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Geochemistry and petrogenesis of late Miocene granitoids, Cyclades, southern Aegean: Nature of source components

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ABSTRACT

Neogene igneous activity in the Aegean region comprised both extrusive volcanism and intrusive granitoid plutonism. Granitoid plutonism in the Cyclades was established in the mid-Miocene period and lasted until late Miocene (18 to 9 Ma). The timing of granitoid intrusion was associated with the initiation of extensional tectonics in the Aegean. These intrusions form a broad belt about 200 km long running from the west (Lavrium and Serifos) to the eastern Aegean. Both S-type and I-type granitoids are present, the former generally being emplaced earlier than the I-types (~15 to 8.3 Ma). Major and trace element variations reveal that three end-member components are involved in the granitoids, but the proportions of these vary in the different plutons. Initial isotopic compositions of all the granitoids are typical of crust-derived magmas from heterogeneous metasedimentary sources (I-type: $^{87}Sr/^{86}Sr = 0.7091–0.712$, $\varepsilon_{Nd} = -6.4$ to -10.4; S-type: 0.710–0715, $\varepsilon_{Nd} = -7.5$ to -10.1). Three end-member sources have been identified: 1) One end-member appears to be a metasedimentary biotite-gneiss (greywacke-type) such as that forming the metamorphic core complexes (Naxos and Paros); this is a dominant (but not the only) component in the S-types. 2a) Major, trace element and Sr–Nd isotopic composition correlations of the S-type granitoids with basement gneiss require an extra source of Sr and Ca, having lower initial $^{87}Sr/^{86}Sr$ indicating a more depleted metasedimentary source at depth, due to possible interaction, of metamorphic fluids with marbles and amphibolites and infiltration through the gneissic units, at mid-crustal levels. 2b) A possible second end-member could be the marble component, as indicated by the buffered values of the Initial Sr isotopic ratios. Major element variation of the mafic microgranular (quartz diorites and tonalites) enclaves are compatible with dehydration melting of a mafic source similar to the amphibolites (island arc tholeiites) at medium pressure (~8 kb) conditions. 3) Amphibolite is another end-member which may contribute mostly to the source of the younger intrusions, along the western flank of the arc.

1. Introduction

Partial melting within the crust is a widely accepted model for the production of some, if not most, granite magmas (White et al., 2003). Dehydration melting, involving the breakdown of hydrous minerals, is inferred to be the main melt-producing process in the crust (e.g. Thompson, 1982; Vielzeuf and Holloway, 1988; Brown, 1994; Gardien et al., 1999; White et al., 2003). It is considered that partial melting is a result of melt-forming reactions as temperatures and possibly pressure increase (e.g. Wolf and Wyllie, 1991; Wyllie and Wolf, 1993; Skjerlie and Johnston, 1996; White et al., 2003). Metapelite melting can occur by dehydration melting of muscovite at about 700 °C (at ~5 kb), followed by biotite at 750 °C, whereas dehydration melting of hornblende in amphibolites appears to require temperatures near 900 °C in a pressure range from 5 to 10 kb (e.g. Wolf and Wyllie, 1991; Rushmer, 1991; Wyllie and Wolf, 1993).

However, in terms of source fertility, greywacke-type metasediments contain the appropriate components (plagioclase, quartz, biotite, amphibole and possibly epidote) to form a granitic liquid, under dehydration melting conditions (Skjerlie and Johnston, 1996). Melting of metagreywacke produces larger volumes of granitic melt than melting of metapelites as a result of its Na_2O content and the increased Fe/Mg of biotite (Patiño-Douce and Beard, 1995; Thompson, 1996). Some examples of hornblende-bearing felsic igneous rocks have been interpreted as being products of anatexis of biotite + plagioclase + quartz gneisses (Gardien et al., 2000). Experimental studies on a wide range of synthetic and natural biotite + plagioclase + quartz assemblages have

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shown that amphibole forms during partial melting of a previous amphibole-free assemblage; however external H_2O is required to stabilize amphibole during anatexis of a biotite + plagioclase + quartz assemblage (Gardien et al., 2000; Johnston and Wyllie, 1988).

In the Attic–Cycladic Massif, metasedimentary gneisses are often interlayered with basaltic and other metavolcanic rocks (amphibolites), marbles and other metasediments in a regional metamorphic terrain. The Cycladic Blueschist Unit underwent HP–LT regional metamorphism (M1) between 55 and 40 Ma ago (Andriessen et al., 1979; Altherr et al., 1982; Wijbrans and McDougall, 1988; Bröcker et al., 1993; Baldwin and Lister, 1994, 1998), followed by greenschist to amphibolite (M2) facies metamorphism dated from 25 to 16 Ma (Andriessen et al., 1979; Altherr et al., 1982; Wijbrans and McDougall, 1988; Bröcker et al., 1993). On several Cycladic islands these two metamorphic units were intruded by granitoids.

In contrast to most other Cycladic islands, the Miocene Barrovian-type metamorphism reached anatectic conditions on Naxos (670 ± 50 °C and 5–7 kb) (Jansen and Schuiling, 1976; Buick and Holland, 1989) and created an onion-shaped migmatite dome in the central part of the island. It has been proposed that the recorded rapid uplift triggered decompression melting in the gneiss dome of Naxos at progressively deeper structural levels, with the final intrusion of I-type granodiorites at about 12.5 Ma, based on zircon dating (Henjes-Kunst et al., 1988).

The source of specific Cycladic granitoids still remains to be clarified. Previously proposed petrogenetic models for the formation of the Miocene Cyclades I-type granites have been formulated mostly in terms of two component mixing, either, between mantle-derived magmas (arc-type basalt) and/or, mantle-derived igneous rock (i.e. obducted ophiolites) and upper crust end-members (Juteau et al., 1986; Altherr et al., 1988). Recently, it has been suggested that both I- and S-type granitoids originated by dehydration melting of metaluminous upper crustal sources (Altherr and Siebel, 2002). U–Pb systematics of zircon populations suggests a high proportion of assimilated crustal material in these magmas (Juteau et al., 1986; Altherr and Siebel, 2002).

In the present paper we extend our investigation of the involvement of the different basement rocks of the Attic–Cycladic Massif, in the generation of the I- and S-type plutons. We present new Rb–Sr, Sm–Nd isotope data as well as precise chemical data (major and trace elements) for all the Cycladic granitoids and for a variety of basement rocks from the Cycladic islands (Paros, Naxos and Serifos) and are evaluated along with existing isotope data. Because Sr and Nd isotopic compositions alone cannot distinguish between the different hypotheses for the petrogenesis of the igneous rocks in a given region, an overall evaluation of geochemical, mineralogic, regional tectonics and field observation data is attempted.

2. Regional setting and field relationships

In the central Aegean, the Attic–Cycladic Massif forms a belt of metamorphic rocks exhumed along low-angle detachments (Lister et al., 1984). The polyphase tectonometamorphic evolution of this massif began with an Eocene high-pressure/low-temperature metamorphism evidenced by blueschist to eclogite facies (Andriessen et al., 1979; Wijbrans and McDougall, 1988; Buick and Holland, 1989; Baltatzis, 1996; Avigad et al., 1998; Keay and Lister, 2002).

The high-pressure/low-temperature metamorphism was overprinted by a Miocene medium pressure/medium temperature event evidenced by a greenschist to amphibolite-facies locally reaching partial melting conditions (Jansen and Schuiling, 1976; Andriessen et al., 1979; Altherr et al., 1982; Buick and Holland, 1989; Keay, 1998; Keay et al., 2001; Keay and Lister, 2002) (Fig. 1). The *P–T–t* evolution of the Cyclades metamorphic belt is best documented on the island of Naxos (Buick and Holland, 1989).

The Attic–Cycladic Massif is a structurally complex pile of tectonic units separated by faults. It is possible to distinguish at least two major tectonic units (Andriessen et al., 1987; Ring et al., 1999b; Brichau, 2004). The island of Naxos in the Attic–Cycladic Massif displays the most complete structural cross section of the Cyclades (van der Maar and Jansen, 1983; Andriessen et al., 1987; Henjes-Kunst et al., 1988; Buick and Holland, 1989) where three tectonic units have been distinguished. The upper tectonic unit, structurally above the detachment, is composed of low-grade marble, schists and serpentinites that are unconformably overlain by dominantly detrital Cenozoic sediments. The middle and lower units are composed of high-grade metamorphic rocks located below the detachment. The middle unit is composed of a sequence of schists (at the bottom) and marbles (at the top) sequence containing mafic and ultramafic boudins (Jansen and Schuiling, 1976). The lower unit is made of felsic metasedimentary gneisses and marbles. The lower unit gneisses become migmatites and occupy the core of dome of the Metamorphic Core Complex of Naxos and Paros, mantled by metamorphic rocks of the middle unit.

On Naxos, a structural section through the middle and lower units is marked by a medium pressure/medium temperature metamorphic gradient ranging from greenschist facies to amphibolite facies reaching partial melting (10 kb, 750 °C) as demonstrated by migmatites exposed in the centre of the dome (Jansen and Schuiling, 1976; Buick and Holland, 1989; Avigad and Garfunkel, 1991; Duchêne et al., 2006). High pressure/low temperature metamorphism is only represented by relics of blueschist facies metamorphic minerals, such as Na-amphibole and jadeite (10 kb, 350 °C), in the south of the island.

Based on isotopic age studies, the gneisses from the basal units of the central Cyclades islands (Naxos, Sikinos, and Ios) have been described by several authors as pre-Alpine basement, consisting of metamorphosed Variscan granites (Andriessen et al., 1987; Pe-Piper et al., 1997; Reischmann, 1998). However, more recent work on the petrological and geochemical character of the core gneisses of Naxos migmatite dome (cf. Buick, 1988) and the provenance of their zircons (Keay, 1998) suggest the core may be comprised of Mesozoic metasediments or S-type granites, interlayered with rare thin slivers of Variscan orthogneiss, making the use of the term “Basement” of questionable value (Keay et al., 2001).

Miocene extension was accompanied by the emplacement of I- and S-type granites which intruded the detachments and/or affected syn-extensional shearing (Altherr et al., 1982, 1988; Henjes-Kunst et al., 1988; Lee and Lister, 1992; Pe-Piper et al., 1997; Bröcker and Franz, 1998; Pe-Piper, 2000; Altherr and Siebel, 2002; Pe-Piper et al., 2002; Iglseder et al., 2008; Brichau et al., 2008). Most of the Cycladic granites are assigned to the I-type category (Altherr et al., 1982, 1988; Altherr and Siebel, 2002), some of which constitute composite intrusions (Serifos and Ikaria). S-type granites (two-mica fine grained leucogranites) are mostly associated with zones of migmatisation in the high-grade metasedimentary gneisses of the lower unit, with typical examples that of the Metamorphic Core Complexes of Naxos and Paros.

3. Petrography of Cyclades granitoids and basement rocks

3.1. I-type granitoids

Most Cycladic plutons conform to the I-type category of Chappell and White (1974, 1992) (cf. Altherr et al., 1982, 1988; Altherr and Siebel, 2002) (Fig. 1). The petrography of these rocks has been established in previous studies (Altherr et al., 1982; Salemink, 1980; Altherr et al., 1988; Pe-Piper, 2000; Altherr and Siebel, 2002; Pe-Piper et al., 2002; Skarpelis et al., 2008). They contain, hornblende, titanite, allanite, biotite and therefore are metaluminous in composition (lacking primary muscovite, garnet and monazite). Details of the sample description for representative granite samples, are given in Table 1.

Commonly the I-type granites consist of compositionally different rock-types ranging from granite, granodiorite to minor tonalite in composition (Altherr et al., 1982, 1988). Mafic microgranular enclaves are found in all the I-type granitoids but in variable abundance in each pluton. Their compositions vary from diorite, to quartz diorite to tonalite (Altherr et al., 1982; Stouraiti, 1995; Pe-Piper et al., 2002) and are