ACTA VULCANOLOGICA

20 · 1-2 · 2008 / 21 · 1-2 · 2009

A VOLUME DEDICATED TO PROFESSOR FABRIZIO INNOCENTI

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OFFPRINT

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PUBLISHING HOUSE INFORMATION
«Acta Vulcanologica» is published six-monthly (June and December)
by *Fabrizio Serra editore*®, Pisa · Roma.

Subscriptions should be sent to Fabrizio Serra editore®, Casella postale no. 1, Succ. no. 8, I 56123 Pisa (Italy),
tel. +39 050 542332, fax +39 050 574888
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Direttore responsabile: Alberto Pizzigati

Autorizzazione del Tribunale di Pisa n. 14 del 24 maggio 1991

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«Acta Vulcanologica» is a Peer-Reviewed Journal

THE 40-YEAR CONTRIBUTION OF FABRIZIO INNOCENTI TO UNDERSTANDING THE GEODYNAMIC EVOLUTION OF THE EASTERN MEDITERRANEAN

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Abstract

In the last decades Fabrizio Innocenti was a mentor to many scientists. As a highly acknowledged researcher with a long career, he was very influential, particularly in Italy. We review his major findings in the study of the magmatic and geodynamic evolution of the Eastern Mediterranean. His most relevant contributions were the analytical description of a large number of peculiar magmatic rocks in the area, and the development of new geodynamic models to explain their origin.

Keywords: Eastern Mediterranean, Cenozoic Volcanism, Geodynamics, Petrology, Geochemistry

1. Introduction

Fabrizio Innocenti had a vast scientific culture with a solid background in the humanities. Owing to this rare combination, he undertook scientific research with an open mind. He was dedicated to science in the most positive acceptation. Always looking ahead to new challenges, Fabrizio was willing to discuss alternative views without prejudice. With these invaluable qualities, Fabrizio tackled research through a deeply rooted multidisciplinary approach in which magma genesis was always considered in the context of the tectonic and geodynamic setting. His field study area was the earth; process-oriented, he worked in the Andes, Dinarides, Hellenides and Taurides, and in Patagonia, Central America and Italy. Fabrizio Innocenti spent most of his scientific career studying magmatism in these regions, mostly focusing on lithosphere-asthenosphere interaction in subduction settings.

Fabrizio involved many researchers in these studies, with the foremost aim of describing unknown or very poorly described magmatic activity in the various regions. Through the study of erupted products, he and his co-workers described mantle modification processes driven by subduction dynamics. Research on these topics was undertaken in collaboration with scientists from different countries (Italy, Bulgaria, Greece, Macedonia-fYRoM and Turkey); petrologic and geochemical findings were merged with geological and geophysical data in order to build a comprehensive geodynamic model.

Fabrizio's interest in these topics never waned, and he continued to work until the very last. His last field trips date back to November 2006 in Central Anatolia (Fig. 1) and June 2007 in Greece, to study the volcanic products of the Volos-Evia area. In the second half of 2008 he worked on a paper (Innocenti *et alii* 2010) stemming from this research.

Fabrizio was the best friend a person could wish for. He was generous and had a wonderful sense of humour. He was also rigorous, but ready to listen, stimulating and sympathetic.

This paper briefly summarizes his main research interests and most relevant achievements in the Eastern

Fig. 1. Fabrizio Innocenti and the Ercyes Dağ Volcano (Cappadocia, Turkey; November 2006).

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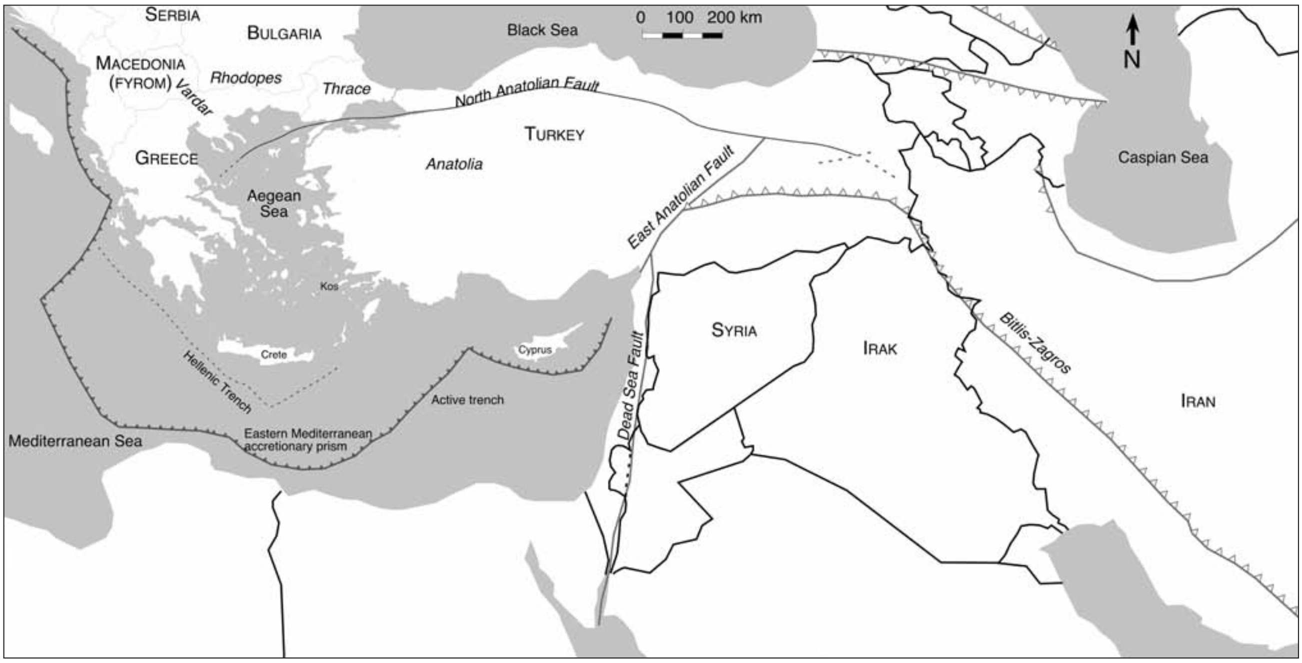

Fig. 2. Sketch map of Eastern Mediterranean-Middle East region (redrawn after Agostini *et alii* 2010).

Mediterranean, where subduction processes have been active from the Late Cretaceous to the present day (Fig. 2). The area is thus one of the best case studies for investigating subduction processes and their relationship with magmatism and the geodynamic evolution of converging zones.

The Eastern Mediterranean is characterized by the northeastward subduction of the African plate beneath the Eurasia plate (*e.g.*, Innocenti *et alii* 2005). This is a highly complex boundary due to the presence of several intervening microplates which have played an important role in the evolution of the system. The syn-subduction extensional velocity gradient of the upper plate has dismembered the lithosphere, creating a widespread area of rift with very diffuse and geochemically varied igneous activity that has continued almost without interruption from the Eocene to the present day.

2. A 40-Year Study of the Eastern Mediterranean

2.1. *The first Period: from Western Anatolia to N-W Iran (1969-1982)*

In 1969 F. Innocenti and R. Mazzuoli were the first researchers from the University of Pisa and the CNR (Italian National Research Council) to undertake a field trip to the Eastern Mediterranean (Western Anatolia and the Island of Lesvos in Greece) in the framework of a collaboration with the MTA (Maden Tetik ve Arama, the Mineral Research and Exploration Institute of Turkey). Volcanic rocks were known to be abundant in this area, but their characterization, the description of relationships with the surrounding rocks, as well as petrographic and geochemical data were lacking.

The occurrence of hot springs, *e.g.* in Lesvos, Kızıldere and Kula, and evidence of past geothermal activity, for example the travertine rocks in Pamukkale and the pervasive hydrothermal alteration of many volcanic rocks, highlighted the geothermal potential of the region. Research in this area was thus spurred by both scientific curiosity and a need to obtain background information on the area for the purpose of geothermal exploitation.

The first results were reported in a paper on the petrology of the Izmir-Karaburun volcanic area (Innocenti and Mazzuoli 1972), soon followed by two more general papers on Western Anatolia and Lesvos (Borsi *et alii* 1972, Benda *et alii* 1974). The first isotopic age determinations, as well as the Sr-isotope composition of selected volcanites, were reported in a paper by Borsi *et alii* (1972). To this day the data are still a point of reference for researchers working on Western Anatolia volcanism and geology. The most important findings were: the volcanic activity was subdivided into (i) an orogenic, mostly calc-alkaline phase, dated to the Early-Middle Miocene (21.5-15.5 Ma ago), and (ii) a later phase of alkali basaltic volcanism emplaced in the Late Miocene (11.9-9.7 Ma ago) at Ezine and Urla and during the Pleistocene (less than 1.1 Ma ago) at Kula.

F. Innocenti subsequently met G. Pasquarè, an Italian geologist who had worked several years for the MTA, which had previously published his studies on central (Pasquarè 1968) and Eastern Anatolia volcanism (Pasquarè 1971). A close friendship developed, and their common scientific interests led to a collaboration which lasted several decades and was not limited to studies on the Anatolia region. F. Innocenti, R. Mazzuoli and G. Pasquarè first worked with L. Villari (CNR) on the petrography, geochemistry and field relations in the Central-Eastern Anatolia volcanic belt (Innocenti *et alii* 1975, 1976 and 1980). In 1975 and 1976, two field surveys were carried out in western Iran together with researchers from Florence University (P. Manetti, M. Boccaletti). This research led to a paper on Western Iran (Boccaletti *et alii* 1977) and another on Eastern Anatolia (Innocenti *et alii* 1982a).

Findings from this period were summarized and reviewed in a chapter of a book devoted to the study of andesites the world over (Innocenti *et alii* 1982b). The work remains to this day an important milestone in understanding the volcanism of the Eastern Mediterranean region. Other general papers on the Eastern Mediterranean were also published in these years (Innocenti *et alii* 1981a and 1982c).

2.2. *Shifting towards the Aegean Area (1976-1995)*

In parallel with studies in Anatolia and Iran, F. Innocenti began to investigate volcanism in the Aegean region, together with a large team comprising researchers from Pisa University (G. Ferrara, R. Mazzuoli and P. Pertusati), Florence University (P. Manetti, G. Poli, A. Peccerillo and L. Francalanci), CNR (L. Villari) and from IGME, the Greek national Institute of Geology and Mineral Exploration (M. Fytikas and N. Kolios). A first geochronological survey on Aegean Sea volcanism (Fytikas *et alii* 1976) was followed by a systematic study of magmatic activity around the Aegean, including several field campaigns in the late 70s and 80s.

A number of papers first focusing on the timing of volcanism, then on its geochemical and petrological characteristics, and lastly on its geodynamic significance were published in this period. Some of these papers gave a detailed description of specific areas (Thessalia and Likhades: Innocenti *et alii* 1979; Voras Mts.: Kolios *et alii* 1980; South Aegean arc: Innocenti *et alii* 1981b; Thrace: Innocenti *et alii* 1984, Del Moro *et alii* 1988, Bigazzi *et alii* 1989; Milos: Fytikas *et alii* 1986; N-W Aegean arc: Fytikas *et alii* 1987; Limnos: Innocenti *et alii* 1994; Nysiros: Francalanci *et alii* 1995 and a later comment, Francalanci *et alii* 2007). The collected data on Cenozoic igneous activity was used to describe the evolution of magmatism in the region and to investigate relationships between volcanism and the geodynamics of the Aegean area (Fytikas *et alii* 1979, Innocenti *et alii* 1982d, Fytikas *et alii* 1984, Francalanci *et alii* 1991).

2.3. *The Progressive Broadening of Study Areas: Rhodopes and Dinarides (1995-2005)*

The studies on Aegean magmatism made it clear that, for a comprehensive reconstruction of the magmatic and tectonic evolution of the entire Central-Eastern Mediterranean region, it was necessary to broaden the study area to include the igneous activity of the Eastern Rhodopes and Western Thrace. Magmatism in these areas seems to trace an older activity related to the same subduction system. F. Innocenti thus began to collaborate with researchers of the Bulgarian Academy of Sciences and of the University of St. Cyril and Metodii of Štip (former Yugoslav Republic of Macedonia-fYRoM).

Recent studies have focused on the potassic and ultrapotassic rocks of the fYRoM (Yanev *et alii* 2006, 2008a and 2008b), an area adjoining those considered in the first papers on the volcanism of the Eastern Rhodopes, Western Thrace (Yanev *et alii* 1995, 1997 and 1998), and the Vardar zone (Yanev *et alii* 2003).

2.4. *The Return to Western Anatolia and Development of a comprehensive Model for the Evolution of the Region*

In the mid 90s a new collaboration began between researchers from Pisa and Florence (Italy) and those from Dokuz Eylül University of Izmir (Turkey): research focused on new areas of Anatolia. The Afyon-Isparta region, comprising a Mio-Pliocene volcanic belt, was studied first. The emitted, mainly ultra-K products are linked to a N-S transfer fault considered to be the northern continuation of the western Aegean-Crete trench and the eastern Cyprus trench (Savaşçın *et alii* 1997, Francalanci *et alii* 2000).

Thirty years after the first field survey by F. Innocenti and his collaborators in the region, the research context had changed radically: over the years the improvement of analytical facilities and geological knowledge, the progressive growth of infrastructures and the development of geological communities in these developing countries greatly facilitated field research, allowing the publication of many papers. A large number of local studies (*e.g.*, Pe-Piper and Piper 2002) and a few regional ones proposing alternative models for the magmatic and geodynamic evolution of the region were published at the turn of the 21st century (*e.g.*, Aldanmaz *et alii* 2000, Seyitoğlu and Scott 1996).

To further the understanding of the area, studies had to address different issues using varied methods. In particular, it was important to: i. better investigate the mantle sources of magmas through isotope geochemistry and new petrologic models; ii. better constrain volcanic stratigraphy through new age determinations; iii. understand relationships between magmatic activity and the geodynamic evolution of the region through geostructural and geodetic studies.

To address these topics, researchers from the Istituto di Geoscienze e Georisorse of the CNR (formerly Istituto di Geocronologia e Geochimica Isotopica) began to collaborate with those from «La Sapienza» University in Rome. In the following sections we review the main findings from research on these topics, up to we have the unique opportunity to work on with Fabrizio.

3. MAJOR RESULTS: NEW INSIGHTS INTO THE EASTERN MEDITERRANEAN

3.1. *Western Anatolia Magmatism*

During the Cenozoic, Western Anatolia was affected by very widespread magmatism with products of different petrological affinity. A detailed description of volcanic rocks cropping out in the area, as well as their petrolo-

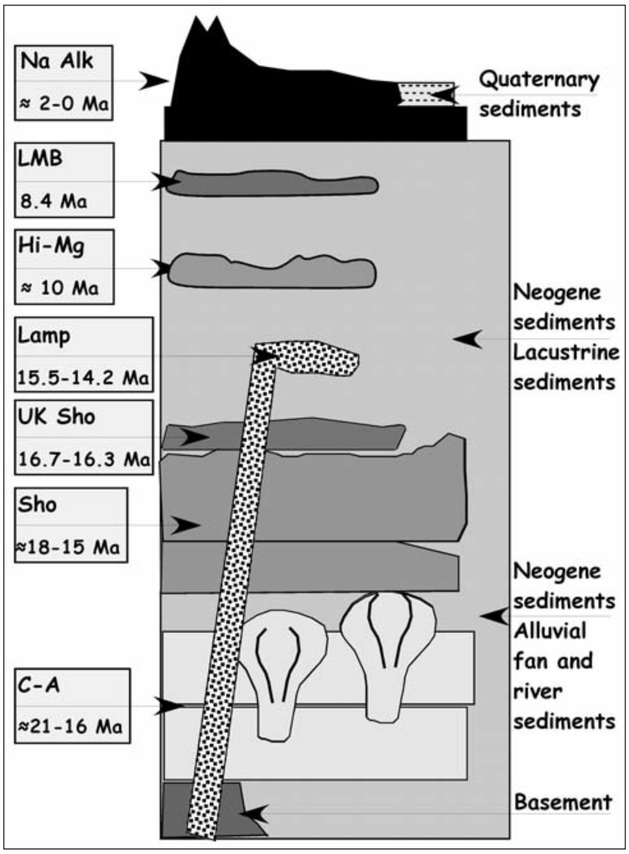

FIG. 3. Schematic stratigraphic column of Western Anatolia volcanic rocks (after Innocenti *et alii* 2005, modified).

gy, geochemistry, and Sr-Nd isotope features was reported in Innocenti *et alii* (2005). Although this paper was submitted to «Marine Geology» in 2002 as part of a special issue dedicated to the Eastern Mediterranean, publication of this issue was postponed to 2005 due to an editorial delay.

Volcanic activity in the region was classed into six magmatic associations with different petrogenetic affinity. New accurate ^{40}Ar-^{39}Ar age determinations better constrained the chronology of these associations. The occurrence of lamproitic rocks in the area between the cities of Kula, Uşak and Gediz was first reported in this paper. Erupted products were thus subdivided into i. calc-alkaline, ii. shoshonitic, iii. Ultra-K with Roman Magmatic Province-type affinity, iv. lamproitic, v. K-alkali basalts, and vi. Na-alkali basalts associations (FIG. 3). It was observed that the products with 'subduction-related' geochemical fingerprints (from calc-alkaline to lamproitic) were part of a large volcanic cycle, which began in the Early Miocene (≈23 Ma in the study area) and ended in the Middle Miocene (≈14 Ma); the transition between the various products was gradual, with no temporal hiatuses. The occurrence of K-alkali basalts was restricted to the Late Miocene, whereas the Na-alkali basaltic rocks with any subduction-related geochemical and isotopic signatures only crop out around Kula and are of Pleistocene age. The following important constraints were identified in the paper by Innocenti *et alii* (2005).

i. All Miocene-Pleistocene activity took place under an extensional tectonic regime. This solved a long-lasting debate among some authors, which linked the change from calc-alkaline to 'alkaline' activity with the shift from compressional to extensional tectonics (*e.g.*, Yilmaz *et alii* 2001), and other authors claiming that all activity took place in an extensional tectonic regime (*e.g.*, Seyitoğlu *et alii* 1997).

ii. A more accurate classification of K-rich products. These rocks, for a long time grouped as alkaline products, were subdivided into shoshonitic, ultra-K and K-alkaline basalts. This was fundamental in establishing that the first two classes of products derive from a supra-subduction mantle, have the same Sr-Nd isotope signature, and the same source as that of calc-alkaline products, *i.e.*, the mantle wedge. In contrast, the K-alkali basalts have intermediate isotopic and geochemical features between the older subduction-related rocks, and the younger Na-alkaline rocks of Kula, and originated in the sub-slab asthenosphere.

iii. According to the new model presented in a companion paper (Doglioni *et alii* 2002), the shifting of magma sources from a supra-slab mantle to a sub-slab asthenosphere was linked to the geodynamic evolution of the region.

The occurrence of high-Mg andesitic products was first described in Western Anatolia (Agostini *et alii* 2005). Similar products found in the Aegean (Pe-Piper and Piper 1994) belong to the same high-Mg andesitic belt. A thermal anomaly affecting a mantle source previously depleted by the extraction of calc-alkaline and shoshonitic magmas was invoked for the genesis of these rocks. This anomaly was produced by the ascent of the deep sub-slab mantle in the context of regional extensional tectonics.

3.2. *Radiogenic and light stable Isotopes: Insights into Mantle Source Evolution*

The large available dataset on rocks of variable geochemical affinity was used to study the role of fluid phases in the genesis of such magmas and in the geochemical evolution of the supra-slab mantle domain. After rigorously selecting the freshest samples, B and Li isotope studies were carried out (Tonarini *et alii* 2005, Agostini *et alii* 2008a). By combining the data on radiogenic (Sr-Nd) and stable light isotopes (B-Li), it was possible to describe the geochemical evolution of slab-released fluids metasomatizing the mantle wedge. The occurrence of very isotopically light B and Li values was ascribed to isotope fractionation due to progressive slab dehydration (FIG. 4). These data had important implications both on the general topic of subduction processes and on the geodynamics of the region: the extremely low B-Li isotope values, which are unusual in normal subduction contexts, were used to describe the progressive dehydration of the slab, up to almost fully dewatered conditions. In turn, the presence of such residual slab fluids suggested that the same portion of slab experienced successive episodes of dehydration,

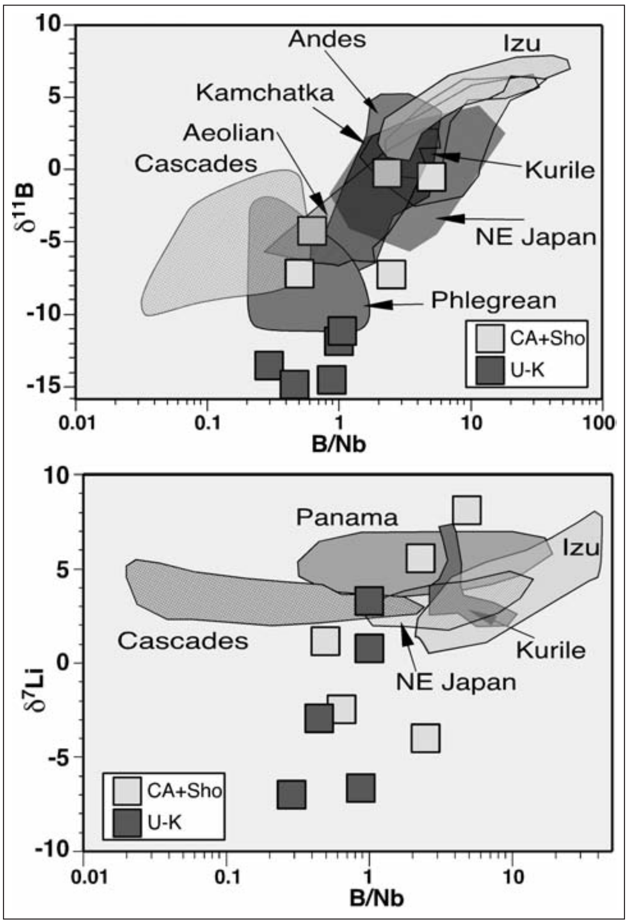

Fig. 4. δ^{11}B and δ^{7}Li *vs* B/Nb ratios (after Agostini *et alii* 2008b). B/Nb ratio can be considered a fluid tracer. Notice that extreme negative values of B and moreover Li isotope ratios are not found in other subduction-related lavas worldwide.

implying that the slab is not sinking into the mantle. Thus, the result of the peculiar geodynamic setting of Western Anatolia is a unique coupling of B-Li isotope systematics, which was predicted by theoretical models, but never observed before.

A more detailed study focusing on Western Anatolia and Aegean alkali basalts (Agostini *et alii* 2007) identified the common genetic origin of these products, which can be divided into two groups: one of mainly sodic affinity, which retains typical intraplate features and displays no subduction-related fingerprint and another, consisting of mildly alkaline basalts with potassic affinity and characterized by a wide variability in both trace elements and Sr-Nd isotope ratios. The latter group marks the transition from subduction-related to intraplate magmatism, as these magmas formed through the interaction between sub-slab magmas and residual slab fluids.

3.3. *Geodynamics*

Doglioni *et alii* (2002) proposed a new geodynamic model for the region based on a multidisciplinary approach involving structural field work, new geodetic computations, magmatic constraints and tectonic modeling. In particular, the plate velocity pattern was computed on the basis of ITRF97 and ITRF2000 (ITRF, International Terrestrial Reference Frame), and extension in the region was ascribed to the faster south-westward motion of Greece with respect to Anatolia in overriding Africa (Fig. 5). This new model differed significantly from other models in the literature (see section 5. 3.), which ascribed Western Anatolian-Aegean extension to i. the westward Anatolia escape, ii. backarc spreading or iii. gravitational collapse (*e.g.*, McKenzie 1972, Le Pichon and Angelier 1979, Gautier *et alii* 1999). In contrast with most of the current literature (*e.g.*, Papazachos *et alii* 2000), the proposed model was the first to consider Aegean subduction as low angle slab subduction (Fig. 5).

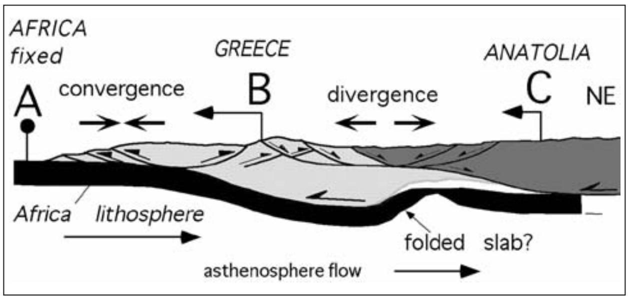

Fig. 5. Schematic cross-section (after Doglioni *et alii* 2002) depicting the proposed geodynamic model for Aegean-Anatolian extension.

4. A summary of Eastern Mediterranean Tertiary-Quaternary magmatism

In the last three years, efforts have been made to build a more comprehensive model of the entire Aegean region by carefully reviewing tectonic and geostructural characteristics as well as magmatic activity throughout the region (Macedonia, Bulgaria, Northern Greece, Thrace, the Central and Southern Aegean Sea and Western Anatolia). Papers by Agostini *et alii* (2008b), Agostini *et alii* (2010) and Innocenti *et alii* (2010) analyze and discuss the current models of Aegean extension (see later) and reconsider the evolution of magmatism (Fig. 6).

To describe the complex magmatic activity of the Eastern Mediterranean region and its evolution, the database of Western Anatolian-Aegean Cenozoic Volcanism (compiled by Agostini *et alii* 2010 and Innocenti *et alii* 2010) was updated and improved to include a total of 2,110 volcanic rock samples from Macedonia (fYRoM), Greece, South Bulgaria and Turkey (Thrace, Western and Central Anatolia) (Table 1). Although intrusive bodies were often associated with volcanic products, plutonic rocks were not included in this database.

Samples were divided into different groups according to their age, location and petrogenetic affinity. In Macedonia - fYRoM, two groups of products were identified: the first is present along the Vardar zone extending from southernmost Serbia to Southern Macedonia and mainly consists of ultrapotassic rocks with either Roman Magmatic Province-type (according to Yanev *et alii*

Fig. 6. Age and distribution of subduction related rocks (a) and alkali basalts (b) of Aegean region. In (c) the evolution of magmatic association throughout the region is schematized.

2008a) or lamproitic affinity (Prelević *et alii* 2008) dating to about 6.5 to 1.5 Ma ago.

Across the fYRoM-Greece border, the products of the Kozuf/Voras volcanic massif have the same age and mainly a shoshonitic affinity (shoshonites, latites, trachytes and rhyolites; Kolios *et alii* 1980; Yanev *et alii* 2008a and references therein).

A large volcanic belt of Upper Eocene to Oligocene age extends from the Rhodopes area (Bulgaria) to Thrace (Greece and Turkey). This is the oldest volcanic activity in the region (37-25 Ma ago): it is characterized by volcanic products with high-K calc-alkaline or shoshonitic affinity, with the predominance of intermediate products such as andesites and dacites, abundant rhyolites and very rare basalts (*e.g.*, Yanev *et alii* 1998). This volcanic activity shifted progressively south-south-eastward, giving rise to a Lower-Middle Miocene volcanic belt with very similar geochemical characteristics in the Northern and Central Aegean and cropping out on the Samothraki, Imbros, Limnos, Lesvos, Aghios Efstratios, Skyros, Psara and Chios Islands (*e.g.*, Fytikas *et alii* 1979, 1984). The same type of volcanic activity is also widespread in Western Anatolia, where it is divided into four different zones of decreasing age shifting south-southeastward: volcanism was mainly Lower Miocene in North-Western Anatolia, Lower-Middle Miocene in the Izmir area, Middle Miocene in inland Western Anatolia (*e.g.*, Innocenti *et alii* 2005 and references therein), and Middle-Upper Miocene in South-Western Anatolia, around Bodrum, Patmos and Samos (Robert and Cantagrel 1977). Farther East, along a N-S transfer fault in the Isparta Angle of the Taurus Mountains, shoshonitic and mainly ultrapotassic lavas crop out from Kirka to Afyon and around Isparta; they are of variable age, ranging from north to south between 15 to 4 Ma (Francalanci *et alii* 2000). In the central part of the Aegean-Anatolian region, scattered high-MgO andesitic lavas were emitted from the Middle to Upper Miocene: from West to East, these products are found in Skyros, Evia (Pe-Piper and Piper 1994), the Karaburun Peninsula, Soma and Ilica near Kutahia (Agostini *et alii* 2005).

The Southern Aegean region is characterized by the presence of the South Aegean Active Volcanic Arc (SAAVA), which may be subdivided into three zones: a western, a central and an eastern sector. The oldest activity is found in the western sector, at Aegina Island (Fytikas *et alii* 1987), whereas the central and eastern sectors are still active at Santorini and Nisyros, respectively. There are two characteristics which distinguish the products of the Southern Aegean arc from those of the older activity: they have tholeiitic and mainly calc-alkaline geochemical affinity, with lower K_2O contents, and basalts and basaltic andesites are frequent (Manetti 1997, Francalanci *et alii* 2005 and references therein). In this period, *i.e.*, the Plio-Pleistocene, in a back-arc position north of Santorini, 5-4 Ma old anatectic rhyolites are found on Antiparos and the nearby islets (Innocenti *et alii* 1982a) and on Ios (Buettner *et alii* 2005). Another group of Aegean Plio-Pleistocene volcanic rocks is found in the Volos-Evia area, which has been recently investigated by Innocenti *et alii* (2010). Volcanism con-

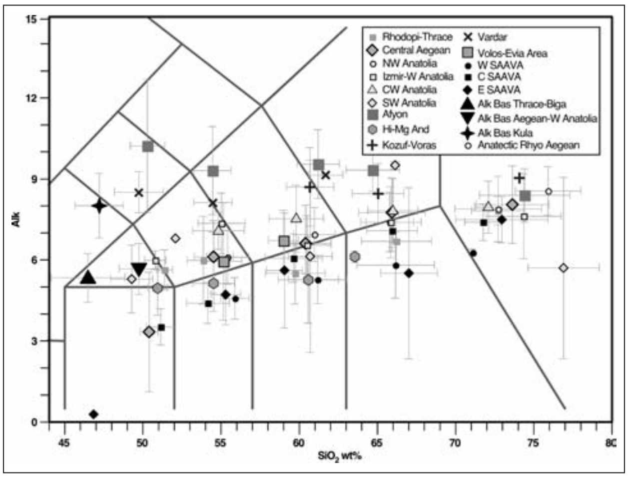

FIG. 7. Total Alkali *vs* Silica (TAS) diagram of Eastern Mediterranean volcanic rocks. Each point represents average values of subgroups of the database built for this paper (TABLE 1). Grey bars are one standard deviation.

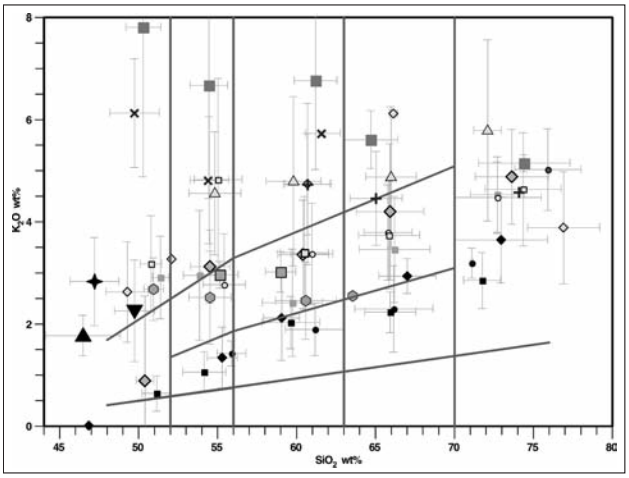

FIG. 8. K_20 *vs* SiO_2 diagram of Eastern Mediterranean volcanic rocks. Groups and symbols as in Figure 7.

sists of small lava flows, mainly high-K calc-alkaline andesites, erupted in the North-Western Aegean.

Lastly, alkali basalts are found scattered throughout the Eastern Mediterranean region. They have K- or Na-affinity and may be grouped into three categories: i. older, sodic alkali basalts and basanites of the Rhodopes (Marchev *et alii* 2004), Thrace (Yilmaz and Polat 1998) and the Biga Peninsula (Aldanmaz *et alii* 2000) dating back to the Oligocene (27 Ma, Rhodopes) and mainly the Late Miocene in Thrace (≈9-5 Ma) and in the Biga Peninsula (≈11 to 8 Ma); ii. Late Miocene K-alkali basalts of the central Aegean (Kalogeri, Patmos, Samos) and Western Anatolia (Aliağa, Foça, Urla and Selendi) (Agostini *et alii* 2007, and references therein), and the remarkably younger (≈0.7 Ma; Fytikas *et alii* 1984) alkali basalts of Psathoura; iii. the strongly SiO_2-undersaturated basanites and tephritic rocks from Kula (*e.g.*, Tokçaer *et alii* 2005 and references therein).

The rocks in the database were split into the three described groups, and averages were calculated for subgroups with different silica contents (recalculated anhydrous), *i.e.* $SiO_2 < 52$ wt%, $52<SiO_2 < 57$, $57 < SiO_2 < 63$, $63 < SiO_2 < 70$ and $SiO_2 > 70$. Averages and standard deviations are reported in Table 1. The Total Alkali *vs* Silica and K_2O *vs* Silica classification diagrams are shown in Figures 7 and 8. Both diagrams highlight how the products of the SAAVA have the lowest alkali K_2O content with respect to that of all other volcanic rocks in the Eastern Mediterranean. Most samples, *i.e.*, the products belonging to the North Aegean Tertiary Arc (NATA: Rhodopes-Thrace, Central Aegean and Western Anatolia) fall in the fields of high-K calc-alkaline and shoshonitic rocks. Figure 9 also highlights the different rock type distribution in the SAAVA and the NATA: SAAVA rocks have a bimodal distribution and basaltic andesites are the most abundant rocks, whereas the andesites are the most abundant rock type in the Tertiary arc and there are small differences in the relative abundance of basalts, dacites and rhyolites.

The K_2O/Na_2O *vs* K_2O diagram (FIG. 10) reveals the ultrapotassic character of rocks from the Afyon-Isparta area and Vardar, and the $K_2O/Na_2O > 2$ of other rocks from Central-Western Anatolia. This diagram reveals, in addition, that the alkali basalts of Kula are clearly sodic and the basalts from the Aegean area are potassic, whereas the basanites and alkali basalt of Rhodopes-Thrace and the Biga Peninsula straddle the dividing curve between sodic and potassic rocks.

The geochemical, petrological and isotope characteristics of these rocks reveal the nature of the magma mantle sources and provide important constraints for the development of a geodynamic model. The Sr-Nd isotope diagram (FIG. 11) once again highlights differences between rocks from the SAAVA and those of the Tertiary arc. It is noteworthy that the Sr and Nd isotope variations observed during evolutive processes in

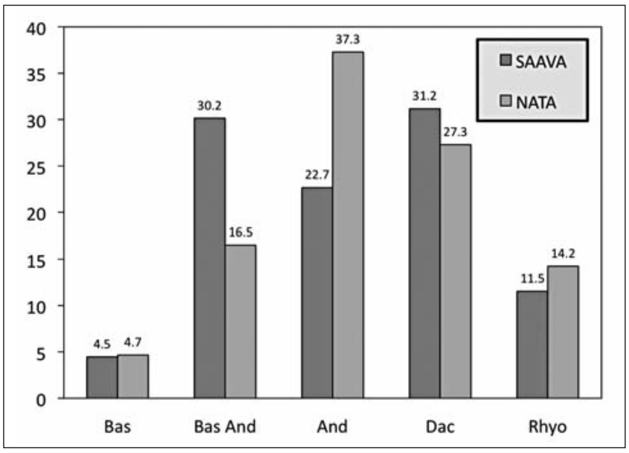

FIG. 9. Histogram with distribution of rock samples of Southern Aegean Active Volcanic Arc (West, Central and East SAAVA groups of Table 1) and the Northern Aegean Tertiary Arc (NATA: groups of Rhodopi-Thrace, Central Aegean, North-Western Anatolia, Izmir-Western Anatolia, Central-Western Anatolia and South-Western Anatolia). Numbers represent relative frequency (%).

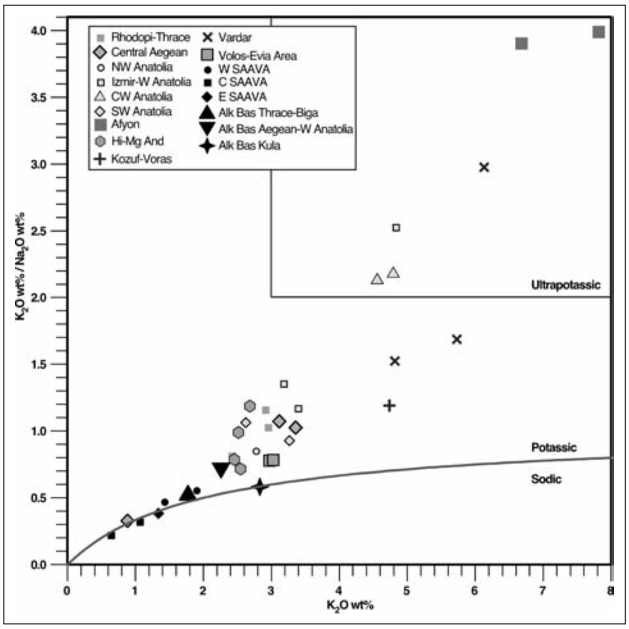

FIG. 10. K_20/Na_2O *vs* K_20 diagram of Eastern Mediterranean volcanic rocks. Each point represents average values with 1 standard deviation error bars as in Figure 7.

crustal environment are significantly smaller than those observed comparing less evolved rocks of each groups, given that both SAAVA and NATA rocks suffered limited extents of crustal assimilation (*e.g.*, Innocenti *et alii* 2005, Innocenti *et alii* 2010). Thus, the strong differences in these isotope ratios are mainly addressed to mantle source characters.

On average, the SAAVA rocks have $^{87}Sr/^{86}Sr$ ratios lower than 0.7055, whereas samples from the Tertiary arc have higher values clustering around 0.707-0.709. The calc-alkaline basalts of Samothraki (Vlahou *et alii* 2006) are the only exception. Note that alkali basalts from Kula, Rhodopes-Thrace and the Biga Peninsula have the typical Sr and Nd isotope signature of asthenosphere-sourced rocks unaffected by any subduction fingerprint ($^{87}Sr/^{86}Sr \approx 0.7030$, $^{143}Nd/^{144}Nd \approx 0.5129$), whereas the potassic basalt of the Central Aegean-Western Anatolia have markedly higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ ratios.

The Ba/Nb *vs* $^{87}Sr/^{86}Sr$ diagram (FIG. 12) highlights the occurrence of two distinct positive trends which can be interpreted (according to Innocenti *et alii* 2010) as follows: both the SAAVA and rocks of the Tertiary arc, along with those of Voras-Kozuf and the Volos-Evia region, were likely sourced in a mantle wedge variably modified by a subduction component that was responsible for the enrichments in ^{87}Sr and in fluid-mobile elements (monitored by the Ba/Nb ratio). The different 'starting points' of these two trends (FIG. 12) may be attributed to the variable characteristics of the mantle wedge before the influx of subduction fluids, *i.e.*, a depleted asthenosphere under the SAAVA and lithosphere farther north. In addition, the greater crustal thickness under the Central-Northern Aegean with respect to the SAAVA is responsible for the wider geochemical variations and the greater abundance of intermediate and acidic products.

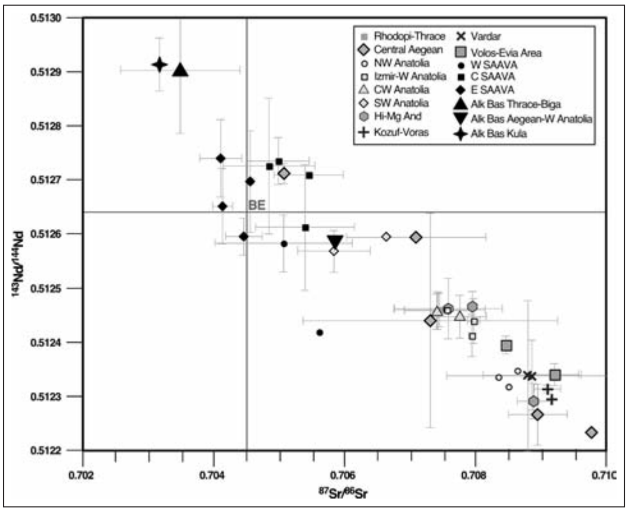

FIG. 11. $^{143}Nd/^{144}Nd$ *vs* $^{87}Sr/^{86}Sr$ isotope diagram of Eastern Mediterranean volcanic rocks. Each point represents average values with 1 standard deviation error bars as in Figure 7. BE, Bulk Earth.

5. GEODYNAMICS OF THE AEGEAN RIFT

5.1. *The Aegean: an atypical Backarc*

In the last two decades researchers have suggested that there are differences between the rotational velocity of the lithosphere and that of the asthenosphere; as a consequence, subduction zones are asymmetric as a function of the subduction polarity, which may be west- or east-north-east-directed (*e.g.*, Doglioni *et alii* 1999). In this view, the westward drift of the lithosphere facilitates backarc spreading in the hangingwall of west-directed subduction zones only. In contrast with this global model, the Aegean is a rare example (the only other being the Andaman) of a backarc basin located in the hangingwall of a north-east-directed subduction zone.

For this reason F. Innocenti and his collaborators decided to merge geodetic, geophysical, geostructural data and the petrology of magmas to elaborate a new geodynamic model for the Eastern Mediterranean region.

The Aegean has some peculiar physiographical and morphological characteristics with respect to other backarc basins. Most backarcs, like the Western Pacific ones or the Southern Tyrrhenian Sea, are located in the hangingwall of a west-directed subduction, are characterized by fast extension rates and oceanization, and are floored by a young (<20 Ma old) oceanic crust. On the contrary, in the Aegean the stretching is quite limited when compared to the duration of subduction (from Upper Cretaceous to Present, ≈60-90 Ma). As a result, the crust is still continental and thicker than 20 km (Makris *et alii* 2001). In addition, Hellenic subduction shows a number of characteristics that fall into the E- or NE-directed class of subduction zones (Agostini *et alii* 2010), including: the shallow dip of the foreland monocline at the base of the accretionary prism in the Mediterranean Ridge (0°-2°); the shallow depth of seismicity (<200 km); the down-dip extension of intraslab seismicity. Moreover, extension does not take place only in the backarc area, but also in the forearc (*e.g.*, between Crete and the active Aegean arc) and on the Island of Crete (Papanikolau and Vassilakis 2008, van Hinsbergen and Meulenkamp 2006).

Lastly, note that seismicity reveals a low-dipping slab, which is <16° according to earthquake hypocenters, and tends to flatten north-eastward. This data could be in contrast with seismic tomography, which identifies a faster high angle body, similar to a subducted slab, under the Aegean region (*e.g.*, Wortel and Spakman 2000).

5.2. *Different Models for Aegean Extension*

At least three different models have been proposed in the literature to explain Aegean-Western Anatolia extension:

i. Some authors consider the Aegean to be a typical backarc basin (Fig. 13a) and link extension to slab retreat and steepening (*e.g.*, Le Pichon and Angelier 1979, Berckhemer 1977). In this view, the engine driving extension is both the 'margin push force' and the 'slab pull force'. This model requires a progressive steepening of the African subducted slab and has recently gained a lot of popularity because of the aforementioned tomographic images showing a steep slab sinking down through the upper mantle into the mesosphere.

ii. Since the early contribution of McKenzie (1972), extension in the Aegean-Western Anatolia has been ascribed to the Africa-Eurasia collision and the westward extrusion of Anatolia, driven by the Arabia indenter on Eurasia, and its lateral escape bounded to the north by the North Anatolian Fault (NAF; Fig. 13b). In this view, the extrusion spreads out towards the less constrained Ionian margin, and subduction is a consequence of the Anatolian escape.

iii. The Aegean extension has also been ascribed to post-orogenic collapse, *i.e.*, gravity spreading of a continental lithosphere over-thickened during the 'Alpine' collision (Fig. 13c - Seyitoğlu and Scott 1996, Gautier *et alii* 1999, Jolivet 2001).

The accumulated geological and geophysical data on the region highlight a few weaknesses in these models, as reviewed in Agostini *et alii* (2010). In particular, recent precise geodetic measurements of plate velocities (*e.g.*, McKlusky *et alii* 2000, Doglioni *et alii* 2002) show that the speed of the Anatolian plate increases from east to west (Fig. 13b). This velocity pattern is not compatible with model ii., because the velocity field should instead decrease moving away from the energy source, *i.e.* the Arabian indenter. The westward Anatolian escape would instead close the Aegean Sea.

Model iii. lacks a quantitative balance of the acting forces. The topographic gradient, which has a slope of less than 1° (Doglioni *et alii* 2002), would not be enough to activate gravitational sliding of a brittle crust, even combined with slab retreat.

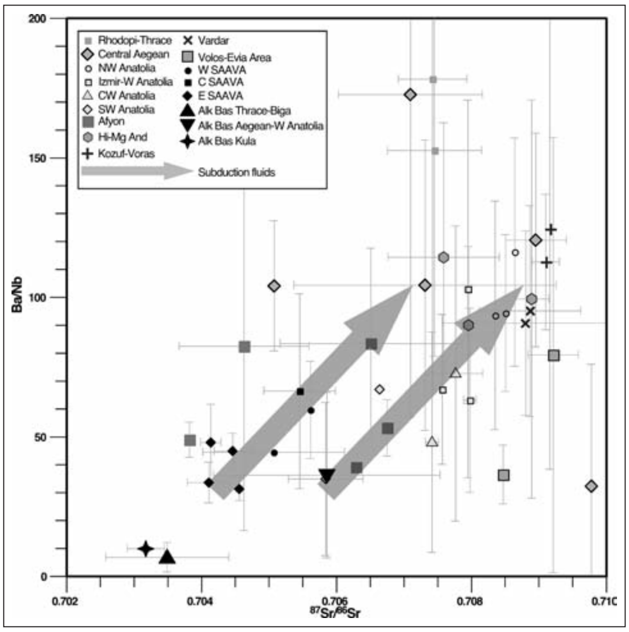

Fig. 12. $^{87}Sr/^{86}Sr$ *vs* Ba/Nb diagram of Eastern Mediterranean volcanic rocks. Ba/Nb ratio is used as an indicator of mantle source metasomatism induced by slab-released fluids. Each point represents average values with 1 standard deviation error bars as in Figure 7.

Model i. is strictly linked to the occurrence of slab rollback and its progressive steepening. The presence of a steep slab under the Aegean is inferred on the basis of model-dependent tomographic images, but is not confirmed by seismic data.

5.3. *A new geodynamic Model for Aegean Extension*

GPS data relative to a fixed Africa indicate that the speed at which the Greek microplate is overriding Africa at the Crete trench in a south-westward direction is faster than that at which the Anatolia microplate is overriding Africa at the Cyprus trench (Doglioni *et alii* 2002). Extension in the region may thus simply derive from this velocity pattern, which is responsible for the onset of a diffuse extensional margin between the two plates. The different velocities of the Greek and Anatolian microplates (Fig. 13d) could be due to the fact that the Aegean subduction system is coupled with a relatively fast southwestward migration of the Crete trench (about 4 cm/yr along the AA' section of Figure 13d), whereas the Anatolian subduction is coupled with very limited slab retreat of the Cyprus trench (1 cm/yr along the BB' section of Figure 13d; Doglioni *et alii* 2002). In other words, the hangingwall has a differential velocity that has to be accommodated by rifting between the Greek and Anatolian microplates.

In Agostini *et alii* (2010), this model was better discussed and presented in the light of new available data:

i. The difference between the velocity of the Greek microplate and that of the Anatolia microplate was investigated. Slab-released fluids are able to decrease the

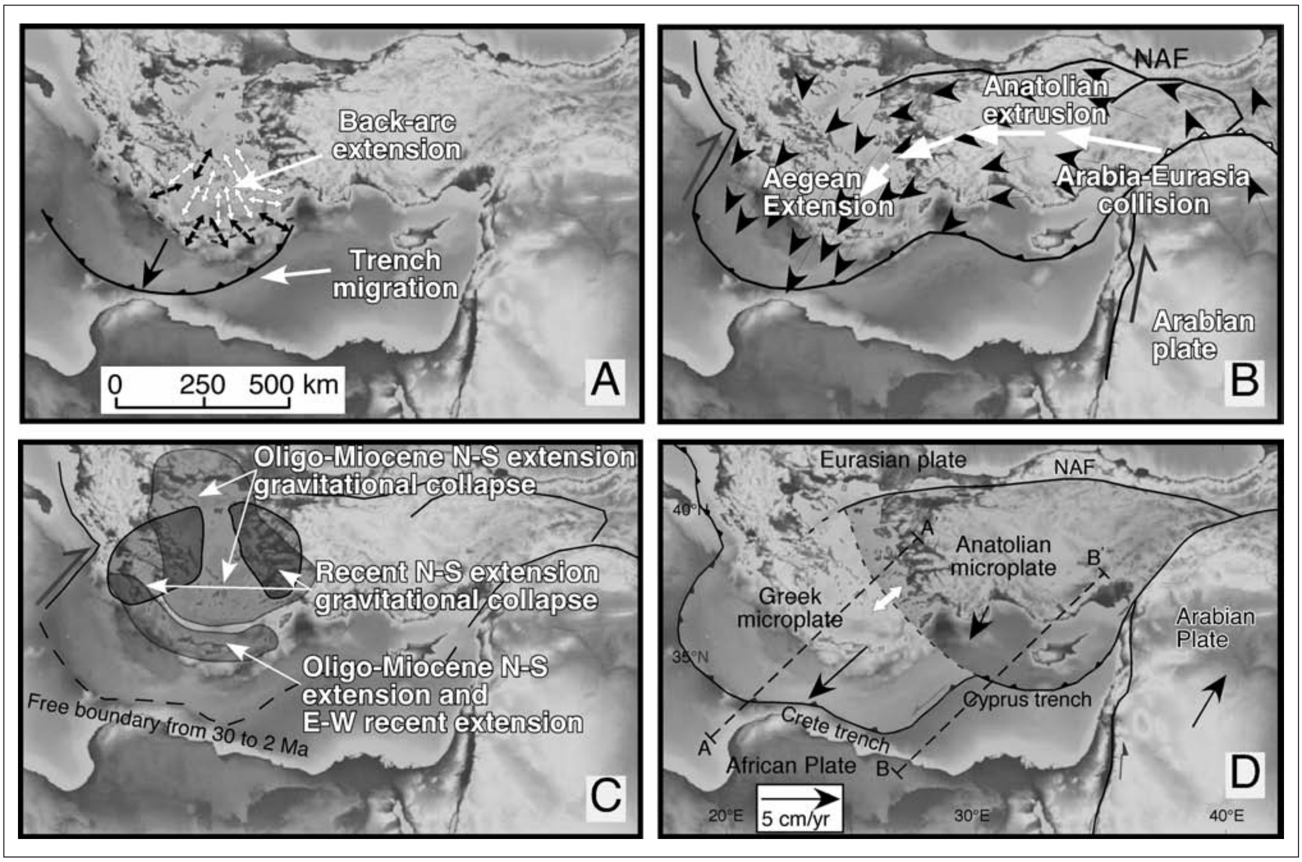

Fig. 13. Different models for explaining Aegean extension (redrawn after Agostini *et alii* 2010): A) Backarc matched by trench migration, induced by slab rollback and steepening. Extensional faults detected in land (black arrows) and sea (white arrows) reported in Angelier *et alii* (1982) are shown. However all slabs have the subduction hinge retreating relative to the lower plate, the slab is still shallow and with low dip; B) Anatolia extrusion and Aegean spreading induced by Arabia–Eurasia collision. Black arrows represent GPS-velocity pattern with respect to a fixed Eurasia (after McClusky *et alii* 2000). In this model we would rather expect the velocity of sites decreasing (*e.g.*, the white arrows) from the energetic source (the Arabia indenter), which is not; C) Gravitational collapse of an overthickened lithosphere (redrawn after Jolivet 2001). In this model the spreading should be active in spite of a practically absent topographic gradient between the center of the Aegean and the foreland; D) Geodynamic setting of Eastern Mediterranean region, evidencing the occurrence of two separate upper plates (Greek and Anatolian microplate), and their kinematics relative to Africa. White arrow indicates the diffuse extensional margin between the two upper plates. NAF, North Anatolian Fault. AA' and BB', see text.

viscosity of the low-velocity layer (Manea and Gurnis 2007), thereby triggering a faster decoupling between lithosphere and underlying mantle. The western portion of the subducting lithosphere is oceanic (the crust is 11-16 km thick, including a 4-6 km thick sedimentary cover; Makris and Stobbe 1984, de Voogd 1992), whereas its eastern portion is represented by a continental margin. The larger amount of fluids released by the Hellenic subduction with respect to the Anatolian subduction could therefore explain the faster south-westward migration of the Greek microplate with respect to the Cyprus-Anatolia segment of the African plate subduction.

ii. It was argued the slab is not sinking into the mantle. In the hotspot reference frame (Gripp and Gordon 2002), the Hellenic slab, which is attached to the African plate, is moving westward relative to the mantle. It is therefore moving in a direction opposite to that of subduction, suggesting that it actually moves out of the mantle; however, the subduction is active and continues to retreat relative to Africa because of the faster speed at which the upper plate (Greek lithosphere) is overriding Africa south-westward (Doglioni *et alii* 2007).

iii. The occurrence of a suction flow was inferred. From ii. it derives that the slab is supposed to rise upward, generating a suction flow from the underlying mantle (Doglioni *et alii* 2009).

Such interpretation has also the advantage of explaining why the tomographic images show relatively fast velocities along the ideal prolongation of the slab: it is not a real high-angle slab, but it could be a volume of uplifted mantle sucked up by the slab.

5.4. *Geodynamics and Magmatism*

Evidence from the study of magmatism was used to better constrain the geodynamic model:

i. The progressive southward shift of magmatic activity in the Eastern Mediterranean region suggests that the front of compression and backarc extension followed the same path.

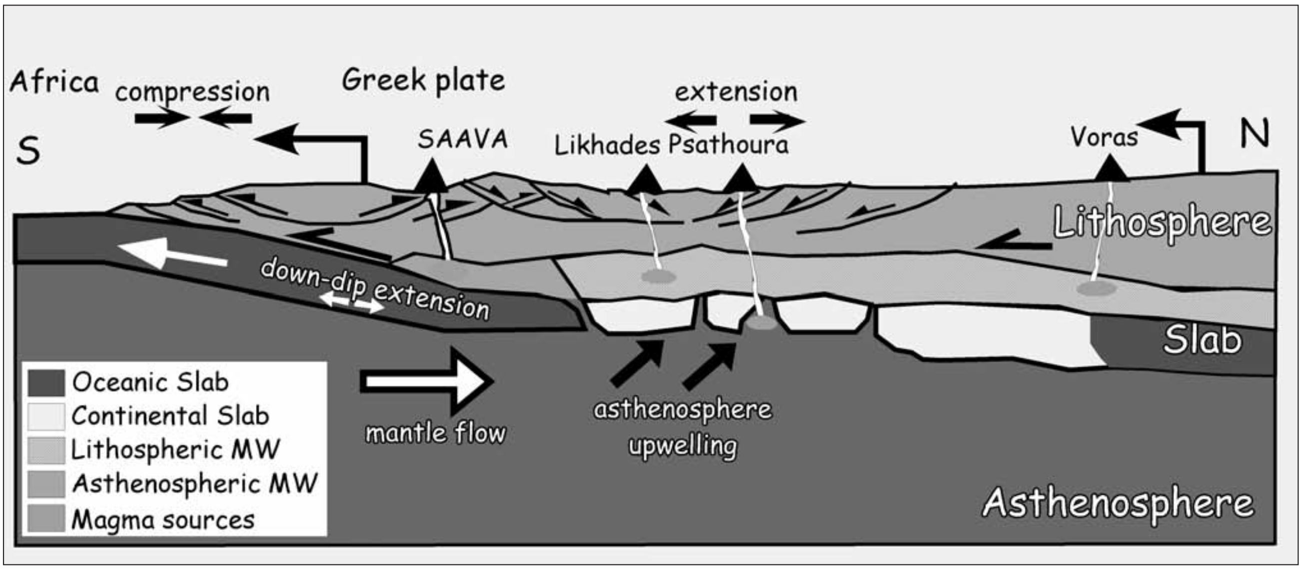

Fig. 14. Schematic cross section of Aegean-Anatolian subduction system (after Innocenti *et alii* 2010), evidencing the magma sources. Notice the different nature of the mantle wedge under Southern Aegean (depleted asthenosphere) and more Northern (lithosphere).

ii. The evolution from calc-alkaline to ultra-K magmas, the progressive decrease in slab-released fluids and the extreme, negative B-Li signatures indicate the presence of a stagnant slab (*i.e.*, sinking very slowly or not at all, and dehydrated as a consequence of progressive thermal perturbation) and of a non-convecting mantle wedge.

iii. The alkaline basalts, sourced in the sub-slab asthenosphere, testify to the occurrence of asthenosphere upwelling and partial melting linked to extension and to the opening of a slab window through which magmas reach the surface.

iv. The systematic differences between the volcanic rocks of the South Aegean arc and the subduction-related Cenozoic rocks erupted farther north have been linked (Innocenti *et alii* 2010) to different pre-subduction mantle features north and south of the Pelagonian-Actic-Cycladic-Menderes (PACM) massifs. In particular, the mantle wedge north of the PACM was never a depleted asthenosphere, not even prior to the metasomatism induced by subduction, but has lithospheric characteristics, whereas an asthenospheric mantle wedge occurs only below the South Aegean. Subduction dynamics could therefore be responsible for the occurrence of a lithospheric mantle wedge beneath the Central and North Aegean regions, Rhodopes, Thrace and Western Anatolia, whereas a thin asthenospheric layer developed between the upper and lower plates only more recently, and only south of the PACM massifs (Fig. 14). The occurrence of such a mantle domain in the mantle wedge under the Southern Aegean may be linked to the fact that, in the mantle reference frame, the African slab is moving out of the mantle, triggering a suction flow from the underlying mantle.

ACKNOWLEDGEMENTS

The authors are grateful to Marina Soriani Innocenti for information on early field trips and scientific collaborations. G. Poli is acknowledged for constructive revisions.

APPENDIX

Viajar
Asimilar horizontes.
Que importa si el mundo es plano o redondos?
Imaginarse como desgregado
En la atmosfera que lo abraze todo.
Crear visiones de lugares venideros y saber
Que siempre seran lejanos,
Inalcanzables como todo ideal.
Huir lo viejo.
Mirar el filo que porta un agua espumosa y pesada,
Arrancarse de lo conocido.
Beber lo que viene,
Tener alma de proa.

RICARDO GUIRALDES 1914

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Fabrizio Serra editore®, Pisa · Roma

www.libraweb.net

Stampato in Italia · Printed in Italy

ISSN 1121-9114
ISSN ELETTRONICO 1724-0425

A VOLUME DEDICATED TO PROFESSOR FABRIZIO INNOCENTI

Pietro Armienti, Massimo D'Orazio and Sergio Rocchi Editors

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ISSN 1121-9114

ISSN ELETTRONICO 1724-0425