*Geol. Mag.* **146** (*2*), *2009, pp. 252–265.* © *2009 Cambridge University Press*
doi:10.1017/S001675680800592X *Printed in the United Kingdom*

# Triassic rift-related meta-granites in the Internal Hellenides, Greece

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(*Received* 9 December 2007; *accepted* 26 August 2008; First published online 20 January 2009)

**Abstract –** The Serbo-Macedonian Massif is a basement complex in the Internal Hellenides of northern Greece, situated between the Vardar Zone to the west and the Rhodope Massif to the east. The Serbo-Macedonian Massif comprises several distinct basement units interpreted as terranes, the largest of which is the Gondwana-derived Vertiskos Terrane in the northwestern and central parts of the massif. A series of leucocratic meta-granites intrude the Silurian orthogneiss basement of the Vertiskos Terrane. No similar granites are found in any of the other units of the Internal Hellenides. The meta-granites have a pronounced crustal within-plate signature which is visible in lithology, major- and trace-element geochemistry and the Sr isotopic compositions. These intrusions were dated using the Pb–Pb single-zircon evaporation method, and yielded a Triassic age of between 240.7 ± 2.6 Ma and 221.7 ± 1.9 Ma on 17 samples, with a mean age of 228.3 ± 5.6 Ma. The zircons are purely magmatic, indicating that ages are primary crystallization ages. A Rb–Sr errorchron of the whole-rock samples of the Arnea granite yielded an age of 231.6 ± 9.9 Ma (MSWD = 82), and a mean $^{87}Sr/^{86}Sr$ initial ratio is 0.7142, indicating a crust-dominated source, and suggesting an A-type origin for the granites. The A-type meta-granites together with mafic intrusive bodies (amphibolites) in the Vertiskos Terrane may be evidence of Triassic rifting that led to the formation of a branch of Neotethys (Vardar–Meliata Ocean). Similar rock associations are also exposed in the Cyclades, and in massifs of the wider eastern Mediterranean realm related to the Gondwana-derived Hun Terrane, indicating that the Arnea-type granites are representatives of a major regional rifting event in Triassic times.

Keywords: Triassic rifting, Hellenides, A-type magmatism, Gondwana-derived terranes, geochronology, Serbo-Macedonian Massif.

## 1. Introduction

The Internal Hellenides form the crystalline hinterland of the Hellenic orogen and are mainly composed of basement gneisses and granitic intrusions. Previous geochronological investigations of granites in the Serbo-Macedonian Massif and the eastern Vardar Zone were carried out mainly using the K–Ar, Ar–Ar and Rb–Sr systems on micas (Papadopoulos & Kilias, 1985; De Wet *et al.* 1989; Lips, White & Wijbrans, 2000 and references therein). These studies resulted in a subdivision of the granites in the Serbo-Macedonian Massif and adjacent areas into two groups: a younger group of essentially Tertiary age (Vathi, Sithonia, Ierissos and Ouranopolis; see Fig. 1 for localities) and an older group of essentially Jurassic age (Fanos, Kerkini, Arnea and Monopigadon).

The age of the Arnea Granite determined by Ar–Ar is 136 ± 1 Ma and by Rb–Sr isochron 155 ± 11 Ma (composite isochron: De Wet *et al.* 1989). The Kerkini Complex has a similar K–Ar age of 130 ± 3 Ma (Bio) and 133 ± 3 Ma (Musc; Christofides *et al.* 1999). The age of the Fanos granite is 148 ± 2 Ma (Spray *et al.* 1984). For the Monopigadon Granite an age of 192.5 ± 3.8 Ma (Kostopoulos, Reischmann & Sklavounos, 2001) has been obtained.

The focus of the present study is the crystallization age of the 'Jurassic' granites that occur solely in the Vertiskos Terrane (Kerkini, Arnea). These and related smaller bodies which span the entire length of the Serbo-Macedonian Massif in northern Greece from the Bulgarian border to the Athos Peninsula will be referred to as the 'Arnea Granite Suite'. 'Suite' is the term used in the case of granites to differentiate between intrusions and basement, as there are several allochthonous basement units present in the Serbo-Macedonian Massif.

The geochemical and isotopic characteristics together with the primary intrusion ages will be used to constrain the plate tectonic context of the Serbo-Macedonian Massif and to determine the relationship between the smaller intrusions, the basement and the Arnea Granite Suite.

## 2. Geological setting of the Hellenides

The Hellenides form a part of the Alpine orogenic system and are composed of a series of subparallel arcuate zones characterized by specific lithotectonic

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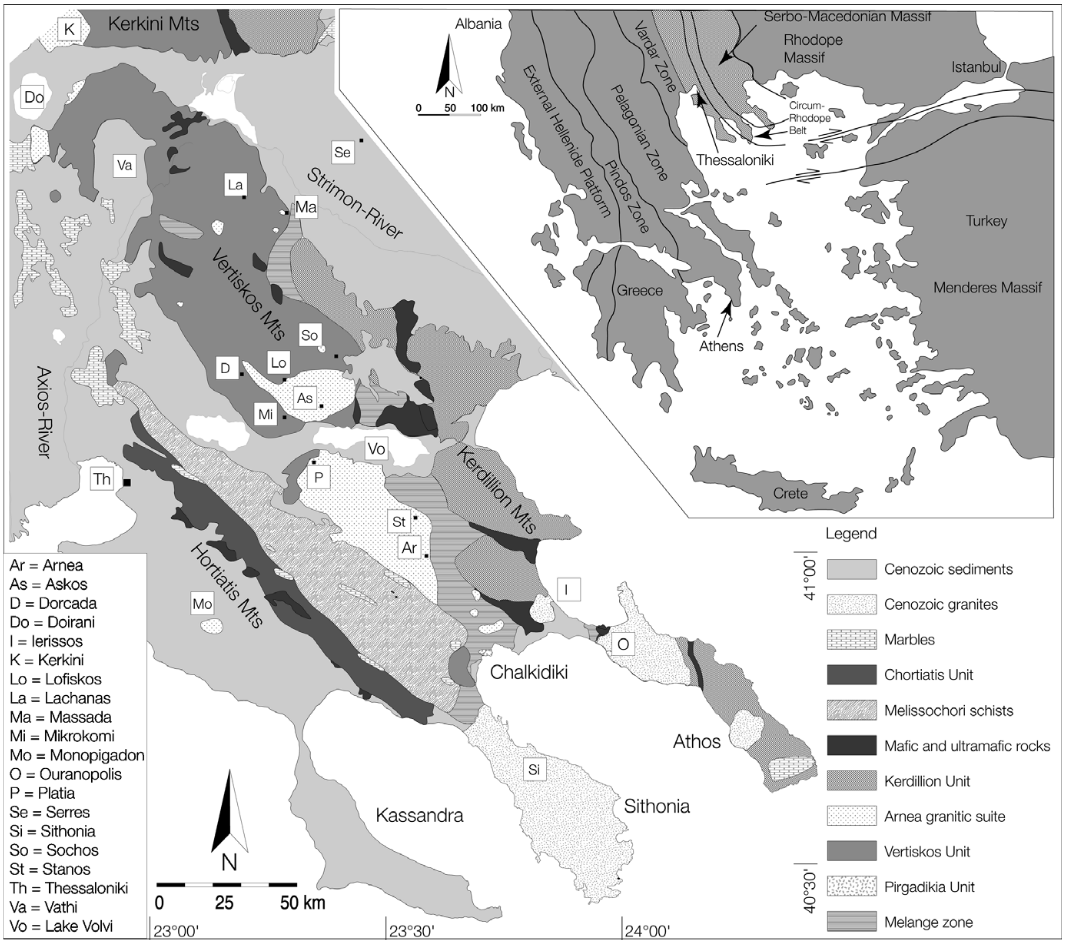

Figure 1. Geological map of the Greek part of the Serbo-Macedonian Massif, modified after Kockel, Mollat & Walther (1977). The Arnea Pluton is the large body east of Thessaloniki. The smaller intrusions of the Arnea Suite span the entire area from Kerkini Mountains in the north to Chalkidiki Peninsula in the south. The names of the various localities refer to outcrops mentioned in the text. The Pb–Pb ages of the granites are shown in Figure 6.

features (Jacobshagen, 1986; Papanikolaou, 1997); those to the west belong to the Hellenic foreland (External Hellenides) and comprise mainly supracrustal rocks, whereas those to the east belong to the Hellenic hinterland (Internal Hellenides) and are mainly composed of crystalline basement plus cover units (see Fig. 1, inset). A major ophiolite-bearing suture zone (Pindos Ocean) separates the External from the Internal Hellenides (Smith & Rassios, 2003; Liati, Gebauer & Fanning, 2004); similar suture zones (e.g. Vardar Ocean) also occur within the Internal Hellenides (e.g. Mercier, 1968; Mercier, Vergely & Bébien, 1975; Dixon & Dimitriadis, 1984; Himmerkus, Reischmann & Kostopoulos, 2006). The Hellenides are an accretionary orogen, which originated from the closure of the Tethyan oceans and the subsequent accretion of the terranes along the Eurasian margin (Stampfli & Borel, 2002).

The Internal Hellenides are composed of three crystalline massifs which, from the west, are: the Pelagonian Massif (Mountrakis, 1986; Anders, Reischmann & Kostopoulos, 2007), which merges to the south with the Attic–Cycladic Massif (Dürr *et al.* 1978), the Serbo-Macedonian Massif (Dimitrijevic, 1974, 1997) and the Rhodope Massif (Burg *et al.* 1996; P. Turpaud, unpub. Ph.D. thesis, Johannes Gutenberg-Univ. Mainz, 2006).

The Serbo-Macedonian Massif is defined as an elongated crystalline basement unit stretching from Serbia to central northern Greece and can be subdivided into two major units (Kockel, Mollat & Walther, 1977; Burg, Godfriaux & Ricou, 1995; Kilias, Falalakis & Mountrakis, 1999): the Kerdillion Unit in the east and the Vertiskos Unit in the northwest and central Serbo-Macedonian Massif. The Kerdillion Unit is formed of dark foliated biotite gneiss intruded by Tertiary granites and has a strong affinity to the adjacent Rhodope Massif in terms of lithology, structure and crystallization ages.

The relationship between the Serbo-Macedonian Massif and the Rhodope Massif has long been a matter of debate (Jacobshagen, 1986; Ricou *et al.* 1998) that was settled only recently by the identification of the western and central parts of the Serbo-Macedonian Massif as an independent terrane, named the Vertiskos Terrane (Himmerkus, Reischmann & Kostopoulos, 2006, 2009). The presence of the meta-granites of the Arnea Suite in only one of the terranes clarifies the relation between the massifs.

## 3. Geology of the Vertiskos Terrane

The exotic Vertiskos Terrane is characterized by two main rock types that can be distinguished by lithology, intrusion age and geochemical affinity.

The basement comprises Silurian coarse-grained augen gneisses of the Vertiskos Unit. The geochemical and isotopic signature of the gneisses indicates that they originated in a volcanic-arc environment with a significant contribution from pre-existing crustal material (Himmerkus, Reischmann & Kostopoulos, 2009). The variably deformed leucocratic meta-granites of the Arnea Granite Suite occur as intrusions and cross-cutting dykes in this basement.

Fieldwork, together with geochemical and geochronological studies, revealed that the granites of the Arnea Granite Suite occur exclusively in the Vertiskos Terrane and are distinctly different from all other intrusives, especially from the Tertiary biotite granites of the southeastern Serbo-Macedonian Massif (Frei, 1996; Bébien *et al.* 2001) (see Fig. 1) and the intrusives in the adjacent basement complex of the Rhodope Massif in both their lithology and deformation.

The Arnea Granite Suite is named after the Arnea Granite, the largest granitic intrusion of this age situated in the central Chalkidiki Peninsula (Fig. 1). This pluton has already been the focus of numerous geochemical and geochronological studies (De Wet *et al.* 1989; Jones *et al.* 1992; Kostopoulos, Reischmann & Sklavounos, 2001). Similar rocks crop out all across the Vertiskos Terrane and occur also as tectonic slices in the adjacent suture zones.

The Vertiskos Terrane is bordered by two crustal-scale shear zones comprising ophiolites: the Vardar Zone to the west (Mercier, Vergely & Bébien, 1975; Stampfli, Rosselet & Bagheri, 2004; Anders *et al.* 2005) and the Athos–Volvi Suture Zone (Thermes–Volvi–Gomati (TVG) Complex of Dixon & Dimitriadis, 1984) to the east (Himmerkus, Reischmann & Kostopoulos, 2006).

The eastern part of the Vardar Zone is occupied by the Circum-Rhodope Belt, a low-grade metasedimentary and meta-igneous succession, which was originally interpreted as the original Mesozoic sedimentary cover of the crystalline basement (Kauffmann, Kockel & Mollat, 1976). In this study, the succession of the Circum-Rhodope Belt is interpreted as a tectonic mélange that belongs to the Vardar Zone, bordering the Vertiskos Terrane to the west. All contacts between the Circum-Rhodope Belt and the Serbo-Macedonian Massif are of tectonic origin and the unit is characterized by strong non-coaxial deformation and contrasting rock types including ophiolitic material, metasediments, highly sheared gneisses from the basement and granitic material of the Arnea Granite Suite. The Circum-Rhodope Belt is also characterized by Eocene greenschist-facies metamorphism (Kockel, Mollat & Walther, 1977).

The Athos–Volvi Suture Zone represents the boundary between the Vertiskos Terrane and the Kerdillion Unit of the eastern Serbo-Macedonian Massif. This suture zone stretches from the Strimon valley to the NW end of the Athos peninsula and is characterized by large bodies of amphibolites and serpentinites highlighting the ophiolitic character. Within the mélange, splinters of granitic material from the Arnea Granite Suite also occur. The metamorphic grade of this unit is amphibolite facies in contrast to the Circum-Rhodope Belt. The two units also differ in the provenance of sediments and detrital zircons (G. Meinhold, unpub. Ph.D. thesis, Johannes Gutenberg-Univ. Mainz, 2007).

The presence of rocks similar to those of the Arnea Granite Suite was recently reported from the northern continuation of the Serbo-Macedonian Massif in southwestern Bulgaria (Peytcheva *et al.* 2005), just north of the Kerkini Intrusion (Christofides *et al.* 1999), northeast of Lake Doirani at the border with Bulgaria and in the Ograzhden Unit (Zidarov *et al.* 2004). This study concentrates on the Greek part of the Serbo-Macedonian Massif.

## 4. Petrography

The granites of the Arnea Granite Suite can be grouped into three types: large granite bodies, small intrusions in the Vertiskos Terrane (100 m to 1000 m in diameter) and dykes and apophyses intruding the basement.

The larger intrusions are medium- to coarse-grained and generally have a light-reddish appearance in the field as the result of the high proportion of K-feldspar. Their mineralogy is typical of that of continental granites, with alkali-feldspar and quartz being the dominant phases.

The main Arnea pluton and intrusions from the central Vertiskos Mountains and the Kerkini intrusion contain two micas. In the Arnea granite, chlorite is a common secondary mineral replacing biotite. Typical accessory minerals are zircon and apatite, and in the Arnea granite also fluorite, which is an indicator of within-plate character for granites (Kostopoulos, Reischmann & Sklavounos, 2001).

Smaller leucogranites like the Dorcada intrusion (SM 29) and the majority of the dykes, which are granitic or pegmatitic in composition, contain only white mica. Several granitic dykes and apophyses from the northern margin of the Arnea granite were injected into the basement gneisses of the southern Vertiskos Mountains and are represented by samples SM 115 to SM 118. They are rich in quartz and albitic feldspar and contain large plates of white mica which can reach several centimetres in size.

In the northern Vertiskos Mountains, a special type of granite occurs along the main Thessaloniki–Serres road (see Section 5). SM 42 is a representative sample from this locality; it is a fine-grained leucocratic granite with small enclaves of restitic melanosome composed of garnet and biotite, representing material from the metasedimentary source of the granite. These enclaves are several centimetres in size and are homogeneously dispersed in the rock. In some cases larger rafts of

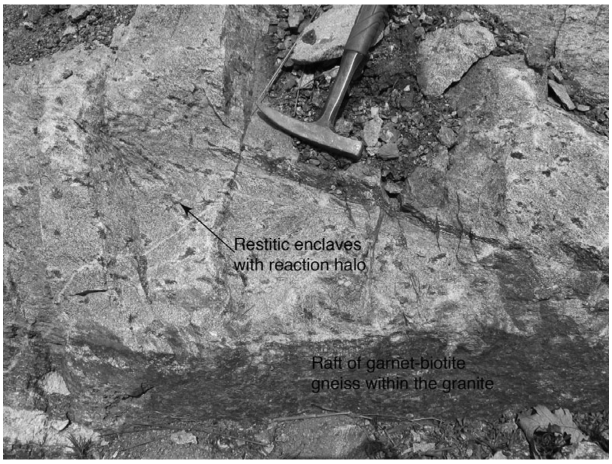

Figure 2. Outcrop photograph of sample SM 42 along the main road from Thessaloniki to Serres. The rock is a leucocratic homogeneous granite, which contains rafts and patches of restitic garnet–biotite gneiss. The smaller enclaves are usually surrounded by pale reaction zones between the restite and the granite. This rock indicates a derivation of the granites of the Arnea Suite from the basement rocks of the Vertiskos Unit. The intrusive relationships clearly indicate that the granite intruded into the Vertiskos basement. Length of the hammer head is 15 cm.

centimetre to metre size may occur (see Fig. 2). The surrounding matrix is composed of quartz, feldspar and white mica. Some of the enclaves have a whitish halo of about one centimetre in width, indicating a reaction between the enclaves and the granitic matrix (see Fig. 2). Bodies of similar rocks can be found further south intruding the migmatized basement. This group of granites is interpreted as being pure S-type granite resulting from partial melting of extending basement crust during rifting, as well as by the intrusion of granitic material of the Arnea Granite Suite. The presence of small volumes of Triassic rift-related meta-basalts with a strong within-plate signature scattered throughout the Vertiskos Terrane supports the above scenario (Dimitriadis & Asvesta, 1993; S. Dimitriadis, pers. comm. 2005).

## 5. Field relations and contacts

The large granite outcrops of the suite are the Kerkini intrusion (named after the Kerkini Mountains, NE of Lake Doirani, samples SM 21, SM 36 and SM 37) (Christofides *et al.* 1999) and the Arnea body itself (De Wet *et al.* 1989), which occupies the area both to the north and south of the Lake Volvi depression (see Fig. 1, samples AR 1, AR 2, SH 10, SH 11, SM 113). In the case of granitic intrusions not genetically associated with migmatization, a thermal imprint is to be expected in the immediate vicinity of their contact with the basement. However, the only true intrusive contact of undeformed granite into metasediments showing a thermal imprint can be seen southeast of the village of Lofiskos. There, large porphyroblasts of andalusite grow randomly on the foliation surfaces. The size of the porphyroblasts depends on the distance from the contact and ranges from a few millimetres to about 3 cm.

In the southern Vertiskos Mountains, the contact between coarse-grained orthogneisses and the Arnea Granite crops out near Mikrokomi village, north of Lake Volvi (see Fig. 1 for locations). South of the lake, north of the village of Platia, this contact is tectonized and the exposure of leucocratic granite intruding into coarse-grained augen gneisses can be observed repeatedly. Further south, homogeneous reddish granite crops out over a large area. The spacing and orientation of the foliation in the meta-granites are highly variable.

Outcrops of smaller intrusions occur in the central Vertiskos Mountains along the main road to the town of Serres (SM 29, SM 42 and SM 102), south of Askos town (SM 52) and NW of Sochos town (SM 87, SM 88, and SM 89) (for sample localities see Fig. 7; and Table 1, in Appendix available as supplementary material online at http://www.cambridge.org/journals/geo).

On the main Thessaloniki–Serres road, northwest of the town of Lachanas, intrusive relations are exposed in the road-cut. Here, migmatized garnet–biotite gneisses are intruded by granites which were most probably extracted from this migmatized basement. The granites contain enclaves of garnet–biotite country-rock which occur as layers and, in places, as patches within the granites.

Apophyses of granitic material occur in the basement in the vicinity of the Arnea Granite, but they are separated from the granite by later deformation and generally show no thermal contact. The majority of the leucocratic dykes cannot be dated because zircons are highly metamict leading to a high $^{204}Pb/^{206}Pb$ ratio, but the structural style together with the mineralogy and the Sr-isotopic composition suggest that the dykes and the pegmatites are closely related to the Arnea Granite Suite.

South of Thessaloniki, the Monopigadon granite occurs within the Circum-Rhodope Belt (Kockel, Mollat & Walther, 1977 and references therein). The Monopigadon granite itself is a dark biotite-bearing I-type granodiorite at the centre of the village of Monopigadon. Sample CR 20 is a sample from leucocratic biotite-free granites which crop out west of the village. The latter resemble the Arnea granite in terms of texture and leucocratic appearance and will be regarded as part of the Arnea Granite Suite in this study. The field relations of the two granite types are not clear due to faulted contacts; both units, however, are not genetically related and are in tectonic contact with metasediments of the Svoula Schist Formation.

The southwestern contact of the Arnea pluton with the metasediments of the Svoula Schist Formation of the Circum-Rhodope Belt is strongly tectonized (Kockel, Mollat & Walther, 1977 and references therein; G. Meinhold, unpub. Ph.D. thesis, Johannes Gutenberg-Univ. Mainz, 2007; see also Fig. 1). The foliation in the partly mylonitic country rocks is parallel to the contact with the granite, while near the contact, the granite itself is deformed only to a minor extent. This suggests a shear zone that affected the weaker sediments but not the more competent granite. Leucocratic dykes like those in the basement are not present in the metasediments of the Svoula Schist Formation adjacent to the Arnea granite, which also indicates a tectonic contact between the granite (Serbo-Macedonian Massif) and the Circum-Rhodope Belt (Vardar Zone).

At the eastern margin of the Arnea pluton, northeast of Stanos village, the foliation in the granite becomes progressively stronger towards the contact with the schists of the Athos–Volvi Suture Zone (Himmerkus, Reischmann & Kostopoulos, 2006). The microfabrics here indicate non-coaxial deformation. The shear deformation becomes more intense at the contact, though the contact is not visible in the field due to strong alteration and vegetation cover. There are also no granitic dykes intruding the country rocks in the Athos–Volvi Suture Zone but only tectonic rafts of meta-granite present in the mélange zone.

## 6. Geochemistry

In order to identify rock types, possible magma sources and probable tectonomagmatic settings of the Arnea Granite Suite rocks and to distinguish them from other granites that occur in the region, we performed major- and trace-element analyses. The results are listed in Table 2 (in Appendix available as supplementary material online at http://www.cambridge.org/journals/geo). A representative amount of fresh unaltered material from each sample was milled in an agate or tungsten carbide mill. The sample size was between 5 kg for the dykes and fine-grained meta-granites and 10 to 15 kg for coarser-grained rocks. Fused discs and powder pellets were produced from the whole-rock powder for major- and trace-element analysis by wavelength dispersive XRF.

The Arnea Granite Suite rocks are very leucocratic granitoids which are all mildly peraluminous. The majority of them have a very high $SiO_2$ content (73 to 78 wt %). In the TAS diagram (Le Maitre, 1989) and the R1-R2 projection after De La Roche *et al.* (1980) (both not shown), they plot in the fields of granite/alkali-granite and anorogenic granite, respectively. Ca and Mg are only present in minor concentrations. K is generally the dominating alkali element; only in sample SM 89, which is a metalliferous leucogranite impregnated with hematite, the microcline is altered to albite and Na is therefore strongly enriched. In Figures 3 and 4 the granites of the Arnea Granite Suite are plotted against the basement gneisses of the Vertiskos Unit to demonstrate the geochemical differences between the two rock types.

The rocks of the Arnea Granite Suite are enriched in large-ion lithophile (LIL) elements, suggesting a crustal source. The incompatible elements show high concentrations. Rb is strongly enriched in comparison to Sr (see Fig. 3), due to the presence of K-rich minerals such as feldspar and mica. In the ternary Ba–Rb–Sr diagram of Bouseley & Sokkary (1975) (Fig. 3), the samples of the Arnea Granite Suite are plotted against samples of the surrounding Vertiskos basement (geochemical data for the Vertiskos basement gneisses: see Himmerkus, Reischmann & Kostopoulos, 2009). In this diagram, the rocks of the Arnea Suite mainly plot in the fields of granites and differentiated granites spanning the base of the ternary between Ba and Rb, whereas the basement gneisses fall in the fields of granites, granodiorites and diorites, spanning the right side of the ternary between Ba and Sr.

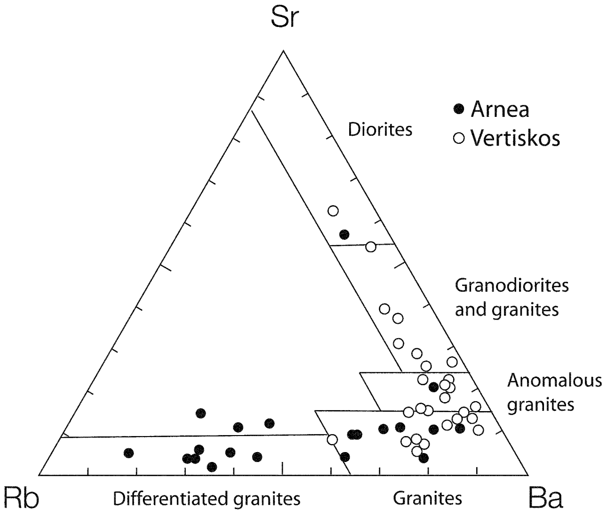

Figure 3. Ba–Rb–Sr ternary plot for the Arnea Granite Suite (after Bouseley & Sokkary, 1975). The granitic orthogneisses of the Vertiskos basement into which the Arnea Granite Suite intrudes are shown for comparison. The rocks of the Arnea Suite are mainly enriched in Rb, whereas the basement gneisses are mainly enriched in Sr (geochemical data for Vertiskos basement gneisses: see Himmerkus, Reischmann & Kostopoulos, 2009).

The high-field strength elements (HFSE) show relatively low concentrations except for Zr. The content of $TiO_2$ is also low (0.08–0.5 wt % in the unaltered rocks), and this can be ascribed to the retention of this element in Ti-bearing phases during melting of the source rocks of the granites. Phosphorous levels are also low, ranging between 0.03 and 0.2 wt % $P_2O_5$, possibly suggesting residual apatite.

Th and U concentrations are high, and this is reflected in the zircon compositions which are enriched in radiogenic Pb (see Section 7). By contrast, all compatible trace elements, like Sc and V, are strongly depleted. Sample SM 42 is a granite with restitic garnet–biotite enclaves (see Fig. 2). This explains the unusually high concentration of Cr in this sample.

In the classical discriminant diagrams of Pearce, Harris & Tindle (1984) using Nb, Y and Rb, some of the Arnea Granite Suite rocks plot in the field of within-plate granites, but the majority straddle the boundaries between within-plate and volcanic-arc granites (see Fig. 4). The gneisses of the Vertiskos Unit, which are also plotted for comparison, have lower concentrations of Nb, Y and Rb. This distribution

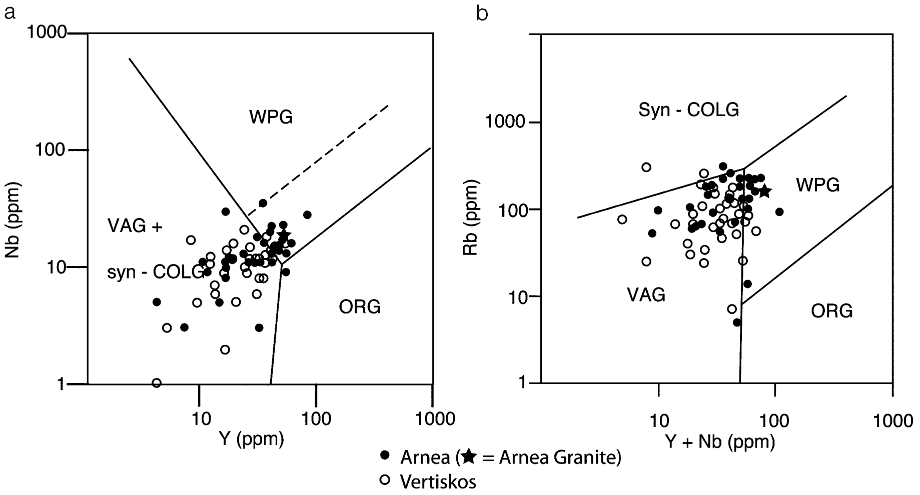

Figure 4. Discrimination diagram for the tectonic setting of the Arnea Suite and the Vertiskos Unit granitic rocks (after Pearce, Harris & Tindle, 1984). The majority of the basement gneisses plot in the field of volcanic-arc granites. The Arnea Granite Suite plots clearly in the field of within-plate granites that characterizes rift-related granites. The Arnea Pluton itself is represented by the star. The tailing of the rocks of the Arnea Granite Suite towards the field of volcanic-arc granites may be related to assimilation of arc material in the source of the granites. VAG – volcanic arc granite; Syn-COLG – syn-collisional granite; ORG – orogenic granite; WPG – within-plate granite.

indicates a derivation, at least partly, from a pre-existing magmatic arc, which was partially molten and gave rise to granitic magma. The granites seem to have integrated the signals transmitted from both the parent rock(s) and the rifting event.

The plate-tectonic setting of the Arnea Granite Suite rocks is unique throughout the Internal Hellenides. The granitic rocks of the Pelagonian Zone, the Rhodope Massif and the Cyclades are exclusively I-type granites, some being hybrid to S-type (B. Anders, unpub. Ph.D. thesis, Johannes Gutenberg-Univ. Mainz, 2005; Anders, Reischmann & Kostopoulos, 2007; P. Turpaud, unpub. Ph.D. thesis, Johannes Gutenberg-Univ. Mainz, 2006; M. Engel, unpub. Ph.D. thesis, Johannes Gutenberg-Univ. Mainz, 2006). The lithology, mineralogy, and major- and trace-element characteristics of the Arnea Granite Suite show that these granites had a high proportion of crustal material in their source. With regard to the Kerkini Intrusion, in the northwestern part of the Vertiskos Terrane (Samples SM 21, SM 36, and SM 37 of this study; see Fig. 7), Christofides *et al.* (1999) also proposed an A-type setting, in agreement with the data presented here.

The dykes which occur adjacent to the Arnea pluton in the southwestern Vertiskos Mountains (SM 115–SM 118) show a different distribution of major and trace elements. They are also characterized by a very high $SiO_2$ content. However, in these dykes, sodium predominates over potassium, indicating albite-rich feldspars. The rocks are generally depleted in trace elements, but Sr predominates over Rb, and elements like Ba and Pb are strongly enriched.

## 7. Geochronology

### 7.a. Methodology

One of the main objectives of this study was the determination of the age of the Arnea Granite Suite. We applied the Pb/Pb single-zircon evaporation method established by Kober (1986, 1987). Several kilograms of each sample were crushed and sieved to a grain-size smaller than 0.5 mm. The heavy-mineral fraction was separated using a Wilfley table, a Franz isodynamic magnetic separator and heavy liquids. The zircons were hand-picked and analysed on a MAT 261 Finnigan mass spectrometer at the Max-Planck-Institut für Chemie, Abteilung Geochemie, Mainz.

In the evaporation method, single hand-picked zircons are mounted on a pair of rhenium filaments in the mass spectrometer. The zircon grains are evaporated at 1500 to 1600 °C and deposited on the ionization filament from which the $^{207}Pb/^{206}Pb$ ratio is measured in a second step at temperatures of around 1100 to 1200 °C. The measured $^{207}Pb/^{206}Pb$ ratio is corrected for common lead, assuming the lead isotopic evolution model of Stacey & Kramers (1975; also see Fig. 8).

In order to glean information on the internal structure of the zircons, a representative zircon fraction from each sample was investigated under a scanning electron microscope using back-scattered electron and cathodoluminescence images. The cathodoluminescence images were made on a Hitachi scanning electron microscope at the Max-Planck-Institut für Chemie, Mainz. The zircons found in the granites of the Arnea Suite are generally small, yellow to brownish in colour and have a simple habit (see Fig. 5). Many of them display only the (100) and (110)/(101) faces. They are not translucent and have a high amount of radiogenic lead resulting from their high uranium content (see Section 6). The zircons that are not metamict display an internal oscillatory zoning interpreted as a magmatic structure. This observation, together with the shape of the zircons, leads to the conclusion that the measured ages are primary magmatic ages and that no later event disturbed the U–Pb system of the minerals.

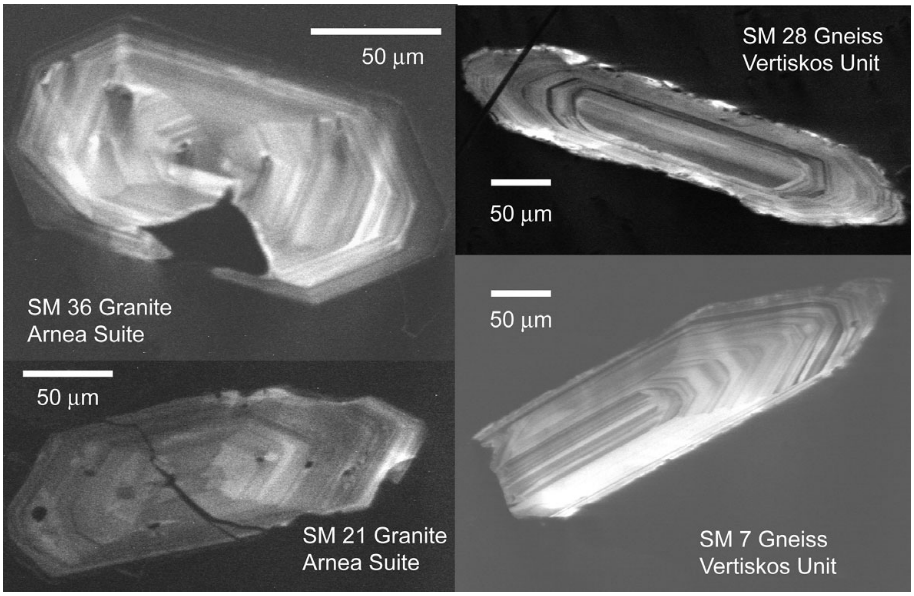

Figure 5. Cathodoluminescence images of typical zircons from granites of the Arnea Suite and from granitic gneisses of the Vertiskos basement Unit, into which the Arnea Granite Suite has intruded. The zircons of the granites of the Arnea Granite Suite are small and have a simple habit with few crystal faces. Many of them show only the (100) and (110)/(101) faces. The internal structure of the zircons from both units indicates a purely magmatic origin.

In contrast to the zircons from the basement of the Vertiskos Terrane, which are large, elongated, colourless and translucent showing large pyramids, the zircons of the granites of the Arnea Granite Suite are small, have a simple habit with few crystal faces (see also Fig. 5). Their internal structure also indicates a purely magmatic origin.

### 7.b. Results

The granites of the Arnea Suite intruded between 240.7 ± 2.6 Ma (SM 84, Chortiatis Mountain) and 221.7 ± 1.9 Ma (SM 29, central Vertiskos Mountains) and are therefore Triassic (M. Anisian–M. Carnian) in age (see Fig. 7 for sample locations). The results are listed in Table 3 (in Appendix available as supplementary material online at http://www.cambridge.org/journals/geo) and Figures 6 and 7. Figure 6 displays the weighted-average diagrams of the individual samples, whereas Figure 7 is a simplified geological map of the Greek Serbo-Macedonian Massif and shows the spatial distribution of the analysed samples. The errors reported are $2\sigma$ errors calculated with Isoplot 2 (Ludwig, 2003; see Fig. 6). Because the Pb–Pb method on whole zircon crystals is affected by artefacts like lead-loss and inheritance, the dataset was verified by statistical methods (outlier tests) to prevent bias of the age determination by erroneous analyses.

The samples appear to have intruded within a rather narrow time-window. Except for sample SM 102 (251.2 ± 4.7 Ma, not used), which is significantly older than the other samples, and SM 29, which is slightly younger, the errors of the ages among samples overlap, therefore a single mean age may be assumed for the entire suite, which is 228.3 ± 5.6 Ma ($1\sigma$). A plot of the uncorrected $^{207}Pb/^{206}Pb$ ratio versus the measured $^{204}Pb/^{206}Pb$ ratio used for common lead correction yields a regression with a mean age of 227.4 ± 7.1 Ma (see Fig. 8) which is, within error, identical to the mean age of the individual zircons from the whole suite. This indicates that the common lead correction of the individual measurements, used for the weighted-average ages, is correct.

It is important to emphasize here that we have identified numerous Silurian-inherited zircon grains in the granites analysed (see zircon grains labelled 'Basement' in Table 3, in Appendix available as supplementary material online at http://www.cambridge.org/journals/geo). This indicates that the Arnea Granite Suite bears a genetic relation to the Silurian basement of the Vertiskos Terrane into which it was emplaced. Two explanations are possible: either that the granites partly assimilated Vertiskos basement upon intrusion, thus picking Silurian zircons en route, or that the Vertiskos basement itself served as the main source for the granites and many zircons preserved their Silurian inheritance from the parent rocks. Several samples from the mélange zone bordering the Vertiskos Terrane were not used, as the age distribution was dominated by inherited zircon grains or grains that experienced lead loss due to the tectonic overprint (samples SM 26, SM 68, SM 102 and SH 19; they are marked as 'not used' in Table 3 (in Appendix available as supplementary material online at http://www.cambridge.org/journals/geo). The Triassic age of the Arnea Granite Suite determined in this study is in marked contrast with the Late Jurassic

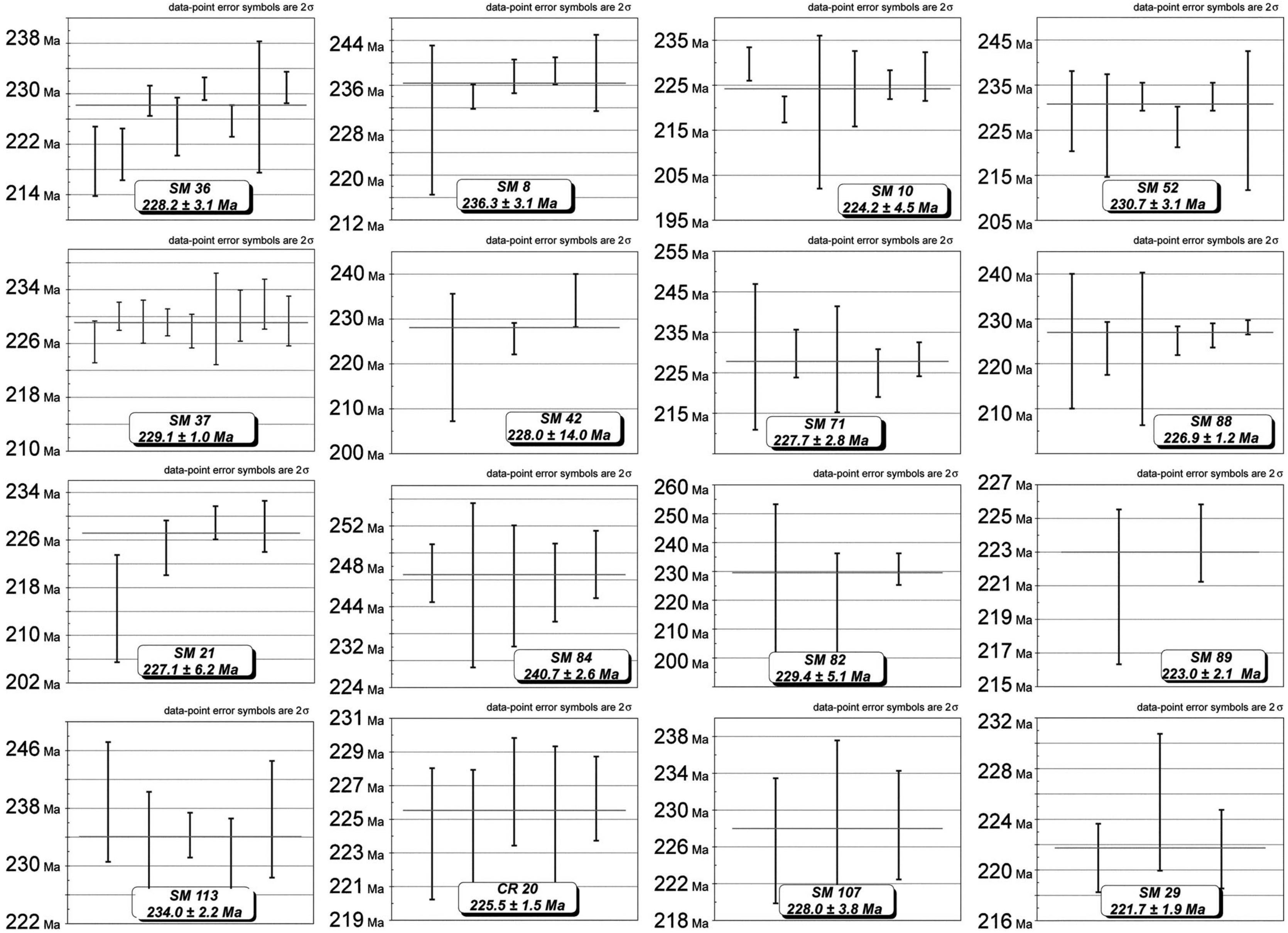

Figure 6. Weighted average plots of the measured Pb–Pb ages of individual samples. The sample localities are shown in Figure 7. Samples SM 36 and SM 37 are from the Kerkini Complex (Christofides *et al.* 1999), including the Miriofiton granite (SM 21).

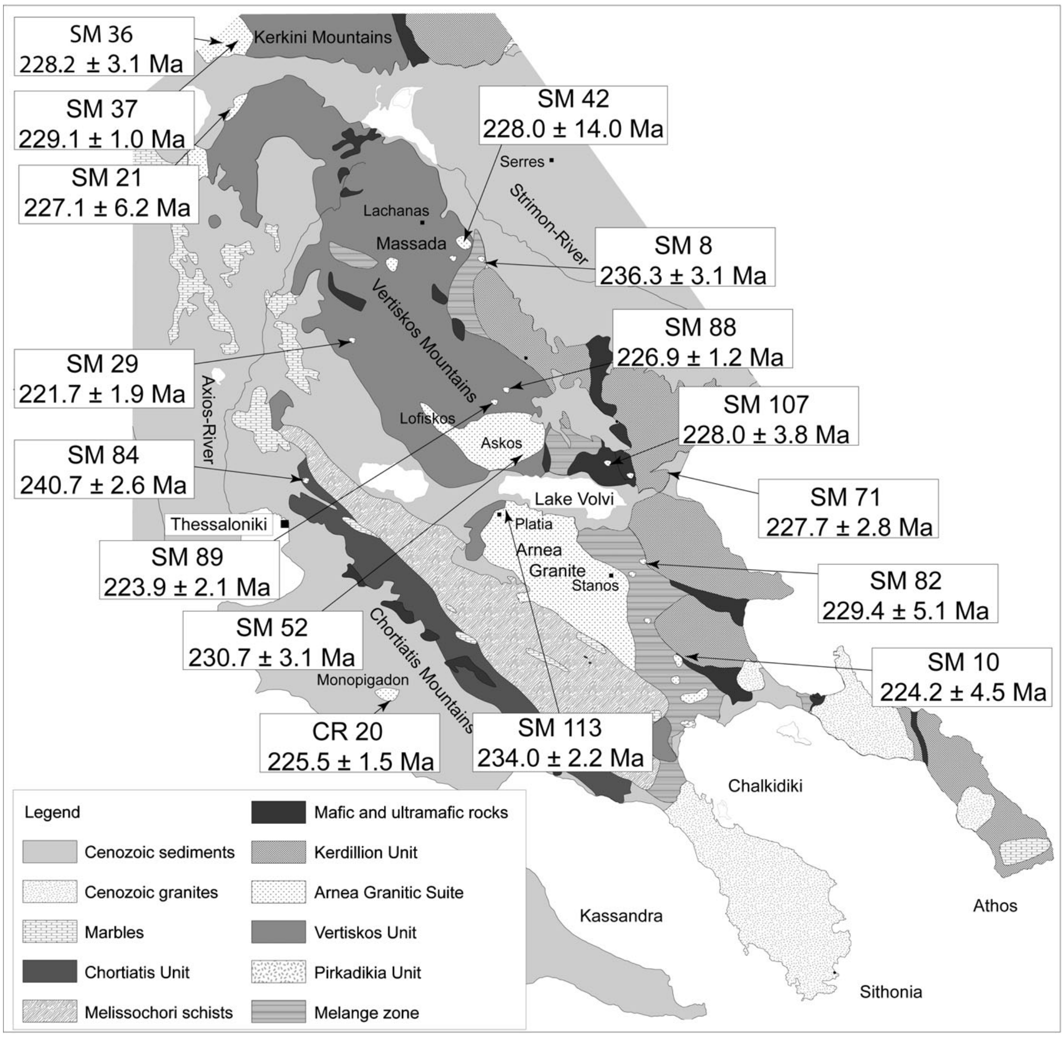

Figure 7. Simplified geological map showing the spatial distribution of the dated samples of the Arnea Granite Suite. The results for individual samples are listed in Table 4 (in Appendix available as supplementary material online at http:// www. cambridge.org/ journals/geo). Samples with high analytical error due to inherited components or with too limited results do not appear in Figures 6 and 7.

and Early Cretaceous ages obtained by Rb–Sr and Ar–Ar radiometric determinations on micas and whole rocks (De Wet *et al.* 1989).

## 8. Strontium isotope systematics

The geochemical indicators presented earlier show that the leucogranites of the Arnea Suite are S- and/or A-type granites that originated in a within-plate tectonic setting. In order to confirm this finding, we performed further investigations using the Rb–Sr isotopic system. The isotope measurements were made at the Max-Planck-Institut für Chemie, Mainz. For the isotopic analyses, a representative amount of the whole-rock powder (100 mg) was dissolved in HF following the procedure described by White & Patchett (1984). The elements Rb and Sr were separated using a cation-exchange resin and the isotope ratios were measured on a MAT 261 Finnigan mass spectrometer. For quality assurance the Sr-standard NBS 987 was analysed prior to each analysis.

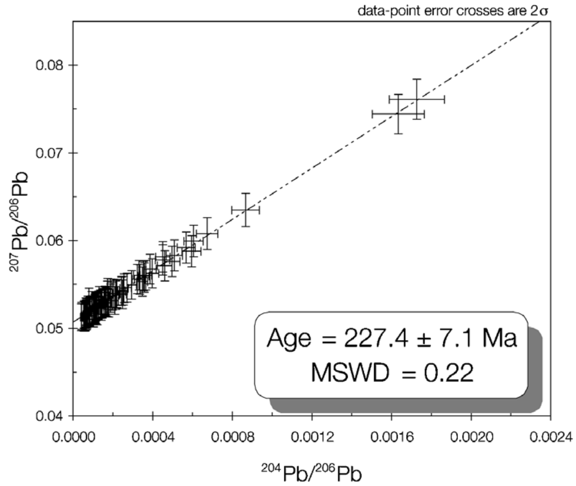

Figure 8. Uncorrected $^{207}Pb/^{206}Pb$ ratio versus measured $^{204}Pb/^{206}Pb$ ratio for the Arnea Granite Suite to constrain the validity of the common lead correction following the two-stage model of Stacey & Kramers (1975). The calculated age shown is in excellent agreement with individual ages and the Rb–Sr errorchron age (see Fig. 9).

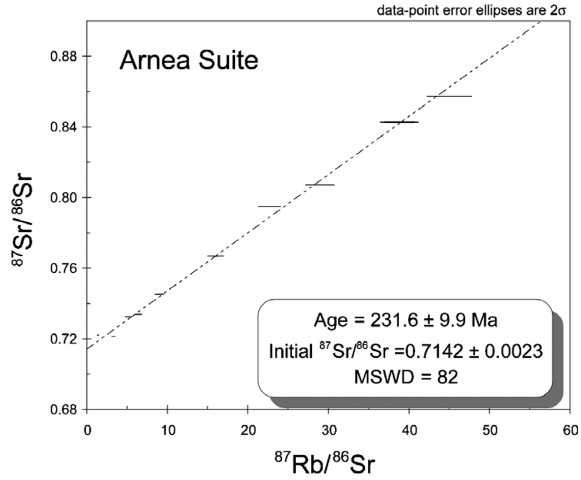

Figure 9. Rb–Sr errorchron diagram for the Arnea Granite Suite. The common $^{87}$Sr/$^{86}$Sr initial ratio supports the individual ratios and shows a close relationship between the scattered intrusions as regards provenance and time of emplacement. The rather high common $^{87}$Sr/$^{86}$Sr initial ratio is a tracer of pre-existing crustal material in the source and indicates an S- or A-type granite affinity (Chappell & White, 1992). The slope of the errorchron constrains the Triassic zircon age.

The Rb–Sr system can be used as a geochronological tool, but the $^{87}$Sr/$^{86}$Sr initial ratio is also an indicator of crustal influence in a magmatic system. The $^{87}$Sr/$^{86}$Sr initial ratio is therefore an indicator of the Rb concentration in the magma source and of possible crustal influence. The results of the Rb–Sr isotopic analyses are listed in Table 4 (in Appendix available as supplementary material online at http://www.cambridge.org/journals/geo). The initial ratios were calculated using XRF values for the element concentrations, the relevant decay equation and the zircon ages (see Section 7). In a plot of $^{87}$Sr/$^{86}$Sr against $^{87}$Rb/$^{86}$Sr, the samples define an errorchron of 231.6 ± 9.9 Ma (MSWD = 82), which is identical to the average zircon age (see Fig. 9). This errorchron is in contrast to the one published by De Wet *et al.* (1989) for the Arnea granite not showing a bimodal distribution. However, the samples do not represent one single magmatic event, but a suite of granites which originated in a discrete time and a specific tectonic environment.

The common $^{87}$Sr/$^{86}$Sr initial ratio is 0.7142 and supports the calculated mean $^{87}$Sr/$^{86}$Sr initial ratio of 0.714224 ± 0.002700 (Samples SM 68, AR 2 and CR 20 were excluded because they have a significantly higher $^{87}$Sr/$^{86}$Sr initial ratio). The fact that the samples, which span the entire Greek part of the Vertiskos Terrane, fit on a single errorchron indicates that the meta-granites are closely related and that the accretion may have affected single crystal systems but not the whole-rock isotopic composition.

Generally, the rocks show elevated $^{87}$Sr/$^{86}$Sr initial ratios, which may be due to the fact that the granites originated as partial melts of the Silurian basement during a rifting phase. This reasoning is supported by field observations in the central Vertiskos Mountains (see Section 5). Samples SM 42 and SM 102 (containing patchy inclusions of garnet–biotite restite; see Fig. 2) have $^{87}$Sr/$^{86}$Sr initial ratios of 0.716. This $^{87}$Sr/$^{86}$Sr initial ratio is slightly higher than the mean of the entire suite, which may be explained by the high content of crustal material in these samples.

The basement rocks of the Vertiskos Terrane have an $^{87}$Sr/$^{86}$Sr initial ratio of 0.70956 ± 0.00079 at a mean zircon age of 432.2 ± 3.2 Ma (Himmerkus, Reischmann & Kostopoulos, 2009). This $^{87}$Sr/$^{86}$Sr initial ratio is higher than that of typical I-type granites, but lower than the value of typical S-type granites, indicating a hybrid character. The granites of the Arnea Granite Suite are isotopically completely different from the basement rocks. At an assumed age of 433 Ma, which corresponds to the emplacement age of the Vertiskos basement granitoids, the $^{87}$Sr/$^{86}$Sr initial ratio of the Arnea Granite Suite rocks would have been in the range of 0.63, a value which is well below that for the BABI (Basaltic Achondrite Best Initial = 0.69897 ± 3: Papanastassiou & Wasserburg, 1969), and therefore unreasonable. On the other hand, at 225 Ma, the $^{87}$Sr/$^{86}$Sr initial ratio of the basement gneisses of the Vertiskos Terrane would still be at 0.712875 ± 0.000332, which is below the value for the Arnea Granite Suite. The mean Rb content of the basements rocks (106 ppm) is far lower than that of the Arnea Granite Suite (168 ppm). Therefore the lower $^{87}$Sr/$^{86}$Sr initial ratio of the basement gneisses will change less with time than that of the meta-granites.

To summarize, the Sr isotopic signature highlights the crustal influence in the source of the Arnea Granite Suite and also pinpoints the inherent difference between the granites and the basement gneisses of the Vertiskos Terrane into which they intruded.

## 9. Discussion and plate tectonic implications

The results presented here characterize a suite of granites which form a distinct group within the Internal Hellenides in terms of intrusion age, lithology and geochemical affinity. The geochemical and isotopic investigations of the granites of the Arnea Suite add valuable information to the puzzle of the pre-Alpine history of the area, indicating a major phase of magma underplating and rifting in the Serbo-Macedonian Massif of northern Greece during Triassic times.

The Triassic age established in this study for the Arnea Granite Suite is in hot dispute with the Late Jurassic age (Kockel, Mollat & Walther, 1977) that had been previously adopted for this group of granites based primarily on mica ages (Dixon & Dimitriadis, 1984; Papadopoulos & Kilias, 1985; De Wet *et al.* 1989; Ricou *et al.* 1998; Lips, White & Wijbrans, 2000). The Triassic age of the Arnea Granite Suite is none the less in harmony with the sedimentary record of the area suggesting Triassic rifting of a passive continental margin (Stais & Ferriére, 1991; A. Stais, unpub. Ph.D.

thesis, Université des Sciences et Technologies de Lille, 1993), as well as with the coeval extrusion of within-plate basalts in the same area (Pe-Piper, 1998; Pe-Piper & Piper, 2002; Liati & Fanning, 2005).

As micas have a relatively low closure temperature of 300 °C to 450 °C, these ages are unlikely to represent primary crystallization ages for the granites and are instead interpreted as cooling ages associated with the Cretaceous exhumation of the Vertiskos Unit after accretion to the Hellenic orogen. The presented zircon ages are much less prone to resetting by thermal effects (Lee, Williams & Ellis, 1997; Cherniak & Watson, 2000) and represent the crystallization age of the meta-granitoids.

The Internal Hellenides are an amalgamation of various terranes bordered by several ophiolitic mélange zones (Himmerkus, Reischmann & Kostopoulos, 2006; Anders *et al.* 2006; Himmerkus *et al.* 2007), therefore the accretionary history of this part of the Hellenic orogen can only be unveiled by integrating the data from all rock units involved.

The granites of the Arnea Suite are only present in the Vertiskos Terrane in the northwestern and central Serbo-Macedonian Massif. Tectonic slices of this terrane also occur in the Circum-Rhodope Belt of the eastern Vardar Zone (leucogranites west of the Monopigadon granite, sample CR 20) and in the Chortiatis Mountains just east of Thessaloniki (sample SM 84). Tectonic inliers are also present in the eastern mélange, the Athos–Volvi Suture (Himmerkus, Reischmann & Kostopoulos, 2006) that separates the Vertiskos Terrane from the Kerdillion Unit (samples: SM 10, Megali Panagia; SM 71, Arethousa; SM 107, Volvi and SM 82, Varvara; see Fig. 7 for localities).

Triassic granites are also known from the eastern Vardar Zone (Anders *et al.* 2005), the eastern Pelagonian Zone (T. Most, unpub. Ph.D. thesis, Univ. Tübingen, 2003; Anders, Reischmann & Kostopoulos, 2007) and the Cyclades (Reischmann, 1998; Tomaschek *et al.* 2001; Keay, Lister & Buick, 2001; Bröcker & Pidgeon, 2007). These Triassic granites intrude Permo-Carboniferous basement common to both the Pelagonian Zone and the Attic–Cycladic Massif (Dürr *et al.* 1978; Engel & Reischmann, 1998) and are accompanied by mafic rocks of the same age (e.g. Pe-Piper, 1998).

Anorogenic granites like those of the Arnea Suite are not present in the Pelagonian Zone, the Kerdillion Unit (*s.s.*) or the terranes of the Rhodope Massif (e.g. P. Turpaud, unpub. Ph.D. thesis, Johannes Gutenberg-Univ. Mainz, 2006). However, in these units, Late Jurassic granites exist that are associated with the accretionary event, but which are not to be found in the Vertiskos Terrane. Such a distribution places key constraints on the accretionary history of the internal part of the Hellenic orogen.

We propose that the Vertiskos Terrane was part of the so-called Hun superterrane (Stampfli & Borel, 2002; von Raumer, Stampfli & Bussy, 2003), which originated in the northern active continental margin of Gondwana during the early to middle Palaeozoic (Himmerkus, Reischmann & Kostopoulos, 2006, 2009) in response to southward subduction of Prototethys. Slices of this superterrane are present all along the Variscan and Alpine orogenic belt in Europe and continue along the Palaeotethyan suture to southern Russia and China (Neubauer, 2002).

The Vertiskos Terrane was most probably accreted to the southern European margin before Triassic times, as indicated by contemporaneous extrusive (rhyolitic) rocks of the Examili Formation (Kockel, Mollat & Walther, 1977), which forms that part of the Circum-Rhodope Belt closest to the Vertiskos Terrane. This volcano-sedimentary unit is of Permo-Triassic age and contains detrital zircons of mainly Ordovician–Silurian age but also of Permo-Carboniferous and Neoproterozoic ages (G. Meinhold, unpub. Ph.D. thesis, Johannes Gutenberg-Univ. Mainz, 2007).

The Triassic rifting affected the remnants of the Hun Terrane that were assembled during the Variscan Orogeny and led to the formation of one of the numerous oceanic basins of the Tethyan oceanic system (Vardar/Meliata Ocean). Triassic sedimentary rocks in the Vardar Zone and the surrounding units of the Internal Hellenides indicate a submergence following this rifting event giving rise to the Meliata Ocean (Bonev & Stampfli, 2003, 2007).

An important upper time limit to the accretion of different units in the Internal Hellenides is set by the intrusion of I-type granites in the southeastern Serbo-Macedonian Massif during Early Tertiary times. These granites are virtually undeformed, thus indicating that they intruded after the last tectono-metamorphic event that affected the area. The Greek part of the Internal Hellenides does not display signs of major tectonic activity in the Early Cretaceous (Lips, White & Wijbrans, 2000). All ages known either belong to the upper Jurassic Cimmerian event or to the Late Cretaceous to Miocene extensional phase, which was a time of major extension and exhumation in the Internal Hellenides (Sokoutis *et al.* 1993; Gautier *et al.* 1999; Dinter & Royden, 1993; Dinter, 1998; Bonev, Marchev & Singer, 2006).

At the present time, the zones that bear witness to the Triassic rifting event are all in close proximity to the proposed Palaeotethyan suture (Şengör, Yılmaz & Sungurlu, 1984; Stampfli, Rosselet & Bagheri, 2004), which was active during the Eoalpine or Cimmerian Orogeny in late Jurassic times. The latter is also the most prominent tectonic phase in the Internal Hellenides (Himmerkus, Reischmann & Kostopoulos, 2006) and can best account for terrane accretion as attested to by granite emplacement, deformation, metamorphism and cooling ages of micas. The presence of the Triassic rift-related granites of the Arnea Granite Suite in the Vertiskos Terrane underscores the allochthonous character of this unit and gives valuable information on the accretionary history of the Internal Hellenides and the entire Alpine belt in the eastern Mediterranean.

## 10. Conclusions

The leucocratic granites of the Arnea Suite intruded into the Silurian basement of the Vertiskos Terrane during Middle Triassic times between 240.7 ± 2.6 Ma and 221.7 ± 1.9 Ma (mean age: 228.3 ± 5.6 Ma). The lithology, trace-element concentrations and the Sr isotopic signature indicate highly evolved granites of A-type affinity (Christofides *et al.* 1999). The granites of the Arnea Granite Suite mark a rear-arc-type rifting of parts of the southern European margin (including the accreted parts of the Hun Terrane like the Vertiskos Terrane) in response to northward subduction of Palaeotethys (Stampfli & Borel, 2002; von Raumer, Stampfli & Bussy, 2003). The amphibolites also present in the Serbo-Macedonian Massif along the Athos–Volvi Zone (Dixon & Dimitriadis, 1984; N. H. Berry, unpub. Ph.D. thesis, Univ. Leicester, 1997) may represent the mafic counterpart of a bimodal rift-related magmatism.

To the best of our knowledge, this rifting event is unique to the Internal Hellenides, as it is only present within the Vertiskos Terrane of the Serbo-Macedonian Massif (Zidarov *et al.* 2004), although similar ages have been reported from the Cyclades and the Menderes Massif in western Turkey (Koralay, Satir & Dora, 2001). This demonstrates that rifting was of regional importance and resulted in terrane separation from Pangaea while concomitantly creating a major branch of Neotethys.

**Acknowledgements.** F. Himmerkus would like to thank the Deutsche Forschungsgemeinschaft and the county of Rheinland Pfalz for funding of the project of the Graduiertenkolleg ‘Stoffbestand und Entwicklung von Kruste und Mantel’. Special thanks go to P. Zachariadis, P. Turpaud and G. Meinhold for useful discussions, J. Huth for the CL images and W. Todt, U. Poller and I. Raczek for support in the laboratory.

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