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MESOZOIC MAGMATISM IN THE AREA BETWEEN
THE VARDAR (AXIOS) ZONE AND THE SERBO-MACEDONIAN MASSIF
(NORTHERN GREECE)

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Abstract: The petrology and geochemistry of Mesozoic granites from the Serbo-Macedonian Massif (SMM) and the Vardar (Axios) Zone (VAZ) are investigated in relation to their granite type. They are all highly evolved leucocratic, more or less deformed rocks. The SMM granites (Kerkini and Arnea) are Late Triassic in age and have characteristics of A-type granite. On the contrary, the VAZ granites (Fanos and Monopigadon) are at least Late Jurassic in age and have I- to S-type granite characteristics. The origin of both SMM and VAZ granites is related to crustal melting.

Key words: Monopigadon granites, Fanos, Arnea, Kerkini, Serbo-Macedonian Massif, Vardar Zone, Greece

1. INTRODUCTION

In the area between the Vardar (Axios) Zone (VAZ) and the Serbo-Macedonian Massif (SMM) in northern Greece occur numerous granitoids of Late Triassic to Tertiary age (Fig. 1 and Table 1). The presence of granitoids in such complex geotectonic units is of particular importance, because through their investigation they can potentially constrain the timing of the main tectonic events in them. Although the petrology and the geochemistry of some of the Tertiary granitoids have been extensively studied, the Mesozoic granitoids have been given less attention. In this work a comparative petrological and geochemical study, in relation to the granite type, of the main Mesozoic granitoids is made. The Fanos and Monopigadon granites are studied from the VAZ and the Kerkini and Arnea granites from the SMM.

2. GEOLOGICAL SETTING

The Kerkini granite intrudes the SMM in Mt. Kerkini straddling the Greece-F.Y.R.O.M. border line (Fig. 1). The country rocks comprise two-mica and amphibole gneisses, schists and amphibolites. Mylonitic fabrics in the granite are well developed. No contact metamorphism has been observed.
The Arnea granite intrudes the SMM near its boundary with the Circum Rhodope Belt (CRB). It extends from southwest of the Lake Volvi to the Arnea village in a NW-SE direction followed by several smaller intrusions. Its southwestern contact is strongly deformed with well-developed mylonitic fabrics near the contact (De Wet, 1989; Oladezi, 1997).

The Fanos granite intrudes the Guevgueli ophiolite complex in the VAZ, near the border with the F.Y.R.O.M. In Greece, the Guevgueli complex comprises a migmatitic and gneissose basement and slivers of dismembered ophiolite thrust upon a Jurassic volcano-sedimentary sequence (Bébién, 1977; Spray et al., 1984).

The Monopigadon granite is a small intrusion outcropping on the western side of the Chalkidiki ophiolite belt near the Monopigadon village. It intrudes a carbonate-bearing volcanioclastic sequence (amphibolite and calc-silicate hornfelses) (Michard et al., 1998).

3. PETROGRAPHY

The Q-ANOR diagram (Fig. 2) of Streckeisen & Le Maitre (1979) has been used for the classification of the rocks studied. The Kerkini, Arnea and Fanos rocks are classified as granite to alkali granite while the rocks of Monopigadon as granodiorite to granite.

The Kerkini granite is intensively deformed and weathered. The main rock-type is two-mica granite with subordinate biotite granite and muscovite granite. The rocks are mostly medium- to coarse-grained, leucocratic to mesocratic. Perthitic K-feldspar phenocrysts are common in inequigranular texture. Graphic intergrowths are often developed. Accessories include opaques, zircon, allanite, apatite, fluorite and titanite. Plagioclase is albite, often poorly zoned. Biotite is close to annite end-member. It is late in the crystallization sequence occurring as interstitial flakes between feldspar and quartz.

The Arnea granite is extensively deformed. The main lithology is muscovite granite followed by two-mica granite. The rocks are strongly leucocratic, fine- to medium- and sometimes coarse-grained. Rare perthitic feldspar phenocrysts result in a hypidiomorphic inequigranular texture. Graphic texture is common. Muscovite appears to be mostly secondary. Less frequent is subhedral biotite. Opaques, allanite, often rimmed by epidote, and titanite occur as accessories. Among accessories purple-colored fluorite grains are characteristic.
The Fanos granite is a leucocratic intrusion comprising aplite granite, granite and microgranite. Quartz, K-feldspar, plagioclase and biotite are the main rock-forming minerals while titanite, apatite, zircon, alalanite and rare hornblende are accessories. Plagioclase is albite to oligoclase. K-feldspar is a perthitic microcline. The aplitic granite is confined to the outer part of the intrusion, intruding the granite. Granite is the main rock type. Microgranite, which is finer-grained than the granite and richer in biotite, occurs as small exposures.

The Monopigadon granite consists of biotite granodiorite and biotite to two-mica granite. Enclaves and xenoliths are quite common in the biotite granodiorite. The granite intrudes the granodiorite. Perthitic K-feldspar exists only in granodiorite. Plagioclase is slightly zoned with an oligoclase to andesine core and a more sodic rim. Biotite is reddish-brown, brown or yellow brown with zircon inclusions. Apatite and sphene are present as accessories. Muscovite forms small subhedral crystals. Its TiO₂ content is lower than 0.6 wt.% meaning that it is not candidate for magmatic origin.

Table 1. Radiometric ages of the Mesozoic granites considered in this study

<table>
<thead>
<tr>
<th>Granite</th>
<th>No in Fig. 1</th>
<th>Geotectonic unit</th>
<th>Method</th>
<th>Mineral rock</th>
<th>Age (Ma)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kerkini</td>
<td>1</td>
<td>SMM</td>
<td>K-Ar</td>
<td>Bt</td>
<td>130 ± 3 to 131 ± 3</td>
<td>Christofides et al. (1999)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>K-Ar</td>
<td>Ms</td>
<td>133 ± 3</td>
<td>Christofides et al. (1999)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Rb-Sr</td>
<td>WR</td>
<td>215 ± 5</td>
<td>Christofides et al. (1999)</td>
</tr>
<tr>
<td>Arnea</td>
<td>2</td>
<td>SMM</td>
<td>Ar-Ar</td>
<td>Phl</td>
<td>136.0 ± 0.9</td>
<td>De Wet (1989)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Rb-Sr</td>
<td>WR</td>
<td>144 ± 1 to 155 ± 11</td>
<td>De Wet (1989)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>U-Pb</td>
<td>Zrn</td>
<td>212 ± 7</td>
<td>Vital (1987, in Frei, 1992)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pb-Pb</td>
<td>Zrn</td>
<td>Late Triassic</td>
<td>Kostopoulos et al. (2000, in press)</td>
</tr>
<tr>
<td>Fanos</td>
<td>3</td>
<td>VAZ</td>
<td>Rb-Sr</td>
<td>Bt</td>
<td>147 to 153</td>
<td>Borsi et al. (1966)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>K-Ar</td>
<td>Bt</td>
<td>150</td>
<td>Borsi et al. (1966)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>K-Ar</td>
<td>Bt</td>
<td>113 ± 3 to 148 ± 4</td>
<td>Marakis (1969)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>K-Ar</td>
<td>Bt</td>
<td>148 ± 3</td>
<td>Spray et al. (1984)</td>
</tr>
<tr>
<td>Monopigadon</td>
<td>4</td>
<td>VAZ</td>
<td>K-Ar</td>
<td>Bt</td>
<td>180</td>
<td>Ricou (1965)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>K-Ar</td>
<td>Bt</td>
<td>141.5 ± 3.1</td>
<td>Michard et al. (1998)</td>
</tr>
</tbody>
</table>

Explanation: WR - whole-rock, Bt - biotite, Ms - muscovite, Phl - phlogopite, Zrn - zircon.
4. GEOCHRONOLOGY

Table 1 shows the isotopic age data of four Mesozoic granites. All the mineral ages define a time span between the Late Jurassic and Early Cretaceous. There are several possible interpretations for these ages. They may result from partially resetting, they may represent cooling ages or they may reflect the latest event (deformation, metamorphism). The Arnea granite whole-rock Rb-Sr errorchron age is considered as a minimum Late Jurassic age (De Wet, 1989). Vital (1987, in Frei, 1992) obtained a zircon U-Pb intrusion age of 212±7 Ma for the Arnea granite. A Late Triassic, zircon Pb-Pb age was also obtained by Kostopoulos et al. (2000, in press). Moreover, Christofides et al. (unpubl. data) obtained a whole-rock Rb-Sr isochron age of 215±5 Ma interpreted as the intrusion age of the Kerkini granite. It is obvious that the magmatic activity that gave the “Jurassic” granites (Kockel et al., 1977) started earlier (Late Triassic) at least regarding the SMM granites.

5. GEOCHEMISTRY AND TECTONIC SETTING

A geochemical database based on published and new data, consisting of more than 70 analyses, was used for the present study. All analyzed samples are highly evolved rocks (Fig. 3). The highest SiO₂ content is found in the Arnea granite ranging from 70 to 79 %. In Kerkini it ranges from 70 % to 76 %, in Fanos from 70 % to 78 % and in Monopigadon from 61 % to 74 %. TiO₂, Al₂O₃, P₂O₅, FeO, and CaO decrease in all granites. MgO decreases in Fanos and Monopigadon but it is generally constant in Kerkini and Arnea. In the last two granites CaO and MgO values are relatively low. K₂O increases slightly in Monopigadon, it is rather constant in Kerkini and Fanos, and decreases slightly in Arnea where a cluster of low-K samples also exist. Na₂O is constant in Fanos and Monopigadon, is slightly decreased in Kerkini while in Arnea is highly scattered. FeO/MgO ratio ranges from 1.9 to 5.2 in Fanos and Monopigadon, and from 3.2 to 40.0 in Kerkini and Arnea. It must be noticed here that the Monopigadon granodiorite (SiO₂>65.5 %) has different geochemical behaviour for some elements from the biotite to two-mica granite (Fig. 3). Based on the A/CNK ratio, Kerkini, Fanos and Monopigadon are slightly peraluminous. Arnea shows a wide variation from 0.95 to 1.29 (two samples have values of 1.72 and 1.74) displaying a metaluminous to peraluminous character.

Sr and Ba decrease with silica in all granites except Fanos where the trend is quite steep (Fig. 3). In general, the SMM granites have lower Sr and Ba contents than the VAZ granites. Rb is either constant or shows a slight increase in Kerkini, decreases with some scatter in Arnea, it is almost constant with a slightly concave pattern in Fanos, and increases in Monopigadon. Nb and Y decrease in Kerkini and Arnea, in the latter with some scatter, and it is constant in Monopigadon. In Fanos Nb increases while Y decreases slightly. Zr decreases in all granites with the Kerkini having the steeper trend. V, Cr and Ni decrease in Kerkini (with some scatter in Ni), Arnea, Monopigadon and Fanos (only for V). Trace element differences between the Monopigadon granodiorite and granite also exist (Fig. 3).
Fig. 3. Selected major (wt.%) and trace (ppm) element vs SiO$_2$ variation diagrams of the Mesozoic granites; Symbols as in Fig. 2.
In Batchelor & Bowden’s (1985) R1-R2 diagram (Fig. 4) SMM granites straddle fields of late-orogenic and anorogenic granitoids. This is in agreement with their plot in the within-plate granites (WPG) field of Pearce et al. (1984) diagram (Fig. 4). Some SMM and VAZ samples plot in the syn-collision anatexic granites field of R1-R2 diagram. It must be stressed here that the overlap around this field is predictable, since all granitoids evolve towards minimum melting compositions. A WPG tectonic setting has also been discussed by De Wet (1989) and Baltatzis et al. (1992) for the Arnea Fanos plot in the late-orogenic granites on R1-R2 diagram while Monopigadon is scattered occupying fields 2, 3 and 4. Based on Pearce et al. (1984) and Harris et al. (1986) discriminant diagrams both are related with a volcanic arc or post-collision tectonic environment, although the Fanos genesis is ascribed to continent-arc collision (Pearce et al., 1984). Michaud et al. (1998) suggest that the Monopigadon granite was formed during the Late Jurassic intra-oceanic subduction occurred in the border of a marginal sea, floored with oceanic crust, corresponding to deep parts of the arc.

Fig. 4. Plot of the Mesozoic granites on the (a) R1-R2 diagram (Batchelor & Boyden, 1985); (b,c) Nb vs Y and Rb vs Y+Nb discrimination diagrams (Pearce et al., 1984); (d) Rb/Zr vs SiO₂ discrimination diagram (Harris et al., 1986). Explanation: VAG = volcanic arc granites; syn-COLG = syn-collision granites; WPG = within-plate granites; ORG = ocean-ridge granites; Group II = syn-collision granites. Symbols as in Fig. 2.
6. DISCUSSION

Based on their mineralogy, petrography and geochemistry the investigated granites are distinguished in the SMM (Kerkini and Arnea) and in the VAZ (Fanos and Monopigadon) granites. The plot of the SMM granites in the WPG field (Fig. 4) indicates that they are related with A-type granite magmatism. In fact the SMM granites have features characteristic for A-type granites (cf. Collins et al., 1982; Whalen et al., 1987; Eby, 1990; Landenberger & Collins, 1996). In particular the rocks investigated: (i) plot in the WPG field, (ii) are peraluminous, (iii) are depleted in MgO and CaO, and they have high FeO/MgO ratios, (iv) are enriched in Zr, Nb, Y and Ga, (v) contain fluorite with Kerkini having in addition iron-rich interstitial biotite (annite) (Christofides et al., 1999), indicating dry or almost anhydrous melts with elevated fluorine content; (vi) fall in the A-type granite field of Whalen et al. (1987) and Eby's (1990) discriminant diagrams (Fig. 5 and 6, respectively). On the contrary the VAZ granites show I-type characteristics although some S-type characteristics also exist, and moreover, they plot in the I-, S- and M-type fields of diagrams of Fig. 5 and 6.

Fig. 5. Plot of the Mesozoic granites on the Whalen et al. (1987) discriminant diagrams; Explanation: Rectangular boxes represent I-, S- and M-type granites; rest field – A-type granites; Symbols as in Fig. 2
Based on the Y/Nb and Yb/Ta ratio values of the A-type Kerkini granite and taking into account the fluid-absent melting experiments on a hornblende-biotite tonalitic gneiss, conducted by Skjerlie & Johnston (1993), Christofides et al. (1999) concluded that the most probable genetic model for the origin of this granite is fluid-absent melting of a biotite-rich tonalitic source at 6–10 kbar and 950-975 °C, leaving behind a granulitic residue dominated by orthopyroxene, quartz and plagioclase. Soldatos et al. (1993) suggested an igneous source material for the Fanos granite. Models involving derivation of the Fanos granite magma by partial melting of igneous and sedimentary source materials have been tested by comparing the concentrations of Rb, Ba, Sr and REE of the Fanos granite with the calculated hypothetical abundances of these elements in liquids, which have originated by partial melting of the above-mentioned source materials. The Fanos granite pattern matches very well the patterns of melts derived from an igneous source with quartz dioritic composition.

For the origin of the Arnea granite, De Wet (1989) suggested crustal melting either in response to crustal thickening and temperature increase, perhaps associated with the closure of the Innermost Hellenic Ophiolite Belt (IMHOB) during the Upper Jurassic or in response to extension and decompression, perhaps associated with the initiation of the ocean basins in the IMHOB during the Late Triassic. The latter is in agreement with the Late Triassic ages obtained for the Arnea granite (Table 1).

The major and trace element behaviour indicates that the Monopigadon granodiorite and granite originate from two different melts. On the A-B diagram (Fig. 7) the Monopigadon samples, except two-mica granite and aplite, plot along with experimental, slightly peraluminous, crustal melts, taken from the literature, produced under various P-T conditions. The Monopigadon granodiorite plots in the field defined by melts (SiO₂ 57-62 %) of amphibolitic composition while Monopigadon granite plots in the field defined by melts (SiO₂ 66-69 %) of andesitic and amphibolitic composition formed under different P-T conditions (Beard & Lofgren, 1991; Johannes & Wolfs, 1994; Wolf & Wyllie, 1994; Rapp & Watson, 1995). For the genesis of all Mesozoic granites Perugini et al. (2000, in press) suggested
that they could be the product of partial melting, in different levels, of crustal material consisting of intermediate-acid protoliths with typical calc-alkaline geochemical fingerprint.

In conclusion the main Mesozoic granitic intrusions investigated could be divided into two groups. The SMM granites, which include the Kerkin and the Arna granites, and the VAZ granites, which include the Fanos and the Monopigadon granites. The SMM granites are Late Triassic in age and have characteristics of A-type granite. On the contrary, the VAZ granites have I- to S-type granite characteristics. No data for their intrusion age are available. Based on the existing biotite K-Ar or Rb-Sr ages we can only suggest that it is older than Late Jurassic. The origin of both SMM and VAZ granites is related to crustal melting.

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МЕЗОЗОЈСКИ МАГМАТИЗАМ У ПОДРУЧЈУ ИЗМЕЂУ ВАРДАРСКЕ ЗОНЕ И СРПСКО-МАКЕДОНСКЕ МАСЕ (СЕВЕРНА ГРЧКА)

Georgios Christofides, Antonios Koroneos, Triantafyllos Soldatos, Georgios Eleftheriadis

У овом раду су приказане петролошке и геохемијске карактеристике мезоцентичких гранитних Српско-македонске масе и Вардарске зоне, са посебним освртом на генетијски тип гранита. Проучаване стени су представљене из диференцираним лекократним гранитима који су мање или више деформисани. Гранити Српско-македонске масе (Керкини и Арнеа) су каснотријаске старости и показују карактеристике A-типа гранитоида. Насупрот њима, гранити Вардарске зоне (Фанос и Монопигадон) нису старји од горње јуре и показују одлике I- и S- типа. Порекло их јединих и других гранита везано је за стапање континенталне коре.

Кључне речи: Монопигадон гранити, Фанос, Арнеа, Керкини, Српско-македонска маса, Вардарска зона, Грчка