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Mantle-derived and crustal melts dichotomy in northern Greece: spatiotemporal and geodynamic implications

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Two distinct groups of subduction-related (orogenic) granitoid rocks, one Jurassic and the other Tertiary, occur in the area between the Vardar (Axios) Zone and the Rhodope Massif in northern Greece. The two groups of granitoids differ in many respects. The first group shows evolved geochemical characters, it is not associated with mafic facies, and evidence of magmatic interaction between mantle- and crustal-derived melts is lacking. The second group has less evolved geochemical characters, it is associated with larger amount of mafic facies, and magmatic interaction processes between mantle-derived and crustal melts are ubiquitous as evidenced by mafic microgranular enclaves and synplutonic dykes showing different enrichment in K_2O, Ti, and incompatible elements. This kind of magmatism can be attributed to the complex geodynamic evolution of the area. In particular, we suggest that two successive subduction events related to the closure of the Vardar and the Pindos oceans, respectively, occurred in the investigated area from Late Jurassic to Tertiary. We relate the genesis of Jurassic granitoids to the first subduction event, whereas Tertiary granitoids are associated with the second subduction. Fluids released by the two subducted slabs induced metasomatic processes generating a 'leopard skin' mantle wedge able to produce mafic melts ranging from typical calc-alkaline to ultra-potassic. Such melts interacted in various amounts with crustal calc-alkaline anatectic melts to generate the wide spectrum of Tertiary granitoids occurring in the study area.

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KEY WORDS northern Greece; granitoids; 'leopard skin' mantle; geodynamics

1. INTRODUCTION

The geological evolution of northeastern Greece has attracted the attention of geologists in recent years (e.g. Mountrakis 1986; Jones *et al.* 1992; Sokoutis *et al.* 1993; Dinter 1998; Pe-Piper 1998; Kilias *et al.* 1999). This is mainly due to the complexity of the area having a crucial role in the understanding of the evolution of the dynamics of the Tethyan systems (for a review see Dixon and Robertson 1984). A great deal of research has focused on the tectonic evolution and the magmatic products outcropping in the area (e.g. D'Amico *et al.* 1990; Christofides *et al.* 1998; Ricou *et al.* 1998; Soldatos *et al.* 1998; Barr *et al.* 1999; Liati and Gebauer 1999), but much less effort has been made to couple tectonics and petrology to give a more complete picture. The goal of this paper is to merge together tectonics and petrology considering the geological evolution of this area from the Late Triassic–Early Jurassic to the Tertiary. In particular, the relationships between geodynamics,

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granitoid magmatism, and associated basic intrusive rocks occurring mainly in the Vardar (Axios) Zone, Circum Rhodope Zone and Serbomacedonian and Rhodope massifs are considered to propose a model of the geodynamic evolution of the area during this time window.

2. GRANITOID ROCKS OF NORTHEASTERN GREECE

Figure 1 shows the main geology of the study area and the location of the considered granitoid rocks. Plutons with few associated basic facies in which evidence of magmatic interaction processes are scarce, coexist with plutons associated with higher amounts of basic facies. In the latter, magmatic interaction processes are widespread, as evidenced mostly by the occurrence of mafic microgranular enclaves and synplutonic dykes (e.g. Didier and Barbarin 1991; Poli *et al.* 1996). This petrological distinction is mirrored by the ages of these two groups of rocks: radiometric studies (references in Table 1) show that most of the granitoids belonging to the first group have been generated during Jurassic times (hereafter referred to as Jurassic granitoids, JG; Table 1), whereas the second group shows a Tertiary age (hereafter referred to as Tertiary granitoids, TG; Table 1).

A geochemical database based on literature and new data, consisting of 871 samples coming from both JG and TG, has been organized and used to define the petrological relationships between these two groups of rocks. The majority of the samples have orogenic affinities defining a typical late-orogenic suite with low TiO_2, Ta and Nb abundances. On the basis of Peccerillo and Taylor's (1976) diagram (Figure 2), rocks range from calc-alkaline to shoshonitic, with some samples plotting on the field of potassic series. Even if some rocks plot in the alkaline field of the $K_2O + Na_2O$ versus SiO_2 diagram (not shown), all the samples except the Arnea granite show typical orogenic affinity plotting in the volcanic arc granite (VAG) field (Pearce *et al.* 1984) of the Y versus Nb and Yb + Ta versus Rb diagrams (not shown, e.g. Baltatzis *et al.* 1992; Christofides *et al.* 1998). In Figure 3 JG, TG and other granitoids from various geodynamic settings are compared with each other. A striking similarity can be readily observed among JG, TG and the typical orogenic granitoids irrespective of their age and place of origin. It is important to stress that the same similarity holds true also for Arnea rocks. According to Baltatzis *et al.* (1992) plotting of Arnea granite in the within-plate granite (WPG) field may be due to its source material rather than its tectonic environment. However, controversial hypotheses on affinity and age suggested for the Arnea pluton (e.g. De Wet 1989; Christofides *et al.* 2000b; Table 1) may be ascribed to the fact that Arnea rocks experienced both magmatic and metamorphic processes.

Although both groups of rocks have similar general geochemical features, JG are not associated with basic products ($SiO_2 < 56\%$; Figure 2a), whereas TG are associated with large amount of basic rocks. In particular, TG rocks with the SiO_2 contents ranging from 53% to 56% show different enrichment in K_2O (Figure 2b–e), suggesting the coeval occurrence of different types of basic magmas during Tertiary times. In detail, these rocks are represented by minor amounts of gabbroic masses, mafic dykes, and larger amounts of microgranular mafic enclaves (MME) of quartz-dioritic to monzonitic composition occurring within granitoid rocks. This feature suggests that magmatic interaction processes played a basic role in the petrogenesis of TG in respect to JG where such processes are lacking or very rare.

For the two groups of granitoid rocks, frequency histograms are constructed considering the SiO_2 content distribution within each group (Figure 4). The graph shows that the main contribution to the JG group is due to highly evolved granitoids having SiO_2 content higher than *c.* 68%. On the other hand, the histogram of TG group shows a well-defined maximum at approximately 63% of SiO_2 evidencing the generally less evolved nature of TG with respect to JG.

2.1. Jurassic granitoids—genesis and evolution

Each JG pluton plots within a restricted range of SiO_2 (Figure 2a). This scarce variability in SiO_2 is matched by all other geochemical characters of JG plutons, suggesting that fractional crystallization processes did not play a major role in their genesis. Monopigado samples, however, show a larger range in SiO_2 content and plot in two

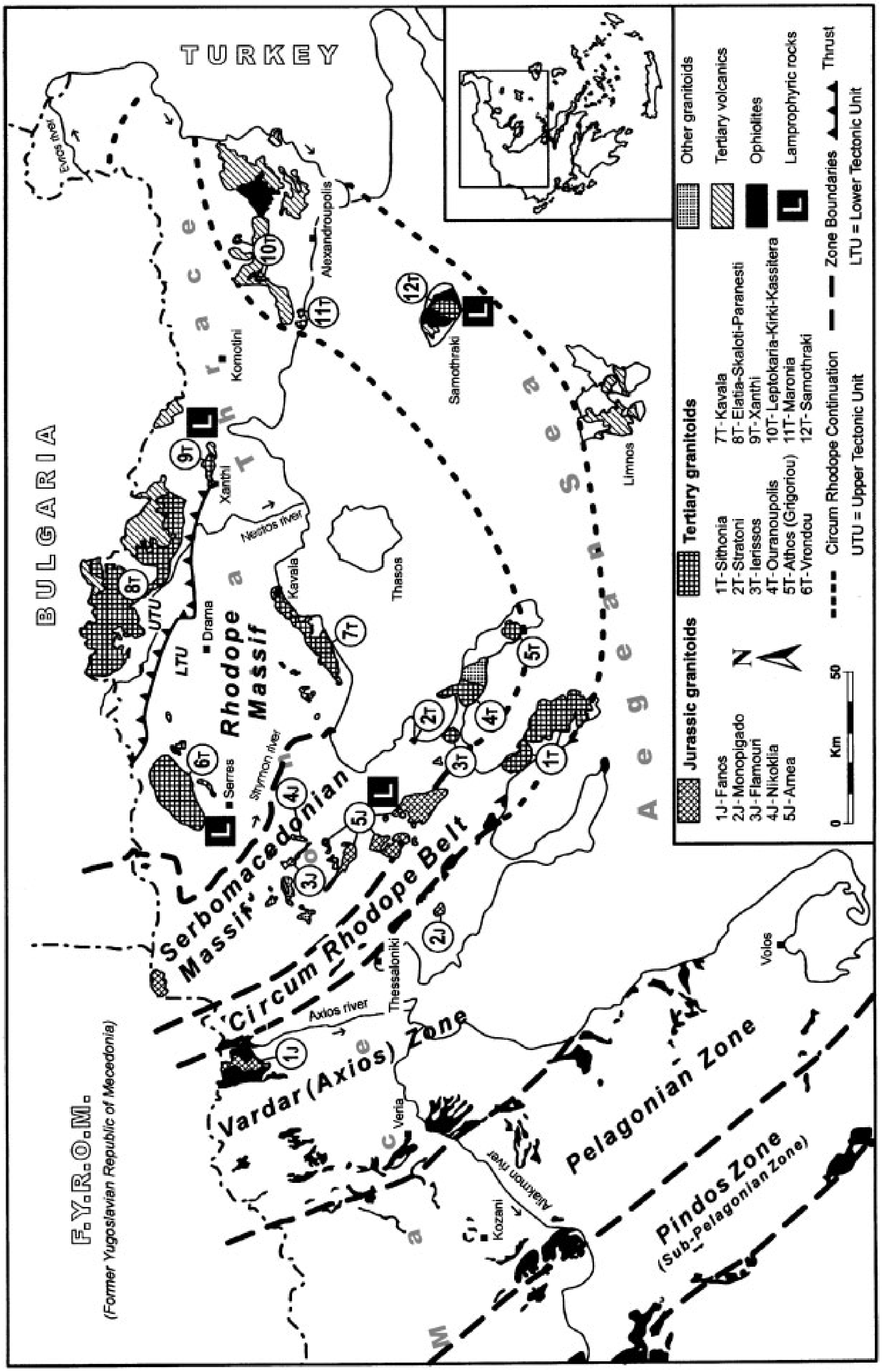

Figure 1. Schematic geological map of northern Greece (see Dinter 1998 for details). The map shows locations of Jurassic and Tertiary granitoids. 'Other granitoids': age not determined. Note the two sub-parallel ophiolitic belts following the NW–SE direction corresponding to the Vardar Zone and the Pindos area.

Table 1. Radiometric ages of the Tertiary and Mesozoic plutons considered in this study

Pluton	No (Figure 1)	Geotectonic zone	Method	Mineral/rock	Age (Ma)	Reference
Mesozoic						
Fanos	1J	Axios (Vardar) Zone	Rb-Sr	Bt	147 to 153	Borsi *et al.* (1966)
			K-Ar	Bt	150	Borsi *et al.* (1966)
			K-Ar	Bt	113 ± 3 to 148 ± 4	Marakis (1969)
			K-Ar	Bt	148 ± 3	Spray *et al.* (1984)
Monopigado	2J	Axios (Vardar) Zone	K-Ar	Bt	180	Ricou (1965)
			K-Ar	Bt	141.5 ± 3.1	Michard *et al.* (1998)
			K-Ar	?	149	Kreuzer (pers. comm.) in Mussalam and Jung (1986)
			Pb-Pb	Zrn	192.5 ± 3.8	Kostopoulos *et al.* (2000)
			U-Pb	Zrn	161	Koroneos *et al.* (2001)
Flamouri	3J	Serbomacedonian Massif	Geological data		Mesozoic	Kockel *et al.* (1977)
Nikoklia	4J	Serbomacedonian Massif				
Arnea	5J	Serbomacedonian Massif	Ar-Ar	PhI	136.5 ± 1.5	De Wet (1989)
			Rb-Sr	WR isochron	144 ± 1 to 155 ± 11	De Wet (1989)
			U-Pb	Zrn	212 ± 7	Vital (1986) in Frei (1992)
			Pb-Pb	Zrn	Late Triassic	Kostopoulos *et al.* (2000)
Tertiary						
Sithonia	1T	Circum Rhodope Belt	Ar-Ar	Bt	42.6 ± 0.4	De Wet (1989)
			Ar-Ar	Ms	50.0 ± 0.9 to 50.5 ± 1.0	De Wet (1989)
			Rb-Sr	WR isochron	50.9 ± 0.5	Christofides *et al.* (1990b)
			Rb-Sr	Bt	28.9 ± 1.1 to 47.7 ± 0.8	Christofides *et al.* (1990b)
			Rb-Sr	Ms	45.6 ± 1.3 to 54.5 ± 3.1	Christofides *et al.* (1990b)
			K-Ar	Bt	40 ± 1.5	Kondopoulou and Lauer (1984)
			Rb-Sr	Bt	40 ± 2.4	Vergely (1984)
			Rb-Sr	Ms	38 ± 2.3	Vergely (1984)
Stratoni	2T	Serbomacedonian Massif	K-Ar	Bt	29.6 ± 1.4	Papadakis (1971)
			U-Pb	Zrn	27.1 ± 1.1	Frei (1992)
			K-Ar	Ms	31.3 ± 2 to 39.8 ± 4	Barbieri *et al.* (1995)
			K-Ar	WR	35 ± 4 to 36 ± 4	Barbieri *et al.* (1995)
Ierissos	3T	Serbomacedonian Massif	U-Pb	Uraninite	54.4 ± 0.3	Frei (1992)
Ouranoupolis	4T	Serbomacedonian Massif	Bt	Bt	47.2 ± 0.7	De Wet (1989)
			Ms	Ms	44.5 ± 1.0	De Wet (1989)
Athos (Grigoriou)	5T	Serbomacedonian Massif	Rb-Sr	WR	40–42	unpublished data
Vrondou	6T	Rhodope Massif	K-Ar	HbI	53.5 ± 4.2	Papadakis (1965)
			K-Ar	HbI	29 ± 1 to 33 ± 2	Marakis (1969)
			K-Ar	Bt	30 ± 3	Dürr *et al.* (1978)
			Rb-Sr	WR errorchron	28.2 ± 14.3 to 30.8 ± 14.8	Kolokotroni (1992)

Kavala	7T	Rhodope Massif	Rb-Sr	WR isochron	16.1 ± 1.8 to 19.4 ± 0.9	Kyriakopoulos *et al.* (1988)
			Rb-Sr	Bt, Ms, Kfs, PI	14.0 ± 0.4 to 16.0 ± 0.5	Kyriakopoulos *et al.* (1988)
			U-Pb & Ar-Ar	Zrn, Ttn & Hbl	21 to 22	Dinter *et al.*(1995)
Skaloti-Elatia-Paranesti	8T	Rhodope Massif	Rb-Sr	WR errorchron	86.7 ± 27.0	Soldatos (1985)
			Rb-Sr	WR errorchron	85 ± 25	Soldatos *et al.* (2001)
			Rb-Sr	Bt	34.1 ± 1.0 to 43.0 ± 1.3	Soldatos *et al.* (2001)
			Rb-Sr	Ms	43.5 ± 0.9 to 47.8 ± 1.0	Soldatos *et al.* (2001)
			K-Ar	Bt	29.1 ± 1.2 to 38.5 ± 1.5	Sklavounos (1981)
			K-Ar	Ms	38.3 ± 1.1	Dürr *et al.* (1978)
Xanthi	9T	Rhodope Massif	K-Ar	Bt	27.1 ± 0.4 to 27.9 ± 0.9	Meyer (1968)
			Rb-Sr	Bt, Kfs, PI	26.3 ± 0.1 to 28.8 ± 0.7	Kyriakopoulos (1987)
			Fission track	Ap	25.5 ± 1.2 to 26.0 ± 1.8	Bigazzi *et al.* (1994)
Leptokaria-Kirki-Kassitera	10T	Rhodope Massif	Rb-Sr	Bt	31.4 ± 0.7 to 31.9 ± 0.5	Del Moro *et al.* (1988)
Maronia	11T	Circum Rhodope Belt	Rb-Sr	Bt	28.4 ± 0.9 to 29.3 ± 0.9	Del Moro *et al.* (1988)
Samothraki	12T	Circum Rhodope Belt	Rb-Sr	Bt	18.5 ± 0.3 to 18.9 ± 0.4	Kyriakopoulos (1987)
			Rb-Sr	Bt	18.1 ± 0.2 to 18.5 ± 0.2	Christofides *et al.* (2000a)

WR, whole rock; Ap, apatite; Bt, biotite; Hbl, amphibole; Kfs, K-feldspar; Ms, muscovite; Phl, phlogopite; Pl, plagioclase; Ttn, titanite; Zrn, zircon.

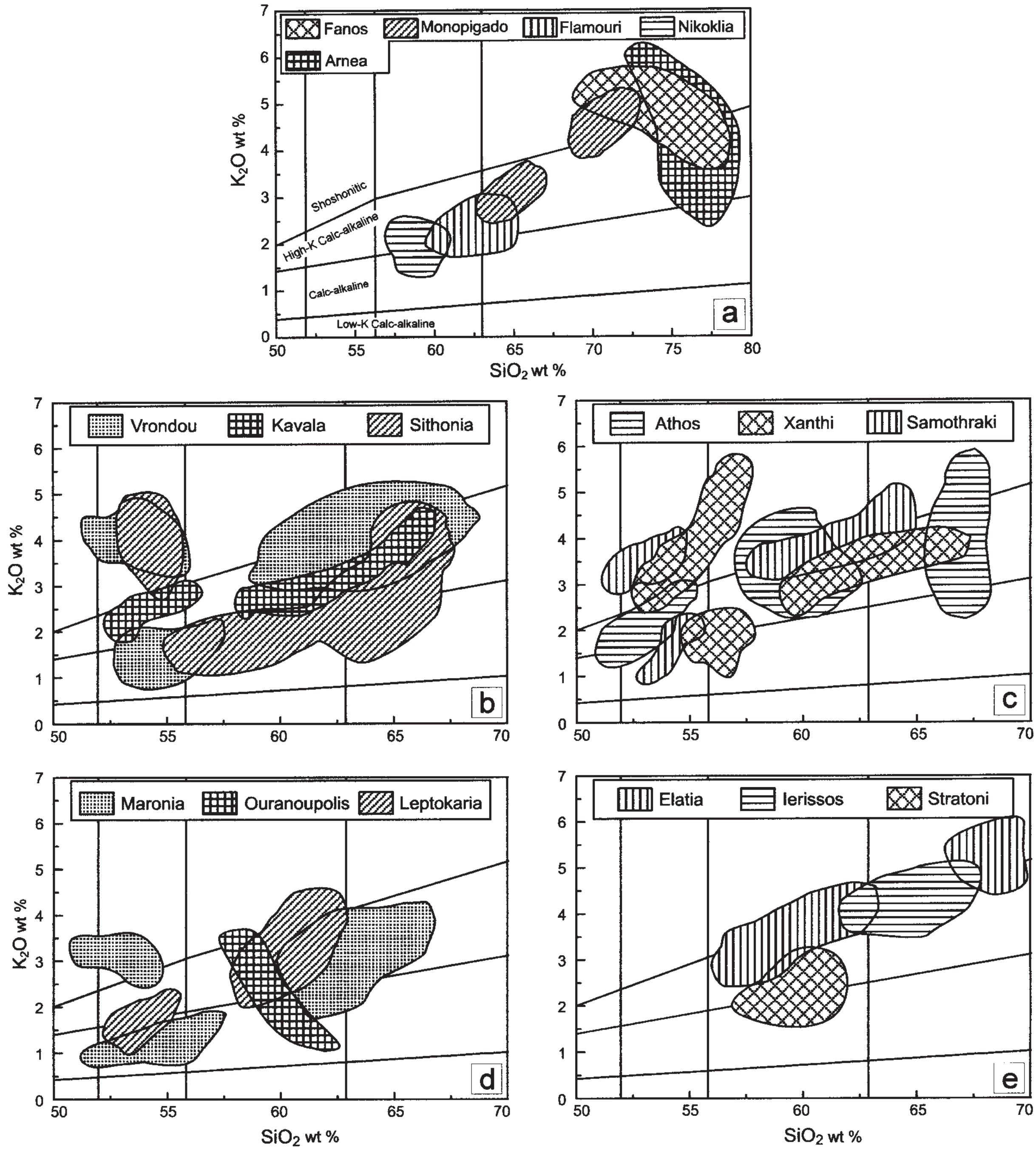

Figure 2. K_2O versus SiO_2 diagrams for the studied granitoids samples. (**a**) Jurassic granitoids; (**b–e**) Tertiary granitoids. Data used in this work: Fanos (Christofides *et al.* 1990a; Soldatos *et al.* 1993); Arnea (De Wet 1989; unpublished data (u.d.)); Monopigado (u.d.); Flamouri (u.d.); Nikoklia (u.d.); Sithonia (D'Amico *et al.* 1990; Christofides *et al.* 1990a,b; u.d.); Ouranopolis Ierissos Stratoni (u.d.); Athos (u.d.); Vrondou (Soldatos *et al.* 1998; Theodorikas 1983; Kolokotroni 1992; u.d.); Xanthi (Kyriakopoulos 1987; Christofides 1977; Sergi 1997; u.d.); Kavala (Neiva *et al.* 1996; Kyriakopoulos 1987; Kyriakopoulos *et al.* 1988; u.d.); Elatia (Soldatos 1985; Jones *et al.* 1992; u.d.); Leptokaria-Kirki-Kassitera-Maronia (Del Moro *et al.* 1988; Mavroudchiev *et al.* 1993); Samothraki (Christofides *et al.* 2000a).

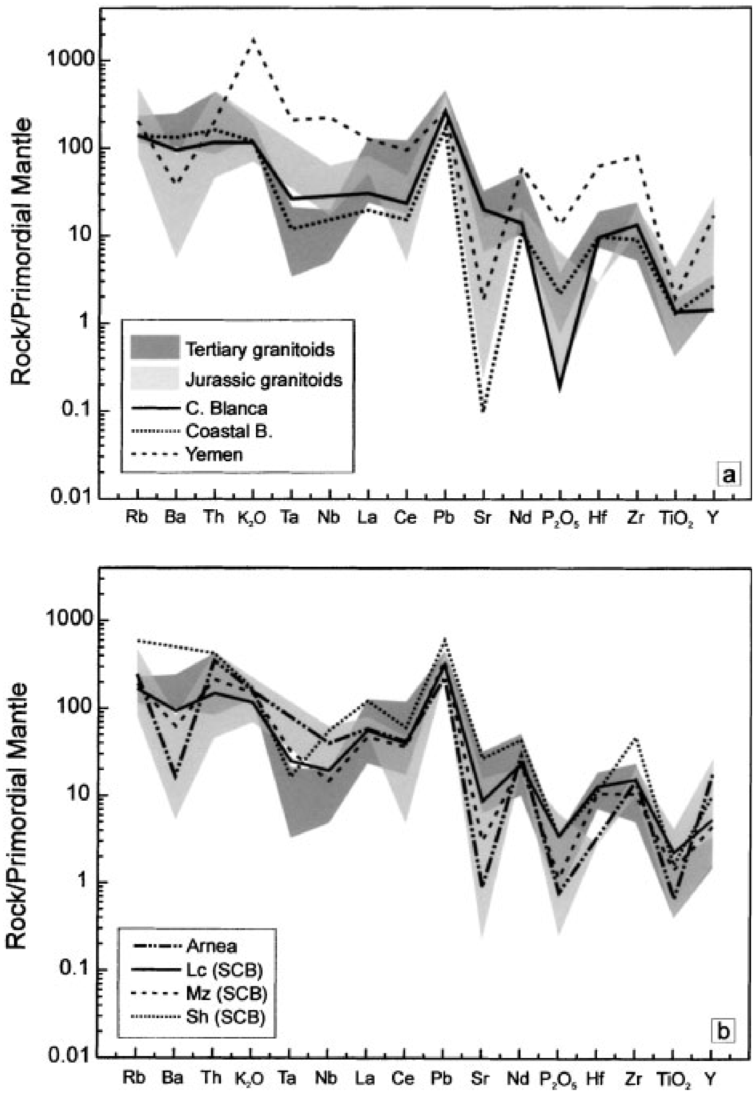

Figure 3. Comparison of geochemical characteristics among JG and TG, and granitoids of similar and different geodynamic settings. (**a**) Calc-alkaline granitoids from Cordillera Blanca (C. Blanca) and Coastal Batholith (Coastal B) (Andes; Atherton and Petford 1996); Yemen: A-type granites from Yemen (Tommasini *et al.* 1994). (**b**) Calc-alkaline leucogranites (Lc), monzogranites (Mz) and shoshonitic granitoids (Sh) from Sardinia–Corsica Batholith (SCB) (Tommasini *et al.* 1995; unpublished data).

different groups. On the other hand, magma interaction processes can also be ruled out because of the lack of petrographic evidence and/or the occurrence of MME. These considerations point to a genesis of JG by partial melting processes of crustal material. This is also revealed by plotting the studied samples together with experimental petrology data obtained by melting experiments of crustal protoliths (Figure 5). Metasedimentary protoliths are not likely to be suitable source rocks for the JG, whereas igneous protoliths with intermediate-acid compositions (amphibolites and gneisses; Figure 5) display major element geochemistry compatible with a possible source rock. However, JG samples plot in two different well-defined groups, suggesting that two different sources can be involved in their genesis: (i) samples with higher CaO, FeO and MgO contents are likely to be derived from amphibolitic and gneissic sources; (ii) samples with lower CaO, FeO and MgO abundances suggest partial melting processes starting from amphibolitic sources. However, the two sources cannot be greatly different since JG trace

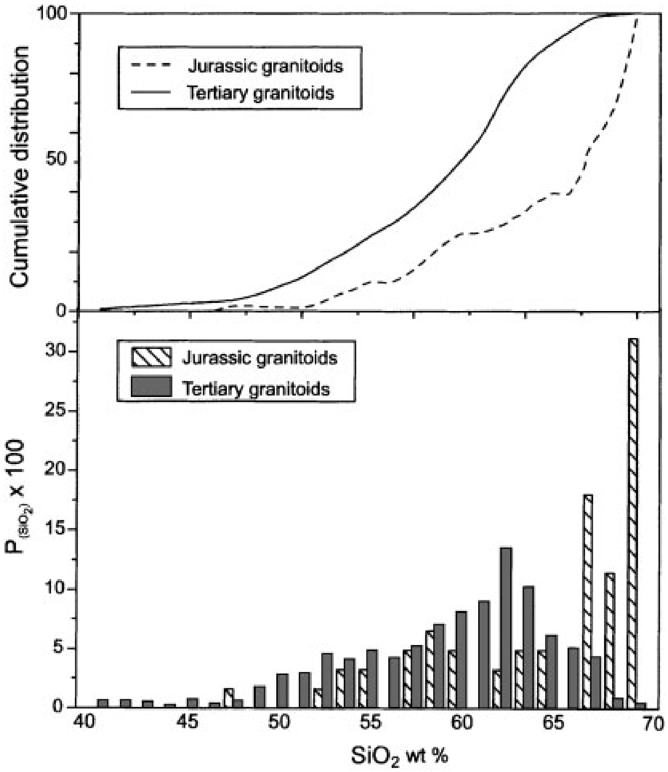

Figure 4. Cumulative distribution function and frequency histograms showing the SiO_2 distribution in Jurassic and Tertiary granitoids (see text for details).

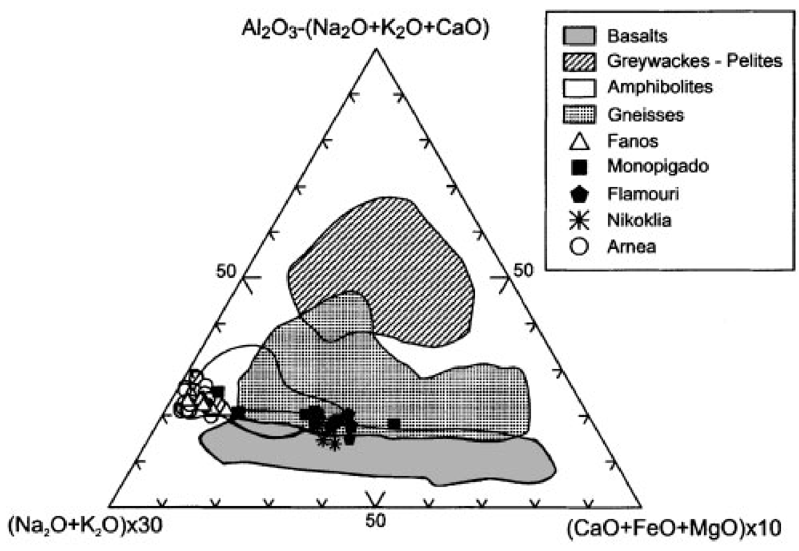

Figure 5. Triangular diagram [Al_2O_3-($Na_2O + K_2O + CaO$)]–[$Na_2O + K_2O$]–[$CaO + FeO + MgO$] (molar) showing the main geochemical character of Jurassic granitoids plotted together with the composition of experimental data on melt compositions from different crustal protoliths: greywackes and pelites (Montel and Vielzeuf 1997; Patino Douce and Beard 1996; Gardien *et al.* 1995; MacRae and Nesbitt 1980; Skjerlie *et al.* 1993; Carrington and Watt 1995; Vielzeuf and Holloway 1988; Pickering and Johnston 1998); gneisses (Patino Douce 1997; Skjerlie *et al.* 1993; Beard *et al.* 1994; Holtz and Johannes 1991; Gardien *et al.* 1995); amphibolites (Beard and Lofgren 1991; Rushmer 1991; Johannes and Holtz 1996; Wolf and Wyllie 1994); basalts (Rapp 1995; Rapp and Watson 1995).

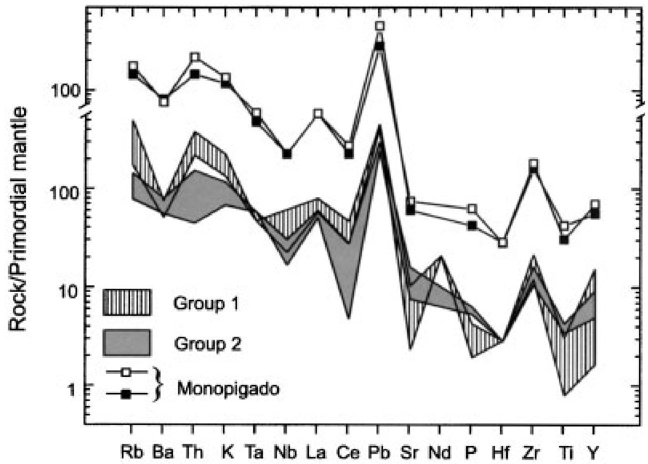

Figure 6. Spider diagram showing the trace element geochemical characters of Jurassic granitoids normalized to primordial mantle (Wood *et al.* 1979). The similar patterns suggest similar crustal source rocks. Group 1 and solid symbols: samples with higher CaO, FeO and MgO; Group 2 and open symbols: samples with lower CaO, FeO and MgO.

element geochemical signatures are quite similar as can be observed on the spider diagram in Figure 6, where the two groups of rocks are plotted. The similarity of the two sources is more striking when two samples from the Monopigado pluton, one from each group, are plotted on the same diagram. The negative anomaly of Nb and Ti, and the positive anomaly of Pb, that point to the calc-alkaline affinity of these rocks, are also noteworthy. Thus, JG can be thought of as having been derived from partial melting of different crustal levels consisting of intermediate-acid protoliths with a typical calc-alkaline geochemical fingerprint.

2.2. *Tertiary granitoids—genesis and evolution*

Genesis and evolution of TG are more complex than those of the JG. From the existing literature (e.g. Eleftheriadis *et al.* 1995; Sergi 1997; Soldatos *et al.* 1998; Christofides *et al.* 1998; Pe-Piper *et al.* 1998; Perugini and Poli 2000) and present data emerges the general picture that magmatic interaction processes between mantle-derived and crustal magmas are likely to be the most important petrogenetic processes. In order to define the evolution processes for TG plutons, we focus our attention on the trace element behaviour of samples from the Vrondou plutonic complex, since these rocks well represent the general geochemical characters of the Tertiary granitoid magmatism. Figure 7 shows that the geochemical evolution of Vrondou rock can be modelled by mixing plus fractional crystallization (MFC) processes, starting from two basic end-members interacting with an acid end-member (Soldatos *et al.* 1998).

Although each single pluton shows its own unique features regarding the degree and the evolution of magmatic interaction processes, the general evolution processes envisaged for the Vrondou plutonic complex can be claimed for all other TG plutons evidencing that magmatic interaction processes took place between crustal calc-alkaline acid melts and different basic end-members having different enrichment in potassium and incompatible elements.

Concerning the more evolved products that represent the acid end-members involved in the magmatic interaction processes, Figure 8 displays spider diagrams for samples with SiO_2 contents higher than 68%. All samples from TG show very similar patterns and, when samples from JG are plotted on the same diagram, no noticeable differences can be observed. This similarity points to a similar crustal source for the most evolved rocks of both Tertiary and Jurassic granitoids.

Regarding the geochemical features of the mafic end-members, mafic rocks (Mg# > 65) associated with TG display a continuous variation between two extreme compositions (Figure 9): (i) potassic rocks (lamprophyres) having high K_2O, and low Al_2O_3 (low Na_2O and CaO, not shown); and (ii) more typical calc-alkaline rocks showing low K_2O, high Al_2O_3 (high Na_2O and CaO, not shown).

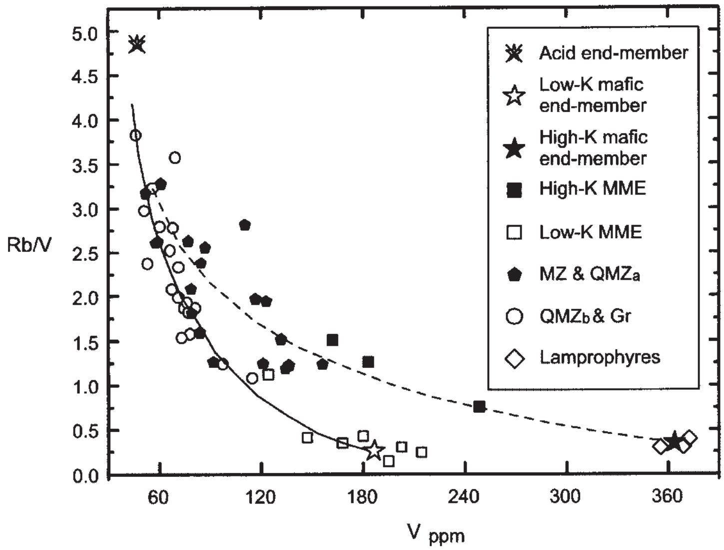

Figure 7. Inter-elemental binary diagram showing the mixing plus fractional crystallization differentiation process responsible for the genesis of granitoids rocks having different potassium enrichment from Vroundou pluton. Solid line represents evolution starting from an average of low-K microgranular mafic enclaves (MME); dashed line represents evolution starting from an average of lamprophyres found in the area. Acid end-member is the host rock having the most evolved geochemical composition. Rate of assimilation over rate of fractional crystallization is 0.35 and 0.2 for high-K and low-K rocks, respectively. Bulk partition coefficients and further explanations can be found in Soldatos *et al.* (1998). MZ, monzonites; QMZa, quartz-monzonites derived from lamprophyres; QMZb, quartz-monzonites derived from low-K MME; Gr, granites.

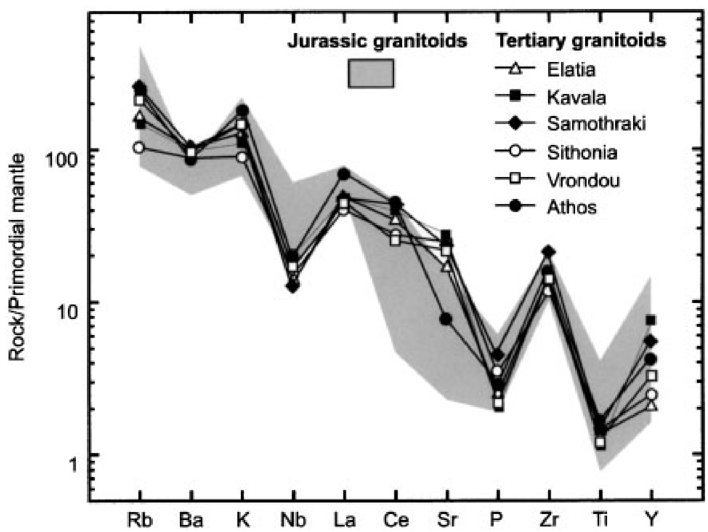

Figure 8. Spider diagrams showing trace element patterns of more evolved products ($SiO_2 > 68\%$) from both Jurassic and Tertiary granitoids (see text for details) normalized to primordial mantle (Wood *et al.* 1979).

Figure 10 shows spider diagrams performed using average compositions of the same mafic rocks selected on the basis of their K_2O enrichment. From the figure it emerges that all samples show a clear enrichment in large-ion lithophile elements (LILE) coupled with high-field-strength elements (HFSE) depletion, with Nb, Ta and Ti negative anomalies typical of subduction-related magmas. The similarity is striking, both in absolute values and relative enrichment of the elements between the high potassium rocks and lamprophyres, compared to the low potassium rocks that show lower contents of LILE and some HFSE.

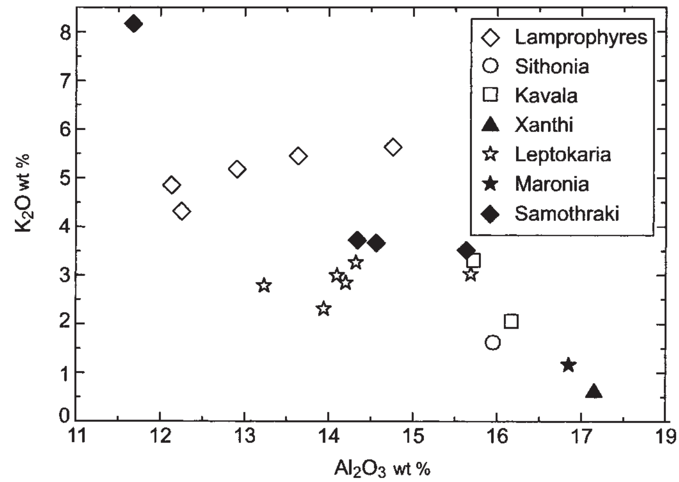

Figure 9. Al_2O_3 versus K_2O plot showing the geochemical variation of mafic rocks coexisting with Tertiary granitoids.

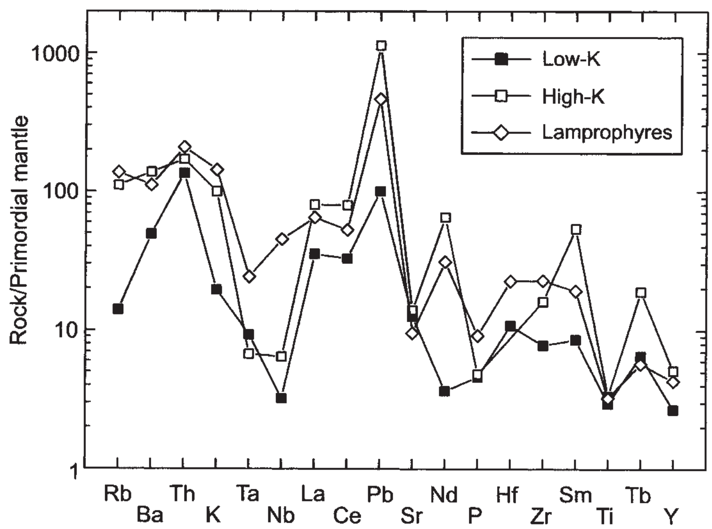

Figure 10. Spider diagram showing the trace elements patterns of mafic (Mg# > 65) low-K_2O and high-K_2O rocks, and lamprophyres associated with Tertiary granitoids normalized to primordial mantle (Wood *et al.* 1979).

The coeval occurrence of mantle-derived melts showing geochemical compositions ranging from lamprophyric to calc-alkaline suggests that a heterogeneous mantle, able to generate a rich compositional variability of melts between these two end-members, existed during the Tertiary beneath the Serbomacedonian and Rhodope massifs. The first end-member can be interpreted to be derived by partial melting processes of a strongly metasomatized mantle source where K-rich phases, such as phlogopite, played a key role. The relatively high silica content of this end-member suggests a genesis at moderate pressure (e.g. Foley 1992), whereas the low Al, Na, Ca, and high compatible elements argue for a restitic peridotitic source. These considerations are corroborated by the fact that lamprophyric mafic products are commonly associated with a metasomatized lithospheric mantle wedge above a subducting slab, the latter being the engine acting to produce the metasomatic process itself (e.g. Mitchell and Bergman 1991). The second mantle end-member shows higher Al, Na, Ca, and lower compatible elements, suggesting a derivation from a fertile metasomatized lherzolitic mantle source. However, these two envisaged mantle source compositions have to be considered just as two extreme end-members occurring in a mantle wedge able to generate melts spanning all intermediate compositions (Figure 9).

The picture depicted above for the magmatic evolution of the study area suggests the presence of a sort of 'leopard skin' mantle wedge during the Tertiary, which was able to produce a wide range of mafic magmas ranging from typical calc-alkaline to lamprophyric.

3. FROM PETROLOGY TO GEODYNAMICS: A POSSIBLE GEODYNAMIC MODEL

The main petrological constraints arising from investigations on the intrusive magmatism from Jurassic to Tertiary in the study area are: (i) existence of two climaxes of intrusive magmatism, one during the Jurassic (JG) and the other during the Tertiary (TG); (ii) JG are crustal anatectic magmas having calc-alkaline geochemical characters; they are not associated with mantle-derived melts; (iii) TG show widespread evidence of mixing between mantle- and crustal-derived melts; (iv) the crustal sources of the JG and the acid end-member of the TG are similar and are represented by an amphibolitic-gneissic protolith; (v) Tertiary mafic end-members are represented by the coexistence in space and time of low-K melts, derived from a fertile metasomatized mantle, and of high-K melts, derived from a more restitic metasomatized mantle. Geochemical features of metasomatism in both mantle sources are typical of orogenic environment, and they do not show evidence of asthenospheric metasomatic imprint. The coexistence in time and space of these two extreme end-members of mantle-derived melts evidences the presence of a strongly heterogeneous mantle.

These petrological constraints are taken into account, along with tectonic and geodynamic data, to propose the following geodynamic model for the area from Late Triassic–Early Jurassic to Tertiary.

Many authors (Boccaletti *et al.* 1974; Robertson and Dixon 1984; Mountrakis 1983, 1986; Robertson *et al.* 1996; Pe-Piper 1998) support the presence, from Late Jurassic to Tertiary, of two closing oceanic areas (the Vardar (Axios) and the Pindos). The occurrence of two closing oceanic areas is also emphasized by the presence of two parallel belts of ophiolites (Figure 1) that can be followed for thousand of kilometres from the Dinarides to Turkey through the Hellenides (e.g. Robertson and Shallo 2000). Subduction processes of these two zones probably did not start at the same time. Before the beginning of the Vardar subduction, an intra-oceanic subduction involving the Meliata plate and directed southward (Figure 11a; e.g. Stampfli and Borel 2002), generated the island arc magmatism of Paikon (Mercier 1966; Bebien *et al.* 1994). During Late Jurassic–Middle Cretaceous the closure of the Vardar Ocean begins, with the Benioff plane directed northward (Channell and Kozur 1997). During Late Jurassic the obduction of Vardar ophiolites on the Pelagonian plate also occurs (Figure 11b; e.g. Baumgartner 1985; Bernoulli and Laubscher 1972).

During the subduction of the Vardar Ocean, the mantle wedge under the Serbomacedonian and Rhodope continents underwent metasomatic processes by fluids released from the dipping oceanic slab and melting of such a mantle wedge produced calc-alkaline basaltic melts. The compressional regime of the area inhibited the uprising of large amounts of such melts. This is confirmed by the absence of effusive magmatic activity during this age. On the contrary, such melts underplated in the lower crust (Figure 11b), where they crystallized and released heat to partially melt the crust above producing acid calc-alkaline melts now outcropping as Jurassic granitoids. Owing to this tectonic context magmatic interaction processes between the crustal- and the mantle-derived melts have been inhibited, as evidenced by the highly evolved character of JG coupled with the absence of magmatic interaction phenomena.

During Late Cretaceous–Palaeocene the Vardar Ocean subduction continues, leading to the genesis of back-arc magmatism of Srednogorie (e.g. Economou-Eliopoulos and Eliopoulos 2000) and to the collision of the Pelagonian and Rhodope continents (Figure 11c).

After collision of the Pelagonian and Rhodope continents, the slab break-off of the subducted Vardar plate occurred (Figure 11c; e.g. Yanev and Bardintzeff 1997). During Eocene–Oligocene, the second subduction event associated with the closure of the Pindos oceanic area continued; a scarce activity of magmatic-arc type is documented at this time (Bulle and Rollett 1970; Mercier 1966). The continuing closure of the Pindos Ocean squeezed

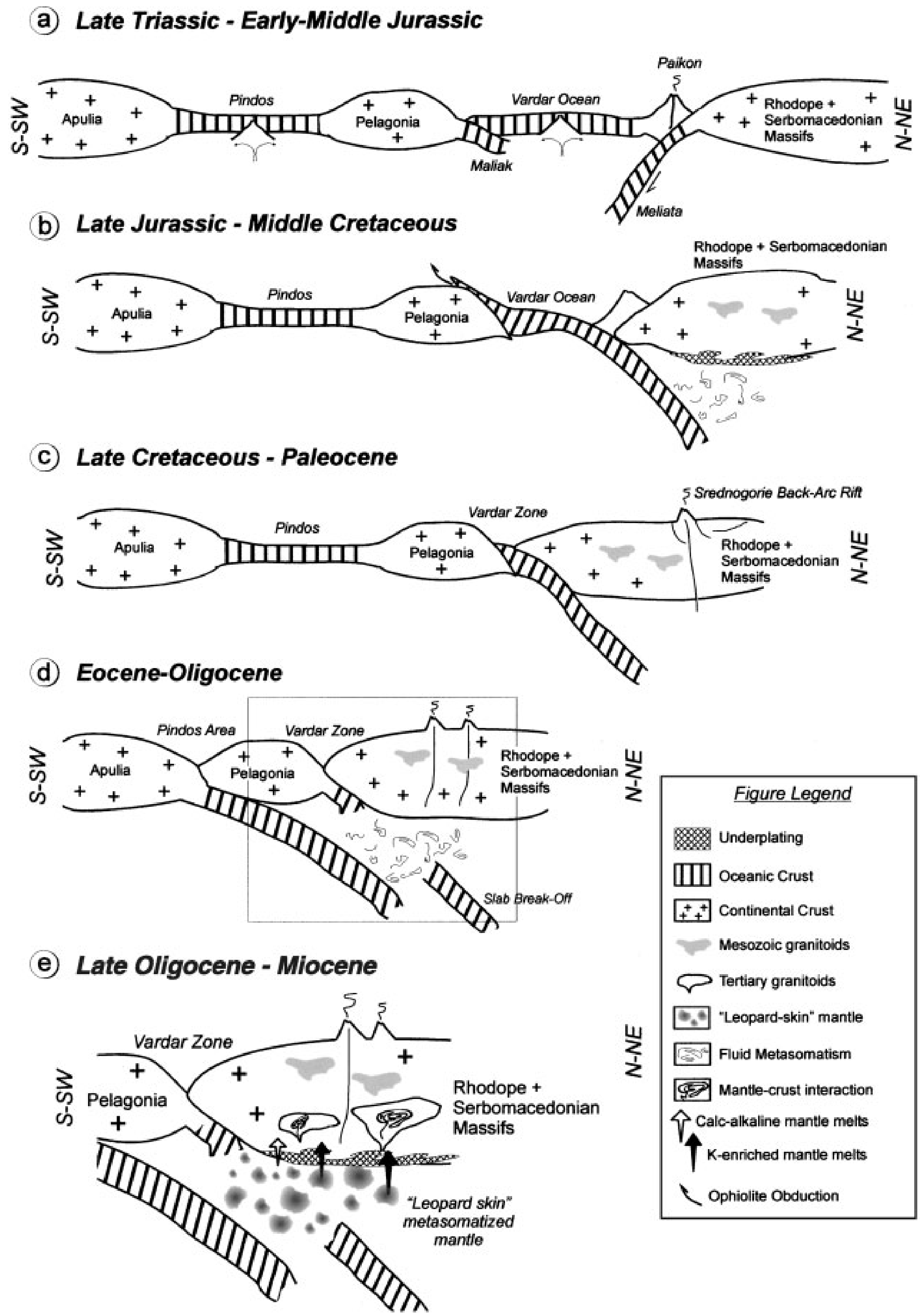

Figure 11. Schematic geodynamic reconstruction of northern Greece from Late Triassic to Tertiary; not to scale. See text for detailed explanation of the various stages.

the Pelagonian continental fragment between the closing Pindos Ocean and the already closed Vardar Ocean. The narrow spatial relationships between the already closed Vardar (Axios) zone and the closing Pindos Ocean allowed the Pindos oceanic slab to release metasomatic fluids that penetrated through the window left open by the detachment of the subducted Vardar plate, on the same mantle wedge that already suffered the metasomatic process induced by the slab of the Vardar Ocean (Figure 11d).

In Eocene times and during the main Alpine deformational event, TG started to intrude the Serbomacedonian–Rhodope continent (e.g. Christofides *et al.* 2001). Compression continued reaching its maximum, and in Late Oligocene–Miocene times the collapse of the Hellenic segment of the Alpine Orogen led to a dramatic change in the geodynamics of the area that evolved from a compressive to an extensional regime (e.g. Jones *et al.* 1992; Barr *et al.* 1999; Kilias *et al.* 1999). The extensional regime allowed uprising of large amounts of mantle melts into crustal levels (Figure 11e). Underplating processes acted at the base of the Serbomacedonian–Rhodope continent, and crustal melts were produced from similar crustal sources that generated the Jurassic calc-alkaline granitoids. The similar geochemical characteristics of JG and acid end-members of TG are in agreement with these considerations.

Mantle-derived melts in the Tertiary intrusive magmatism were strongly heterogeneous as evidenced by the variable enrichment in K_2O, TiO_2 and incompatible elements. Presence of ultrapotassic magmas is also revealed by the occurrence of lamprophyric dykes temporally and spatially related to the Tertiary granitoids. These mantle melts interacted with the crustal calc-alkaline magmas (Figure 11e) generating the wide spectrum of the Tertiary granitoids bearing mafic microgranular enclaves. The monzonitic affinity of a large part of Tertiary granitoids also supports the hypothesis that magmatic interaction processes between K_2O-enriched mantle-derived melts and crustal calc-alkaline melts occurred (Poli *et al.* 1999). In addition, the important role played by magmatic interaction processes between calc-alkaline crustal melts and mantle-derived magmas showing different enrichment in potassium, is corroborated by the presence of coeval volcanism sharing most of the geochemical features associated with intrusive magmatism (e.g. Innocenti *et al.* 1984; Eleftheriadis 1995; Yanev *et al.* 1998).

Thus, the presence of mantle-derived melts showing high-K and ultra-potassic affinity together with typical calc-alkaline mafic melts is the most striking feature of Tertiary magmatism. However, even if the high K_2O content is linked with high LILE abundances, the relatively low Sr and high Nd isotopic values published for these rocks (e.g. Del Moro *et al.* 1988; Christofides *et al.* 1990b, 1998; Sergi 1997; Pe-Piper *et al.* 1998; $Sr^{87}/Sr^{86} = 0.7053–0.7060$, $Nd^{143}/Nd^{144} = 0.51258–0.51250$) require further explanations. Considering that upper–middle continental crust has Sr and Nd isotopes safely higher than 0.712 and lower than 0.5122, respectively, metasomatism induced by such a crust, as suggested by recent works on circum-Mediterranean high-potassium rocks (Tilton *et al.* 1989; Peccerillo 1999) should have strongly increased and decreased Sr and Nd isotopic ratios, respectively. The low Sr and the high Nd isotopic ratios of studied rocks evidence that such metasomatism has to be ruled out or, at most, was of minor importance.

On the other hand, fluids released by the subducting oceanic slab are commonly considered responsible for the enrichment in K_2O and LILE but not for isotopic enrichment. In fact, as reported by Kogiso *et al.* (1997) and Tatsumi and Kogiso (1997), enrichment in trace elements is at least two orders of magnitude higher than enrichment in isotopes; this difference leads to a decoupling in the behaviour of trace elements and isotopes during fluid-induced metasomatism. Thus, to achieve enrichments in potassium and LILE, but relatively low isotopic signatures, particular conditions are needed. A possible explanation is the influence of uprising asthenospheric mantle in response to the break-off of the Vardar subducted slab. Such an influence should have driven the geochemical imprint of mantle-derived magmas toward an oceanic island basalt (OIB) character (e.g. Halliday *et al.* 1995). On the contrary, the high-K and ultrapotassic mafic melts outcropping in the area do not exhibit any geochemical evidence of this imprint. Two main reasons can be invoked to explain these occurrences: (1) the amount of asthenospheric input has been so low that it cannot be recognized; (2) a geometrical control existed in the area that did not allow the asthenosphere to rise. Regarding the first point, it does not explain the enrichment in K_2O and LILE as observed in the mafic magmas associated with TG, and hence it can be discarded. Regarding the second point, a possible geometrical control could be given by a second subduction, whose slab prevented the asthenosphere from rising as suggested in our proposed geodynamic model. Hence, it seems reasonable to propose the hypothesis of a double metasomatism on the same mantle wedge caused by two subsequent subductions. In this geodynamic context, the same mantle wedge beneath the Serbomacedonian and Rhodope continents suffered two metasomatic processes associated with two subduction events related to the closure of two spatially close oceans (the Vardar and the Pindos). These processes acted at different scales and with different intensities by infiltration of fluids through the fractured mantle and produced a 'leopard skin' mantle wedge able to generate a wide spectrum of mafic melts ranging from typical calc-alkaline to highly metasomatized melts such as those outcropping in the studied area.

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