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COMPARISON OF Ti/V- AND K2O- DEPTH RELATIONSHIPS FOR THE VOLCANIC ROCKS OF THE AEGEAN ISLAND ARC

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ABSTRACT

The Aegean volcanic arc formed in responce to northeasterly subduction of the Mediterranean sea floor beneath the Aegean Sea. Although the lavas from all the major volcanic centres of the arc exhibit typical calc-alkaline major and trace element characteristics it is clear that there are consistent differences in trace-element abundances and ratios in the lavas of the various islands located at different sectors of the arc, reflecting compositional differences in the mantle source and/or in melting conditions.

The K_2O content as well as the Ti/V ratios of island-arc related volcanic rocks have been used as indicators of the depth of their parental magma genesis. The comparison of the K_2O- and Ti/V- depth relationships of lavas from different sectors of the Aegean island arc revealed that the parental magma of the rocks from Santorini volcano which is located at the central sector of the arc has been generated at a greater depth than that of the parental magmas of the rocks from the Aegina, Methana and Poros volcanic centres, located at the western sector of the arc. This difference seems to be in accordance to the varying geotectonic structure of the Aegean island arc into its different sectors as it is revealed from geophysical data.

It is shown, finally, that the parental magmas of the lavas from the various sectors of the Aegean island arc have been evolved as complex mixtures of sources available for melting as the subcontinental lithosphere is replaced by uprising asthenosphere material.

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INTRODUCTION

The relationship between the K_2O content of lavas and the depth of the underlying Benioff zones has well been established for island arcs which are considered to be associated with subduction zones (DICKINSON & HATHERTON, 1967; HATHERTON & DICKINSON, 1969; DICKINSON, 1970, 1973, 1975; NINKOVICH & HAYS, 1972; LEFEVRE, 1973).

SHERVAIS (1982) used the Ti-V diagram to distinguishe basalts of different tectonic settings. He demonstrated that Ti vs. V plots clearly distinguishe arc related tholeites, MORB and alkali basalts. According to that Ti-V diagram the Ti/V ratio of the basalts decreases as their depth of origin increases (SHERVAIS, 1982).

HODDER (1985) considered that the Ti/V ratio may be an alternative to the K_2O-depth and enables additional constrains to be placed on the likely developmental stages of island arcs. On that basis he extended the application of the Ti/V-depth relationship to subduction setting volcanism comparing it with the K_2O-depth relationship.

The subduction zone of the Hellenic arc is clear but it shows structural complexity (MAKROPOULOS & BURTON, 1984). Studies on the seismicity of the Aegean region (KONDOPOULOU et al., 1985) have led to the conclusion that the dip values in the east and west edges of the Benioff zone are higher than the dip value in its central part. According to that, the depth of the origin of the parental magmas of the calc-alkaline volcanic rocks may be different at the various sectors of the arc and as a consequence, the Ti/V- and K_2O- depth relationships may also differ. As a contribution to the study of the complex characteristics of the Benioff zone of the Hellenic arc the Ti/V- and K_2O- depth relationships of volcanic rocks from the Aegean island arc, one of the structural elements of the Hellenic arc (BIJU-DUVAL et al., 1974), are compared in the present paper.

GEOLOGICAL AND GEOCHEMICAL SETTING

The Aegean Sea (Fig.1) represents one of the geologically most active regions in Europe. It is a geologically complex area wich is part of the Alpine belt, situated between the Hellenides of mainland Greece and the comparable Turkish ranges (Pontids, Central Ranges and Taurids) wich are largely of Mesozoic age.

The dynamic/kinematic evolution of the Aegean area has been studied by many researchers (e.g. PAPAZACHOS & COMNINAKIS, 1971; BIJU-DUVAL et al., 1974; PAPAZACHOS, 1977, 1990; MAKRIS, 1977; MCKENZIE, 1978; LE PICHON & ANGELIER, 1979, 1981; MAKROPOULOS & BURTON, 1984; SPAKMAN et al., 1988; DE BOER, 1989). The high seismicity and the extensive volcanic activity, even in historic times, has been attributed to the subduction of the Mediterranean sea floor (part of the African Plate) beneath the Aegean Plate at the Hellenic Trench, to the south of Crete (Fig. 1). As a consequense of the subduction there has been southward migration (roll-back) of the Mediterranean lithosphere flexure during the last 13 Ma, creating extensional conditions which have permitted subsidence of the Aegean Sea. Fault plane solutions from recent seismic activity (PAPADOPOULOS et al., 1986) indicate compression beneath the fore-arc region, N-S extension in the back -arc region, with a narrow zone of strike-slip faulting with a thrust component in between.

The Benioff zone of the Hellenic arc dips beneath the south Aegean from SSW to NEE. This zone has a conical shape and its maximum

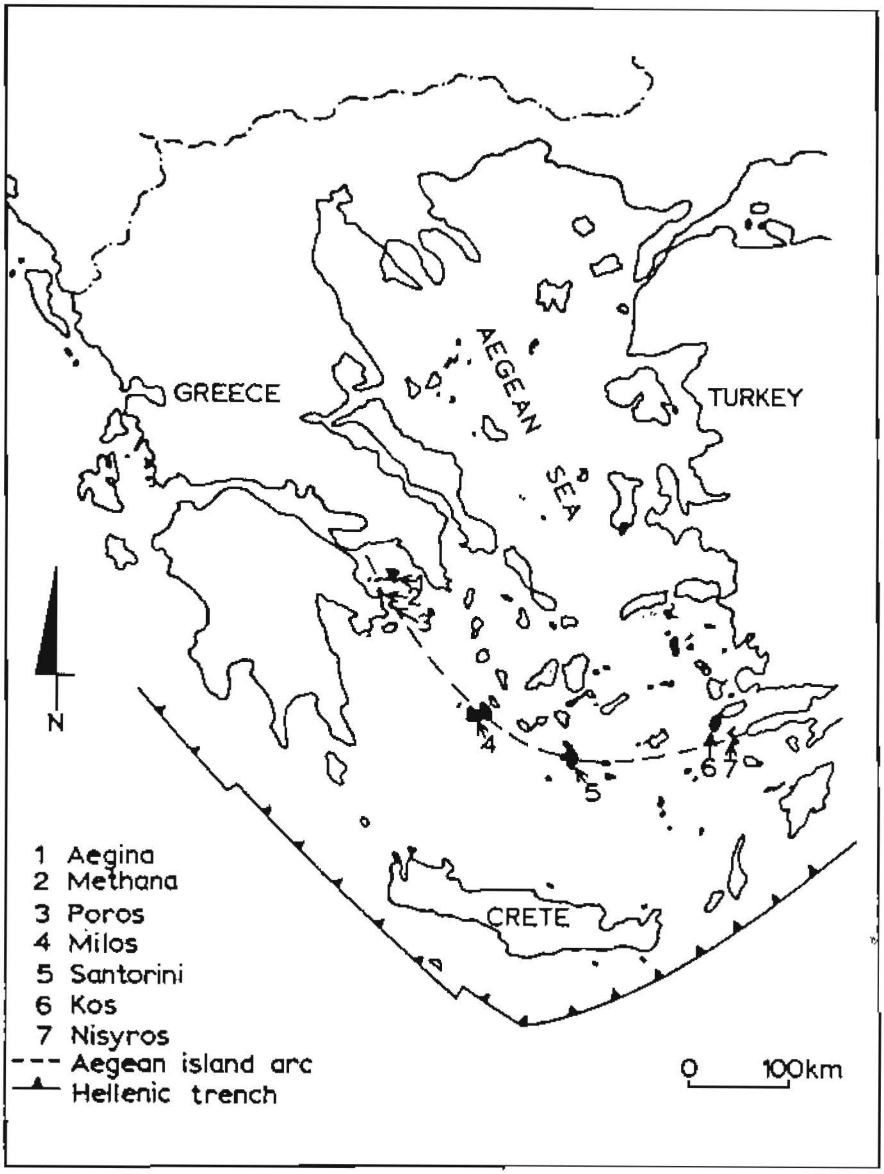

Fig. 1. Sketch map of the Aegean, showing the major volcanic centres of the arc and the Hellenic Trench.

depth is of about 190 km near the middle part of the arc. KONTOPOULOU et al. (1985) found, on the basis of the foci of intermediate depth earthquakes, high dip values in the east and west edges of the Benioff zone (36° and 42° respectively) and low dip value in its central part (about 25°). PAPAZACHOS (1990) defined, on the same basis, two dipping parts of the Benioff zone with clearly different dipping angles. The external part which dips slightly (dip angle 10°) and the internal part which dips steeply with an average dip angle equal to 38°. The internal part of the Benioff zone dips below the volcanic arc.

The volcanic centres of the Aegean island arc have their base on continental crust, the exposed part of which consists of marbles, schists and gneisses of Eocene-Miocene age. Extension has resulted in considerable thinning of the continental crust, estimated to be by as much as 25% just to the south of the arc beneath the sea of Crete (LE PICHON & ANGELIER, 1981). The crust is thicker beneath the western and eastern sectors of the arc (32- 34 km) than in the central sector (23-26 km) (MAKRIS, 1977).

The volcanoes of the Aegean arc appear to have erupted lavas of markedly varied chemistry. All are essentially calc-alkaline in character and exhibit the high LIL/HFS element ratios and low Nb contents typical of magmas generated in the subduction zone environment.

Geochemical study of suites of samples from the different volcanic centres making up the arc (MITROPOULOS et al., 1987) has shown that although major and trace-element ratios within each volcanic centre are consistent and fall within a narrow range, there are a number of important inter-island differences The lavas of Santorini, which is located at the central sector of the arc, have less fractionated REE patterns and are less enriched in LIL elements, relative to the HFS elements, than the lavas of the islands located at the eastern (Nisyros, Kos) and western (Aegina, Methana, Poros) sectors of the arc. Lavas from the eastern and western sectors of the arc also have much higher levels of Ba and Sr and relatively lower Th, K and Rb than those from Santorini.

These inter-island differences cannot be explained by a simple fractional crystallization process of a common/similar source for each volcanic centre. They reflect compositional differences in the mantle source and/or in melting conditions. A major factor controling the melting conditions is the depth of melting.

Studies on the mineral chemistry of the lavas from the various sectors of the arc (MITROPOULOS & TARNEY, 1991) have also shown significant differences which are due to differences in: (1) the composition of the magma involved; (2) the amount of the fluid phase involved in the crystallization process; (3) differences in the fO_2 values which are higher in Santorini than in the other volcanic centres from the eastern and western sectors of the arc.

ANALYTICAL DATA

For the construction of the various diagrams of the present work, XRF and INA analytical data of volcanic rocks from the Aegean island arc obdained by the author, were used. The XRF analyses were carried out at the University of Leicester while the INA analyses were carried out at the Nuclear Research Centre of Greece "Democritos". Details on the analytical methods used as well as a wide range of representative analyses are given in MITROPOULOS et al. (1987).

THE K_2O-DEPTH RELATIONSHIP

The level of the potash content of lavas erupted from active volcanoes is regarded as an effective indicator for discriminating between volcanic rocks overlying different depths to the Benioff zone. On that basis NINKOVICH & HAYS (1972) plotting the K_2O and SiO_2 content for a number of volcanic rocks from the various volcanic centres of the Aegean island arc suggested that these volcanoes lie 120-150 km above the Benioff zone.

It has already been mentioned that there are considerable geochemical differences between the lavas from the volcanoes of the eastern and western sectors and those from the central sector of the Aegean island arc. In order to check if these geochemical differences are related to any obvious physical parameters such as position along the arc, depth to Benioff zone, thickness of continental crust, the K_2O and SiO_2 content of rocks from the volcanic centres of Santorini, Aegina, Poros and Methana were plotted in Fig. 2.

For the purpose of the present work, rock samples from the volcanoes lying on the central (Santorini) and western (Aegina, Poros and Methana) sectors of the arc were used, as the lavas from the above

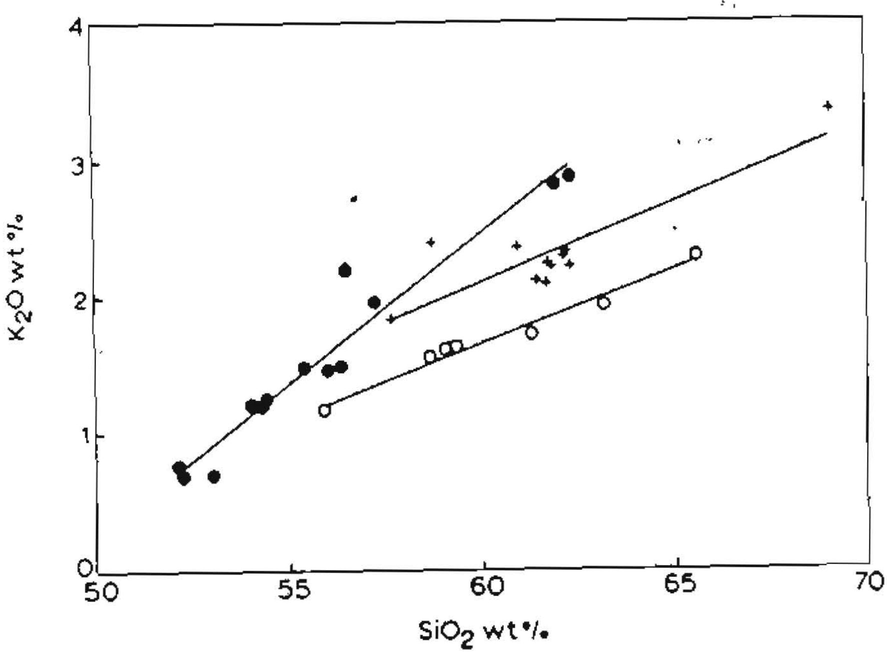

Fig. 2. K_2O vs. SiO_2 plot for the lavas from the various volcanic centres of the Aegean island arc (•: Santorini, o: Methana, +: Aegina-Poros).

volcanic centres exhibit a wide compositional variation. The Santorini volcanic rocks are mainly basaltic andesites to andesites in composition while the lavas of the volcanoes of the western sector of the arc show mainly andesitic to dacitic compositions.

As it is clear from Fig. 2 the volcanic rocks plot in three distinctive groups. The lavas from Santorini forming the first group show high linear relationship (c.c. = 0.94). Similar high linear relationships are shown by the lavas from Methana (c.c. = 0.98) forming the second group as well as by the lavas from Aegina and Poros (c.c. = 0.79) which form the third group. However, the most important point which must be noted from the plot of Fig. 2 is that the volcanic rocks from Santorini show higher K_2O/SiO_2 ratios than the rocks from the volcanoes of the western sector of the arc as it is shown from the higher slope of the regression line of the Santorini rocks in comparison to the slope of the practically parallel regression lines of the other two groups of volcanic rocks from the western sector of the arc. The difference in the K_2O/SiO_2 ratio may be an indication of higher depth to the Benioff zone in the central sector of the Aegean island arc than in its western sector.

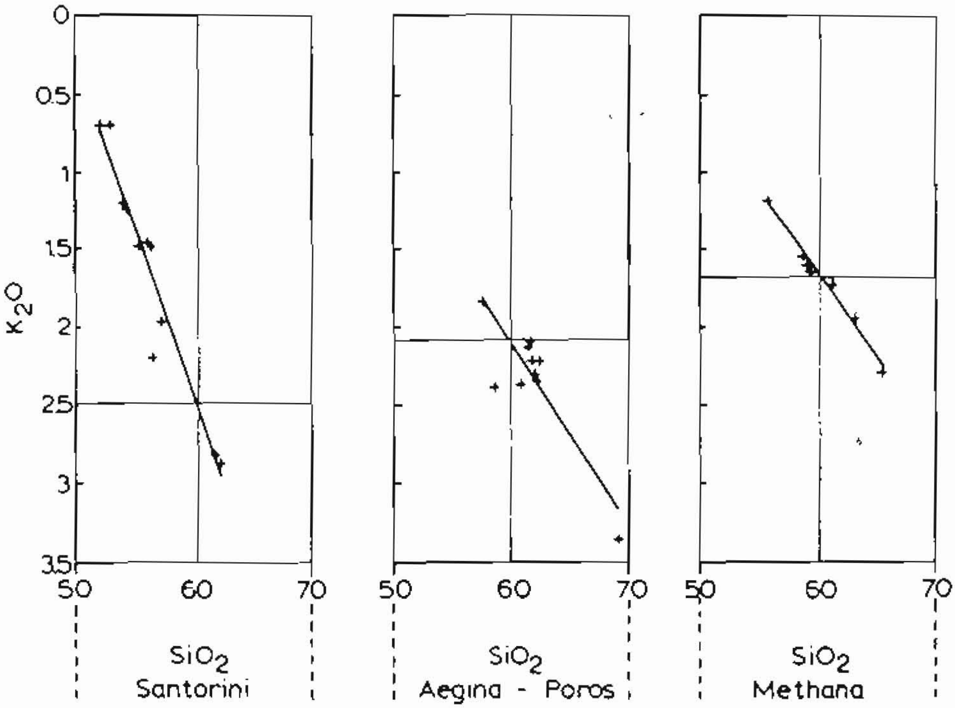

Fig. 3. K_2O vs. SiO_2 variation diagram for the lavas from the various volcanic centres of the Aegean island arc showing the different K60 values.

In order to test the K_2O-depth correlation for the volcanic rocks of the Aegean arc, the K_2O content corresponding to a SiO_2 content of 60% and termed as K_{60}, was chosen as an indicator. The silica content of 60% was chosen because the lavas of the western sector of the arc and especially those of Aegina and Poros are more acidic in composition. The K_{60} value for each group of rocks was estimated by the use of simple Harker variation diagrams of K_2O versus SiO_2 (DICKINSON, 1975) which are given in Fig. 3. As it is shown from these diagrams, the K_{60} value of the Santorini lavas is considerably higher than those of the lavas from the volcanic centres of the western sector of the arc suggesting greater depth of magma genesis.

THE Ti/V-DEPTH RELATIONSHIP

Ti and V are among the transition metals which are considered to be immobile during alteration or metamorphism. The geochemical behavior of Ti is relatively well known and it has been widely used as a discriminator of the tectonic setting of basaltic magmas (e.g. PEARCE & CANN, 1973). A detailed account of the geochemical behavior of V under differing conditions is given by SHERVAIS (1982). SHERVAIS used plots of Ti vs. V to determine possible tectonic settings of ophiolites as well as of modern volcanic rock associations. He considered that since the crystal/liquid partition coefficients for V vary with increasing fO_2 from >1 to <<1 while the partition coefficients for Ti are almost always <<1, the depletion of V relative to Ti is a function of the fO_2 of the magma and its source, the degree of partial melting and subsequent fractional crystallization. On that basis, the Ti/V ratio increases from volcanic rocks from island arcs (≤20) through MORB (20-50) to alkaline rocks (>50). HODDER (1985) related the depth of origin of basaltic magmas with the Ti/V ratios as the order of magma depth origin is the reverse of the ratios of the Ti/V ratios of the basalts in SHERVAIS' (1982) discrimination diagram.

The rock samples from the volcanic centres of the Aegean island arc described above are plotted in the Ti/V diagram in three distinctive groups (Fig. 4). The lavas from Santorini show high linear relationship (c.c. = 0.91). Similarly high linear relationships are shown by the lavas from Methana (c.c.= 0.89) and those from Aegina and Poros (c.c. = 0.81). Although there is evidence of magnetite fractionation (i.e. negative relationship between Ti and SiO_2 or Zr; MITROPOULOS et al., 1987), the low Ti/V ratios of the lavas from the volcanic centres of the Aegean island arc are comparable to those of calc-alkaline rocks from island arc settings (SHERVAIS, 1982; HODDER, 1985).

In order to identify the depth of origin of the parental magmas, the Ti/V ratios of the least differentiated lavas, showing the higher Kuno solidification index (SI) were considered (HODDER, 1985). As it is shown from the diagrams of Fig. 5, where the Ti/V ratios are plotted against the SI, the depth of origin of the parental magma is greater for the lavas of the volcanic centre of Santorini than for those of the volcanic centres of the western sector of the Aegean island arc.

CONCLUSIONS

On the basis of the K_2O-depth and Ti/V-depth relationships applied on lavas from volcanic centers of the Aegean island arc, it is

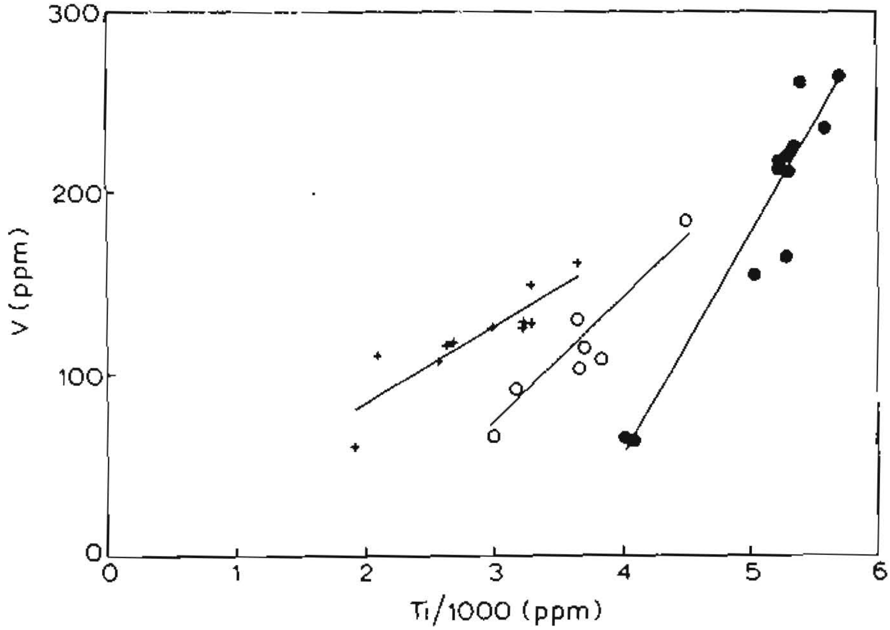

Fig. 4. Ti/V discrimination diagram for the lavas from the various volcanic centres of the Aegean island arc (symbols as in Fig.1)

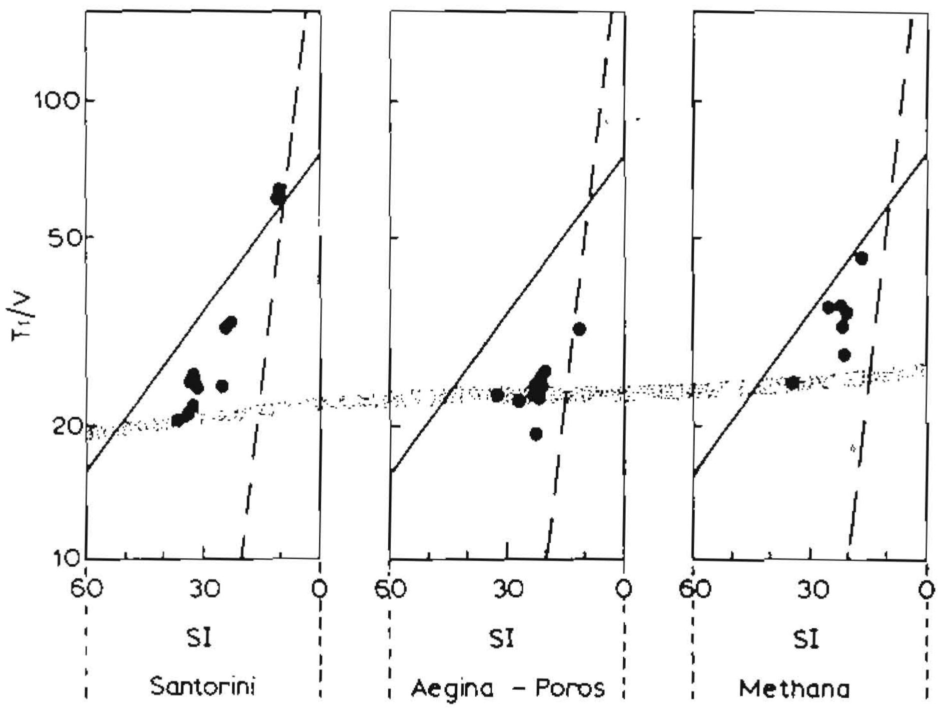

Fig. 5. Variation of Ti/V vs. SI for the lavas from the various volcanic centres of the Aegean island arc. Solid and broken lines are regression lines for MORB and IAB respectively. Band across the plots shows temporal variation of least fractionated lavas.

concluded that the parental magma of the volcanic rocks from Santorini may have been originated at a greater depth than the parental magmas of the volcanic rocks from Aegina, Methana and Poros. This difference is in accordance to the geophysical data giving a higher dip value (42°) in the west edge of the Beniof zone than the dip value (25°) in its central part (KONTOPOULOU et al., 1985) as well as a greater crustal thickness beneath the western sector of the arc (32-34 km) than in the central sector (23-26 km; MAKRIS, 1977).

Although the Ti/V ratio of the lavas from the examined volcanic centres seems to increase with differentiation (fig. 5), almost all the rock samples plot between the MORB and the IAB regression lines (HODDER, 1985) in the Ti/V vs. SI diagrams (fig. 5). MITROPOULOS et al. (1987) showed that the parental magmas of these lavas may have been evolved as complex mixtures of sources available for melting as the subcontinental lithosphere is replaced by uprising asthenosphere material, which is in accordance with the above Ti-V characteristics (HODDER, 1985).

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