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Unique features of the Cenozoic igneous rocks of Greece

Georgia Pe-Piper*
Department of Geology, Saint Mary's University, Halifax, Nova Scotia B3H 3C3, Canada
David J.W. Piper*
Geological Survey of Canada (Atlantic), Bedford Institute of Oceanography,
P.O. Box 1006, Dartmouth, Nova Scotia B2Y 4A2, Canada

ABSTRACT

The relationship between Cenozoic igneous rocks and the geodynamic evolution of the Aegean region is synthesized. A simplified palinspastic reconstruction of the region is attempted for the last 50 m.y., on the basis of published syntheses of paleomagnetic data and estimates of amounts of extension and of shortening in nappes. Variability in magma genesis results from hydrous melting of the asthenospheric mantle wedge during subduction, thermal melting of enriched subcontinental lithospheric mantle as a result of rising asthenosphere, and decompression melting of rising asthenosphere. Break-off of a subducting slab or lithospheric delamination occurred several times during the earlier Cenozoic as a result of Late Cretaceous and Paleogene closure of several Neo-Tethyan Ocean basins, triggering the rise of hot asthenosphere. Magmas underwent assimilation and fractional crystallization during passage through subcontinental lithosphere and crust; these processes were less effective where strike-slip faults provided efficient pathways for magma rise. Available data on the trace elements and radiogenic isotopes are used to identify the magmatic affinities of Cenozoic igneous rocks.

Unusual features of the Cenozoic igneous activity of the Aegean region are the wide range of rock types in "back-arc" settings and the exposure of both upper-crustal and middle-crustal rocks. This is a consequence of (1) the numerous microcontinental blocks within the Aegean area, separated by Neo-Tethyan Ocean strands that were destroyed by subduction; (2) orogen-parallel strike-slip faulting resulting from the progressive collision of Arabia with Anatolia; and (3) the extensional collapse and roll-back of the Hellenic subduction zone over subducting oceanic crust. Magmatism directly related to hydrous melting of subarc asthenosphere lay south of the present south Aegean arc in the Paleogene; it influenced the Cyclades plutons in the Miocene and then moved southward again as a result of extension and roll-back to its present position. Calc-alkaline volcanism in Rhodope may be related to the subduction of the Intra-Pontide Ocean.

Lithospheric delamination or slab break-off produced thermal melting of the subcontinental lithospheric mantle inhomogeneously enriched by earlier subduction, resulting in voluminous shoshonitic volcanism in the Miocene of the northeast Aegean and the Oligocene of Rhodope. In both cases, shoshonitic volcanism was followed by

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*E-mails: Pe-Piper—gpiper@smu.ca; Piper—dpiper@nrcan.gc.ca.

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minor alkaline magmatism related to the decompression melting of upwelling asthenosphere. The thermal effects of upwelling asthenosphere, coupled with increased geothermal gradient from extension, also contributed to the thermal melting of subcontinental lithospheric mantle. The plutonic rocks of the Cyclades and northern Greece resulted from crustal melting by magmas largely derived from the melting of lithospheric mantle.

Keywords: volcanism, plutonism, petrogenesis, paleogeography

INTRODUCTION

The Hellenide orogen of Greece (Fig. 1) resulted from the collision of several microcontinental fragments, culminating in the Eocene, when the Apulian and Pelagonian microcontinents converged with the Rhodope and Serbo-Macedonian fragments that had already accreted to the southern margin of Eurasia. Since that time, the Hellenide orogen has been characterized by widespread extension, particularly since the Miocene, as the orogen-parallel escape of the Aegea-Anatolia microplate led to subduction roll-back over the oceanic crust of the Africa plate.

Ever since Le Pichon and Angelier (1981) presented paleogeographic maps that “unstretched” Greece through the Neogene, there has been widespread awareness of the profound changes that have taken place in the relative positions of Miocene and older rocks. Nevertheless, most reconstructions of both paleogeography and the distribution of igneous rocks continue to be shown on a modern geographic base (e.g., Fytikas et al., 1984; Schröder, 1986; Pe-Piper and Piper, 2002; Vougioukalakis, 2003). However, recent advances in understanding of the movement of crustal blocks based on paleomagnetism (as reviewed by Kondopoulou, 2000) and extension vectors from structural studies (summarized by Walcott and White, 1998) has for the first time made it possible to systematically attempt Cenozoic reconstructions of the Hellenide orogen.

In this article, we present simplified reconstructions of the Hellenide orogen at intervals of 1 m.y. for the Neogene and intervals of 2 m.y. back to 50 Ma (at the end of the early Eocene).

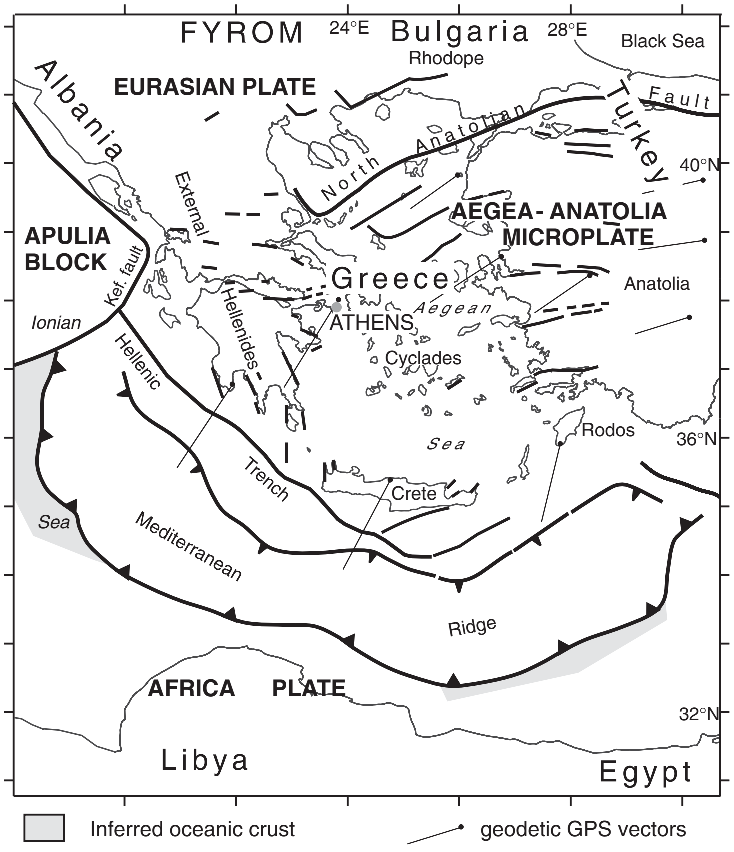


Figure 1. The present geodynamic setting of Greece showing seismically active faults (after Hatzfeld 1999) and geodetically determined plate motions relative to the Europe plate.

The reliability of these reconstructions becomes poorer with increasing age. Whatever their inadequacy, they show previously unrecognized relationships and should stimulate critical assessment and further work. We use the reconstructions as a base for reconsideration of the petrogenesis of the Cenozoic igneous rocks of Greece, emphasizing unique or unusual features of this igneous assemblage. Finally, we summarize the tectonic processes that have led to these unusual features.

PALEOGEOGRAPHIC RECONSTRUCTIONS

Procedure

The paleogeographic reconstructions presented here are modified from earlier reconstructions in the literature, notably those of Walcott and White (1998). They are in part based on the regional position of Greece between converging Gondwana and Eurasia, the kinematics of which is recorded in the magnetic stripes of the north Atlantic Ocean. These allow the relative motions of major plates and of microplates, such as the Aegea-Anatolia and Arabia microplates, to be reconstructed with considerable precision (Garfunkel, 1981; Savostin et al., 1986; Rosenbaum et al., 2002).

Geological criteria have been used to recognize discrete crustal blocks within microplates that have deformed in a relatively homogenous manner when considered on a large scale (Fig. 2). At a local scale, structural and paleomagnetic studies have shown that upper crust has deformed in a complex manner; these complexities are not dealt with here. In some cases, the boundaries of blocks are diffuse, but for the purposes of simplicity in reconstruction, have been identified along a precise line. Three types of operation have been applied to these blocks: rotation, translation, and compression or extension. Rotation is based principally on paleomagnetic data, as summarized by Kondopoulou (2000) and Kissel et al. (2003), and on the orientation of stretching lineations of known ages, as summarized by Walcott and White (1998). Translation is based on present-day geodetic measurements (e.g., McClusky et al., 2000), the interpreted history of major strike-slip faults (e.g., Armijo et al., 1999; Picha, 2002), and geometric requirements. Extension is estimated from basin formation and crustal thickness (Sonder and England, 1989) and from geodetic measurements. Compression is estimated from published cross-sections of stacked nappes (e.g., Jacobshagen, 1986). These estimates are complicated by extruding wedges associated with subduction (e.g., Ring and Reischmann, 2002).

The modern coastline is presented solely to provide a recognizable frame of reference. In older reconstructions, it is misleading because the resolution of the reconstructions is much more general. Thus, for example, no attempt has been made to represent within the island of Crete the complex nappe stacking and extension that took place in the Tertiary so that the modern coastline of Crete is still recognizable within the Eocene reconstruction. In presenting the reconstructions, the position of Athens has been fixed.

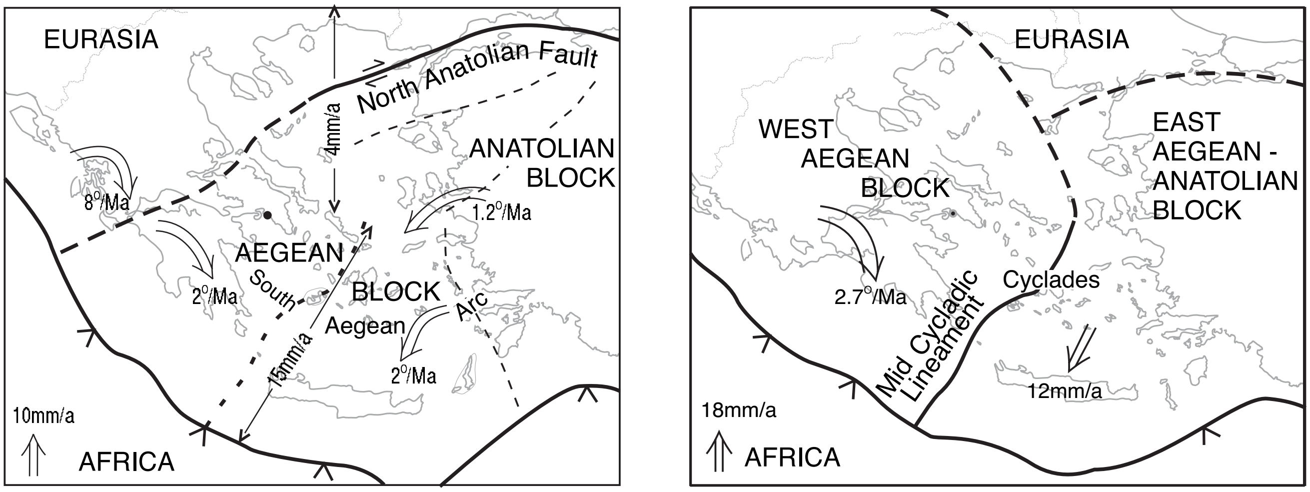
The reconstructions have been simplified by recognizing six phases, each with rather different kinematics. The geometry in the older phases is inferred largely from restoring the present-day distribution of crustal blocks, but to provide a clearer account of the geodynamic processes involved, we describe them from oldest to youngest (Fig. 2). The paleogeographic reconstructions resulting from the application of the inferred kinematics in these blocks are shown in Figures 3–5.

Phase VI: Middle to Late Eocene

By the early Eocene, closure of the Vardar and Pindos Oceans was complete (bottom right panel of Fig. 5). Convergence of Gondwana and Eurasia continued, with subduction of the Africa plate beneath Apulia and progressive shortening across the Apulia-Pelagonia suture to produce the nappes of the External Hellenides, with shortening estimated to average 10 mm/yr. Basins developed in the Bulgarian Rhodope and in places in northern Greece, suggesting crustal extension. As discussed later, strike-slip motion was important in the emplacement of the Sithonia plutons. Therefore, although the kinematics of the extension is unclear, we have assumed extension generally across strike at a rate of 10 mm/yr. The Intra-Pontide Ocean was still present in northeastern Greece and northwestern Turkey. At the margins of the reconstruction, no attempt has been made to model either central Anatolia or the Pontides and the Black Sea.

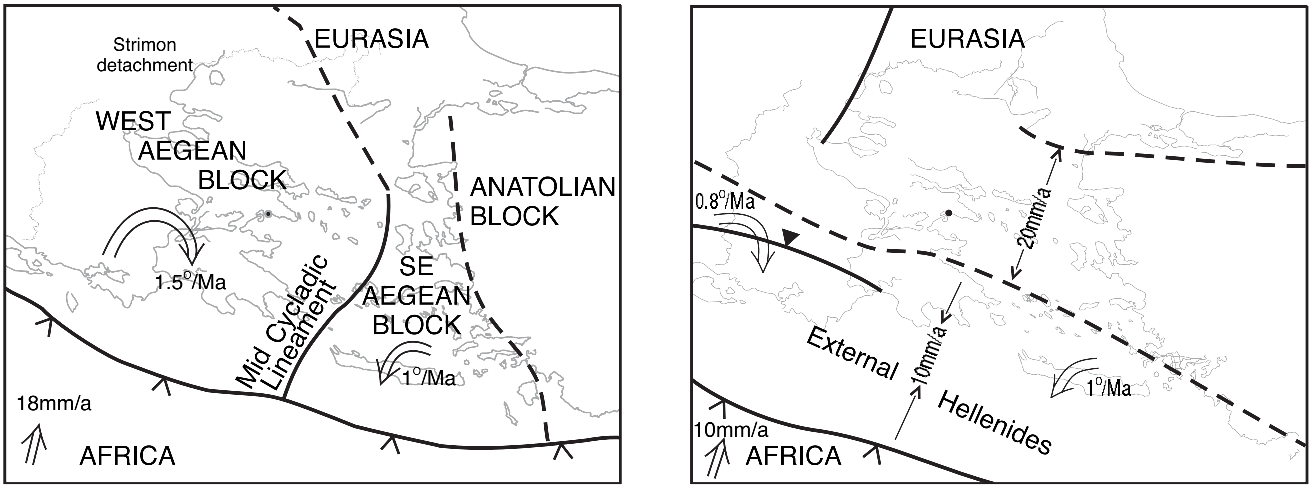
Phase V: Oligocene

Most reconstructions of Gondwana-Eurasia convergence (e.g., Savostin et al., 1986; Dewey et al., 1989) show an increased rate of convergence in the Oligocene and a change in convergence vector to more oblique, although in the recent compilation of Rosenbaum et al. (2002) this is not shown, in part because Oligocene and early Miocene motions were not treated separately. Several geological features changed near the Eocene-Oligocene boundary, including major subsidence of the strike-slip Mesohellenic basin (Zelilidis et al., 2002) and the onset of widespread volcanism in northern Greece (Pe-Piper and Piper, 2002). Robertson (2000) has suggested that final closure of the inner Tauride ocean between eastern Anatolia and Arabia took place in the late Eocene, resulting in westward migration of the collision zone of Gondwana with microplates on the southern margin of Eurasia. Because the high level of uncertainty does not justify a more sophisticated approach, similar simple operations have been used for paleogeographic reconstructions in Phase V as for those in Phase VI: extension of northern Greece, as indicated by basin formation in the Rhodope orogen and elsewhere, compression in the External Hellenides, and northwestward translation of Anatolia in order to close the Intra-Pontide Ocean.



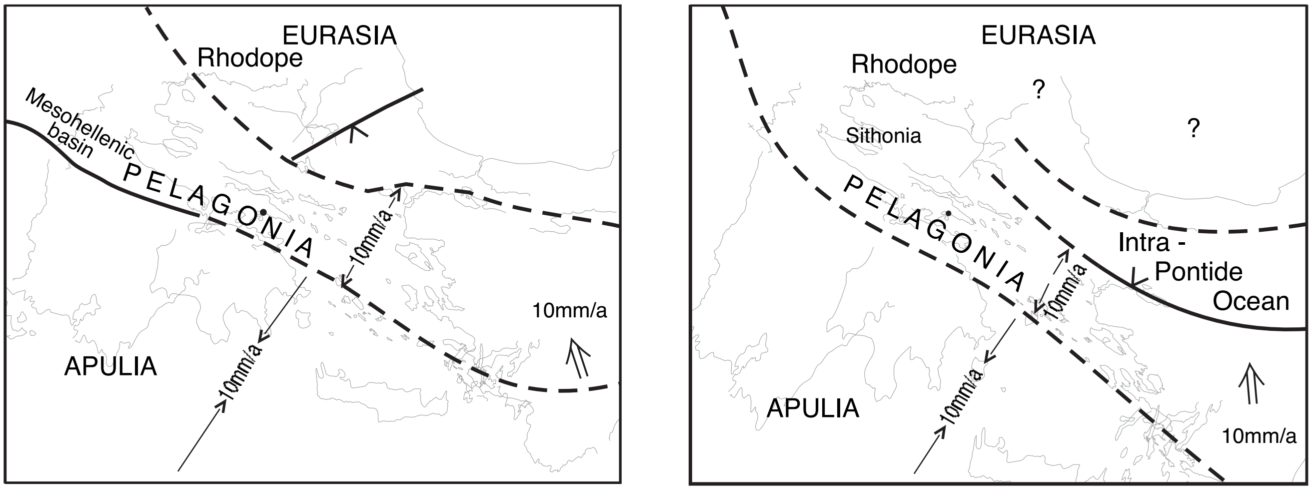
Phase I, 0-5 Ma, Pliocene - Quaternary

Phase II, 5-12 Ma, Late Miocene



Phase III, 12-17 Ma, Middle Miocene

Phase IV, 17-24 Ma, Early Miocene



Phase V, 24-35 Ma, Oligocene

Phase VI, 35-50 Ma, Middle to Late Eocene

Figure 2. Summary of the operations used to prepare paleogeographic reconstructions. The solid lines indicate block boundaries, the dashed lines uncertain boundaries. Extension, compression, translation, and rotation rates used in reconstructions are shown. For further explanation, see text.

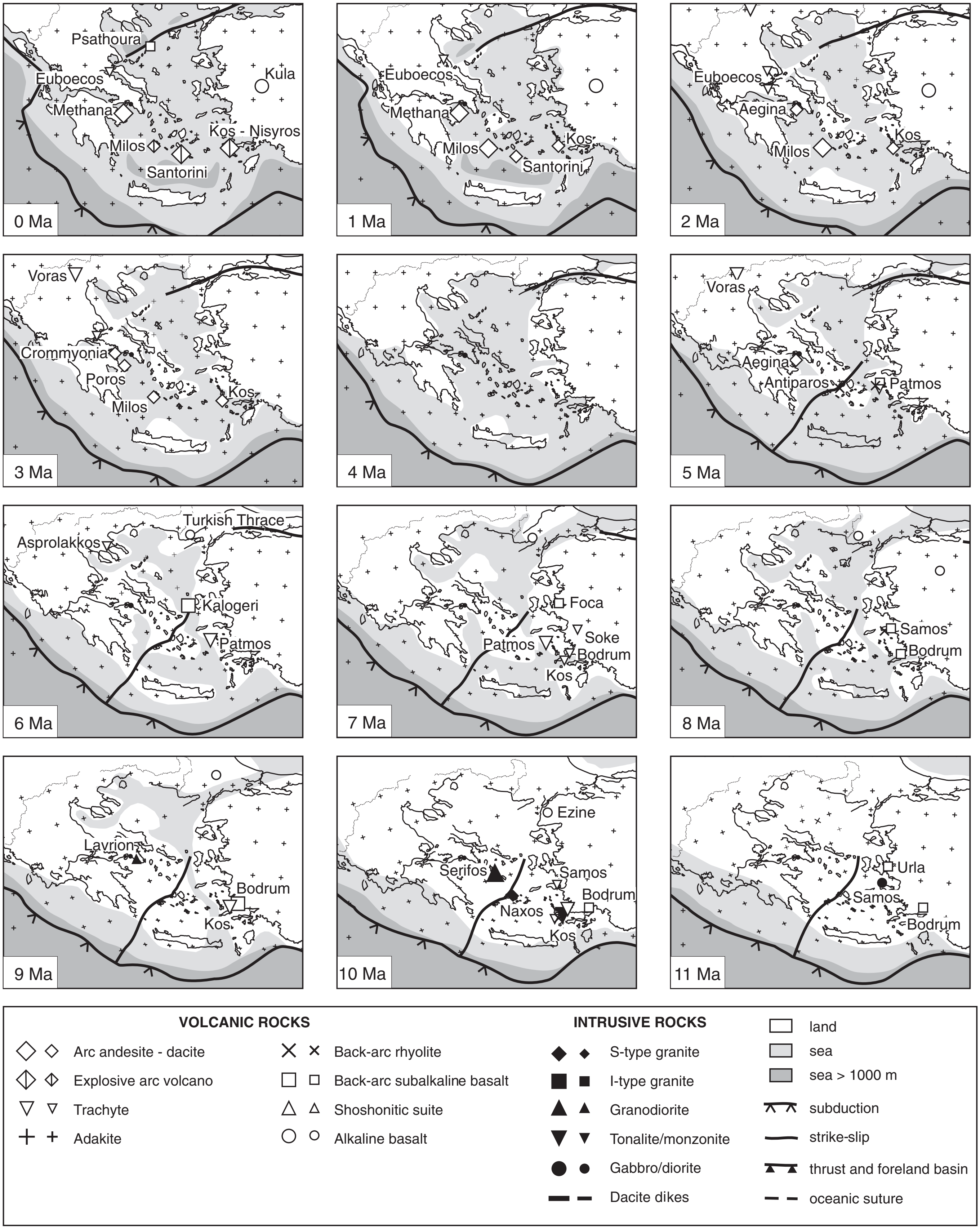


Figure 3. Paleogeographic reconstructions and the distribution of igneous rocks for the period 0–12 Ma. The ages and types of magmatism are summarized from Pe-Piper and Piper (2002). The sizes of symbols indicate the approximate relative sizes of the igneous bodies.

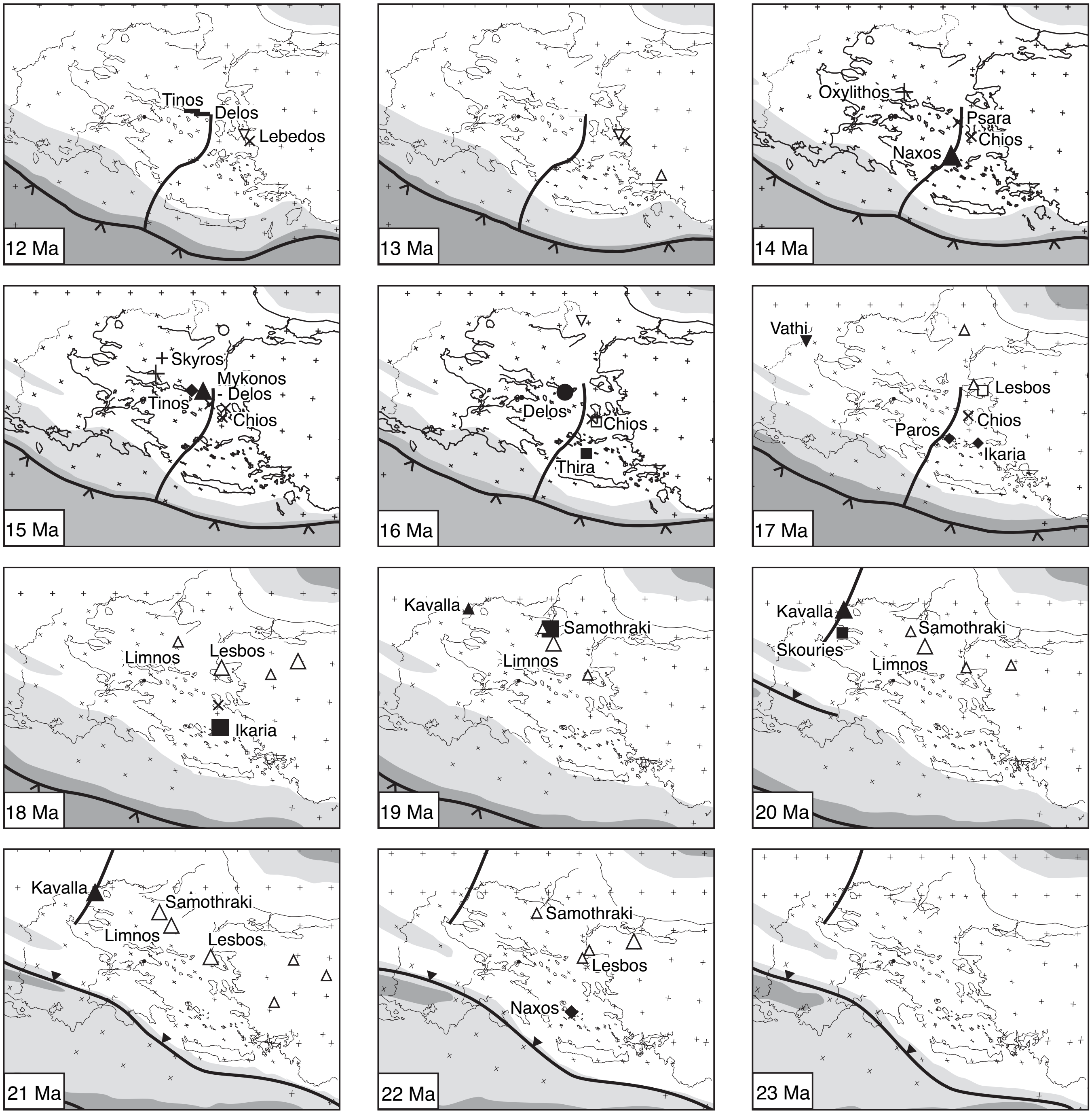


Figure 4. Paleogeographic reconstructions and the distribution of igneous rocks for the period 12–23 Ma. The ages and types of magmatism are summarized from Pe-Piper and Piper (2002). See Figure 3 for symbols.

Phase IV: Early Miocene

In the early Miocene, orthogonal convergence between Gondwana and Eurasia resumed. Blueschist metamorphism near the margins of the present Aegean block, exhumed in a subduction extruding wedge, provides independent confirmation of the plate convergence. North-northeastward translation of the Africa plate is believed to have taken place at 10 mm/yr. Compression of the External Hellenides continued. There was already collision of Arabia with eastern Anatolia, but oceanic subduction was active south of Cyprus, at least in the early Miocene (Robertson, 2000). Widespread north-south extension

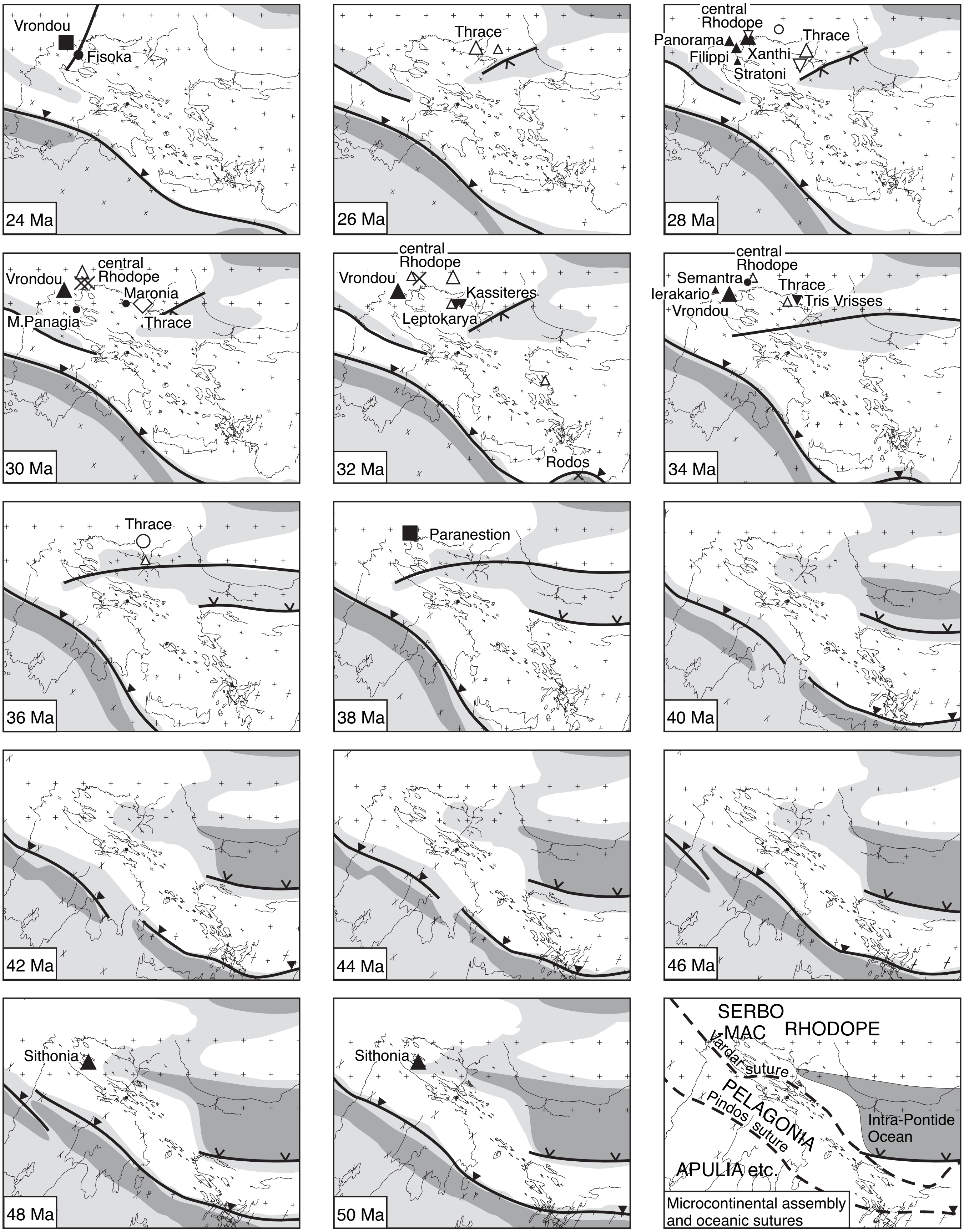


Figure 5. Paleogeographic reconstructions and the distribution of igneous rocks for the period 24–50 Ma. The ages and types of magmatism are summarized from Pe-Piper and Piper (2002). See Figure 3 for symbols.

began in the early Miocene in the Aegean Sea region (Gautier and Brun, 1994) and in northern Greece (Dinter, 1998). There was less extension at this time in western Anatolia, although north-south-trending grabens developed (Yılmaz et al., 2000), parallel to those in northern Greece (Schröder, 1986). Burchfiel et al. (2000) argued that this extension was unrelated to previous back-arc extension. The apparent increase in extension rate has been modeled by applying an extension of 20 mm/yr in northern Greece. At some time in the Miocene, motion across the mid-Cycladic lineament was initiated as a result of rotation of the west Aegean block with respect to the more easterly parts of the Aegea-Anatolia microplate. When this motion began is uncertain (Walcott and White, 1998), but it may have been initiated with the oldest evidence of Cycladic plutonism (migmatite >20.7 Ma in Naxos, Keay et al., 2001; 18.1 Ma in Ikaria, Altherr et al., 1982; Fig. 4) and rapid extension (early Miocene basin in Naxos; development of the Cretan detachment, Gautier and Brun, 1994). A rate of rotation half that for the middle Miocene, when motion across the mid-Cycladic lineament is much more evident, has been applied to the west and southeast Aegean blocks.

Phase III: Middle Miocene

In the middle Miocene, at ca. 17 Ma, there were fundamental changes in the tectonic style in the Aegean region, with the formation of the Strymon detachment in northern Greece (Dinter, 1998) and the termination of shoshonitic volcanism in the northeastern Aegean. Rapid extension continued in the southern Aegean, resulting in the rapid unroofing of blueschists in Crete (zircon fission track ages of ca. 19 Ma and apatite fission track ages of 14 Ma, Thomson et al., 1998; D2 event of Fassoulas et al., 1994). Paleomagnetic data clearly establish that there was rotation of the west Aegean block relative to the east Aegean block along the mid-Cycladic lineament (Walcott and White, 1998). Application of these rotations to the paleogeographic reconstruction in this and later phases results in distributed extension in the central Aegean region.

Phase II: Late Miocene

The mid-Tortonian, at ca. 10 Ma, was a time of change in tectonic style throughout the Aegean (Le Pichon and Angelier, 1979), including northeast-southwest compression in Crete that affected sediments as young as latest Serravallian–early Tortonian (12–11 Ma) (Meulenkamp and Hilgen, 1986; phase 1 of ten Veen and Meijer, 1998). In western Anatolia, east-west graben began to form on the upper-crustal blocks of a major extensional detachment system. Paleomagnetic data suggest that the rotation rate of the west Aegean block may have increased at this time. Paleomagnetic data from Anatolia suggest that rotation likely began in the late Miocene (Platzman et al., 1998; but see Kissel et al., 2003, for a contrary interpretation). Detachment of Arabia from Africa and its faster northward motion along the Dead Sea fracture zone started at ca. 12 Ma (Garfunkel, 1981). Some authors (e.g., Savostin et al., 1986) have interpreted a pronounced change in convergence direction between Africa and Eurasia at magnetic anomaly 5 at this time, but this is less clear in more recent compilations (Rosenbaum et al., 2002).

Phase I: Pliocene–Quaternary

At ca. 5 Ma, westward propagation of the North Anatolian fault reached the northeastern Aegean and relative motion across the mid-Cycladic lineament ceased to be important (Walcott and White, 1998). The Pliocene-Messinian unconformity in Crete marks a change in tectonic style at this time (ten Veen and Meijer, 1998). Nevertheless, the paleomagnetic data reviewed by Walcott (1998) indicate that some continuing rotational deformation took place within the former west and southeast Aegean blocks, but with deformation across new active faults becoming increasingly important. These new faults were related to the propagation of the North Anatolian fault. Block rotation also continued in northwestern Greece (10°–15° clockwise; Kissel and Laj, 1988) as a result of collision with the Apulian block. Roll-back took place all along the subduction zone and has been approximated in the reconstructions by rapid extension of the south Aegean region and rotation of the Aegea-Anatolia microplate. There is a pronounced change in the dip of the tomographically imaged subducted slab at ~150 km depth, which at the present geodetically determined rates of convergence of the Africa and the Aegea-Anatolia plates (McClusky et al., 2000) would have started to subduct at ca. 4.5 Ma. Further changes in faulting and subsidence in the Quaternary resulted from collision of the Aegean block with African continental crust (Piper and Perissoratis, 2003) and westward propagation of the North Anatolian fault (Armijo et al., 1999). Widespread subsidence throughout the Aegean (Piper and Perissoratis, 1991; Anastasakis and Piper, 2005) provides evidence of regional extension.

Distribution of Igneous Rocks

The distribution of igneous rocks in relation to the paleogeographic reconstructions is shown in Figures 3–5. There are several published summaries of Cenozoic igneous rocks in Greece (e.g., Fytikas et al., 1984; Pe-Piper and Piper, 1989, 2001, 2002; Christofides et al., 1998b), so we present only a very brief summary of the major features of igneous rock distribution. In Greece, most volcanic rocks are sufficiently well dated that they can be fitted into the 1 or 2 m.y. time slices shown in Figures 3–5; the exceptions are the Miocene plutons of the Cyclades, for which some estimation (following Altherr et al., 1982) has been necessary.

We have deliberately used the associations of rock types shown in Figure 6, which have implications of petrogenetic affinity, rather than a simple application of the International Union of Geological Sciences system of nomenclature. This is

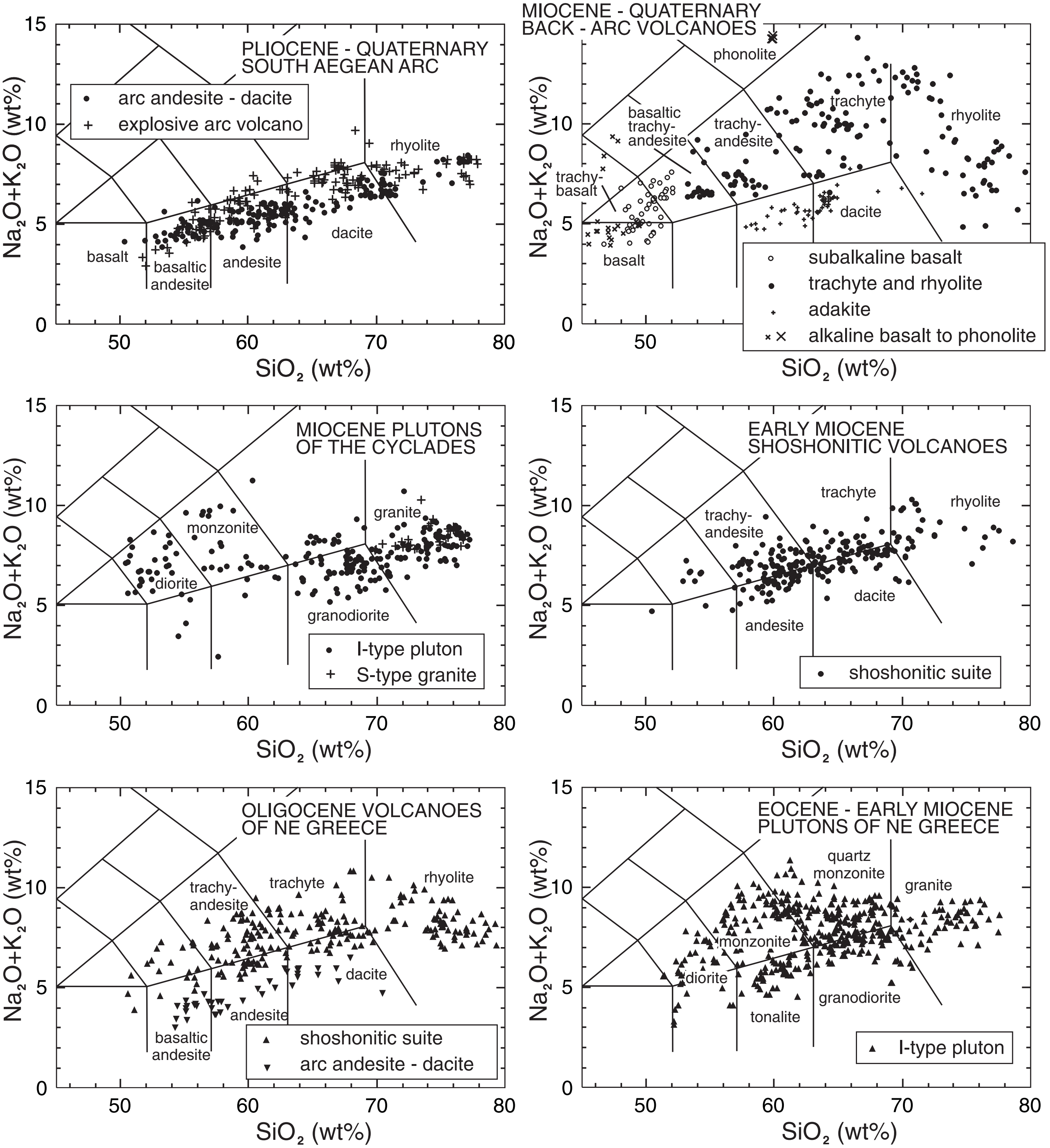


Figure 6. International Union of Geological Sciences nomenclature showing the range of compositions for each of the genetic petrologic types distinguished in this study. The data sources are summarized in Pe-Piper and Piper (2002).

in part to provide a more synthetic analysis of the distribution of rock types and in part because variations in total alkalis and silica alone do not adequately differentiate between rocks that have quite different origins based on trace-element and isotopic data.

In the Pliocene–Quaternary, arc-related calc-alkaline rocks are widespread in the South Aegean arc. Two associations are recognized: classical subduction-related andesites and dacites, principally in the western arc, and more complex volcanoes with abundant explosive volcanism in the eastern arc (Pe-Piper and Piper, 2006). Minor alkaline volcanism (ranging from basalt to phonolite) was active in western Anatolia from the late Miocene to the Quaternary (Aldanmaz et al., 2000). Small-volume volcanism of varied character, but principally trachytic, was active in the "back-arc" region from the middle Miocene to the Quaternary (Pe-Piper and Piper, 1989, 2002). The back-arc rocks also include rhyolite and subalkaline basalt (to trachybasalt). In the Miocene, I-type plutons (principally of monzonite to granodiorite composition) were emplaced at mid-crustal levels in the Cyclades and have been exhumed as a result of widespread extension; minor S-type intrusions are also recognized (Altherr et al., 1982; Pe-Piper et al., 2002). Early Miocene shoshonitic volcanism is restricted to the northeastern Aegean and northwestern Anatolia (Pe-Piper and Piper, 1992; Aldanmaz et al., 2000). It is more voluminous and less alkaline than the back-arc trachytes. A few I-type plutons of the same age are found in northern Greece. Oligocene shoshonitic volcanic rocks as well as minor calc-alkaline lavas and related I-type plutons were emplaced in an extensional strike-slip environment (Koukouvelas and Pe-Piper, 1991). The early Eocene Sithonia and related plutons (Christofides et al., 2001), with I-type geochemistry ranging from gabbro to leucogranite, were also emplaced in a strike-slip environment.

GEOCHEMICAL TYPES OF IGNEOUS ROCKS

Relationship between Geodynamic Context, Petrogenesis, and Geochemistry

The Aegean region has been inboard from the subduction of Africa beneath the Aegea-Anatolia microplate throughout the Cenozoic and has experienced "back-arc" extension throughout most of this time. Figure 7 illustrates the principal processes by which magma is generated in such a setting.

During subduction, dehydration of the subducting oceanic crust and upper mantle releases water and large-ion lithophile elements (LILE), which rise through the subarc asthenospheric mantle wedge, where they trigger voluminous hydrous partial melting. The resulting magma rises and may fractionate and assimilate country rock within the overlying subcontinental lithospheric mantle, at the base of the crust, and within midcrustal magma chambers. Arc magmas show strong depletion in Ti, Ta, and Nb (Fig. 8), which under hydrous conditions are thought to be retained in residual phases in the mantle, but enrichment in LILE, including the light rare earth elements (LREE; Fig. 9). Primitive magmas retain a strong asthenospheric isotopic signature (e.g., Santorini and Nisyros in Fig. 10), but in many arc magmas this is modified by assimilation as the magma rises (other south Aegean arc localities in Fig. 10).

Partial melting of the subcontinental enriched lithospheric mantle may take place if the geothermal gradient increases and the temperature rises. This may occur either as a result of upwelling of asthenosphere following lithospheric delamination or slab break-off or as a result of rapid crustal extension. In the Aegean area, the subcontinental lithospheric mantle is highly enriched in LILE as a result of older subduction (Pe-Piper and

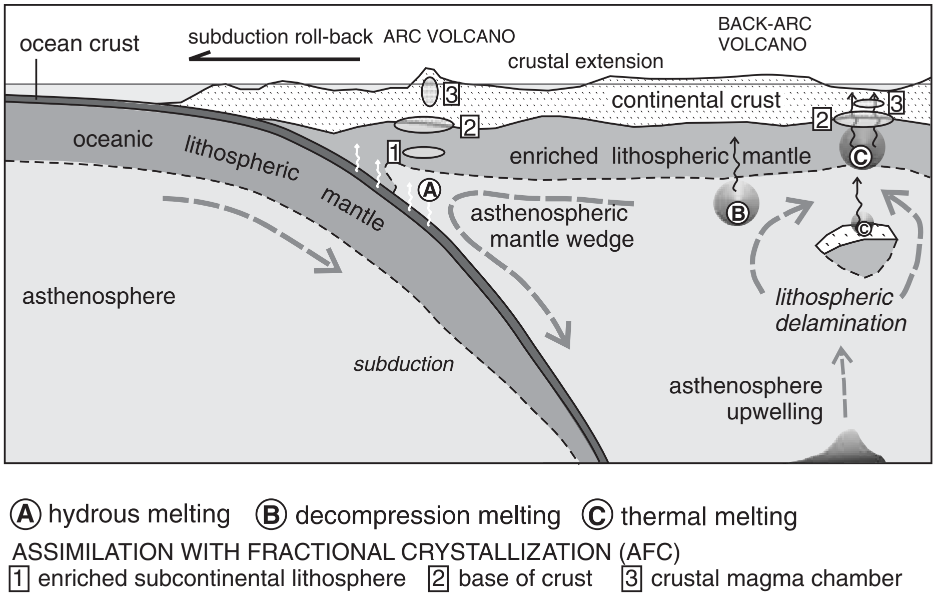


Figure 7. Cartoon showing the relationship between subduction, lithospheric delamination, back-arc extension, and magma generation.

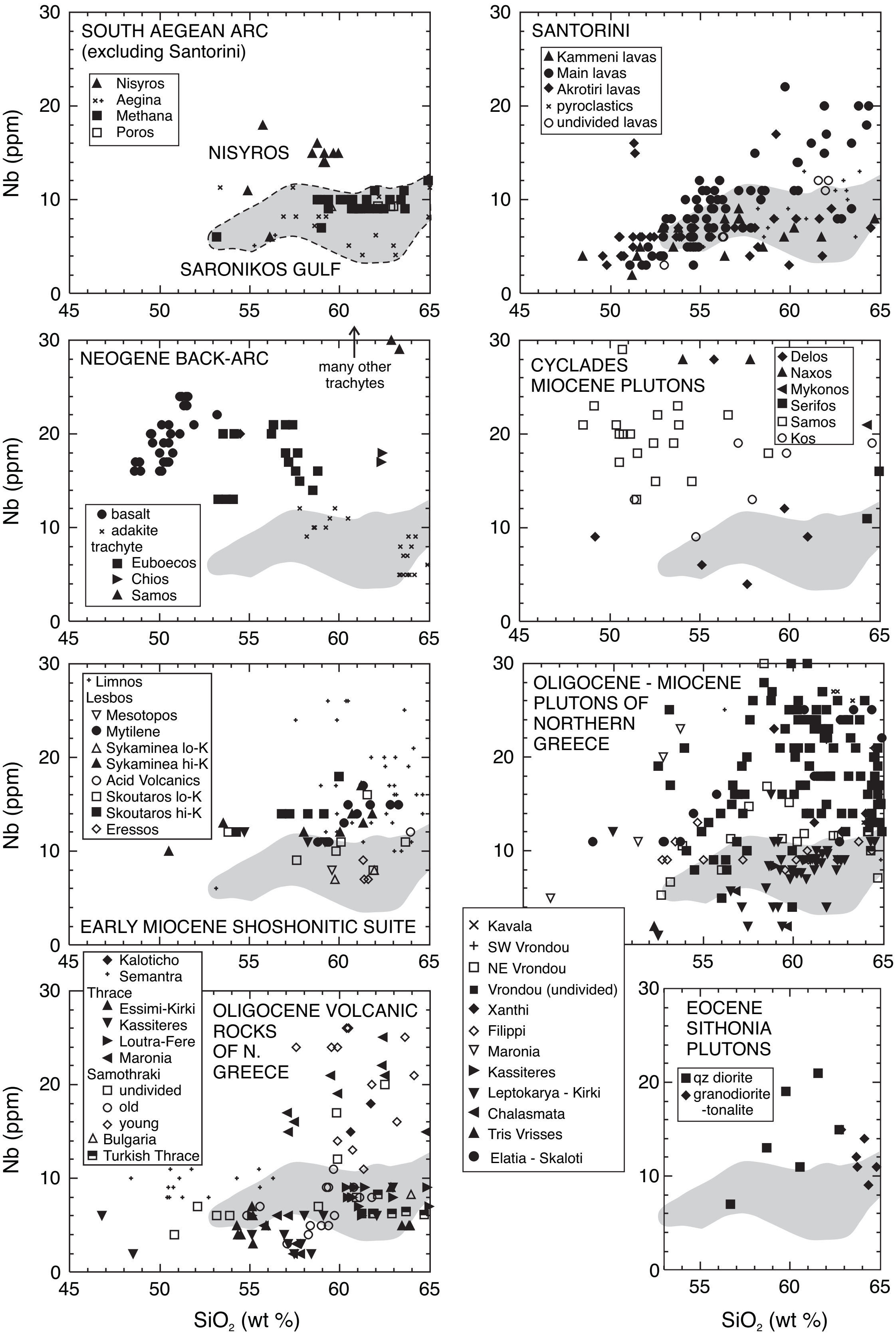


Figure 8. Variation of Nb with SiO_2 for various groups of Cenozoic mafic and intermediate rocks from the Aegean region. The data sources and details of the symbols are summarized by Pe-Piper and Piper (2002). The gray tone indicates the field for subduction-related rocks of the western south Aegean arc.

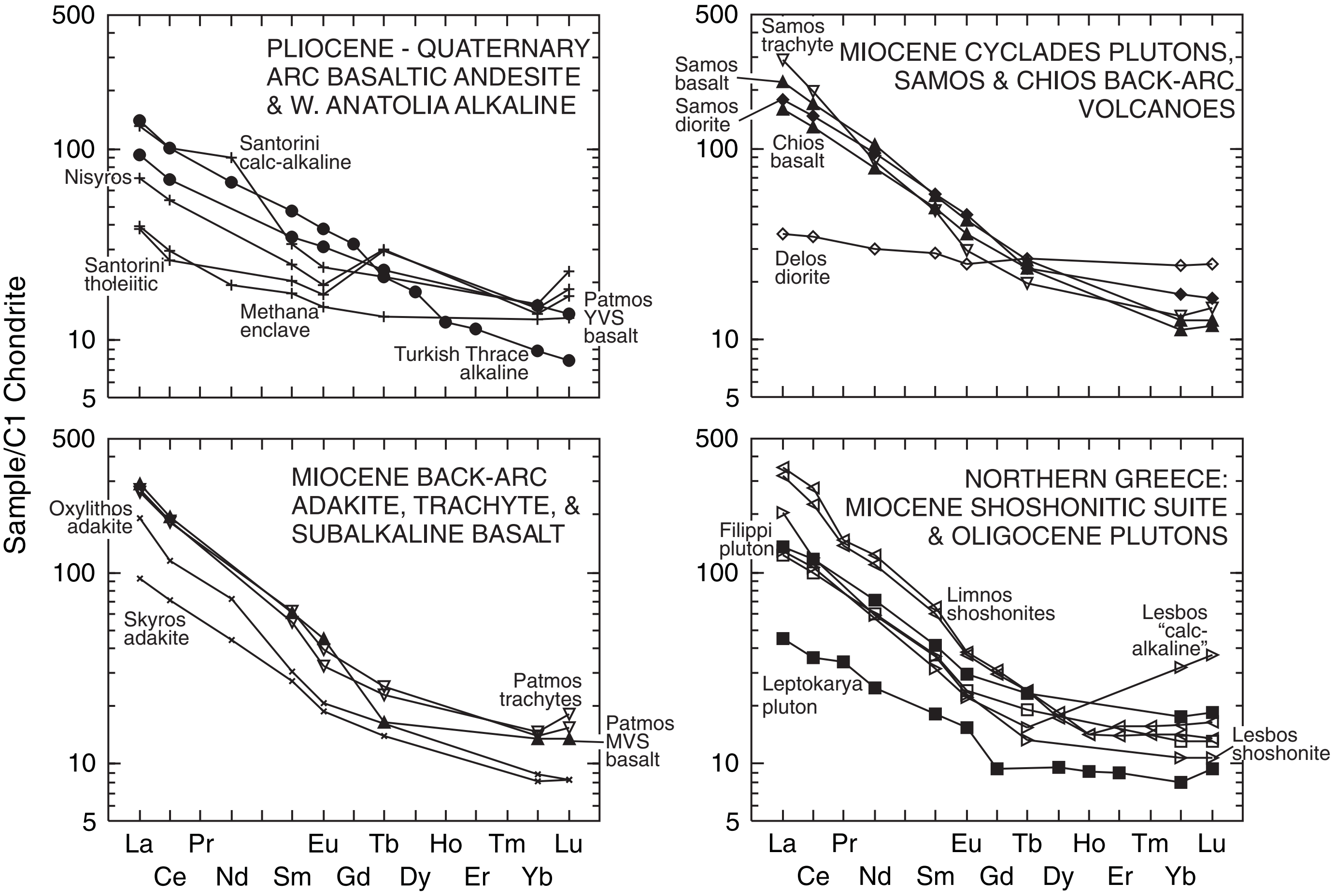


Figure 9. Rare-earth-element patterns for selected mafic and intermediate igneous rocks. The solid symbols represent rocks with <53% SiO_2, the open and line symbols rocks with 53%–63% SiO_2. The data sources are summarized by Pe-Piper and Piper (2002). MVS—main volcanic series; YVS—young volcanic series.

Piper, 2001). Such lithospheric mantle is likely very inhomogenous compared with convecting asthenosphere and in particular is variably hydrated. Thermally induced melting of crustal material may also take place if detached lithosphere sinks into the asthenosphere, with melting of metabasalt (eclogite) producing adakitic magmas. Once again, rising magma may interact with both lithospheric mantle and crust. Partial melting of relatively anhydrous enriched lithospheric mantle commonly takes place at >70 km depth, resulting in a characteristic REE pattern as a consequence of partial melting in the stability field of garnet (Fig. 9). Radiogenic isotopes reflect the effects of earlier subduction on the source mantle and include Pb isotopes with high $^{207}Pb/^{204}Pb$ (Fig. 11) resulting from an increase in Th/Pb ratio during an older subduction event (>1 Ga; Pe-Piper, 1994).

Decompression melting of upwelling asthenosphere, resulting either from small thermal plumes or from upwelling induced by lithospheric delamination with small amounts of partial melting, results in alkali basalts and their differentiates. Such rocks have asthenospheric compositions of radiogenic isotopes (Figs. 10 and 11) and an abundance of incompatible elements, including Nb.

Five Major Groups of Volcanic Rocks

Arc Calc-alkaline Volcanism. Andesite-dacite from the western part of the south Aegean arc shows classical calc-alkaline geochemical characteristics, including 1–3% K_2O; enrichment in LILE; low Nb, Ta, and Ti; and hydrous phenocrystal minerals. REE are less fractionated (Fig. 9) compared with shoshonites, trachytes, and adakites, with similar SiO_2 content, as discussed later. In the eastern part of the arc, Quaternary volcanism at Milos, Santorini, and Kos has been more explosive, with a higher proportion of dacite and rhyolite pyroclastics (Pe-Piper and Piper, 2005). At Santorini, both calc-alkaline and tholeiitic basalts are present (Druitt et al., 1999). Some Oligocene volcanic rocks from Thrace (the Essimi-Kirki basin,

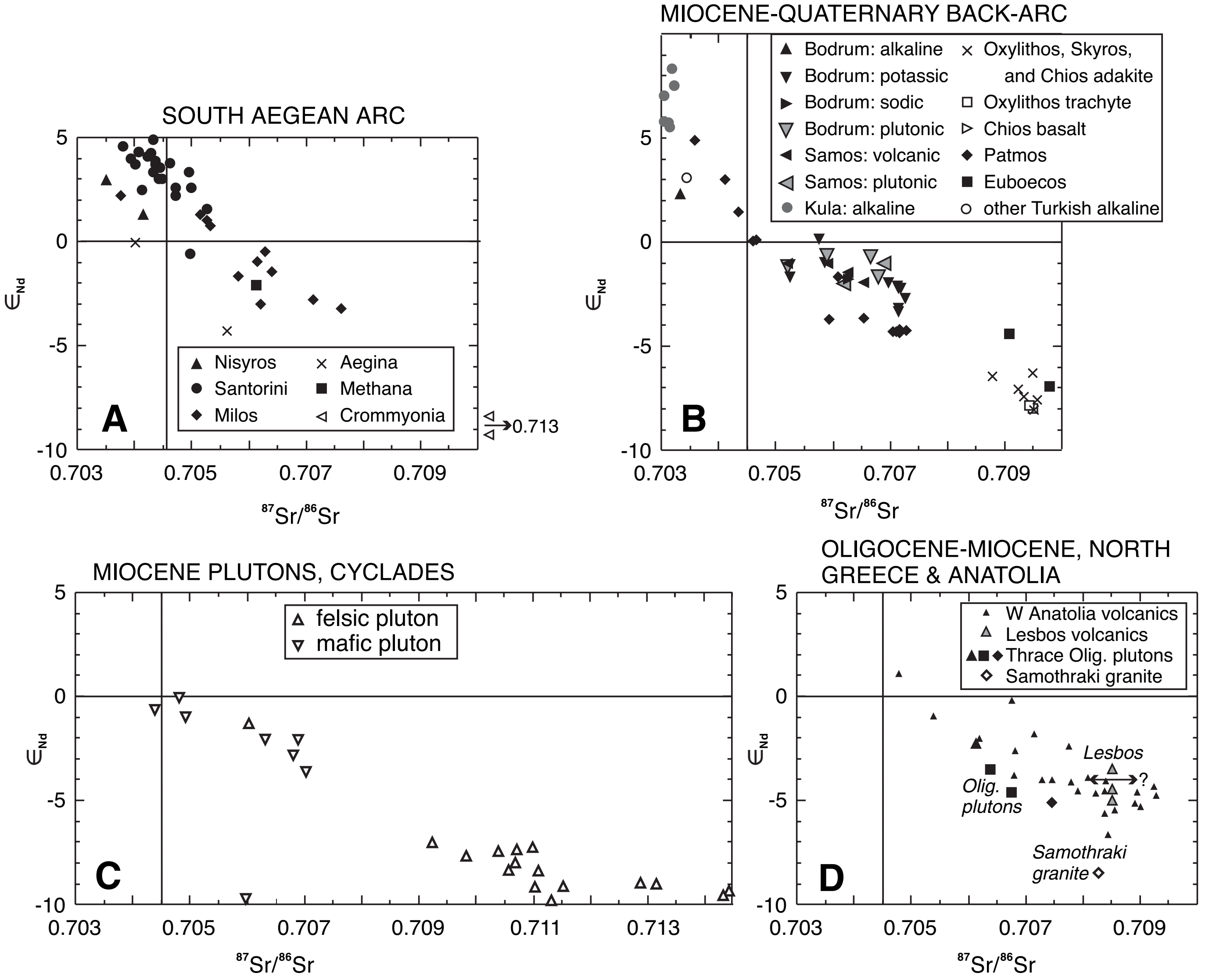


Figure 10. Nd and Sr isotope compositions for the Cenozoic igneous rocks of Greece. The data sources are given in Pe-Piper and Piper (2002); the data on the Cyclades are from Altherr and Siebel (2002).

Kassiteres, Arikas and Voudouris, 1998; Turkish Thrace, Yılmaz and Polat, 1998; see Fig. 5) have geochemical characteristics similar to those of the western part of the south Aegean arc. Plots of alkalis versus silica and multielement plots normalized to primitive mantle are shown in Pe-Piper and Piper (2002, their Figs. 169–171; cf. their Figs. 275–276). In this article, we use the abundance of Nb, which is highly depleted in magmas derived from hydrous melting in the asthenospheric wedge, to characterize calc-alkaline arc-related magmas (Fig. 8). In the south Aegean arc, Nd, Sr, and Pb isotopes (Figs. 10 and 11) vary widely. Primitive asthenospheric magmas at Santorini and Nisyros have positive Nd and low initial Sr^{87}/Sr^{86} ratios, whereas magmas from the western part of the arc show the much greater influence of the overlying lithospheric mantle and crust (Pe-Piper and Piper, 2005).

Shoshonitic Volcanism. The shoshonitic rocks are highly enriched in LILE and in radiogenic Pb isotopes (Fig. 11), suggesting derivation from subcontinental lithosphere enriched by previous subduction, with the Pb isotope characteristics inherited from Proterozoic subduction (Pe-Piper and Piper, 2001). The Nd and Sr isotopes (Fig. 10) are quite different from those of arc calc-alkaline rocks and also indicate a source in enriched mantle. The REE patterns (Fig. 9) are characteristic of the partial melting of garnet peridotite. On the island of Lesbos, shoshonitic rocks are interbedded with lavas with more calc-alkaline characteristics, including less enrichment in K, the pres-

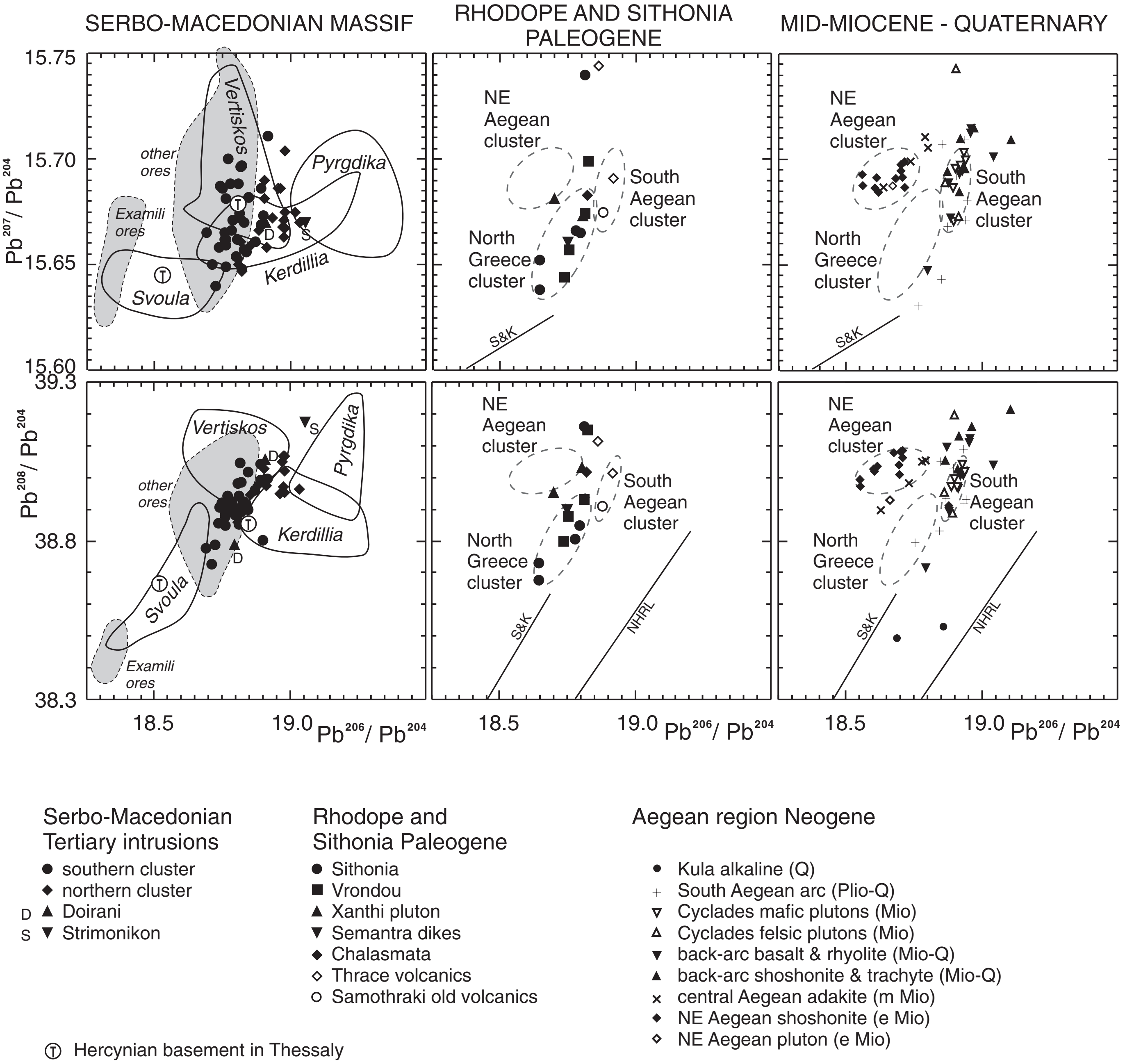


Figure 11. Variation in Pb isotopes in the Cenozoic igneous rocks of Greece. The data on the basement rocks and ores of the Serbo-Macedonian massif are from Frei (1992). NHRL—Northern Hemisphere reference line of Hart (1984); S&K—reference growth curve of Stacey and Kramers (1975). The geographic clusters of Pb isotope values are from Pe-Piper and Piper (2001).

ence of amphibole and biotite phenocrysts, relative depletion in middle REE (indicating that amphibole was a residual phase during partial melting; Fig. 9), and greater depletion in Nb (Fig. 8).

Back-arc Basalt, Rhyolite, and Trachyte Volcanism. The Neogene trachyte volcanism of the "back-arc" area is characteristically present in small volumes and has Pb, Nd, and Sr isotopes and trace elements suggesting a source in enriched subcontinental lithosphere. The trachytes thus show many geochemical similarities to shoshonitic suite, including similar REE patterns (Fig. 9) and radiogenic isotopes (Figs. 10 and 11), but are less depleted in Nb (Fig. 8).

At Patmos, Samos, Bodrum, and Chios, trachytes are spatially associated with subalkaline basalts (some Na-rich, some K-rich) and differentiation products such as mugearite and hawaiite at Kalogeri and Psathoura. On Samos, the geochemical and isotopic similarity of subalkaline basalt, diorite, and trachyte indicates a genetic relationship between these rock types (Pe-Piper and Piper, 2004). None of the back-arc subalkaline basalts resemble the alkali basalts of western Anatolia in trace elements or radiogenic isotopes (Figs. 10 and 11), except for the basalts of the young volcanic series of Patmos (Wyers and Barton, 1987).

Adakite Volcanism. The high-Mg andesite with high Sr/Y ratios (Fig. 12) at Oxylithos (Evia), Skyros, and Chios is quite unlike other back-arc volcanic rocks and has a chemistry and mineralogy indicating affinity with adakite (Drummond and Defant, 1990). Rhyolite from the same volcanic centers has a geochemistry similar to that of "volcanic-arc granites" (the nomenclature of Pearce et al., 1984). The Pb isotopic composition is similar to that of the northeast Aegean shoshonitic rocks (Fig. 11), whereas the Sr and Nd isotopes are very "crustal" (Fig. 9) and the Nb is highly depleted (Fig. 8). The REE patterns (Fig. 9) resemble those of shoshonitic rocks and trachytes inferred to be partial melts in the stability field of garnet.

Alkali Volcanism of Western Anatolia. The alkali volcanic rocks of western Anatolia (Güleç, 1991; Seyitoğlu et al., 1997; Aldanmaz et al., 2000) form an olivine basalt–tephrite–phonolite suite. The geochemistry is characteristic of an enriched mantle ("ocean-island basalt" or OIB) source, with high Nb, fractionation of REE (Fig. 9), high Nd and low initial $^{87}Sr/^{86}Sr$ (Fig. 10), and low $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ (Fig. 11).

Origin of Plutonic Rocks

Independent detailed studies of plutonic rocks of general I-type character of Eocene, Oligocene, and Miocene age suggest formation by mixing and fractional crystallization involving a mantle-derived mafic magma and voluminous crustal felsic magma. In their study of the Sithonia pluton, Christofides et al. (2004) have argued for a lower-crustal amphibolite source for felsic magma and a mantle source similar to the observed monzonitic enclaves. Christofides et al. (1998a) demonstrated a rather similar model for the Oligocene–Miocene plutons of northern Greece, with the mafic component enriched in many incompatible elements and perhaps having a complex multistage history. Altherr and Siebel (2002) have proposed a somewhat similar origin for the Miocene plutons of the central Cyclades, with the crustal source likely metaluminous graywacke. In every case, it is likely that the felsic magma is derived from multiple sources of quite variable character, as indicated, for example, by the variability in felsic sources in the Miocene of Naxos (Pe-Piper, 2000). There is currently insufficient isotopic data to systematically interpret the crustal sources of the

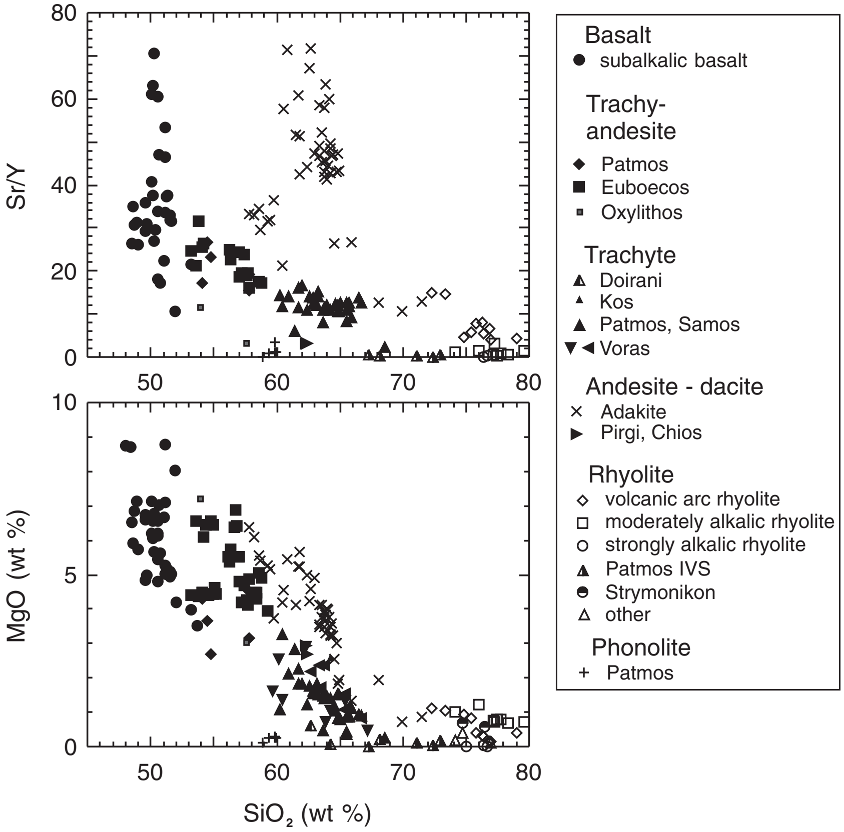


Figure 12. Plots of Sr/Y and MgO against SiO_2 for middle Miocene to Quaternary "back-arc" volcanic rocks showing the distinctive geochemical character of adakite (x) and associated "volcanic-arc" rhyolite. IVS—intermediate volcanic series.

Cenozoic plutonic rocks of Greece. On the other hand, it may be possible to compare the mafic component with mafic and intermediate volcanic rocks. A few mafic rocks closely resemble the arc magmas derived from hydrous melting of the mantle wedge (e.g., diorite from Delos, Fig. 9), but most are richer in incompatible elements, including Nb (Fig. 8), and resemble shoshonitic rocks and trachytes in their geochemistry (e.g., diorite from Samos; Pe-Piper and Piper, 2004).

RELATIONSHIP BETWEEN GEODYNAMICS AND IGNEOUS ROCKS

Southward Migration of the Subduction Zone and Volcanic Arc

The concept that there has been a southward migration of volcanism and the subduction zone throughout the Cenozoic in the Aegean region was stimulated by the reconstructions of Le Pichon and Angelier (1981) and was formulated most clearly in the review by Fytikas et al. (1984). Such a model overlooks the amount of middle Cenozoic compression that has taken place in the External Hellenides (Figs. 3 and 4). Even if the amount of compression were overestimated in our reconstructions, it is clear that with any reasonable dip on the subduction zone, the subduction of the Africa plate cannot be held responsible for subduction-related volcanism in the central and northern Aegean. If any arc-related volcanic rocks were formed, they would have been farther outboard, as proposed by Kuhlemann et al. (2004) from studies of the detrital petrology of the Miocene sediments of Naxos and as represented by the Oligocene Dali ash of Rodos.

Early Miocene Shoshonitic Rocks and Subduction

A corollary of the reinterpretation of the southward migration of the subduction zone and the volcanic arc is that it is unlikely that the early Miocene shoshonitic suite of the northeastern Aegean is related to active subduction. Pe-Piper and Piper (1992) argued that the presence of high-K calc-alkali rocks interbedded with shoshonites in Lesbos indicated some input of melts generated by hydrous melting of mantle. More recent work in Limnos (Innocenti et al., 1994) and western Anatolia (Aldanmaz et al., 2000) has shown that rocks with the calc-alkaline characteristics described earlier (relative depletion in middle REE and Nb) are very rare or absent in other volcanic centers. The rocks from Lesbos with calc-alkaline characteristics are thus not of regional extent and are therefore most readily explained as being derived from a rather wetter area of inhomogenous enriched mantle.

The most likely interpretation of the early Miocene shoshonitic suite is that partial melting of enriched mantle was a consequence of thermal melting following lithospheric delamination or slab break-off, as argued by Aldanmaz et al. (2000) and by Pe-Piper and Piper (2001). Because volcanism is of more limited extent than are extensional basins, we think extension alone (Dinter, 1998) is unlikely to have produced the conditions for magma melting.

Relationship between Miocene Shoshonitic Rocks, Adakites, and Alkali Basalts

The central and northeastern Aegean and the northwestern coast of Anatolia form a geographic region within which three distinctive rock types are found in the Miocene. In the most outboard position, mid-Miocene adakite is found in Oxylithos, Skyros, and Chios. Farther inboard, early Miocene shoshonitic rocks occur in Limnos, Lesbos, and northwestern Anatolia. In the most inboard position, late Miocene alkali rocks occur in Turkish Thrace and along the coast of northwestern Anatolia, with Pliocene to Quaternary alkali rocks from Patmos to Kula. This geographic relationship (Fig. 13) suggests a genetic relationship associated with a detached subducting slab or delaminated lithosphere, with the greatest thermal effect and mantle upwelling inboard from the crustal material that partially melted to produce adakite.

"Back-arc" Volcanism and Subduction

The presence in the Neogene "back-arc" area of adakite with some geochemical features similar to those of arc-related andesite and dacite and of trachytes with lower K content, referred to in the literature as calc-alkaline (e.g., Kolios et al., 1980), led in the past to exploration of the relationship between subduction and the "back-arc" volcanism. Pe-Piper and Piper (1989) compared the distribution of the subducted slab imaged by seismic tomography with the distribution of back-arc rocks and argued that there was a spatial relationship, implying continuing dehydration of the subducting slab at depth. Pe-Piper et al. (1994) pointed out that back-arc volcanism showed a clear temporal relationship to local basin subsidence, but that major extensional basins such as the Cretan Sea and the Orphanou basin lacked volcanism. They argued that the presence of the seismically imaged subducted slab implied that subduction played a role in magma genesis and attempted to correlate variable rates of subduction with variable rates of magma production.

Neither trace elements nor radiometric isotopes show any direct evidence that the back-arc volcanic rocks were related to magma generation from asthenosphere in the mantle wedge of a subduction system. If the petrogenesis of the early Miocene shoshonitic suite is unrelated to contemporaneous subduction, so is the petrogenesis of the back-arc rocks. Rather, they are the result of thermally induced small-volume partial melts in enriched subcontinental lithosphere resulting from regional crustal thinning by extension and are likely the effects of the lithospheric delamination inferred for the early Miocene shoshonitic magmas. The distribution of these rocks is strongly influenced by faulting, with a high proportion of back-arc rocks located

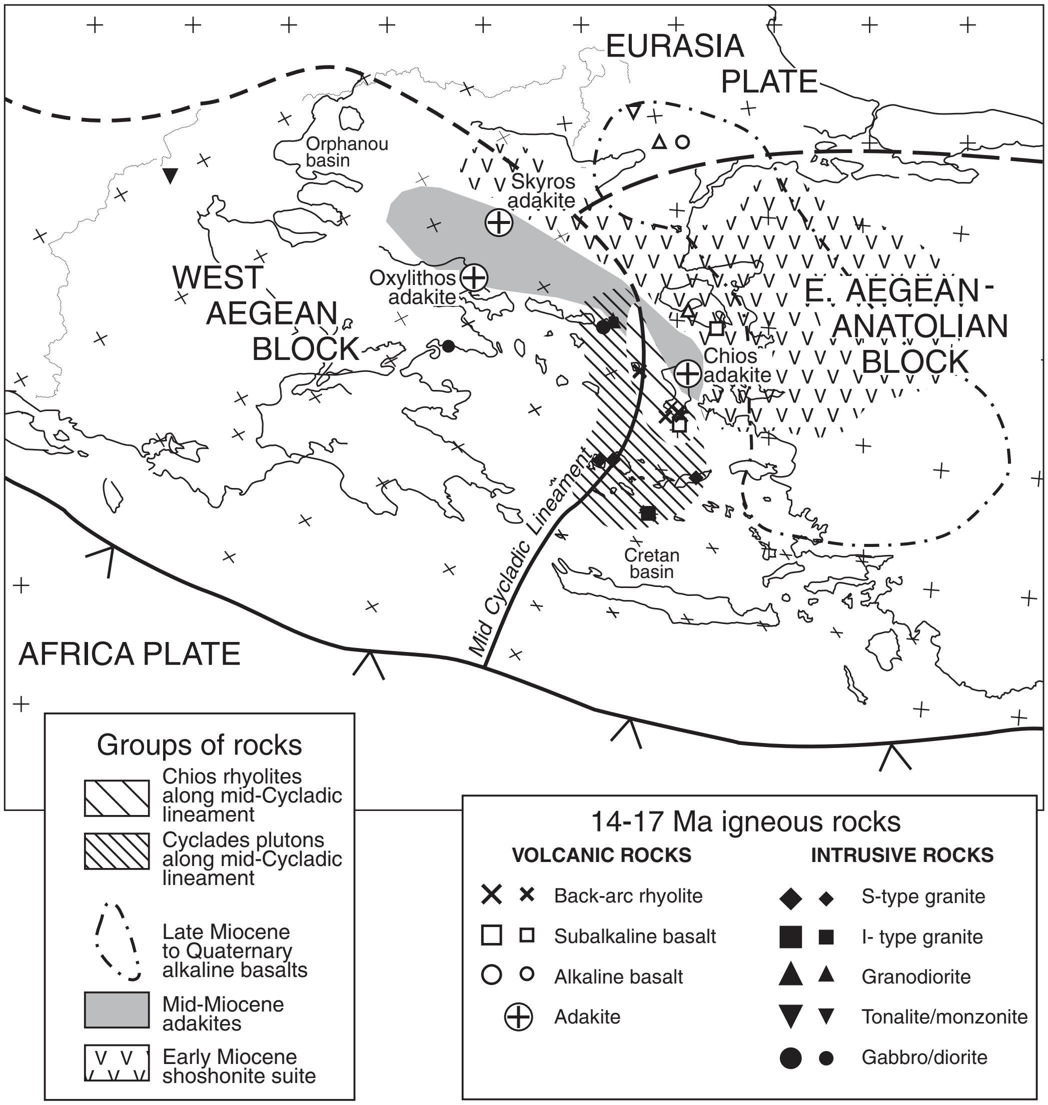


Figure 13. Mid-Miocene reconstruction (14–17 Ma) showing the concentration of igneous activity around the margins of the west Aegean and east Aegean blocks and the general coincidence of early Miocene shoshonites, late Miocene to Quaternary alkaline rocks, and adakites.

along the faulted margins of the west Aegean and east Aegean blocks recognized by Walcott and White (1998; Fig. 13). The notable exceptions are Psathoura and Euboecos, which appear related to the Pliocene–Quaternary prolongation of the North Anatolian fault into the northern Aegean (Fig. 14).

Oligocene Volcanism of Northern Greece

Oligocene volcanism in Macedonia and Thrace, and its northward continuation in Bulgaria, is geochemically and geographically related to Oligocene plutonism (e.g., Fig. 8; reviewed in Pe-Piper and Piper, 2002, Chap. 7). Burchfiel et al. (2000) suggested that it originated from subduction and is related to the final northward subduction of the Vardar zone. As noted by Innocenti et al. (1984) and confirmed by the more recent analyses of Arikas and Voudouris (1998), two types of intermediate volcanic rocks are present, one with high K and P (shoshonitic, e.g., at Maronia) and the other with lower K and P (calc-alkaline, e.g., at Kassiteres and Essimi-Kirki). In addition, slightly younger (28–26 Ma) alkali basalt is found in central Bulgaria (Marchev et al., 1998). This association of shoshonitic rocks with some more calc-alkaline rocks, followed by alkaline basalt, is similar to the association in the Miocene of the northeastern Aegean and northwestern Anatolia and can be interpreted in a similar manner. The Oligocene volcanism of Rhodope is interpreted to have resulted from lithospheric de-

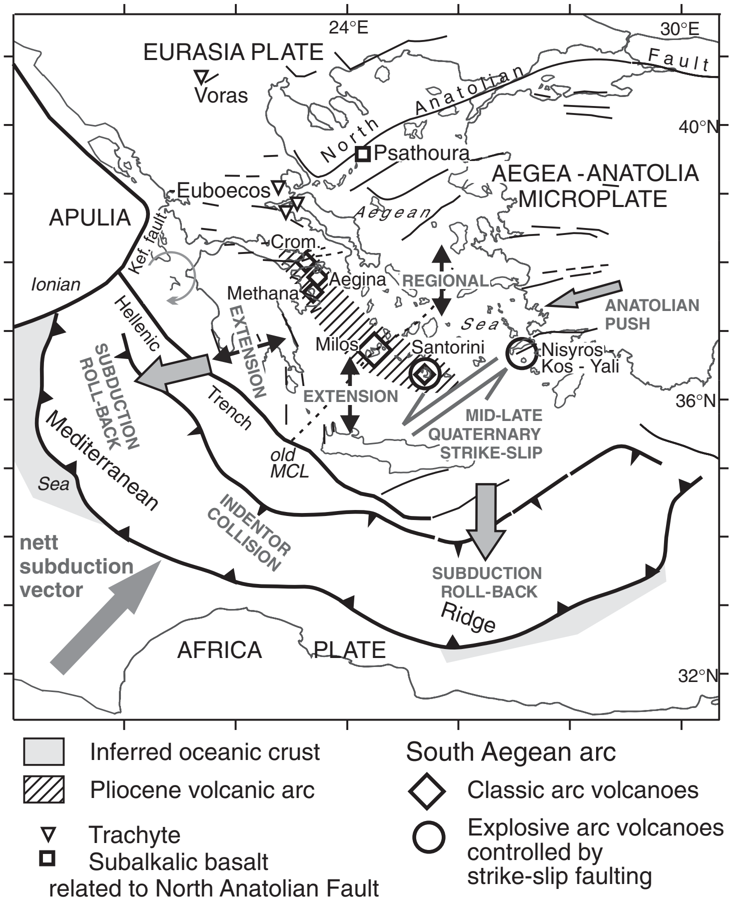


Figure 14. Modern tectonics of the Aegean region showing the relationship of Pliocene–Quaternary volcanism to faulting and subduction.

lamination or slab break-off involving the subduction of the Vardar ocean northward beneath the thickened Rhodope orogen. So the Miocene volcanism of the northeast Aegean may have resulted from the effects of delamination or slab break-off from the next outboard subduction system, that related to the subduction of the Pindos Ocean beneath the Pelagonian orogen.

The calc-alkaline rocks of Rhodope are more voluminous than the calc-alkaline rocks associated with shoshonitic rocks in Lesbos. We do not know if they result from hydrous melting of the subarc asthenospheric wedge or from thermally induced melting of more hydrated parts of the subcontinental lithosphere. Good-quality geochemical data are sparse, but the Pb isotope compositions and Ce/Sr ratio (Pe-Piper and Piper, 2002, their Fig. 177) suggest the former. The paleogeographic reconstruction (Fig. 15) suggests that, if they are related to subduction, they likely result from the final northward subduction of the Intra-Pontide Ocean, which Görür and Okay (1996) interpreted as closing in the Oligocene. Probable subduction-related Oligocene volcanism is also recognized south of the Intra-Pontide Ocean in Limnos and the Biga Peninsula (Ercan et al., 1995). Final closure of this ocean may account for the termination of strike-slip faulting in the Mesohellenic basin, very active in the early Oligocene, and the development of almost orthogonal strike-slip faulting along the Kavalla-Komotini trend, probably in the middle Oligocene.

Can Subarc Hydrous Melting of Asthenosphere and Thermally Induced Melting of Lithospheric Mantle Coexist?

The paleogeographic reconstructions suggest that thermally induced melting of lithospheric mantle to produce the shoshonites of the northeast Aegean did not coexist with subarc hydrous melting of asthenosphere. The paleogeographic situation in the Oligocene of Rhodope is less clear, and the possibility of subduction-related generation of calc-alkaline magma cannot be ruled out. However, during the Miocene emplacement of the Cyclades plutons, the paleogeographic situation is well constrained, and, on the basis of their geographic relationship to the subduction zone of Africa beneath the Aegea-Anatolia microplate, the plutons' arc-related magmatism would be expected in the approximate area of the Cyclades plutons. Some of the plutons—for example, those in Kos and Samos—have mafic phases that are geochemically similar to those of back-arc trachytic volcanic rocks on the same islands and therefore appear to be the result of thermally induced melting of lithospheric mantle. The thermal anomaly is likely the result of both rapid

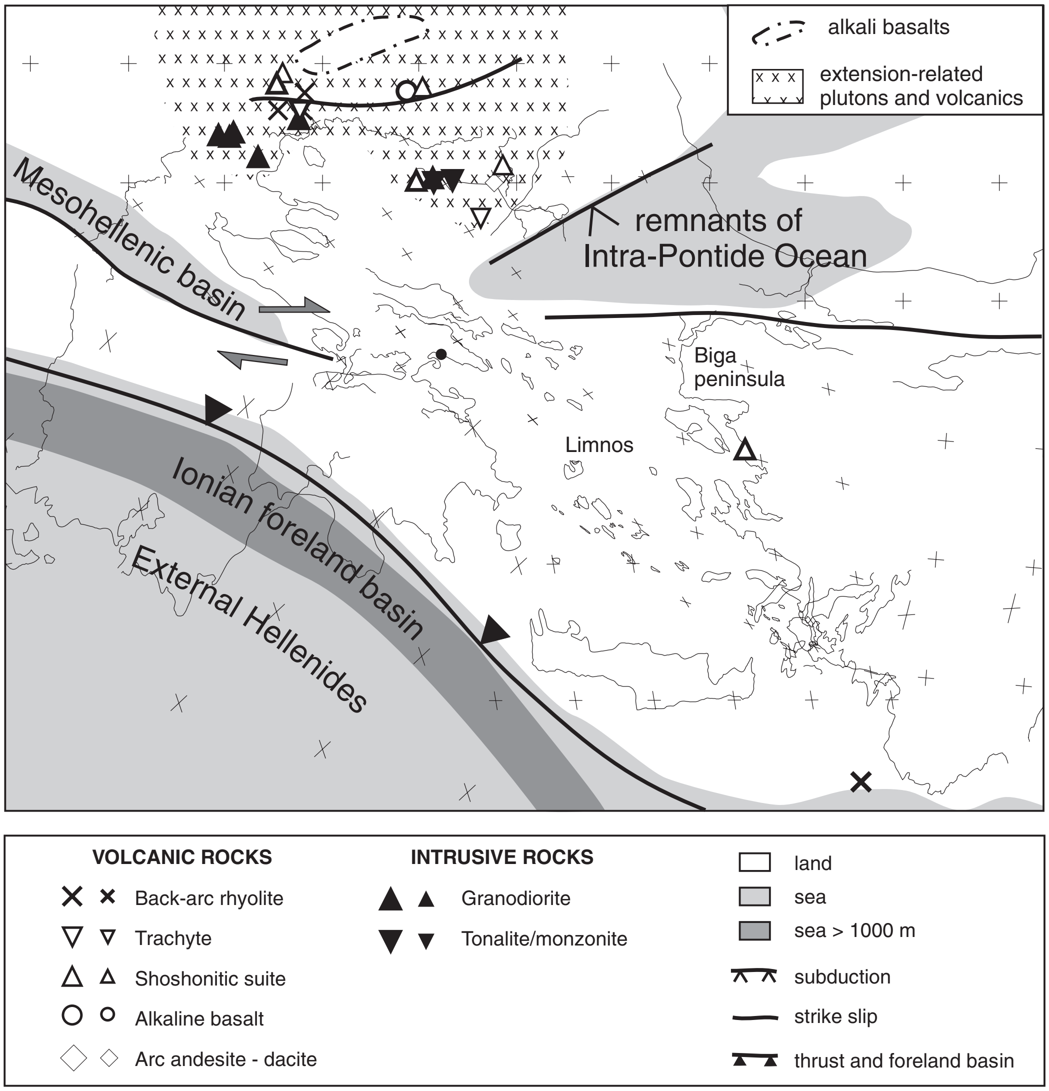


Figure 15. Early Oligocene reconstruction (28–32 Ma) showing the role of strike-slip faulting and of the Intra-Pontide Ocean.

extension that increased the geothermal gradient and upwelling of the asthenosphere that resulted in convective heating. In the central Cyclades—for example, in Delos—some mafic phases and enclaves are enriched in incompatible elements in a manner similar to those in Samos and Kos, whereas others have a more calc-alkaline character, reflected in low Nb in Figure 8 and the tholeiitic character of the REE patterns (Fig. 9). Geological evidence for the growth of plutons from numerous small magma batches is quite clear in Delos (Pe-Piper et al., 2002). On the basis of both paleogeography and geochemistry, it seems likely that both subarc hydrous melting of asthenosphere and thermally induced melting of lithospheric mantle contributed magma to crustal pathways along major shear zones. Nd and Sr isotope data (Fig. 10) clearly show that the Cyclades plutons have a much greater crustal component than the Paleogene plutons of Rhodope.

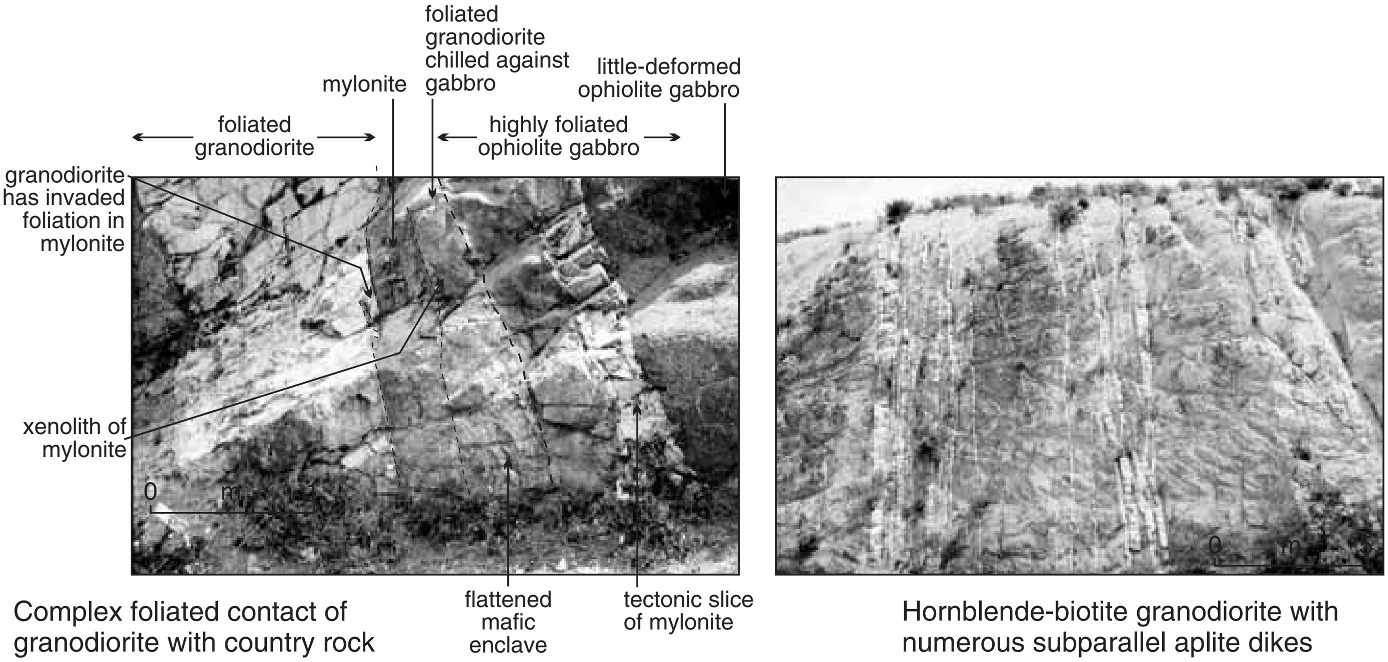
Influence of Strike-Slip Faulting on Volcanism

The paleogeographic reconstructions throw light on the conundrum raised by Pe-Piper et al. (1994) as to why minor back-arc volcanism appeared related to the margins of small active basins, but not to the major extensional basins (the Cretan Sea and the Thermaikos and Orphanou basins). A possibly analogous situation is observed on some rifted continental margins, where magmatism is seen not at the incipient oceanic rift but in more distant half-grabens and was ascribed by Sawyer and Harry (1991) to lateral migration of extension-related melts along brittle crustal faults. Most volcanism is related to strike-slip fault movement, which may also create rapid subsidence in small basins. Strike-slip faults provide ready pathways to deeper magma, and their importance is shown by the widespread occurrence of plutons with "dike to pluton" construction by successive magma pulses in many shear zones worldwide (Hutton and Reavy, 1992). Large-scale listric faulting does not provide the same pathways, and the large basins created by listric faulting (e.g., the Corinth basin, Sorel, 2000; the Cretan and Orphanou basins) lack back-arc volcanic rocks.

Strike-slip faulting has played a major role in localizing igneous activity throughout the Cenozoic of the Aegean region. Middle to late Quaternary strike-slip faulting in the eastern south Aegean arc led to the explosive volcanism of Kos and Santorini and to the extrusion of basalts at Santorini (Pe-Piper and Piper, 2005). By far the greatest volume of volcanic products in the south Aegean arc is at Milos (and its submarine continuation; Anastasakis and Piper, 2005), which is located on the old mid-Cycladic lineament (Fig. 14). Many of the major plutons of the Cyclades are emplaced in shear zones (Pe-Piper et al., 2002; Koukouvelas and Kokkalas, 2003). Back-arc basaltic volcanism in Samos is located along the strike-slip margins of late Miocene basins (Boronkay and Doutsos, 1994; Pe-Piper and Piper, 2004). Similar faulting subparallel to the regional extension direction localized back-arc mid-Miocene rocks of Chios and early Miocene shoshonitic rocks of Lesbos. Oligocene intrusions, such as the Xanthi pluton (Koukouvelas and Pe-Piper, 1991) and the stocks from Maronia to Tris Vrisses (Innocenti et al., 1984), parallel major strike-slip faults (Fig. 15), and the Eocene Sithonia plutons also appear to be of shear zone origin (Fig. 16).

The Greek Enigma

Fifteen years ago, de Boer (1989), in a paper titled "The Greek enigma . . . ," highlighted several features of the Aegean region that appeared inconsistent with Neogene subduction of the Africa plate. He proposed instead that much of the igneous activity was the result of obduction of asthenospheric mantle over an Africa plate that was almost stationary with respect to the Aegean block. It is useful to review the unusual features identified by de Boer in the light of subsequent work. Huguen et al. (2001) and other workers have shown that de Boer's concerns about the unusual character of the Hellenic trench were justified and that the subduction zone lies seaward of the accretionary prism of the Mediterranean Ridge (Fig. 1). De Boer (1989) argued that the South Aegean arc was unusual in lacking arc-tholeiites and low-K calc-alkaline rocks and in showing a decrease in the age of eruption toward the trench. Such low-K rocks are found in island arcs backed by oceanic crust, but in the case of the south Aegean arc, passage of magma through the enriched subcontinental lithosphere has increased the content of elements enriched by subduction processes, including K. The age trend of volcanism in the arc is equivocal: there is trenchward migration of 35 km from Crommyonia to Aegina to Methana and of 25 km from Kos to Nisyros, but the opposite is seen over 40 km from Christiani to Santorini to Columbo Bank



Complex foliated contact of granodiorite with country rock

Hornblende-biotite granodiorite with numerous subparallel aplite dikes

Figure 16. Photographs illustrating evidence for the shear-zone emplacement of the Sithonia plutons.

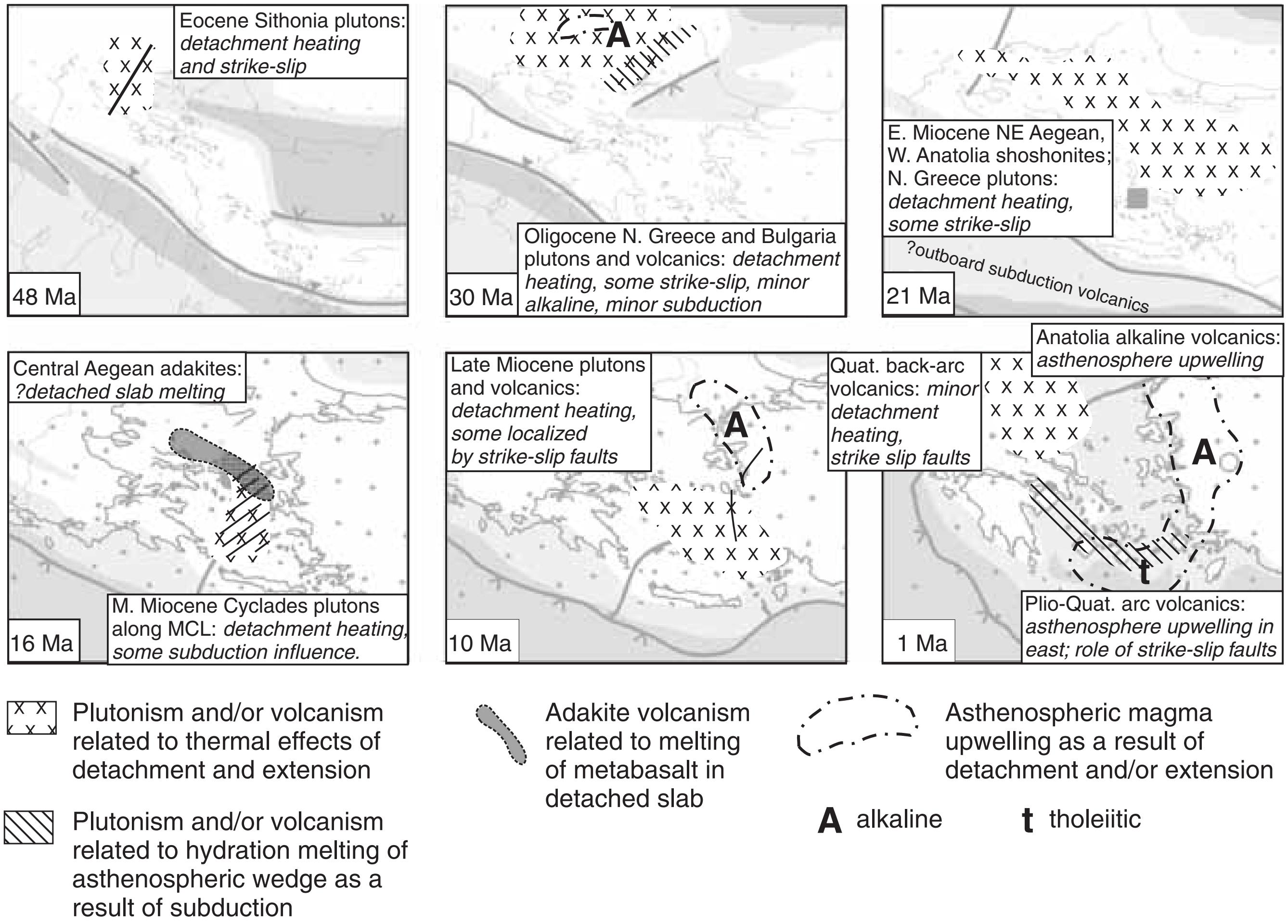


Figure 17. Summary cartoon showing the relationship of different magma types to the geodynamic evolution of the Aegean region. “Detachment” refers to lithospheric delamination and/or subducting slab break-off. MCL—Mid-Cycladic lineament.

(Piper et al., 2004), and the Milos center shows no systematic pattern, with the middle Pleistocene volcanic stratovolcano at Antimilos bordered for 20 km to the south by widespread late Pliocene volcanism (Anastasakis and Piper, 2005). Thus, no general geodynamic conclusions can be drawn from trends in the geographic distribution of Pliocene–Quaternary arc volcanism. De Boer also argued for southward migration of shoshonitic and trachytic volcanism in the Miocene, which he explained by the progressive southward migration of obducting asthenosphere, initially localized along the Vardar zone, causing partial melting. Our synthesis of magmatism presented in Figures 3–4 provides no evidence for a systematic southward migration of Miocene high-K magmatism. Although the distribution of earthquake epicenters and seismic tomography can be argued to indicate the presence of an obducting asthenospheric mantle diapir, geochemical evidence for significant asthenospheric contribution to magma is restricted to the late Miocene to the Quaternary of Anatolia (where the contribution is of OIB type) and to the late Quaternary of Santorini and Nisyros (where the contribution is from a subduction-related mantle wedge). The Miocene shoshonitic rocks and trachytes of the Aegean are strikingly different in their geochemistry and radiogenic isotopes.

CONCLUSIONS: UNIQUE FEATURES OF THE GREEK CENOZOIC MAGMATISM

This article has highlighted several remarkable features of the Aegean region compared with those of typical convergent continental margins, which have been noted by previous workers. First, a very wide range of rock types is present in a region with a back-arc setting relative to the subduction of Africa beneath the Aegean block, which has likely been continuous throughout the Cenozoic (Meulenkamp et al., 1988). Second, widespread extension and detachment faulting have resulted in the exposure of both upper-crustal and middle-crustal igneous rocks of Cenozoic age.

The broad outlines of the geologic history that led to these unusual features have long been recognized (Fig. 17). They are a consequence of the numerous microcontinental blocks within the Aegean area, separated by Neo-Tethyan Ocean strands that were destroyed by subduction in the early Cenozoic. With the progressive collision of Arabia with Anatolia, orogen-parallel strike-slip became increasingly important. However, wrench faulting orthogonal to the zone of subduction of the oceanic crust of the Africa plate beneath the Aegea-Anatolia microplate is recognized from the Oligocene onward. Roll-back of the subduction zone over the ocean crust in the Miocene and the Pliocene was associated with significant block rotation, with strike-slip faulting between blocks. This roll-back resulted in the rapid extension of the Aegean area and the exhumation of middle crust.

Magmatism directly related to the hydrous melting of subarc asthenosphere is relatively rare. Such magmatism related to the subduction of the ocean crust of the Africa plate lay south of the present arc in the Paleogene, migrated northward to the Cyclades plutons in the Miocene, and then moved southward again to its present position as a result of extension and roll-back. Calc-alkaline volcanism in Rhodope may be related to subduction of the Intra-Pontide Ocean.

Lithospheric delamination or slab break-off produced thermal melting of the subcontinental lithospheric mantle inhomogeneously enriched by earlier subduction, resulting in voluminous shoshonitic volcanism in the Miocene of the northeast Aegean and in the Oligocene of Rhodope. In both cases, shoshonitic volcanism was followed by minor alkaline magmatism related to the decompression melting of upwelling asthenosphere. The thermal effects of upwelling asthenosphere, coupled with increased geothermal gradient from extension, also contributed to the thermal melting of subcontinental lithospheric mantle.

Strike-slip faulting, at various times and places, was important in localizing both plutonism and volcanism. In particular, such faults provided pathways for small magma batches to reach the surface. Volcanism is not associated with the major basins developed by listric faulting.

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Georgia Pe-Piper and David J.W. Piper

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