier,1968; IGME,1993, map sheet Evzoni 1:50000). The contacts of the Karathodoro block with recrystallized, possibly Triassic limestones and with Upper Jurassic and Eocene-Oligocene clastic formations are also tectonized. Similarly, tectonized are the limited contacts between the Piyi migmatitic block and the main Guevgueli complex. However, basic dykes of the latter appear to intrude the Piyi block (see below), as is also the case with dykes of the Upper Jurassic Fanos granite (Mercier,1968; Bebien,1982). Parts of both continental blocks are buried under Neogene and Pleistocene formations.

The earliest fabric present in the Karathodoro and Piyi pelites is defined by mm size alternating quartzofeldspathic and biotite + sillimanite + cordierite ± garnet ± spinel microlayers. The quartzofeldspathic microlayers are pinched and swelled, possibly due to the attenuation of a preexisting more typical stromatic fabric. Mesoscopic indications for a regional scale extension abound, especially in the Piyi migmatites (figs 2a,b). A partial melting event which produced cordierite bearing aplitic leucosomes is spatially and temporally related to this extension. This because the leucosomes fully participate in extensional fabrics and at the same time appear to be less competent than biotite or amphibole rich boudinaged mesosomes, evidently because the leucosomes were at a semi-molten stage during the extensional phase (figs 2a,b).

The cordierite bearing aplitic leucosomes have not been affected by any folding. Some tight to isoclinal mesoscopic folds seen in the mesosomes obviously predate the melting event, since the mobilized leucosomes cut through the folds and disrupt them (fig. 3a) or, in cases of high leucosome to mesosome ratios, gostly remnants of folded mesosome appear floating and have been partly "digested" by the leucosome (fig. 3b).

Extensional fabrics have also been imposed with various intensities in most of the other rock types in the Karathodoro and Piyi blocks, especially in the limited exposures of tonalitic rocks and some augen gneisses. The Fanos granite is, however, lacking an extensional fabric.

Partial melting phenomena are not very intense in the Karathodoro block. Cordierite bearing leucosome segregations of mm to cm scale in the pelites are not uncommon, but larger in situ leucosomes are rather scarce. Some sizable aplitic dykes, however, intrude this block. A cupola of cordierite granite exposed near the Karathodoro block (granite of Platania, Mercier,1968) is most probably the product of extensive partial melting of Karathodoro type pelites at deeper levels; the cordierite bearing aplitic dykes within the Karathodoro block could well be offshoots of this granite.



Figs 2a,b: Extensional fabrics in the migmatitic pelites. The quartzofeldspathic leucosome, with dispersed segregations of large cordierite crystals (visible in 2a upper right) is less competent than the biotite rich mesosome. This is possible only if the leucosome was at a semimolten stage during the extension.

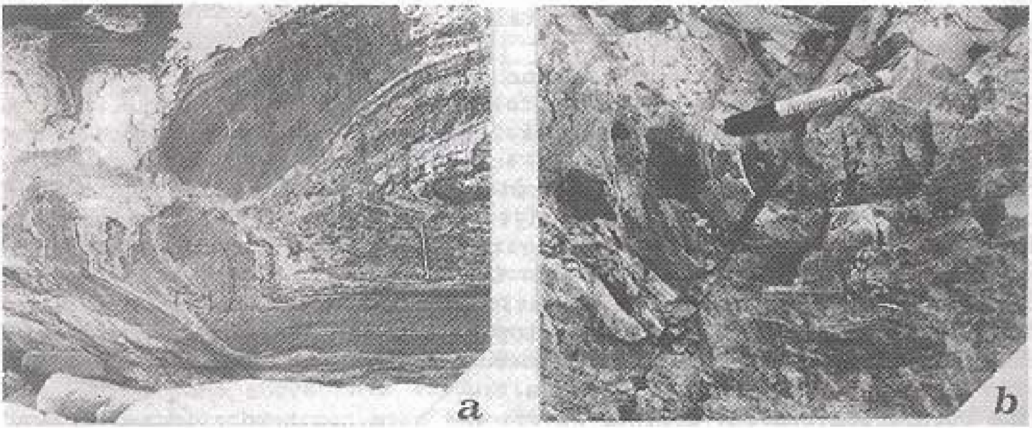


Fig. 3: a) Leucosome disrupting an earlier fold. b) A preexisting folded mesosome has been partly digested by the leucosome (upper left).

Partial melting phenomena are much more intense in the Piyi block. In places, more than 50% of the original pelite appears to be melted and "rafts" of the unmelted or restitic parts are dispersed in a cordierite aplite leucosome (fig. 4).

A strong planar fabric, apparently extensional in the leucosomes and pre- or syn - extensional in the mesosomes, is clearly visible in the field (figs 2a and 4). However, under the microscope a perfectly annealed polygonal granoblastic texture is revealed in both (figs 5a,b). This suggests that the regional extension and partial melting was followed by a static recrystallization, which could have been the result of either:

a. A later, separate high temperature event, or,

b. A slow cooling in static conditions after the ductile extension and partial melting had ceased.

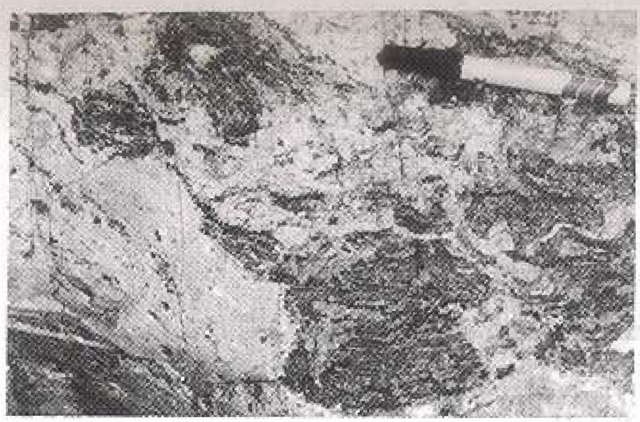


Fig. 4: Large scale melting in the Piyi migmatites. Streaks of cordierite segregations in the leucosome (middle left) define a planar fabric (apparently a fossilized laminar flow parallel to the extension).

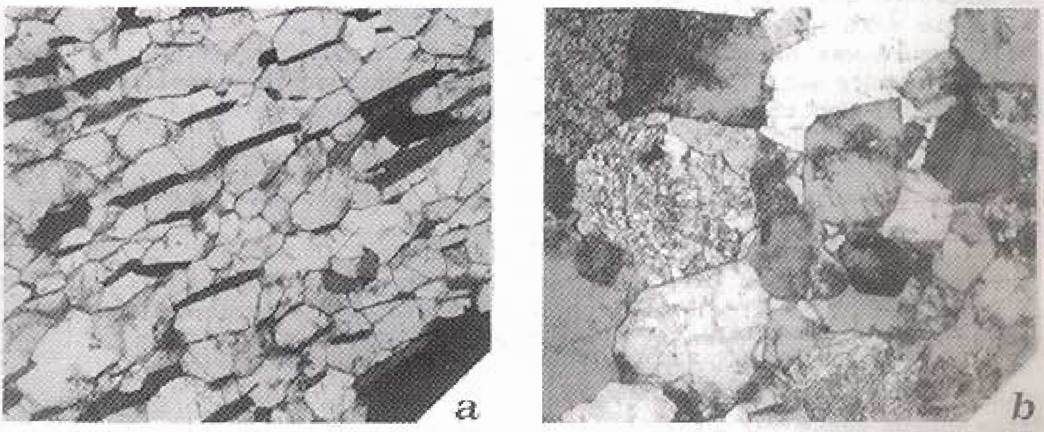


Fig. 5: Annealed textures in a quartzofeldspathic part of: a) a mesosome (x30, N-) and b) a cordierite aplite (x44, N+).

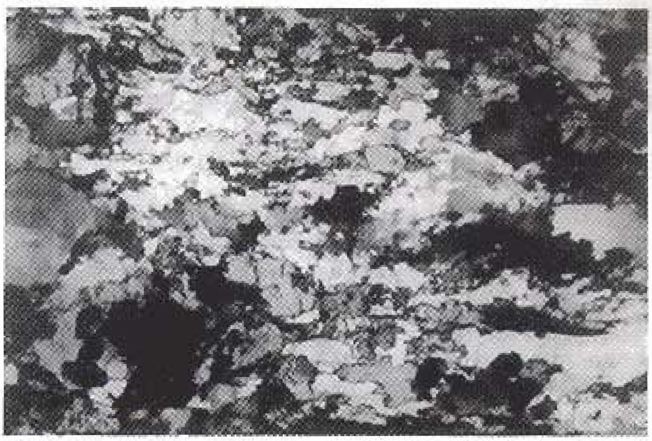


Fig. 6: Formation of quartz subgrains in thin shear zones within the Karathodoro block (x30, N+).

In the Karathodoro pelites however, localized thin shear zones are characterized by dynamic recrystallization of quartz, which shows undulose extinction, formation of subgrains and serrated boundaries (fig. 6). We have not yet been able to determine whether this is a pre- or a post-melting textural feature. Since, however, a similar incipient mylonitization is present in the Platania granite, we favour at present the second possibility.

METAMORPHIC FEATURES

The most common paragenesis in the Karathodoro and Piyi pelites is:

biotite (bio) + sillimanite (fibrolite) (sil) + cordierite (cd)+ quartz (qz) + plagioclase (pl) ± garnet (gt) ± spinel (hercynite) (sp) ± K-feldspar (Kf) ± opaques (ilmenite, magnetite, pyrite)

with some of these minerals being in a reaction relationship.

No primary muscovite has been found, indicating metamorphic temperatures higher than a muscovite breakdown reaction in the presence of quartz, which could have been either the:

mu + qz = sil + Kf + H2O

if pressure was lower than 5 kb (reaction (1) in fig. 7), or:

mu + bio + Kf + qz + H2O = melt

if pressure was higher than 5 kb (reaction (2) in fig. 7).

Orthopyroxenes were not found in the Karathodoro and Piyi pelites. This constrains further the metamorphic temperatures below those corresponding to the reaction:

bio + gt + qz + H2O = melt + opx (reaction (3) in fig. 7),

and the metamorphic pressures above those corresponding to the reaction:

gt + qz + H2O = opx + cd (reaction (4) in fig. 7).

Cordierite is always present around bundles of fibrolitic sillimanite and separates it from neighbouring biotite (fig. 8). Apparently, it has been formed by one or more of the following reactions:

sil + bio + qz + H2O = cd + melt (5)
sil + bio + qz + Kf + H2O = melt (6)

if a fluid phase was present, or:

sil + bio + qz = cd + Kf + melt (7)
sil + bio + qz + pl = cd + (Kf) + melt (8)
sil + bio + qz = cd + Kf + vap. (9)
sil + bio + qz = cd + sp + melt (10)

in fluid absent conditions.

The obvious production of cordierite bearing melts in these rocks suggests that one or more of the reactions (5), (6), (7), (8) and (10) are likely, with reaction (9) also possible in slightly lower subsolidus temperatures.

Reaction (2) can also produce a peraluminous melt, capable to crystallize a cordierite bearing leucosome at pressures lower than about 5.8 kb. The large idiomorphic cordierites in the aplitic leucosomes of the migmatites (figs 2a, 4 and 9) could be either "idioblasts", grown parallel with the formation of the melt (reactions 5,7,8,and 10), or "phenocrysts" crystallized from an anatectic peraluminous melt (reactions 2 and 6).

K-feldspar was in some cases conspicuously present near the reaction site suggesting reactions (6),(7),(8) or (9). Also seen are however cases with spinel crystals present within the produced cordierite and no K-feldspar around, which suggest reaction (10). In fact, melting might have started through reactions (2) (5) or (6), if a vapour phase was originally present; after its quick consumption in the first melts however, reactions (7),(8) or (10) could have taken over.

Since the XMg ratios of analyzed biotites and cordierites in the pelitic

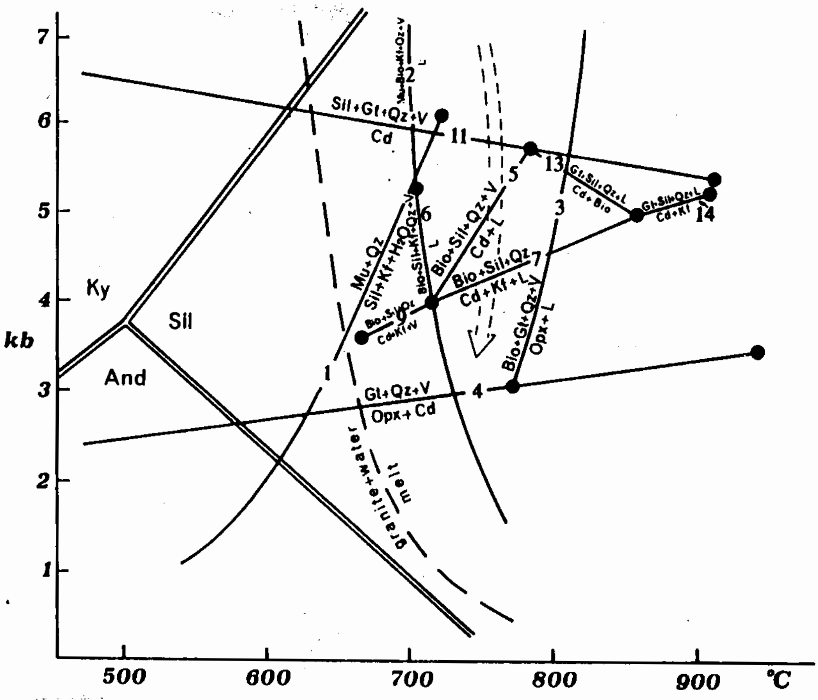


Fig. 7: Petrogenetic grid based mainly on Vielzeuf & Holloway (1988). Numbers of reaction curves correspond to those refered in the text. A possible P-T-t path for the Karathodoro and Piyi pelites is indicated by the arrow.

rocks considered here are both close to 0.4 (our unpublished data), the petrogenetic grid of Vielzeuf and Holloway (1988) (fig. 7) can be used in order to constrain the P-T conditions of melting. Reactions (8) and (10) are, however, not represented in this grid.

The temperature for reaction (8) is, apart from the pressure, also depending on the composition of the plagioclase. According to Clemens and Vielzeuf (1987) and Le Breton and Thompson (1988) it is unlikely that the temperatures needed for this reaction are lower than 700 to 750°C. There are no experimental data available for reaction (10). Spinel plus cordierite in the presence of quartz have been, however, only reported as products of biotite dehydration melting in low pressure terranes, for which temperatures of c. 750°C have been inferred (Hensen and Harley,1990).

Melting thus must have taken place at temperatures higher than 700°C (reactions 2,6,5,8 and 10) and lower than 800°C (reaction 3).

Garnets with compositions around alm75pyr10sp7gro8 are present in the Karathodoro and Piyi pelites. Textural relations (fig. 10) suggest a reaction of garnet with sillimanite producing cordierite. Possible reactions (see fig. 7) are:

gt + sil + qz + H2O = cd (11)

gt + sil + bio = cd + sp + melt (12)

gt + sil + qz + melt = cd + bio (13)

gt + sil + qz + melt = cd + Kf (14)

Reaction (11) is the most likely, since no other phase apart from cordierite is conspicuously present at or near the reaction sites. Reaction (12) is not represented in fig. 7, but according to Harris (1981) and Grant and Frost (1990) the coexistance of cordierite, spinel and melt is possible at temperatures above c. 655°C. The incompleteness of the reaction, with all the potentially reacted solids still present in close proximity, indicates that the reaction stopped either when all the available vapour phase was consumed in it, or when the conditions for vapour present melting reaction(s) (see above) were reached. In the latter case, any remaining vapour preferentially participated in the melting reaction(s) than in the garnet dissolving reaction. The garnets might also have been protected to some extent from further dissolution by their armouring with the cordierite produced. The garnet consuming reaction in the Karathodoro and Piyi pelites indicates pressures lower than 5.5 to 6.0 kb (fig. 7).

In order to reconstruct a part of the P-T-t path of the Karathodoro and Piyi pelites and to, possibly, attribute it to a specific tectonic evolution, the sequence of the aforementioned reactions must be known. We have not found unequivocal textural evidence demonstrating such a sequence; rather, our impression in most cases was that the cordierite and melt producing, as well as the garnet consuming reactions were all roughly synchronous, or else, succeeded one another without the intervension of noticeable tectonic or recrystallization event(s). Since, however, field relations suggest that melting was synchronous with regional extension, a down pressure and probably short t path is suggested. To cross the garnet consuming and the cordierite and melt producing reaction curves (fig. 7), the path must also be rather steep, that is nearly isothermal. We indicate such a possible down pressure path with an arrow in fig. 7. Starting P-T conditions cannot be constrained. Final conditions (for the event discussed) are estimated at around 3.5 kb and 750°C (low P granulite facies), corresponding to a depth of approximately 15 km (the depth of the now exposed parts at the time) and a shallow geotherm with a mean gradient of around 50°C/km.

A shallow crustal geotherm implies the existance of magmatic bodies in the lower crust, a crust underplated by basaltic magma, a thinned lithosphere on top of upwelled asthenosphere, or some combination of the above; they are commonly in any case all mutually related. In our case, taking the field evidence for regional extension and decompression into account, a rising asthenosphere below an extending lithosphere seems like a justified suggestion for the prime cause of the HT-LP metamorphism and partial melting discussed. Mobilized lower crustal or mantle derived melts could have been additional and efficient upward heat transducers, the HT-LP terrane in that case being in fact a regional scale thermal aureole. Basalt underplating is also suggested by the abundance of basic dyke intrusions, especially in the Piyi block, and this could have contributed to the shallow geotherm. There are reasons to believe (see below) that these dyke intrusions were synchronous with the LP-HT metamorphism and the regional extension.

A subsequent metamorphic event that affected both the Karathodoro and Piyi blocks is a locally only significant static greenschist retrogression, apparently related to fluid infiltration during brittle, low temperature faulting.

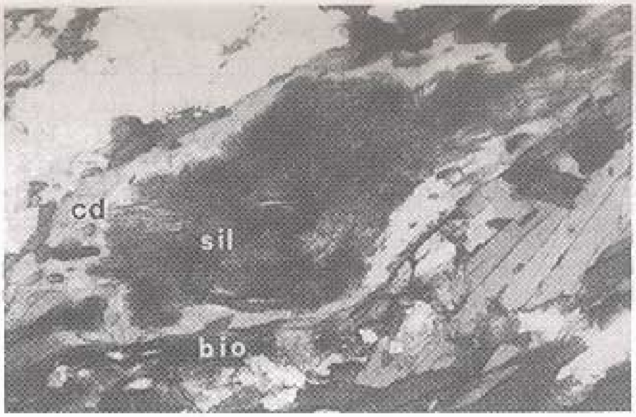


Fig. 8: Reaction relation between fibrolitic sillimanite (sil), cordierite (cd) and biotite (bio) (x44, N+).

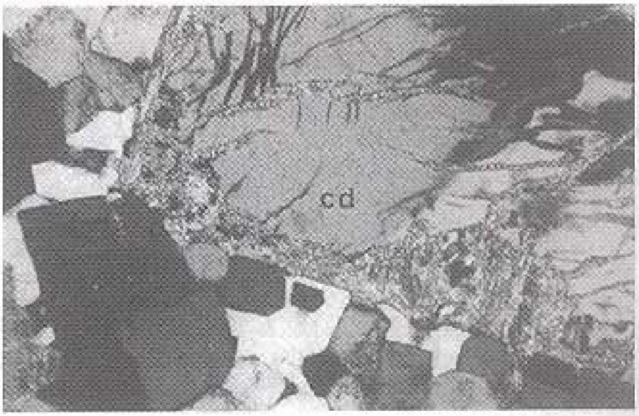


Fig. 9: Large idiomorphic cordierite (cd), partly pinitized, in an aplitic leucosome. The cordierite might be either an idioblast or a phenocryst (x44, N+).

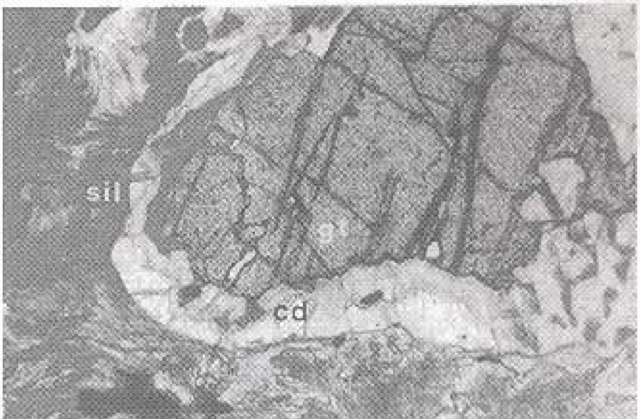


Fig. 10: Garnet (gt) reacts with sillimanite (sil) and produces cordierite (cd). The latter is partly pinitized (x44, N+).

AGE CONSIDERATIONS

The granite of Platania, the aplitic dykes which intrude the Karathodoro gneiss and the gneiss itself have all been dated and yielded the same age (159 to 161 ± 5 Ma (Rb-Sr in biotite, Borsi et al, 1966; Mercier,1968; corrections with new 87Rb constant by De Wet,1989). This age corresponds to the Callovian stage (according to the time scale of Harland et al, 1989, which is used here) and apparently signifies the cooling below approximately 320°C (the closure temperature of the Rb-Sr in biotite system) after the partial melting and aplite intrusion event, or perhaps a separate later heating above that temperature. In any case, the partial melting event cannot be younger than late Mid Jurassic.

No absolute ages of the Piyi migmatites are available. The syn-melting extension must however predate the intrusion of the Fanos granite (Mercier,1968), since Fanos type undeformed dykes intrude the migmatites (Mercier,1968; Bebien,1982) truncating their extensional fabric, whereas the Fanos granite is lacking such a fabric.

The Fanos granite has been dated by the Rb-Sr and K-Ar in biotite methods (Borsi et al,1966; Marakis,1968; Spray et al,1984; see also De Wet,1989) and yielded ages ranging between 156 and 150 Ma (Oxfordian to Tithonian) with the Rb-Sr, and 151 to 116 Ma (Tithonian to Aptian) with the K-Ar method. This discrepancy is obviously due to the difference in the closure temperatures of the two systems. Since a time lapse was needed for the pluton to be cooled down to the closure temperature of the Rb-Sr in biotite system (c. 320°C), an Oxfordian or perhaps a slightly earlier intrusion age is more likely. This is consistent with the suggestion of Mercier (1968) that during Tithonian the Fanos granite was already exposed, supplying clasts in Tithonian conglomerates. It follows that the ductile extensional deformation and the accompanying partial melting of the Piyi pelites had ceased by the Oxfordian. How long before that the extension was active however is a crucial question. Two lines of thought lead us to believe that the extension and partial melting occured not much earlier than the intrusion of the Fanos granite.

The first is that pools of Fanos type granitic material segregated and crystallized in situ in what appears to be the manifestation of the latest stages of the regional extension, that is in semibrittle extensional vughs and cracks mainly in the tonalitic rocks within the Piyi block (fig. 11). A temporal and perhaps genetic relation between the earliest stage of the Fanos granite formation and the vanishing stage of the extension is thus suggested. Geochemical evidence provides additional evidence favouring the derivation of the Fanos granite from a tonalitic parental material (Christofides et al,1990; Soldatos et al,1993).

The second is that the basic dykes which intrude the Piyi block have the same orientation and comparable geochemistry to the basic dykes of the nearby Guevgueli complex and could therefore be of the same age and origin (Bebien,1982; Haenel-Remy and Bebien,1987; Dimitriadis et al,in press). The basic dykes in the Piyi block intruded at high angles to the already imposed ductile extensional fabric of the migmatites, suggesting a stability of the strain field in passing from the ductile to the brittle regime. Inclusions of amphibolitized metabasites (in some cases recognized as ex-pyroxene granulites) within the pelitic migmatites and the tonalites have apparently participated in the ductile extensional deformation. The geochemical signature of these amphibolitized metabasites is undistinguishable from that of the undeformed basic dykes, and we concur with Haenel-Remy and Bebien (1987) that the amphibolitized metabasites are possibly deeper level, and apparently slightly earlier, dyke intrusions of the Guevgueli clan. The igneous age of the Guevgueli complex has been determined as Late Jurassic, with K-Ar in biotie and hornblende ages ranging between 148 and 163 Ma (Spray et al,1984), that is from Bathonian to Tithonian. Extension was therefore active within this time span, the earlier part of it rather than the later, again to allow for a cooling down to closure temperatures and because it had to be succeeded by the Kimmeridgian-Tithonian JE1 compressional phase.

Taking all the above into consideration, the evolution that emerges is as follows:

A crustal segment was actively extending during late Mid Jurassic and was being subjected to LP-HT metamorphism and partial melting. This crustal segment was being at the same time intruded by basic dykes. The latter were quickly converting to amphibolites (or basic granulites) at deep crustal levels and were being subjected to ductile extensional deformation. The

Fig. 11: Fanos type granitic material segregated and crystallized in situ in late extensional cracks.

extension was continuously bringing deep crustal parts at shallow levels, where they were cooling and passing into the brittle regime. Basic melts reaching these shallow levels were intruding as dykes cutting at high angles the already imposed ductile extensional fabric. These late stage basic intrusions, plus perhaps the proximity of the crystallizing Fanos granite, could have provided the heat nessesary for the textural annealing of the previously stretched rocks.

The today exposed Serbomacedonian margin opposite the Guevgueli complex do not comprise pelites and migmatites analogous to the Karathodoro and Piyi ones. However, the supposed transtensional regime during Mid and Late Jurassic certainly produced lateral translations within the massif. It is perhaps significant that in other parts of the Serbomacedonian massif there are pelitic rocks having a deformational and metamorphic evolution (Dixon and Dimitriadis,1987) matching in many respects that of the Karathodoro and Piyi pelites.

Pearce (1989) suggested that it was the thrusting of the Guevgueli ophiolite which caused high grade metamorphism and melting in the metasediments buried below the thrust. We presented, however, evidence that melting was related to decompression and extension rather than to overthrusting. Also, the fact that undeformed basic dykes intrude the pelites cutting the preexisting extensional fabric of the migmatites is against Pearce's suggestion.

CONCLUSIONS

The Karathodoro and Piyi continental slivers bear evidence that a previously folded and metamorphosed basement (supposed to be a westward extension of the Serbomacedonian massif) has been subjected to HT-LP metamorphism and partial melting during a late Mid Jurassic extensional phase accompanied by basic dyke intrusions. We propose that this extensional phase is related to the opening of the Guevgueli marginal basin and interprete the Karathodoro and Piyi slivers as remnants of the continental crust that floored this basin prior to its rifting.

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