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GEOCHEMICAL AND ISOTOPIC (Sr,Nd) VARIATION IN MAGMATIC SERIES FROM THE BODRUM VOLCANIC COMPLEX (SE AEGEAN)

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ABSTRACT

The Bodrum (Halikarnassos) igneous complex represents the eroded remains of a large Miocene stratovolcano. It is built of a large variety of subalkaline rock types with K_2O/Na_2O values usually greater than unity, ranging from basaltic rocks which include unusual ultrapotassic high-Mg varieties, to rhyolites or alkali-trachytes. The volcanics follow two differentiation trends, one towards slightly silica-undersaturated, trachyphonolitic compositions, the other towards oversaturated trachydacites and rhyolites. The petrographic and geochemical characteristics of the differentiated Bodrum rocks suggest that they were generated by crystal fractionation from mafic parental magmas.

Sr and Nd isotopic characteristics of the basaltic rocks have initial $^{87}Sr/^{86}Sr$ values (9 Ma) ranging from 0.7055 to 0.7071 and $^{143}Nd/^{144}Nd$ values ranging from 0.51264 to 0.51246. Differentiated rocks of the two series show isotopic differences: the alkali-rich undersaturated sequence displays less radiogenic Sr isotopic ratios of 0.706 to 0.7062 and Nd isotopic ratios around 0.51253, whereas the silica-oversaturated rocks have more radiogenic $^{87}Sr/^{86}Sr$ values extending from 0.7067 to 0.707 with $^{143}Nd/^{144}Nd$ varying from 0.51256 to 0.51250. These values fall well within the range for the various basalts, and tnere seems to be no need to invoke crustal involvement in the origins of the felsic differentiated volcanics of Bodrum.

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INTRODUCTION

Upper Miocene magmatism in the Aegean Sea stretches eastwards from the Cyclades towards the turkish coast (Fig.1). The products of this magmatism are mainly granitoids in the Central Aegean (Schliestedt et al., 1987; Altherr et al., 1988), whereas in the eastern Aegean and western Turkey, the igneous rocks include mafic, intermediate and felsic rock types (Robert, 1973, 1976, Altherr et al., 1988), which occur as both intrusive and extrusive facies. Intermediate rocks are the most important volumetrically in this eastern part of the Aegean region, and are associated with mafic rocks which are subalkalic in character with potassic affinities. These compositional differences led Robert et al (1992) to assign the igneous activity to two separate igneous provinces, the Central Aegean or Cycladic Province to the west and the Dodecanese Province to the east. The latter comprises the islands of Samos, Patmos, Kos and the Bodrum peninsula (fig. 1). The characteristic igneous activity of the Dodecanese Province is best-developed in the Bodrum Volcanic Complex on the Turkish coast and islands immediately offshore. Upper Miocene potassic rocks are also known from further East in Afyon (Keller, 1982, 1983).

The topic of this study is to discribe the geology of the Bodrum volcanic complex, to summarize geochemical and isotopic (Sr,Nd) data for the Bodrum rocks and present new isotopic (Sr,Nd) data for felsic rocks from the volcano and to discuss the relative importance of possible differentiation processes such as fractional crystallization and crustal assimilation in the genesis of the differentiated rocks of Bodrum in the light of the isotopic data available.

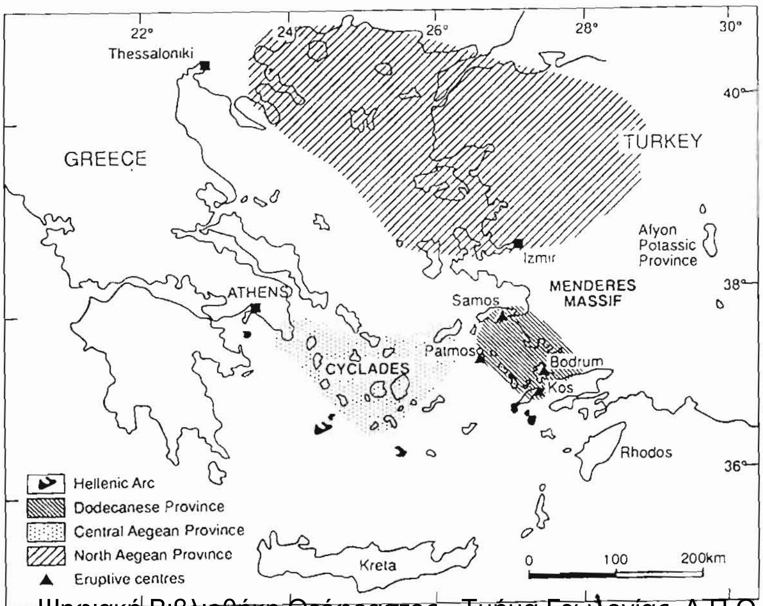

Fig. 1. Distribution of Neogene magmatism in the Aegean region.

VOLCANOLOGY AND GEOCHRONOLOGY

The Bodrum-(Halikarnassos) peninsula is made of an E-W striking pre-volcanic basement horst composed of Mesozoic sedimentary rocks of the Lycian nappes (Bernoulli et al, 1974) which overlie the parautochthonous Menderes Massif and are overlain themselves by an Eo-Paleocene Wildflysch.

The Bodrum igneous complex on the western end of the peninsula overlies Jurassic limestones in the north and the Wildflysch in the south. Some volcanic rocks from Bodrum have earlier been described by Burri et al. (1967). D'Archiadi (1902, in Burri et al, 1967) reported the presence of monzonite. Robert and Cantagrel (1977) and Robert et al. (1992) have described and discussed the geochemical characteristics of mafic volcanic rocks from the Bodrum area.

The igneous rocks were part of a large stratovolcano (Fig.2) which has been eroded in places and was also disturbed during Neogene extensional tectonics which affected the region, so that different levels of the original volcanic edifice are now thrown together. A complete spectrum of rock types can be observed from mafic and ultramafic varieties which occur as subvolcanic bodies or coarse-grained xenoliths within lavas, through to dykes, and extrusive rocks including lavas and pyroclastic flows, and airfall tuffs and pumices, with compositions ranging from ultramafic xenoliths to rhyolites or alkali-trachytes.

The different rock-types show restricted distribution: the lavas and fragmental rocks outcropping in the central area are predominantly mafic, whereas pyroclastic units up to 400 m thick which form the peripheral parts of this volcanic structure are generally latites and trachydacites. These peripheral rocks show a range of pyroclastic features and are characterized by inhomogeneous textures or by the presence of quenched mafic blobs which attest to magmatic mixing processes before eruption.

K-Ar and ^{39}Ar-^{40}Ar analyses have been performed both on whole rocks and on minerals (biotite, amphibole, sanidine). Ages range from 12 to 7.8 (Robert and Cantagrel, 1977; Robert and Montigny, 1989 and in prep.; Montigny and Robert, 1991) but the major part of this volcano was built in a relatively short period at around 9-10 Ma. No clear relationship between age and composition has yet been established for the major part of the extrusive and intrusive sequences, but rhyolitic rocks are restricted to the oldest layers. These rhyolitic rocks, and some trachyandesites which might also have been erupted during the early stages of the growth of the volcano are not particularly abundant. They are intruded by monzodiorite. At a later stage, a series of alkali-trachytes was emplaced in the central region of the volcano as a thick layer of ignimbrites and breccias. Deposition of the ignimbrites was followed by the eruption of a sequence of hyaloclastites alternating with basaltic pillow-lavas and thin subaerial flows. These basaltic rocks seem to have accumulated within a caldera formed after the eruption of the ignimbrites. This caldera-forming stage was followed by the intrusion of small bodies of monzonitic rocks which form ring-dykes or

The peripheral regions of the Bodrum volcano are made largely of latitic domes and dome avalanches which include numerous rounded mafic xenoliths showing a bulk basaltic composition and quench textures. A contemporaneous unit of pyroclastics, about 250m thick, was deposited mainly in the north. It is composed of pumice- and ash-flows, combined with intercalated surge deposits and thick breccia units. This series shows a continuous evolution from plinian to strombolian-type eruption and a compositional change from trachydacitic rocks at the base towards mafic trachyandesites at the top of the sequence, erupted as lava flows or scoriaceous ejecta.

A swarm of more or less parallel dykes with a dominant NW-SE orientation were intruded in a NW-trending zone, north and south of the central area of the volcano. These dykes, some of which yield whole rock K-Ar ages of 7.9 and 7.7 Ma (Robert and Cantagrel,1977), include alkali-trachytes, mafic trachytes and various types of basalts.

Hydrothermal alteration, ore mineralisation and silicification later developed in several zones in the centre of the volcano and may be linked to another magmatic event in this area, represented in the southern outer zone by a second series of domes and in the central area by multiple radiating dykes, all trachyandesitic in composition

PETROLOGICAL CHARACTERISTICS

Mafic, intermediate, and felsic volcanic rock types from Bodrum are named according to the scheme proposed by Le Bas et al. (1986). The Bodrum igneous rocks are alkaline with K_2O/Na_2O values commonly greater than unity and accordingly fall into the central field of the total alkali-silica diagram (Fig.3). Figure 3 also shows that their compositions follow two trends, one towards slightly undersaturated, trachy-phonolitic compositions, the other towards oversaturated trachydacites and rhyolites, whereas the various mafic rocks form a rather

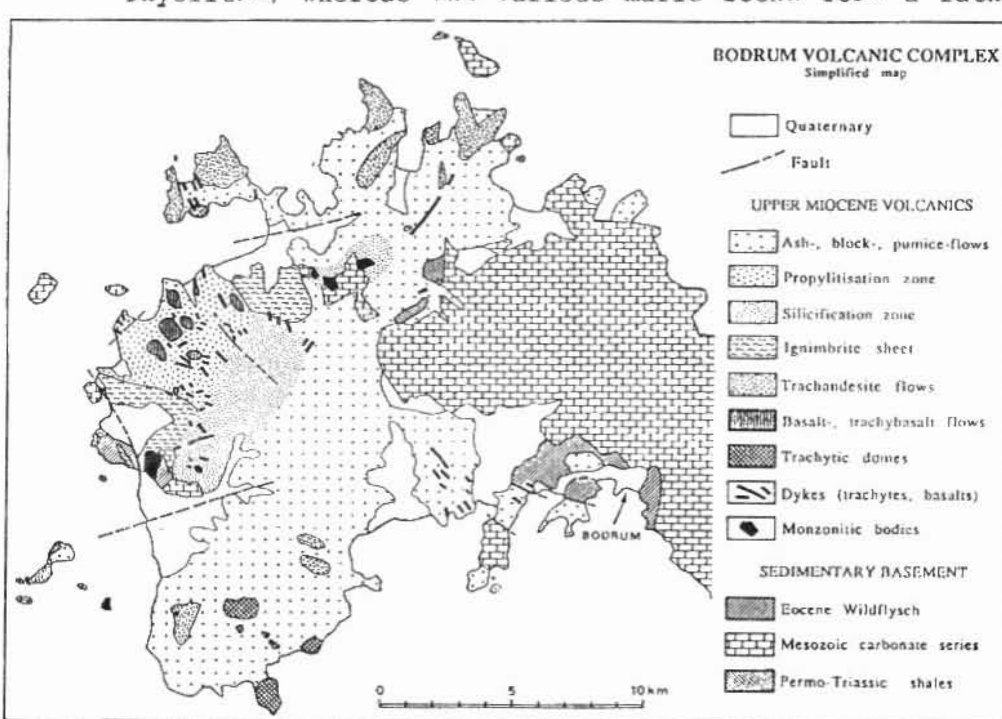

Fig. 2. Simplified map of the Bodrum Volcanic Complex from Robert et al., 1992.

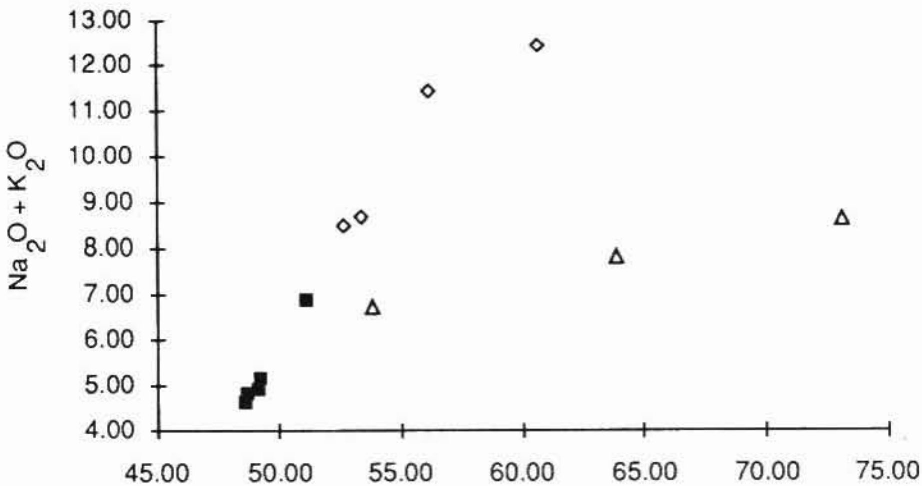

Fig. 3. Total alkali vs. silica diagram (wt.%) for the studied samples from the Bodrum Volcanic Complex. Full squares: basaltic rocks; open diamonds: silica-undersaturated rocks; open triangles: silica-oversaturated rocks.

Table 1. Phenocryst assemblages of the studied samples

	ol	cpx	opx	plag	amph	bio	oxides	apatite	alk-fe
B 23	x	x		x					
B 85	x	x		x					
B 32	x	x		x					
B 27	x	x		x					
B 71		x		x	x				
NeTA 180		x		x		x	x	x	
NeTA 14	x	x		x		x	x	x	
TP 14		x		x		x	x	x	x
T 23		x		x		x	x	x	x
S 43		x	x	x					
TD 1		x		x		x			
R				x	x	x			x

B=basalts, NeTA= Ne-trachyandesites, TP= tephritic phonolite, T= alkali-trachyte
S= shoshonite, TD = trachydacite, R= rhyolite

extended common field from 46 up to about 52% of silica. Their phenocrysts assemblages are represented in table 1.

The basaltic rocks vary in composition from unusual ultrapotassic high- Mg varieties to high-Al trachybasalts. Their petrographical and geochemical characteristics have been described by Robert et Cantagrel (1977) and by Robert et al. (1992). The high-Mg-basalts (B23) are generally aphyric and rich in forsteritic olivine; clinopyroxenes are salitic, and the late-crystallizing portion of the rocks is made up of rare plagioclase, abundant alkali feldspar and idiomorphic analcime, with traces of nepheline. The high-Al varieties (B27) are moderately porphyritic and have phenocrysts of olivine (70-60 Fo), augite, the latter occasionnally with opx-cores, and a normal basaltic groundmass. Some varieties show intermediate characteristics. Sample B71 is a mafic xenoliths bearing plagioclase, pyroxene and amphibole in a glassy groundmass.

The oversaturated series includes mafic trachyandesites (shoshonites), latites, trachydacites and rhyolites. Mafic members (52% SiO_2) are rare and limited to late-stage activity. The sample analyzed (S43) shows plagioclase, clinopyroxene and hypersthene phenocrysts making up about 25-30% of the rock; the same mineral phases joined by magnetite form a second generation of crystals. About 50% of the rocks is vitreous groundmass.

From latites to trachydacites (56% to 65% of silica) there is a continuous range of compositions, and rocks of this intermediate group make up most of the Bodrum volcanic complex. Most of these intermediate rocks are heterogeneous flows with large partly resorbed alkali feldspar crystals, but they also occur as pumices. Sample TD1 is a trachydacitic pumice from the base of the pyroclastic sheet and is composed mainly of plagioclase phenocrysts with some clinopyroxene, biotite, magnetite. There is a compositional gap with the rhyolites (72-73% SiO_2). Sample R from a rhyolitic dome bears plagioclase and alkali feldspar phenocrysts together with amphibole, titanite, allanite and a glassy groundmass, locally devitrified.

The saturated to undersaturated series includes nepheline-normative trachyandesites or mafic trachytes, tephry-phonolites and alkali-trachytes. The more mafic rocks with silica contents around 52-53% are relatively abundant. Sample NeTa180 is composed of about 20% of phenocrysts of plagioclase, augitic cpx, phlogopite, Ti-magnetite, apatite. Sample NeTa14 contains about 10% of the same phenocrysts except magnetite, but also bears microphenocrysts of olivine (Fo65). The groundmass is largely composed of plagioclase laths and interstitial alkali feldspar and analcime, with clinopyroxene, oxides, and additional biotite in sample NeTa14. The intermediate and most felsic members of this association form ignimbrites and pyroclastic brecchias in the central part of this volcano and also a number of dykes in the NW and SE external zones. Many of these rocks carry only few phenocrysts of plagioclase, alkali feldspar, augite and biotite in a groundmass mainly composed of alkali feldspar with some biotite, clinopyroxene and analcime (TP14,T23). Some samples show a tendency towards peralkalinity with interstitial arfvedsonite.

GEOCHEMISTRY

The analysed samples cover the whole range of compositions available and extend from 52 to 73% silica in the Si-oversaturated series, and from 52 to 63% silica in the Si-undersaturated series. Selected major and trace element data for representative types of these rocks are shown in table 2.

Variable enrichment in K-group elements, particularly Rb and to a lesser degree Ba and Sr, together with REE data, suggest that the mafic Bodrum rocks display both alkaline and subalkaline characteristics, and chondrite-normalized magmaphile element plots show that chemical characteristics are those of rocks formed at destructive margins.(Robert et al .,1992).

Element variations in these series are illustrated by plotting them against SiO_2. Major and minor elements such as Fe_2O_3 or TiO_2 (fig. 4), and trace elements such as Sc show a simple relationship with silica throughout the whole range of compositions both for the oversaturated series and for the saturated to undersaturated series, consistent with the intermediate and felsic Bodrum rocks being differentiates of the mafic varieties. Other elements, such as Al_2O_3 and most of the K-group elements, and Nb and Zr among the Ti-group elements, follow distinct trends in the two series (Fig.4). Alkali trachytes show trace element abundances indicative of highly fractionated residual liquids, strongly enriched in Zr and Nb, which behave incompatibly in the alkaline suite, whereas in the felsic oversaturated rocks, these elements show compatible behavior.

All the basalts are LREE enriched with high normalized La/Yb (15-30) and a slight Eu anomaly. The high-K basalts are the most enriched in LREE and lithophile elements, but also the most Mg, Cr and Ni-rich, showing values indicative of mantle derived magmas. La/Yb values for the most differentiated rocks are similar to those of the basalts but their La/Sm are higher reflecting the upward concave-shaped REE patterns (Fig.5) of some of these rocks, particularly the rhyolites. REE patterns for mafic trachandesites whether over- or undersaturated, are very similar to those of the basaltic rocks. REE abundances of the trachydacite are lower but show no Eu anomaly, and rhyolites are clearly distinct by the upward curved pattern. The latter suggests sphene and amphibole fractionation. From the basalts to the alkali trachyte T23, abundances of light and heavy REE increase but are similar for MREE as Nd, Gd and lower for Sm. The negative Eu anomaly is usually attributed to plagioclase fractionation.

Table 2. Selected major and trace elements of rocks from the Bodrum Volcanic Complex

	SiO_2	TiO_2	Fe_2O_3	Na_2O	K_2O	mg	Sc	Zr
B 23	51.14	1.29	7.54	2.19	4.67	73	25.2	463
B 85	49.26	1.27	7.83	3.35	1.80	74	19.3	297
B 32	48.64	1.16	8.29	1.98	2.64	70	27	211
B 27	48.74	1.53	9.82	2.51	2.32	57	28.4	241
B 71	49.13	1.15	9.29	2.80	2.12	59	28.6	171
NeTA 180	53.97	0.99	7.50	3.53	5.24	46	12.4	338
NeTA 14	52.63	1.06	7.81	3.79	4.71	46	13.2	354
TP 14	56.47	0.82	5.85	4.06	7.47	44	8.2	780
T 23	60.61	0.53	4.65	5.32	7.13	23	5.9	972
S 43	54.12	0.84	7.87	3.28	3.47	45	18.6	253
TD 1	63.87	0.43	4.22	3.47	4.36	49	6.8	193
R	73.15	0.22	1.24	3.94	4.72	1	2.7	157

B= basalts, NeTA= Ne-trachyandesite, TP= tepritic phonolite, T= alkali-trachyte, S= shoshonite, TD = trachydacite, R= rhyolite

Total iron as Fe_2O_3, mg= Mg/(Mg+Fe) in cations

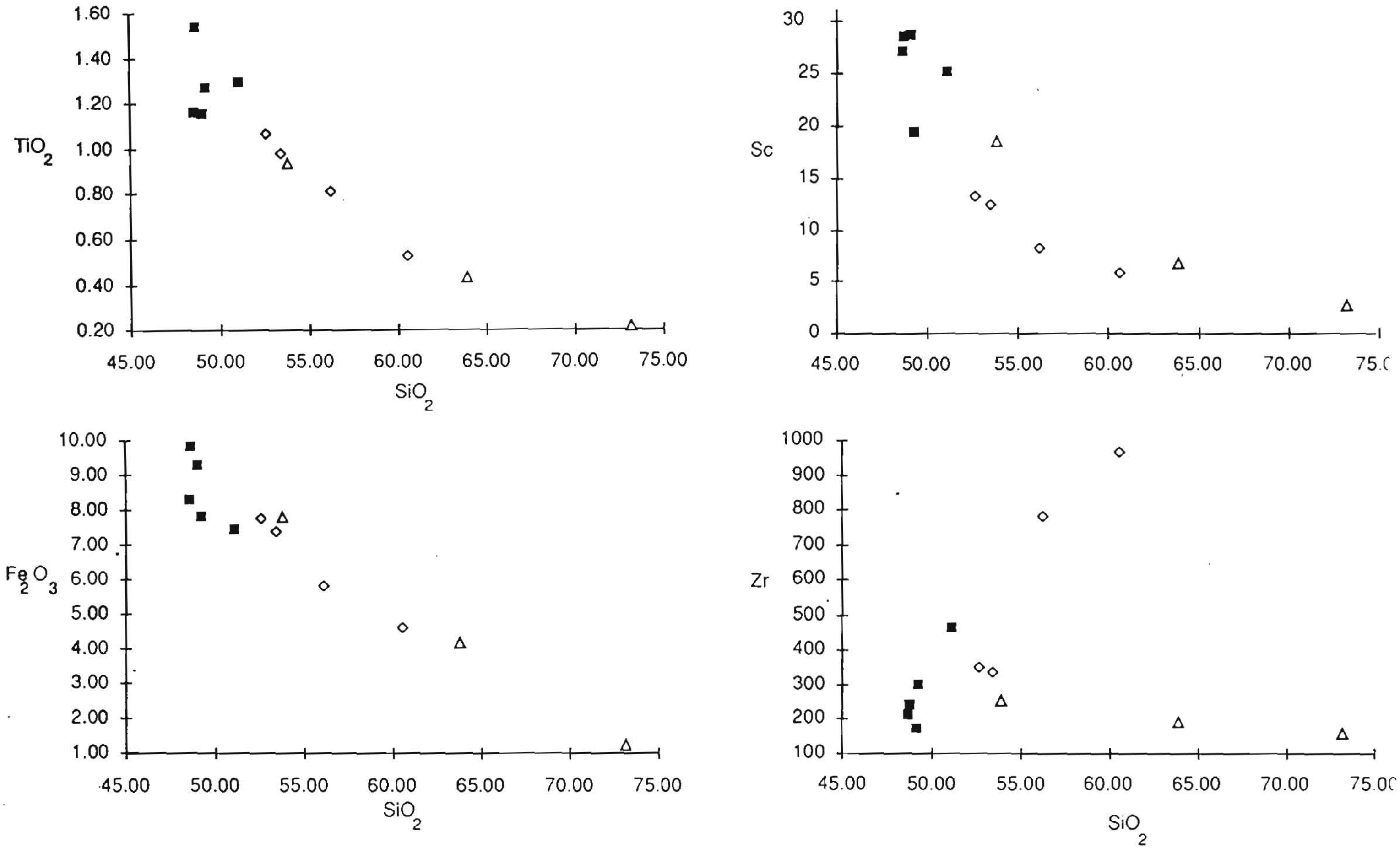

Fig. 4. Variation of selected elements vs. silica for the studied samples. Oxides in wt%, Sc, Zr in ppm. For symbols see figure 3.

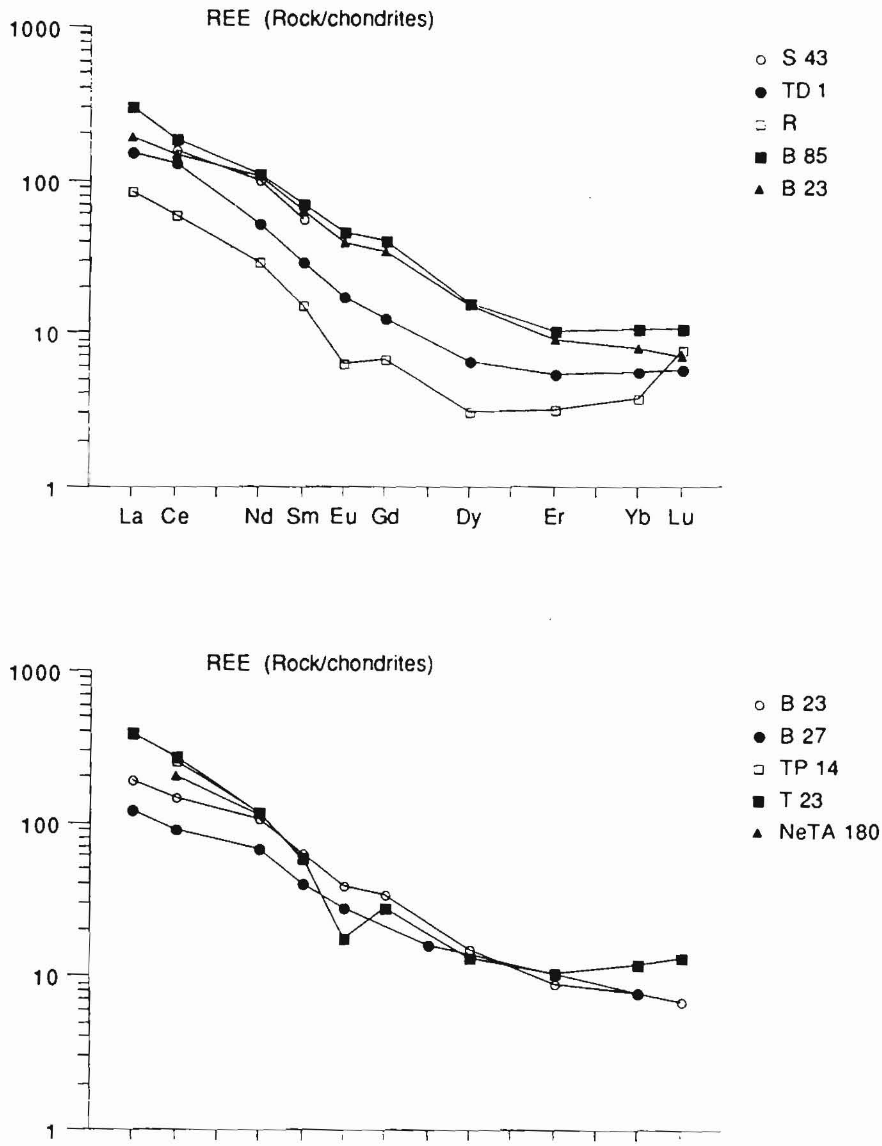

Fig. 5. Chondrite-normalized REE patterns. a. patterns of the undersaturated rocks (TP tephritic phonolite, NeTA Ne-trachyandesite, T alkali-trachyte) compared to basalts (B). b. patterns of the oversaturated rocks (S shoshonite, TD trachydacite, R rhyolite) compared to basalts. Plotting program by Wheatley and Rock, 1988.

SR AND ND ISOTOPIC DATA

Sr and Nd compositions of Bodrum mafic, intermediate, and felsic rocks are shown in table 3.

Sr and Nd isotopic characteristics of the basaltic rocks show a range of compositions with initial $^{87}Sr/^{86}Sr$ values (9Ma) from 0.7055 to 0.7071 and $^{143}Nd/^{144}Nd$ values ranging from 0.51264 to 0.51246 where the high-K basalts occupy the high-Sr and low-Nd end of the range. These values could be thought of as representing those of mantle sources of the mafic magmas (Robert et al., 1992).

The differentiated rocks of the two series show distinct isotopic compositions: the alkali-rich undersaturated sequence displays less radiogenic Sr isotopic ratios of 0.706 to 0.7062 and Nd isotopic ratios around 0.51253 (variations lower than the error values), whereas the the silica-oversaturated rocks have more radiogenic $^{87}Sr/^{86}Sr$ values extending from 0.7067-0.707 with $^{143}Nd/^{144}Nd$ varying from 0.51256 to 0.51250. These values are, however, well within the range of values for the various basalts. There seems to be no need to invoke an upper crustal origin for the differentiated rocks.

The $^{87}Sr/^{86}Sr$ isotopic values of the basalts are positively correlated with their K2O or SiO2 contents but neither Sr nor Nd isotopic compositions show any noteworthy correlation with differentiation parameters in the alkaline rocks (Fig.6). Among the oversaturated rocks only the rhyolite (R) has significantly higher Sr and lower Nd values but its isotopic characteristics are very similar to those of the high-K basalts which are clearly mantle magmas (Robert et al., 1992).

Sr isotopic data for the central Aegean province and other centers of the Dodecanese have been published by Juteau et al (1986) and Altherr et al (1988). A plot of Sr isotops against 1/Sr contents (fig. 7) shows that the values for monzodiorites and monzonite (Samos, Kos, Bodrum) from these authors also form two horizontally extending trends, similar to the Bodrum samples studied here, while rocks evolve towards more Sr poor compositions, such as plagioclase fractionation would produce. This diagram also shows that the rocks from the central Aegean are well distinguished isotopically.

SUMMARY AND CONCLUSIONS

The Bodrum volcanic complex contains a great compositional range of igneous rocks whose geochemical cracteristics are those of rocks formed at convergent margins. The rocks fall into two differentiated series, one which is oversaturated and ranging from basalts to rhyolites by way of mafic trachyandesites (shoshonites), latites, trachydacites, and another which comprises saturated to undersaturated volcanics including basalts, nepheline-trachyandesites, tephryphonolites and alkali-trachytes, some with peralkaline characteristics.

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Table 3. Isotopic composition data

	Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$(^{87}Sr/^{86}Sr)_T$	$^{143}Nd/^{144}Nd$	eNd
B 23*	155	1145	0.382	0.707195(38)	0.70714	0.512470(26)	-3.3
B 85	36	865	0.1206	0.706262(70)	0.70625	0.512542(36)	-1.9
B 32*	100	1079	0.2695	0.705874(40)	0.70584	0.512582(20)	-1.1
B 27*	114	851	0.3871	0.705802(31)	0.70575	0.512641(24)	0.6
B 71+	51	1549	0.095	0.705248(59)	0.70524	0.512532(25)	-2.1
NeTA 180	163	1430	0.3302	0.706067(38)	0.70601	0.512527(32)	-2.2
NeTA 14	156	1411	0.3141	0.706035(49)	0.70599	0.512570(52)	-1.3
TP 14	321	803	1.156	0.706043(32)	0.70588	0.512526(86)	-2.2
T 23	356	207	5.088	0.706613(195)	0.70597	0.512548(49)	-1.8
S 43	145	1163	0.3811	0.706756(68)	0.70671	0.512560(50)	-1.5
TD 1	193	1018	0.5492	0.706791(122)	0.70673	0.512542(29)	-1.8
R	245	393	1.8059	0.707285(43)	0.70703	0.512504(26)	-2.6

* Rb,Sr by isotopic dilution (CRPG, Nancy); + Rb,Sr by ICP (Pierre Süe, Saclay), all other samples by X-ray fluorescence (University of Adelaide)

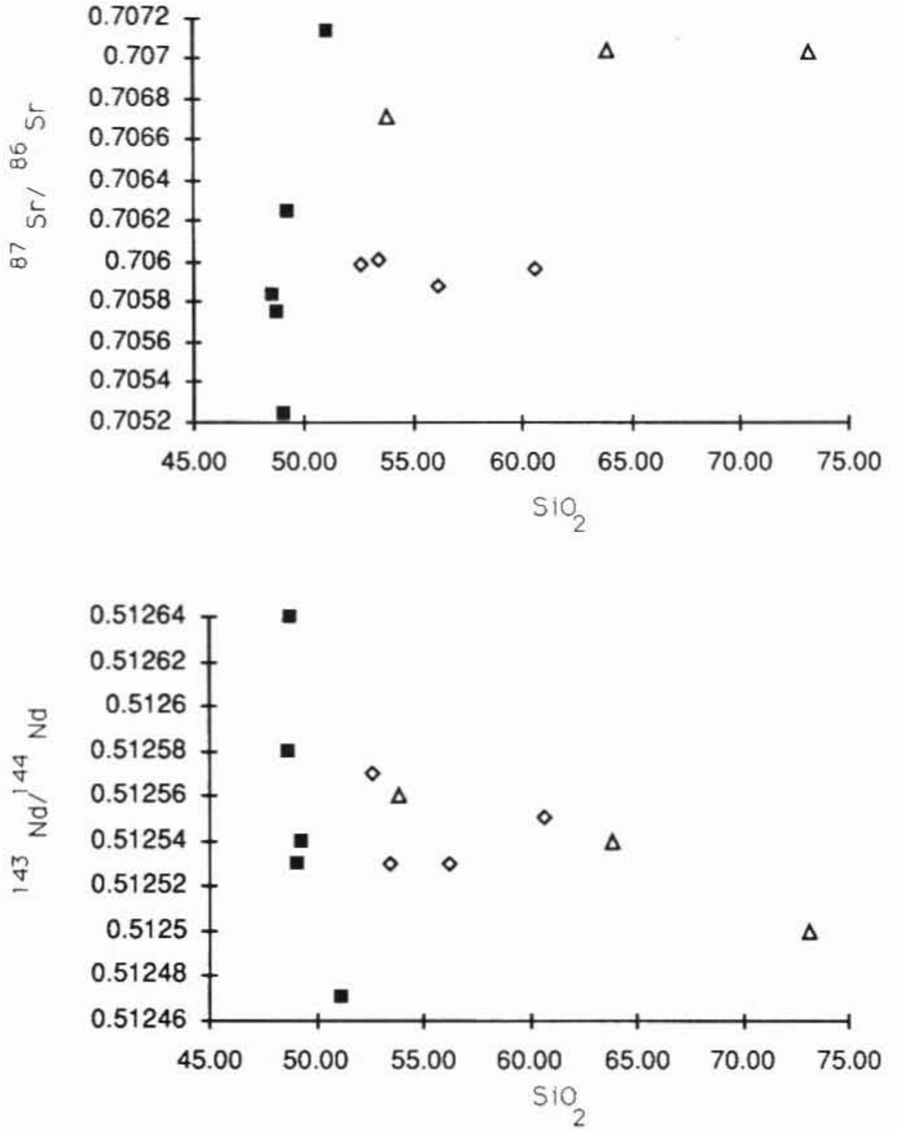
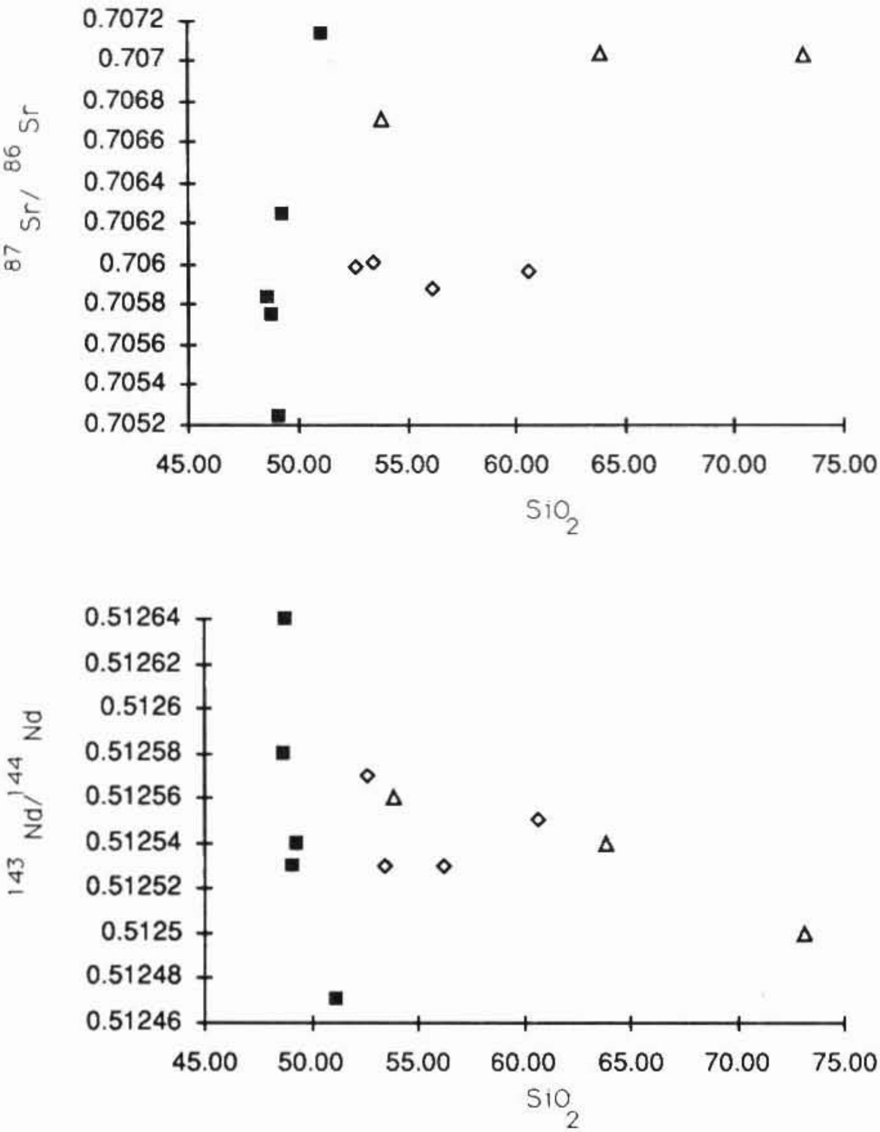


Fig. 6. Sr and Nd isotopic compositions vs. silica content of th samples. For symbols see figure 3.



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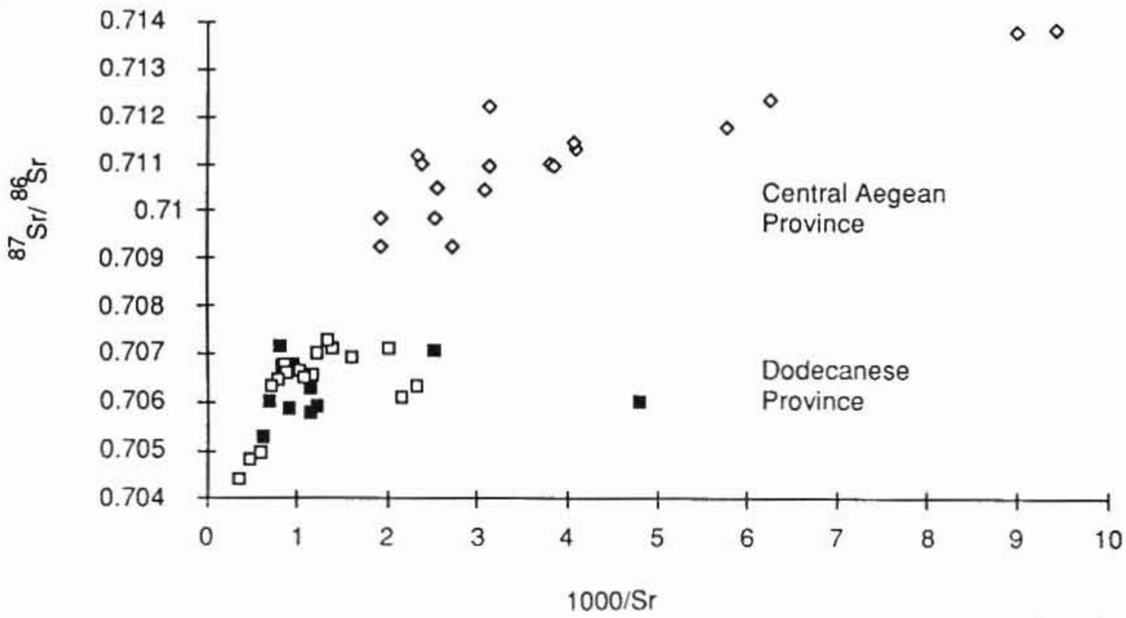

Fig. 7. 87Sr/86Sr vs. 1000/Sr for samples from this study (full symbols), and data from Altherr et al., 1988: Kos and Samos (open squares) and granitoids from the Central Aegean Province (open diamonds) .

Phonolitic rocks with peralkaline affinities have already been discribed from the island of Patmos (Robert, 1973). Felsic peralkaline differentiates are rare among igneous suites with the geochemical characteristics of convergent margin magmatism.It is interesting to note that other principal examples, such as the volcanic rocks of Dobu, in the Woodlark Basin, Papua New Guinea, and Major Island, off North Island, New Zealand, also occur where local extension is taking place in a region of convergent tectonism at a continental margin.

There is no clear relationship at Bodrum between time and geochemical evolution, except that rhyolites seem to be the oldest products. Alkaline undersaturated felsic rocks are relatively small in volume compared with the silica-oversaturated activity, which is mainly represented by rocks of intermediate compositions that appeared at several stages in the life of the volcano.

Many of these volcanic rocks of intermediate composition are heterogeneous and include numerous mafic xenoliths with basaltic compositions, suggesting that magma mixing may have occurred and played an important role for the abundance of intermediate compositions. However, the general petrographic and mineralogical characteristics of the rocks, coupled with systematic geochemical variations for many elements, are consistent with the evocation of crystal fractionation as the major process responsible for the wide variety of felsic rocks. The presence of two different series and the differing behavior of K-group elements and LREE in felsic magmas from the oversaturated and undersaturated sequences, could suggest that more complex processes may also have occurred, although crystal fractionation starting with slightly different parental magmas or taking place in different magma chambers under different physical conditions might be enough to explain the variety of fractionates.

If the differentiated Bodrum rocks are simple fractionates of parental mafic magmas, as their petrographic and geochemical characteristics suggest that they could be, then it would be anticipated that their isotopic signatures would be similar to those of their postulated parent magmas. On the other hand, input from the crust could be a possible explanation for the compositional differences between the oversaturated series culminating in rhyolites, and the undersaturated series culminating in trachyphonolites and alkali-trachytes. The differentiated rocks of both series have $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ values well within the range of Sr,Nd isotopic ratios of the various basalts which could include representatives of the postulated parental magmas. Among the oversaturated rocks only the rhyolite (R) has significantly higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ than the bulk of the mafic rocks (fig.7) but even these isotopic characteristics are very similar to those of the high-K basalts which are particularly strong candidates for primary mantle magmas (Robert et al., 1992).

It is therefore concluded that although other processes such as crustal assimilation and magma mixing may have occrurred at Bodrum, there is little evidence from geochemistry or Sr, Nd isotopes to indicate that substantial crustal assimilation was an essential factor in the generation of the differentiated rocks of Bodrum.

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