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TERTIARY PLUTONIC ROCKS FROM EAST RHODOPE IN BULGARIA AND GREECE

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ABSTRACT

The east Rhodope is characterized by an intensive Tertiary orogenic activity manifested by both plutonic and volcanic magmatism. The plutonic rocks of two areas from the east Rhodope, one from Bulgaria and one from Greece, namely the Zvezdel and Leptokarya-Kirki intrusions, are studied and compared.

The magmatism in both areas is strongly controlled by tectonic activity. The distribution of the various intrusions is related to deep faults of mostly N-S and NE-SW direction. The Zvezdel plutonics comprise rocks ranging in composition from monzogabbro to tonalite through qz-gabbro, qz-monzogabbro/qz-monzodiorite and qz-monzonite. They are medium-grained with monzonitic to ophitic and porphyritic textures. Their modal composition is plagioclase, K-feldspar, quartz, ortho- and clinopyroxene. Less abundant is biotite and olivine. The Leptokarya-Kirki intrusions are classified as qz-gabbro, qz-diorite, qz-monzogabbro/qz-monzodiorite, tonalite and granodiorite. Their mineralogical composition is plagioclase, K-feldspar, quartz, ortho- and clinopyroxene, biotite and hornblende.

The Zvezdel rocks have characteristics of the high-K calc-alkaline to shoshonitic series while those of Leptokarya-Kirki of the calc-alkaline to high-K calc-alkaline series. An overall increase of potassium towards Zvezdel is obvious. Chondrite-normalized REE patterns are similar in both areas except HREE which are almost unfractionated in Leptokarya-Kirki. ΣREE is lower in Leptokarya-Kirki. Discrimination diagrams show a volcanic arc granites setting for the Zvezdel and Leptokarya-Kirki rocks.

Major, trace and REE abundances along with the presence of cumulitic phases support an evolution of the rocks by fractional crystallization. The relatively flat HREE patterns and the enrichment in LREE and other LILE are compatible with an "enriched" upper mantle source region. The evolution of the rocks is related to the subduction of the African plate under the European plate. Partial melts and/or hydrous fluids contributed to the enrichment of the mantle during the process of the subduction.

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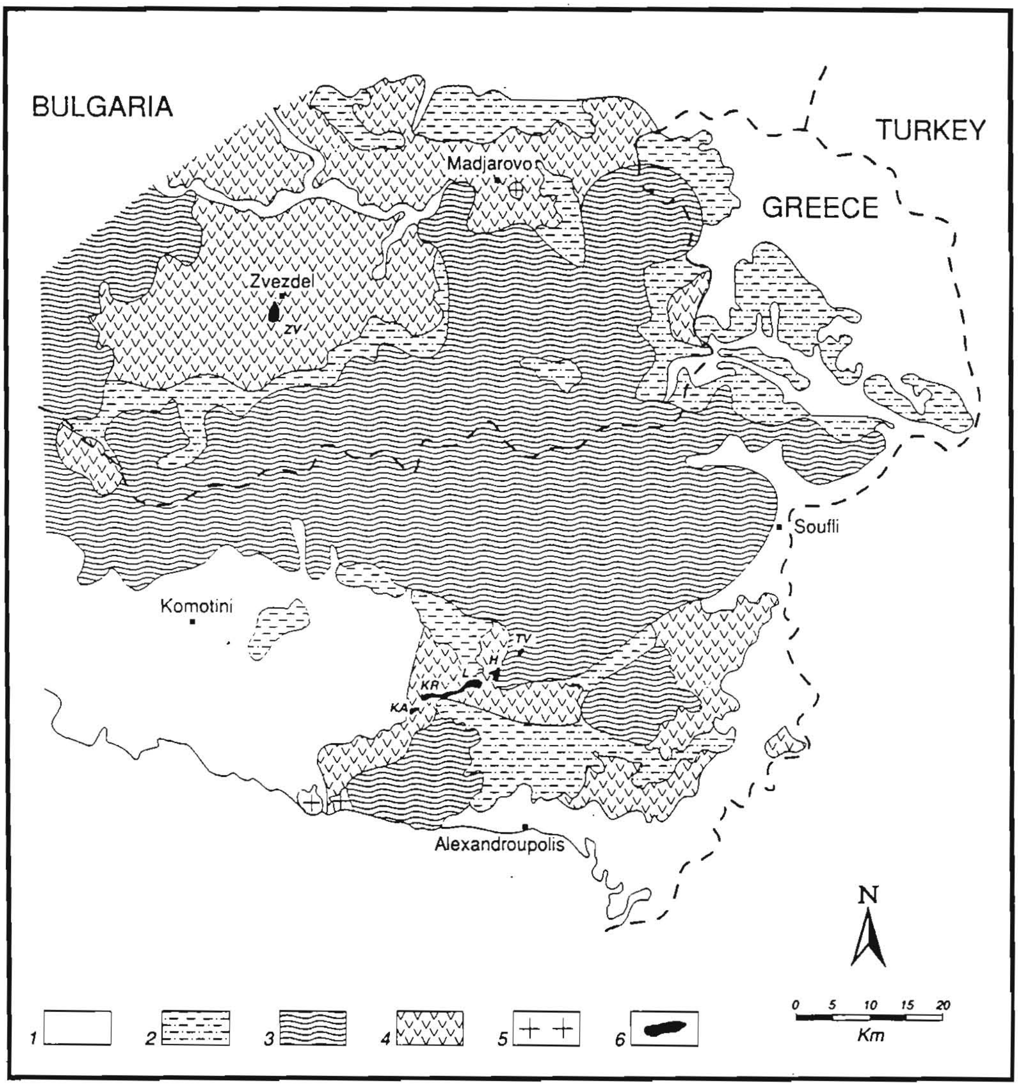

Fig. 1. Simplified geological map of East Rhodope (modified after Yovchev, 1960 and Konstantinides et al., 1983).

1. *Quaternary and Neogene deposits: lacustrine, coastal and alluvial sediments (limestones, sandstones, clays, pebbles, gravels);*
2. *Upper Lutetian - Oligocene: sediments (conglomerates, clays, marls, sandstones, limestones, pelites, tuffs and tuffites);*
3. *Precambrian - Upper Cretaceous: "basement" (metamorphic rocks, ultrabasic rocks, diabase bodies);*
4. *Upper Eocene - Oligocene: volcanic rocks (basalts to rhyolites) in the form of dykes, subvolcanic masses, pyroclastics; volcanosedimentary formations;*
5. *Oligocene: plutonic rocks (gabbro to granodiorite);*
6. *Plutonic rocks of present study*

INTRODUCTION

The east Rhodope, including both the Bulgarian and the Greek territories (Fig. 1), is characterized by an intensive Tertiary orogenic activity (Rentzeperis, 1956; Ivanov, 1960, 1963, 1968; Mavroudchiev et al., 1973; Sideris, 1973; Fyticas et al., 1985; Lilov et al., 1987; Del Moro et al., 1988; Eleftheriadis et al., 1989a,b). This activity, manifested by both volcanic and plutonic magmatism, is interpreted in terms of plate tectonics and particularly with the underthrusting of the African plate beneath the southern margin of the European plate.

The importance of this magmatic activity for the tectonomagmatic evolution of the east Rhodope has been pointed out by many geologists. A comparative study between the volcanic rocks from the Momchilgrad region (Zvezdel volcano) in Bulgaria and the Evros region (Alexandroupolis volcanics) in Greece has already been done (Eleftheriadis et al., 1989a). The main conclusions of this study are: a) the volcanics of both areas, with andesite as the predominate rock type, have the same geological setting, b) K_2O increases from south to north and c) chemistry of major and trace elements supports a crystal-liquid fractionation process for the evolution of the volcanic rocks.

The present paper, dealing with the plutonic magmatism in the corresponding regions, and particularly with the Zvezdel pluton in Bulgaria and the Leptokarya-Kirki intrusions in Greece, aims to a better understanding of the Palaeogenic magmatic evolution in the Rhodope massif.

GEOLOGICAL OUTLINES

The Tertiary magmatism of the east Rhodope, both in Bulgaria and Greece, is strongly controlled by tectonic activity. In particular the distribution of the Zvezdel plutonic rocks (ZV) is governed by the intersection of deep N-S and NE-SW faults (this structure cannot be shown on the simplified map of Fig. 1 due to the relatively small dimensions of the outcrops). These rocks occur in the form of stocks, sills and dykes and intrude in stratovolcanoes building up volcano-plutonic structures; in deeper levels they intrude metamorphic rocks. The Zvezdel plutonic bodies are composed of several magmatic phases such as gabbroids, intermediate and acidic plutonics and seem connected by a clear differentiation process (Nedyalkov, 1986). There are also acidic and basaltic dykes intersecting the intrusions (Athanasov et al., 1963; Nedyalkov, 1986; Eleftheriadis et al., 1989a, Yanev et al., 1989). The above rocks have in general a high-K calc-alkaline to shoshonitic character. Their age, according to geochronological data (Lilov et al., 1987) is about 33 m.y.

The Leptokarya-Kirki plutonic rocks in the Greek east Rhodope outcrop along a faulty zone of mostly NE-SW direction subparallel to the northern margins of the Aesymi-Kirki basins, thus indicating a tectonic controlled origin (Eleftheriadis et al., 1989b). They appear in the form of small, usually elongated, intrusive bodies which from SW to NE are: Kassitera (KA), Kirki (KR), Leptokarya (L), Chalasmata (H) and Tris Vryses (TV) (Fig. 1). The biggest of them is the Leptokarya body. All these bodies refer to as Leptokarya-Kirki intrusions. The Leptokarya-Kirki plutonic bodies, comprising similar rock types with the Zvezdel ones, intrude the metamorphics of the Rhodope massif (Tris Vryses, Chalasmata) or are in contact with the

Priabonian volcanosedimentary series and the volcanics of mostly andesitic composition. The Leptokarya and the Chalsmata bodies and to a lesser extent the rest are intruded by acidic dykes of mainly rhyolitic composition (Alfieris et al., 1989; Eleftheriadis et al., 1989b). The above magmatic bodies show a calc-alkaline to high-K calc-alkaline affinity (Del Moro et al., 1988; Eleftheriadis et al., 1989b). Their age was found to be Oligocene on the basis of both stratigraphic (Papadopoulos, 1982) and geochronological data (35-32 m.y.) (Bitzios et al., 1981; Kyriakopoulos, 1987; Del Moro et al., 1988).

PETROGRAPHY AND MINERALOGY

The classification of the plutonic rocks of Zvezdel and Leptokarya-Kirki has been done on the basis of the Q'-ANOR diagram of Streckeisen & Le Maitre (1979) for a more objective comparison of the two rock series.

In this term, the Zvezdel complex comprises plutonic rocks ranging in composition from monzogabbros to tonalites through qz-gabbros, qz-monzogabbros/qz-monzodiorites and qz-monzonites (Fig. 2). Aplitic rocks (granitic, syenitic) crosscut the above petrographic types. In the north part of the complex a sheet-like body of noritic to monzonitic composition with cumulitic features is present.

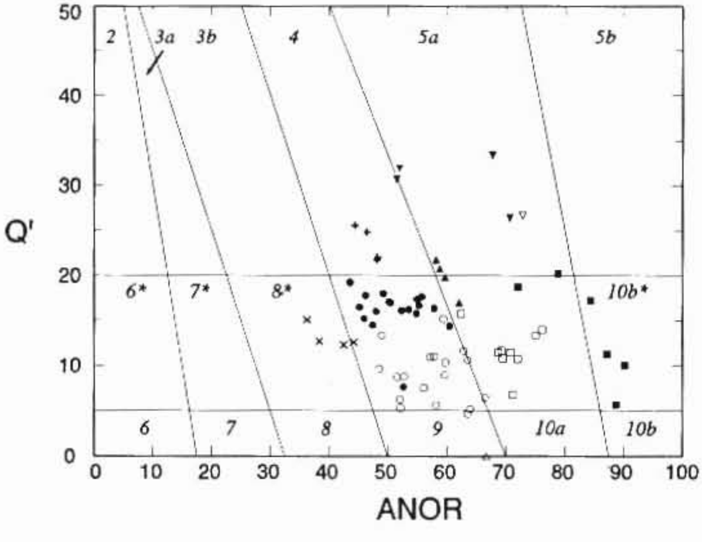

Fig. 2. Classification of the Zvezdel and Leptokarya-Kirki plutonic rocks after Streckeisen and Le Maitre (1979).
*ANOR = 100*An/(Or+An) and Q'= 100*Q/(Q+Or+Ab+An).*

△ = *Monzogabbro* *Mzgb(ZV)*
□ = *Qz-gabbro* *QGb(ZV)*
○ = *Qz-monzogabbro/ Qz-monzodiorite* *QMzg(ZV)/ QMzd(ZV)*
▽ = *Tonalite* *Ton(ZV)*
× = *Qz-monzonite* *QMz(ZV)*
ZV = Zvezdel

■ = *Qz-gabbro* *QGb(AL)*
▲ = *Qz-diorite* *QDr(AL)*
● = *Qz-monzogabbro/ Qz-monzodiorite* *QMzg(AL)/ QMzd(AL)*
▼ = *Tonalite* *Ton(AL)*
· = *Granodiorite* *Grd(AL)*
AL = Leptokarya-Kirki.

The texture of the Zvezdel rocks is mainly monzonitic to ophitic and sometimes porphyritic. In general the rocks are medium-grained. The mineralogical composition is plagioclase, K-feldspar, quartz, ortho- and clinopyroxene as well as biotite and olivine. Plagioclase (bytownite to oligoclase) occurs in all rock types. K-feldspar is either interstitial or subhedral, very often with poikilitic texture. Quartz is present in almost all the rocks reaching up to 18 vol%. Among the ferromagnesian minerals clinopyroxene, of diopsidic to augitic composition ($Wo_{37-42}En_{51-57}Fs_{6-9}$) occurs in all the rock types in varying amounts (1-15 vol%), whereas orthopyroxene ($Wo_{2-4}En_{66-73}Fs_{25-31}$) is confined mostly to the qz-monzogabbro (Nedyalkov, 1986). Biotite and olivine were found in subordinate amounts in some rocks. In the noritic sheet-like body, however, olivine ($Fo_{62}Fa_{38}$) reaches up to 25 vol%. In the gabbroic rocks amphibole is also present as a pyroxene uralitization product. Accessory minerals are apatite, zircon and titanomagnetite. Sericite and clay minerals as well as epidote, calcite and chlorite are alteration products of feldspars and pyroxene and biotite respectively.

The Leptokarya-Kirki plutonic rocks are classified as qz-gabbros, qz-diorites, qz-monzogabbros/qz-monzodiorites, tonalites and granodiorites (Fig. 2). Rarely, rocks of anorthositic composition occur while acidic dykes of mainly rhyolitic composition intrude some of the rock types. The texture is mostly granitic and to a lesser extent monzonitic and rarely subophitic. Some bodies (Kassitera, Chalasmata) have at their margins porphyritic texture while the qz-gabbros and qz-diorites show in some places characters of cumulitic rocks. The Leptokarya-Kirki rocks are medium-grained but coarser than in Zvezdel.

The rocks of the Leptokarya-Kirki complex consist of plagioclase, K-feldspar, quartz, amphibole, biotite and pyroxene (ortho- and clinopyroxene). Plagioclase is the most widespread mineral phase ranging in composition from bytownite to oligoclase. K-feldspar occurs in significant amounts in all rock types except qz-gabbros and qz-diorites, where it is subordinate (2-3 vol%). Quartz follows K-feldspar concerning its distribution and abundance in the various rock types. Among the ferromagnesian minerals, amphibole (magnesio-hornblende to actinolite) predominates in the qz-diorite (18-22 vol%). In most cases, amphibole appears as a reaction or more often as an alteration product of pyroxene, occurring both as a rim around crystals and along cleavage planes. Clinopyroxene, of augitic to diopsidic composition ($Wo_{40-48}En_{40-44}Fs_{12-16}$), occurs as an essential constituent in the qz-gabbros (up to 30 vol%) and in subordinate amounts in the rest rock types. In some rocks, clinopyroxene is accompanied by minor amounts of orthopyroxene ($Wo_{3}En_{63-67}Fs_{34-30}$) which sometimes constitutes the core of the first (cf. Eleftheriadis et al. 1989b). Biotite is found in almost all the rocks with contents up to 8 vol%. Apatite, titanite, zircon and iron-titanium oxides occur as accessories. In many cases feldspars are altered to sericite and clay minerals while hornblende and biotite to epidote, calcite and chlorite.

Table 1. Chemical analyses for major (wt%) and trace elements (ppm) of selected samples from Zvezdel plutonic rocks.

Sample	ZV01	ZV02	ZV03	ZV04	ZV05	ZV06	ZV07	ZV08	ZV09	ZV10	ZV11	ZV12	ZV13	ZV14	ZV15	ZV16	ZV17
Location	X9	W12	1210	W9	W6	W3b	1027a	1212	1214	1198	1032	108	119a	101	W1	4	127
Type	Mzgb	QGb									QMgb/QMzd						
											#		#		#	#	
SiO2	46.16	52.74	53.73	54.60	54.82	54.86	54.93	55.06	55.48	58.33	51.76	53.05	54.36	54.53	54.57	55.31	55.33
TiO2	0.26	0.99	0.97	1.70	1.06	1.13	1.01	1.02	0.90	0.73	0.86	1.03	0.98	2.06	1.06	2.05	0.95
Al2O3	17.37	16.00	18.98	16.03	17.90	17.96	17.21	19.52	18.12	17.54	18.26	17.02	16.47	17.84	17.35	16.95	17.71
Fe2O3*	13.18	9.83	9.40	8.35	8.83	9.22	8.97	8.96	8.61	8.32	10.30	9.66	9.35	7.60	9.11	8.59	7.99
MnO	0.20	0.16	0.16	0.14	0.12	0.13	0.16	0.18	0.12	0.16	0.20	0.15	0.14	0.13	0.13	0.20	0.16
MgO	11.34	6.69	3.87	5.09	3.88	3.73	4.51	3.17	4.62	2.72	3.66	4.98	4.76	4.56	3.79	4.45	3.86
CaO	7.92	9.14	8.52	8.90	8.39	7.74	8.46	8.13	7.23	6.28	8.68	8.37	8.35	7.48	7.95	6.78	7.23
Na2O	1.53	2.82	2.58	2.90	2.84	3.07	3.02	2.67	3.14	3.38	2.96	3.30	2.81	3.68	2.68	2.81	3.22
K2O	2.74	1.76	2.21	1.92	1.64	1.69	1.93	2.53	2.15	2.56	2.75	2.35	2.76	2.19	2.72	3.10	3.22
P2O5	0.04	0.12	0.20	0.08	0.11	0.11	0.19	0.32	0.20	0.23	0.27	0.39	0.14	0.35	0.17	0.27	0.26
Rb	32	55	79	80	150	90	64	117	86	90	53	58	80	49	100	80	103
Ba	261	580	976	760	650	870	672	976	695	697	645	750	770	875	1000	1350	1150
Sr	451		500				520	457	490	433	575						
Cr	32	90	18	85	29	25	29	15	20	22	11	30	25	40	25	24	24
Ni	77						10					12	3	5		2	
Zr	74		154					184	185		148						
Nb	1.0								3.0		4.0						
Hf	1.0	1.7	3.2	5.7	4.0	5.5	3.8	4.7	4.5	3.8	2.2	2.5	2.7	4.8	4.9	3.6	4.9
Ta	0.20	1.00	0.60	0.70	0.60	0.80	0.50	0.70	0.70	0.60	0.40	0.40	0.50	0.60	0.60	0.70	0.80
Th	6.3	6.9	11.7	13.8	15.9	14.0	8.8	14.5	12.4	13.0	8.4	7.7	12.0	10.7	16.1	15.4	16.5
Y	11		25					30	28		25						

Sample	ZV18	ZV19	ZV20	ZV21	ZV22	ZV23	ZV24	ZV25	ZV26	ZV27	ZV28	ZV29	ZV30	ZV31	ZV32	ZV33
Location	118	124	1215	6d	6b	123	116	105	W11	1323a	W15	W3a	128	115	7	1246
Type	QMzg/QMzd (continucd)											Ton	QMz			
	#															
SiO2	55.41	55.41	55.44	55.49	55.96	56.05	56.65	56.74	56.87	58.79	59.59	57.85	60.05	60.40	60.41	60.88
TiO2	1.10	0.98	0.91	1.22	1.38	1.00	1.12	1.62	0.83	0.88	1.05	1.11	0.84	0.91	0.96	0.77
Al2O3	17.80	16.98	17.27	17.40	17.28	16.95	17.89	17.65	18.54	16.23	16.87	17.21	17.54	16.77	15.52	18.51
Fe2O3*	8.51	8.54	8.51	7.88	7.73	7.98	7.56	7.77	6.41	7.20	8.51	9.06	5.61	6.62	6.40	5.24
MnO	0.14	0.16	0.13	0.17	0.13	0.13	0.10	0.14	0.13	0.10	0.11	0.14	0.12	0.12	0.10	0.09
MgO	3.97	3.47	3.86	4.33	3.33	3.93	2.91	3.48	3.49	3.99	4.23	4.04	2.73	2.34	3.02	1.91
CaO	7.70	7.72	7.28	6.75	7.16	6.93	6.22	6.40	6.56	6.89	7.43	6.21	4.87	4.83	5.29	4.21
Na2O	2.97	3.78	3.30	3.92	3.29	3.18	2.93	3.35	3.24	2.98	3.03	1.85	3.36	3.57	3.07	3.70
K2O	2.65	3.12	3.44	2.67	3.38	3.45	4.18	2.99	3.07	3.58	2.79	1.90	4.29	4.48	4.52	4.47
P2O5	0.17	0.27	0.07	0.20	0.31	0.23	0.19	0.17	0.16	0.28	0.09	0.13	0.23	0.38	0.27	0.27
Rb	98	88	165	85	155	100	100	94	150	100	80	105	120	195	180	225
Ba	450	1010	980	880	1100	790	840	950	1270	889	750	770	1220	1125	860	1279
Sr			443							387						546
Cr	18	20	19	20	17	25	14	25	20	18	30	45	15	15	22	13
Ni			23		8	6				3					7	
Zr			188													232
Nb																7.0
Hf	3.8	3.9	5.5	4.8	4.2	3.2	3.2	6.0	5.8	3.6	3.8	6.0	3.8	6.0	7.0	6.1
Ta	0.60	0.60	1.00	0.60	0.80	0.50	0.50	0.70	1.10	0.70	0.60	2.70	0.70	1.00	1.10	1.00
Th	12.2	14.3	20.1	8.2	17.7	12.0	11.3	14.3	20.3	19.9	15.0	16.3	17.5	27.2	26.9	26.4
Y			33													41

* Total iron as Fe2O3

\# These samples are classified as qz-monzogabbros according to normative plagioclase composition (the rest are qz-monzodiorites)

Table 2. Chemical analyses for major (wt%) and trace elements (ppm) of selected samples from Leptokarya-Kirki plutonic rocks.

Sample	AL01	AL02	AL03	AL04	AL05	AL06	AL07	AL08	AL09	AL10	AL11	AL12	AL13	AL14	AL15	AL16	AL17	AL18
Location	TV10	L52	L54	SA63	TV01	SA64	L02	SA84	L07	CK20	KR08	L57	SA87	L25	KA59	L14	KR10	KR01
Type	QGb						QDr				QMzg/QMzd							
														#	#			#
SiO2	50.09	52.22	52.79	56.49	58.72	59.37	59.57	59.89	61.02	63.31	57.15	57.52	57.99	58.17	58.53	58.73	58.80	58.88
TiO2	1.15	0.89	0.58	0.74	0.68	0.74	0.76	0.67	0.68	0.66	0.67	0.59	0.72	0.59	0.60	0.69	0.63	0.59
Al2O3	16.42	16.38	23.79	18.30	17.30	17.38	16.21	13.68	16.28	16.98	15.68	13.93	13.33	14.97	14.10	14.19	14.21	14.29
Fe2O3*	11.12	9.42	5.24	8.31	6.99	7.07	6.62	7.54	6.17	5.47	6.25	6.97	7.29	6.31	6.14	6.78	6.28	6.24
MnO	0.17	0.19	0.11	0.14	0.17	0.13	0.07	0.13	0.05	0.06	0.06	0.10	0.11	0.21	0.02	0.09	0.06	0.14
MgO	8.07	7.65	2.24	3.98	3.73	3.28	6.05	6.54	4.25	3.07	7.68	9.57	6.99	6.59	9.29	7.17	8.06	7.80
CaO	10.41	9.87	11.55	7.76	7.13	7.22	5.86	6.43	5.77	5.55	6.20	6.55	6.85	7.36	5.77	6.28	5.96	6.03
Na2O	1.94	2.34	3.10	3.05	3.03	3.33	2.91	2.67	3.07	3.38	3.10	2.46	2.56	2.42	2.07	2.69	2.30	2.14
K2O	0.63	0.79	1.03	1.04	1.85	1.30	2.47	2.27	2.62	2.74	3.03	2.25	2.79	2.71	2.98	2.82	3.43	3.27
P2O5	0.21	0.34	0.15	0.19	0.21	0.17	0.21	0.17	0.22	0.16	0.20	0.21	0.23	0.18	0.16	0.21	0.02	0.18
Rb	27	20	28	27	60	21	78	56	80	71	95	56	99	72	138	86	120	123
Ba	187	311	396	400	508	478	713	578	650	560	539	679	548	762	780	736	761	728
Sr	574	495	734	412	429	640	338	282	329	312	320	294	290	299	338	318	247	281
Cr	30	46	36		33		80		63		138	246		186	325	190	251	233
Ni	6	4	2		12		32		23		92	161		87	137	87	151	124
Zr	76	150	192	86	185	28	148	127	125	144	177	149	134	139	183	154	187	176
Nb	12.0		1.0	5.7	4.0	2.0	11.0	7.7	9.0	9.0	4.0	2.0	8.4	6.0	16.0	11.0		4.0
Hf				2.8		3.6		3.5					3.8					
Ta				0.57		0.75		0.87					1.00					
Th				5.2		9.0		11.0					13.0					
Y	18	16	18	14	39	11	22	19	21	21	25	26	17	36	23	20	26	37

Sample	AL19	AL20	AL21	AL22	AL23	AL24	AL25	AL26	AL27	AL28	AL29	AL30	AL31	AL32	AL33	AL34	AL35	AL36
Location	L23a	L22	KR07	L09	SA66	CK49	L12	L55b	L13	SA68	L51	SA57	SA61	H106	CK23	CK22	SA82	SA65
Type	QMzg/QMzd (continued)										Ton				Grd			
SiO2	58.99	59.04	59.82	59.98	60.16	60.46	60.77	60.89	60.96	61.19	61.82	69.10	69.45	69.85	61.22	61.86	64.30	65.29
TiO2	0.65	0.68	0.62	0.79	0.59	0.67	0.71	0.69	0.63	0.71	0.63	0.39	0.38	0.39	0.70	0.70	0.64	0.59
Al2O3	14.30	14.24	15.37	16.46	14.00	13.60	16.13	14.59	16.43	15.84	16.25	15.98	15.30	15.35	13.95	14.47	14.24	15.24
Fe2O3*	6.29	6.28	5.98	6.13	6.65	6.73	5.83	5.17	5.95	6.41	6.80	2.97	3.14	2.97	6.65	6.42	5.48	4.81
MnO	0.10	0.09	0.05	0.04	0.10	0.04	0.04	0.05	0.04	0.06	0.12	0.07	0.06		0.13	0.10	0.09	0.08
MgO	7.69	7.53	5.58	4.28	6.17	6.43	4.35	5.95	4.96	3.28	3.75	1.94	1.52	1.26	6.01	4.85	4.06	2.99
CaO	5.66	5.58	6.61	5.92	5.98	5.96	5.98	5.90	5.09	5.62	5.90	4.25	3.74	3.80	5.89	5.91	4.86	4.27
Na2O	2.31	2.46	2.94	3.25	3.03	2.49	3.21	2.71	3.10	3.34	2.64	3.54	3.48	3.33	2.36	2.67	2.70	3.19
K2O	3.40	3.48	2.80	2.99	3.14	3.44	2.91	3.44	2.97	3.25	1.89	1.66	2.83	2.86	3.24	3.25	3.48	3.37
P2O5	0.17	0.18	0.21	0.23	0.17	0.17	0.21	0.20	0.22	0.17	0.19	0.10	0.09	0.13	0.17	0.17	0.15	0.15
Rb	143	142	64	103	97	123	101	107	99	97	73	56	88	96	113	123	88	109
Ba	682	671	744	562	637		664	808	699	711	678	348	584	773	659	637	694	659
Sr	271	265	327	390	275	265	346	269	300	325	369	341	286	355	260	273	247	284
Cr	234	229	97	53			65	172	64		34			8				
Ni	129	128	42	18			28	103	23		2							
Zr	174	176	185	138	116	160	135	154	141	152	186	100	101	106	142	151	164	135
Nb	8.0	9.0	7.0	8.0	7.6	9.0	7.0	8.0	10.0	8.7	4.0	9.0	7.3	29.0	9.2	9.7	11.0	9.4
Hf					3.1					4.6		3.1	3.0					4.2
Ta					0.60					0.73		1.00	0.87					1.20
Th					10.6					11.3		13.7	13.2					14.9
Y	19	15	23	21	17	22	22	29	22	21	31	17	14	19	18	19	22	20

For * and # see Table 1

KA: Kassitera, KR: Kirki, L: Leptokarya, H: Chalasmata, TV: Tris Vryses

CK- and SA-analyses were taken from Del Moro et al. (1988)

Table 3. REE abundances (ppm) of selected samples from Zvezdel and Leptokarya-Kirki plutonic rocks.

Sample	ZV01	ZV02	ZV03	ZV04	ZV07	ZV08	ZV11	ZV15	ZV16	ZV17	ZV20	ZV21	ZV25	ZV29	ZV30	ZV31
Location	X9	W12	1210	W9	1027a	1212	1032	W1	4	127	1215	6d	105	W3a	128	115
Type	Mzgb	QGb					QMzg/QMzd							Ton	QMz	
La	15.70	19.80	20.80	44.00	25.00	37.20	16.40	34.20	25.00	39.00	28.00	35.00	42.00	46.80	30.00	45.00
Ce	21.40	51.00	40.00	87.00	55.10	63.50	30.30	67.00	44.00	65.00	55.40	60.00	76.00	91.00	53.00	76.00
Pr																
Nd					21.00		16.00			32.00		23.00	30.00		15.00	30.00
Sm	2.30	3.70	5.50	6.10	4.40	7.70	6.20	5.60	5.70	7.00	8.50	5.20	6.30	6.10	5.70	8.20
Eu	0.70	1.40	0.90	2.90	1.10	1.70	0.70	1.50	0.88	1.30	0.80	2.08	1.92	1.60	1.02	1.46
Gd																
Tb	0.50	0.80	1.30	1.10	1.00	1.20	0.80	1.40	1.00	1.20	1.40	1.00	1.30	1.40	1.10	1.70
Dy																
Ho																
Er																
Yb	0.80	0.90	2.20	4.00	2.10	2.80	1.70	3.50	2.00	2.40	2.60	2.10	2.80	3.50	2.00	2.90
Lu	0.01		0.29		0.25	0.48	0.17		0.24	0.17	0.22	0.27	0.38		0.29	0.45
ΣREE*	41.40	77.60	70.70	145.10	88.70	114.10	56.10	113.20	78.58	115.90	96.70	105.38	130.32	150.40	92.82	135.26
Eu/Sm	0.30	0.38	0.16	0.48	0.25	0.22	0.11	0.27	0.15	0.19	0.09	0.40	0.30	0.26	0.18	0.18
(La/Yb)cn	13.23	14.83	6.37	7.42	8.03	8.96	6.50	6.59	8.43	10.96	7.26	11.24	10.11	9.01	10.11	10.46
(La/Sm)cn	4.29	3.37	2.38	4.54	3.57	3.04	1.66	3.84	2.76	3.50	2.07	4.23	4.19	4.83	3.31	3.45
(Tb/Yb)cn	2.76	3.92	2.61	1.21	2.10	1.89	2.07	1.76	2.20	2.20	2.37	2.10	2.05	1.76	2.43	2.58

Sample	AL03	AL04	AL05	AL06	AL08	AL13	AL17	AL18	AL19	AL21	AL23	AL26	AL28	AL30	AL31	AL36
Location	L54	SA63	TV01	SA64	SA84	SA87	KR10	KR01	L23a	KR07	SA66	L55b	SA68	SA57	SA61	SA65
Type	QGb				QDr	QMzg/QMzd								Ton		Grd
La	10.69	20.00	17.94	21.00	24.00	21.00	22.49	22.72	22.34	20.34	22.00	23.50	25.00	22.00	23.00	25.00
Ce	21.90	37.00	36.43	44.00	43.00	45.00	42.94	43.38	42.36	39.86	42.00	45.33	50.00	40.00	52.00	52.00
Pr	3.21		4.75				5.16	5.18	4.90	4.89		5.55				
Nd	11.67	18.00	19.53	22.00	20.00	22.00	19.24	19.36	18.85	18.66	16.00	20.37	21.00	17.00	16.00	24.00
Sm	2.77	3.20	4.43	4.00	4.30	4.30	3.95	4.02	3.90	3.97	2.90	4.16	5.10	3.70	5.30	4.10
Eu	0.89	1.00	1.08	1.00	0.93	0.91	0.84	0.84	0.83	0.92	0.81	0.85	1.20	0.74	0.79	1.10
Gd	1.94		4.06				3.31	3.38	3.38	3.41		3.42				
Tb		0.60		0.63	0.48	0.65					0.51		0.71	0.50	0.44	0.66
Dy	2.44		4.18				3.26	3.32	3.18	3.40		3.41				
Ho	0.51		0.83				0.66	0.67	0.64	0.69		0.69				
Er	1.48		2.61				2.07	2.11	2.00	2.18		2.14				
Yb	1.35	2.00	2.41	2.40	2.20	1.80	1.90	1.97	1.88	2.04	1.90	1.99	2.30	2.10	1.70	2.20
Lu	0.24	0.31	0.37	0.40	0.42	0.36	0.30	0.30	0.29	0.31	0.39	0.31	0.43	0.40	0.30	0.43
ΣREE*	37.60	63.80	62.29	73.03	74.91	73.66	72.12	72.93	71.31	67.13	70.12	75.83	84.31	69.04	83.23	85.06
Eu/Sm	0.32	0.31	0.24	0.25	0.22	0.21	0.21	0.21	0.21	0.23	0.28	0.20	0.24	0.20	0.15	0.27
(La/Yb)cn	5.34	6.74	5.02	5.90	7.35	7.87	7.98	7.78	8.01	6.72	7.81	7.96	7.33	7.06	9.12	7.66
(La/Sm)cn	2.43	3.93	2.55	3.30	3.51	3.07	3.58	3.56	3.60	3.22	4.77	3.55	3.08	3.74	2.73	3.84
(Tb/Yb)cn	1.16	1.32	1.36	1.16	0.96	1.59	1.41	1.38	1.45	1.35	1.18	1.39	1.36	1.05	1.14	1.32
**	**		**				**	**	**	**		**				

* ΣREE is the sum of La, Ce, Sm, Eu, Tb and Yb,

** Due to lack of Tb the (Gd/Yb)cn is given

GEOCHEMISTRY

Thirty three representative samples from the Zvezdel pluton and thirty six from the Leptokarya-Kirki intrusions have been analysed for major and trace elements. Selected samples from Zvezdel and from Leptokarya-Kirki have also been analysed for REE. The compositional variation of the samples analysed are given in Tables 1 to 3.

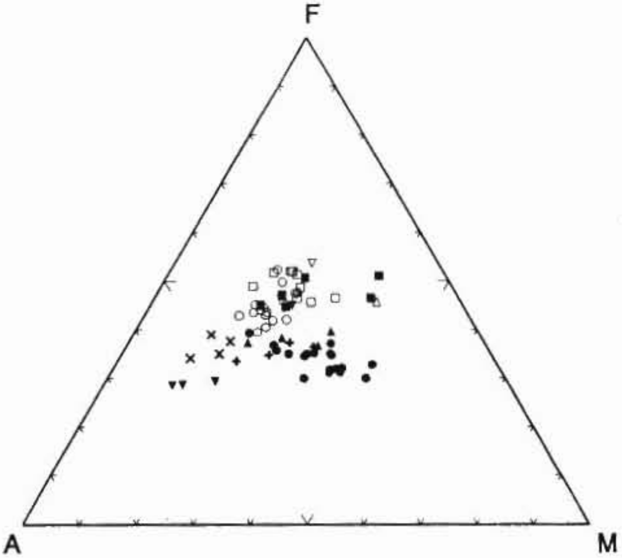

Fig. 3. AFM diagram of the Zvezdel and Leptokarya-Kirki plutonic rocks. Symbols as in Fig. 2.

The plutonic rocks of the Zvezdel and the Leptokarya-Kirki intrusive bodies, like the volcanic rocks of the corresponding regions (Eleftheriadis et al., 1989a), have roughly the same range of SiO_2 content, the Zvezdel compositonal trend being characterized in general, relative to the Leptokarya-Kirki, by lower SiO_2 and higher K_2O contents. Thus, plotting the available analyses on the K_2O-SiO_2 diagram (not shown) of Peccerillo & Taylor (1976) the Zvezdel rocks fall in the fields of the high-K calc-alkaline and shoshonitic rock series while those from Leptokarya-Kirki in the calc-alkaline and high-K calc-alkaline ones. The generally calc-alkaline character of both rock series is also shown in the AFM diagram (Fig. 3) (Irvine & Baragar, 1971). Moreover, the alkali-lime index (Peacock, 1931) is higher in Leptokarya-Kirki (60) and lower (56) in Zvezdel. Concerning the rest oxides they show similar variation trends for the rocks of both regions (Fig. 4). Al_2O_3, Fe_2O_{3t}, MgO, CaO, TiO_2 and P_2O_5 decrease with increasing silica while Na_2O and K_2O increase. In general, however, the Zvezdel plutonic rocks have relatively higher values for Na_2O, K_2O, Fe_2O_{3t} and TiO_2 and lower for MgO and CaO compared to those from the Leptokarya-Kirki ones.

Regarding trace element variations Rb, Ba and Ta increase with silica in both the Zvezdel and Leptokarya-Kirki rocks being relatively higher in the former. Similarly, Sr which is negatively correlated with silica, seems to be relatively more abundant in the Zvezdel rocks (Fig. 4).

Chondrite-normalized REE patterns from each of the main rock types of both complexes are depicted in Fig. 5. The Zvezdel rocks have subparallel REE patterns displaying strong LREE enrichment ($(La/Sm)_{cn}$=1.66-4.83) and small to moderate HREE fractionation ($(Tb/Yb)_{cn}$=1.21-3.92). Also, almost all the analysed samples, except some qz-gabbros and qz-monzodiorites, have negative Eu anomalies which increase from the basic to the acidic rocks (Eu/Sm=0.09-0.48).

Similarly, the Leptokarya-Kirki intrusive rocks have subparallel chondrite-normalized REE patterns and show, like the Zvezdel plutonic

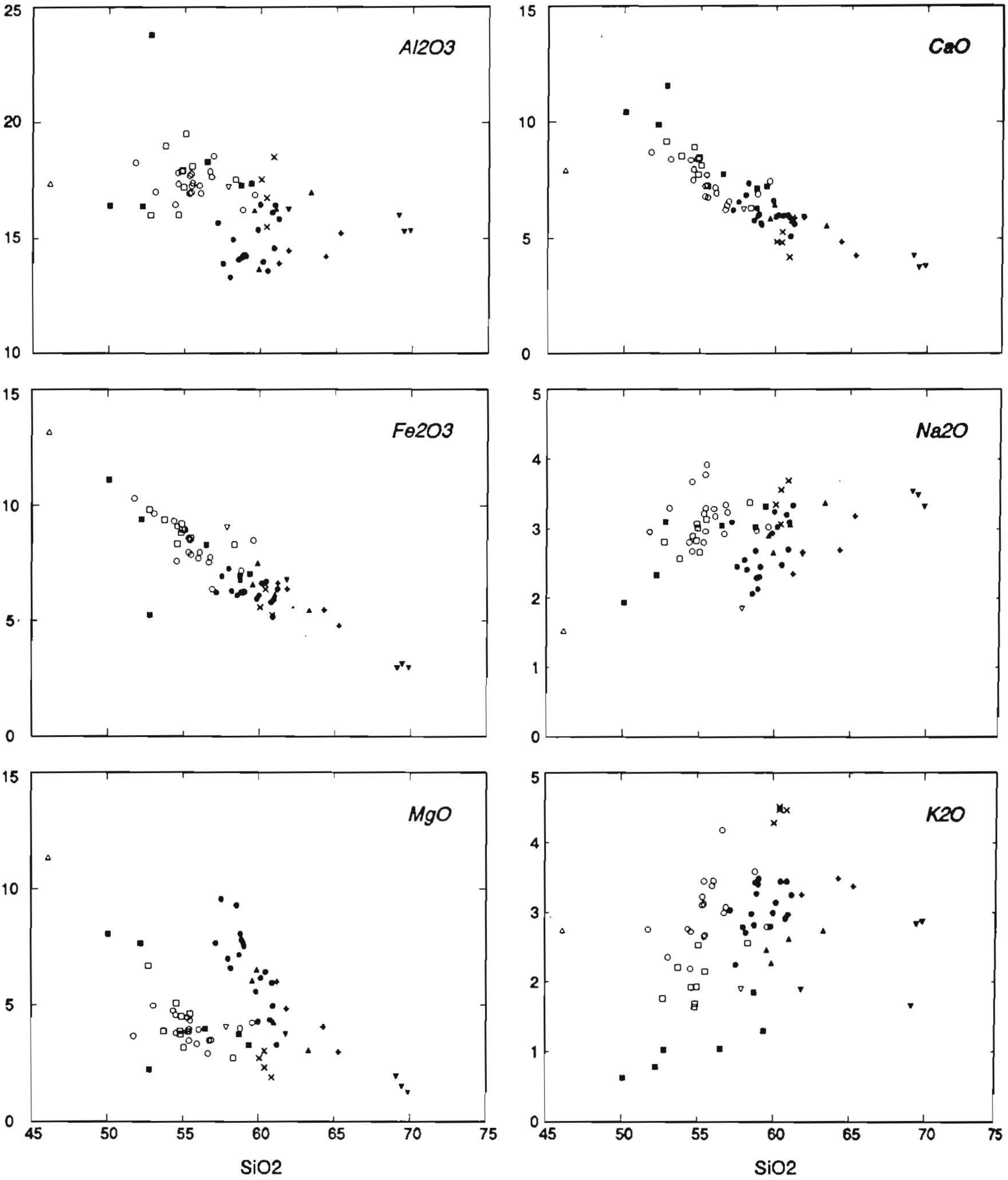

Fig. 4. Variation diagrams for selected major and trace elements from the Zvezdel and Leptokarya-Kirki plutonic rocks. Symbols as in Fig. 2.

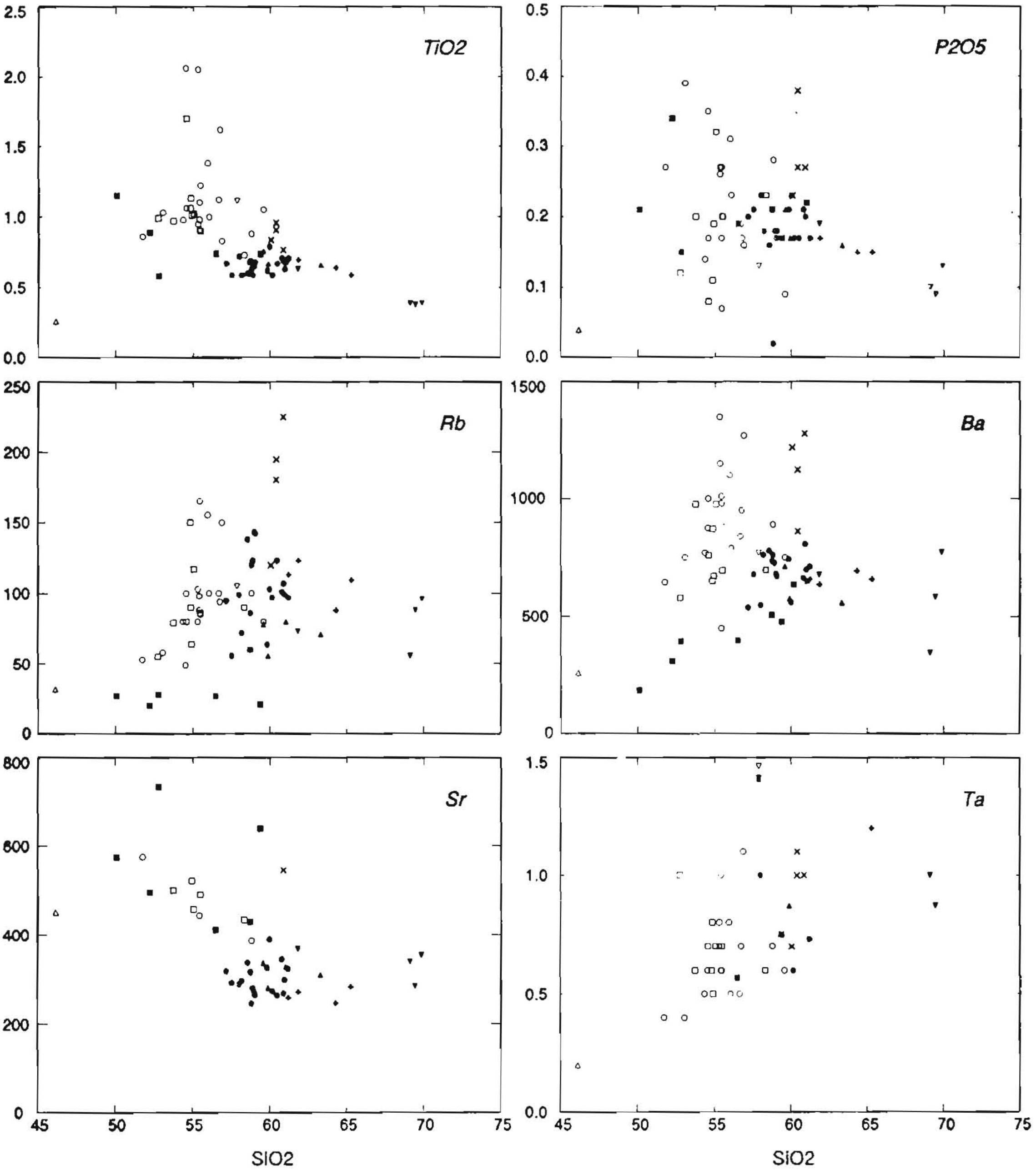

Fig. 4 (continued). Variation diagrams for selected major and trace elements from the Zvezdel and Leptokarya-Kirki plutonic rocks. Symbols as in Fig. 2.

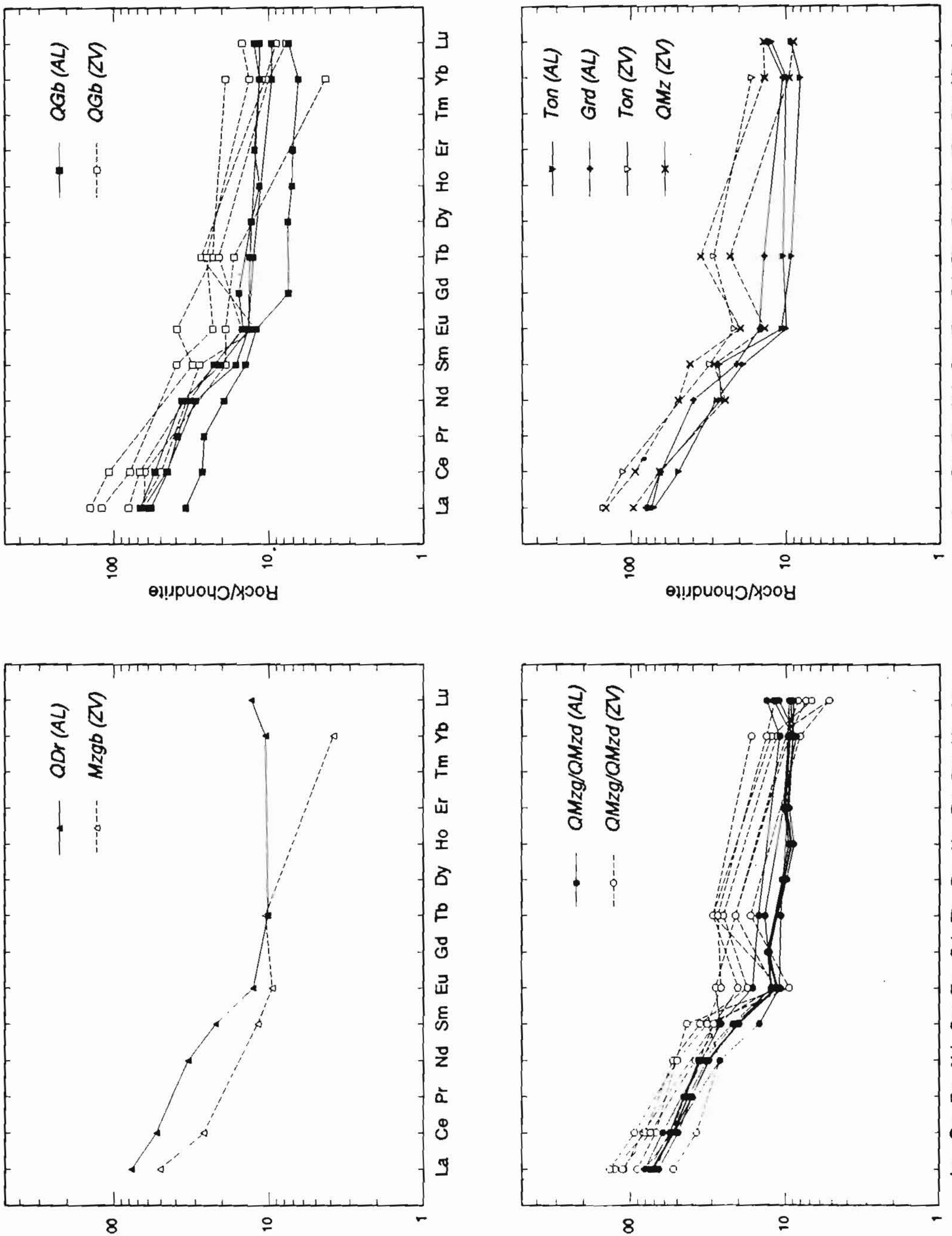

Fig. 5. REE patterns for selected samples from the Zvezdel and Leptokarya-Kirki plutonic rocks. Symbols as in Fig. 2.

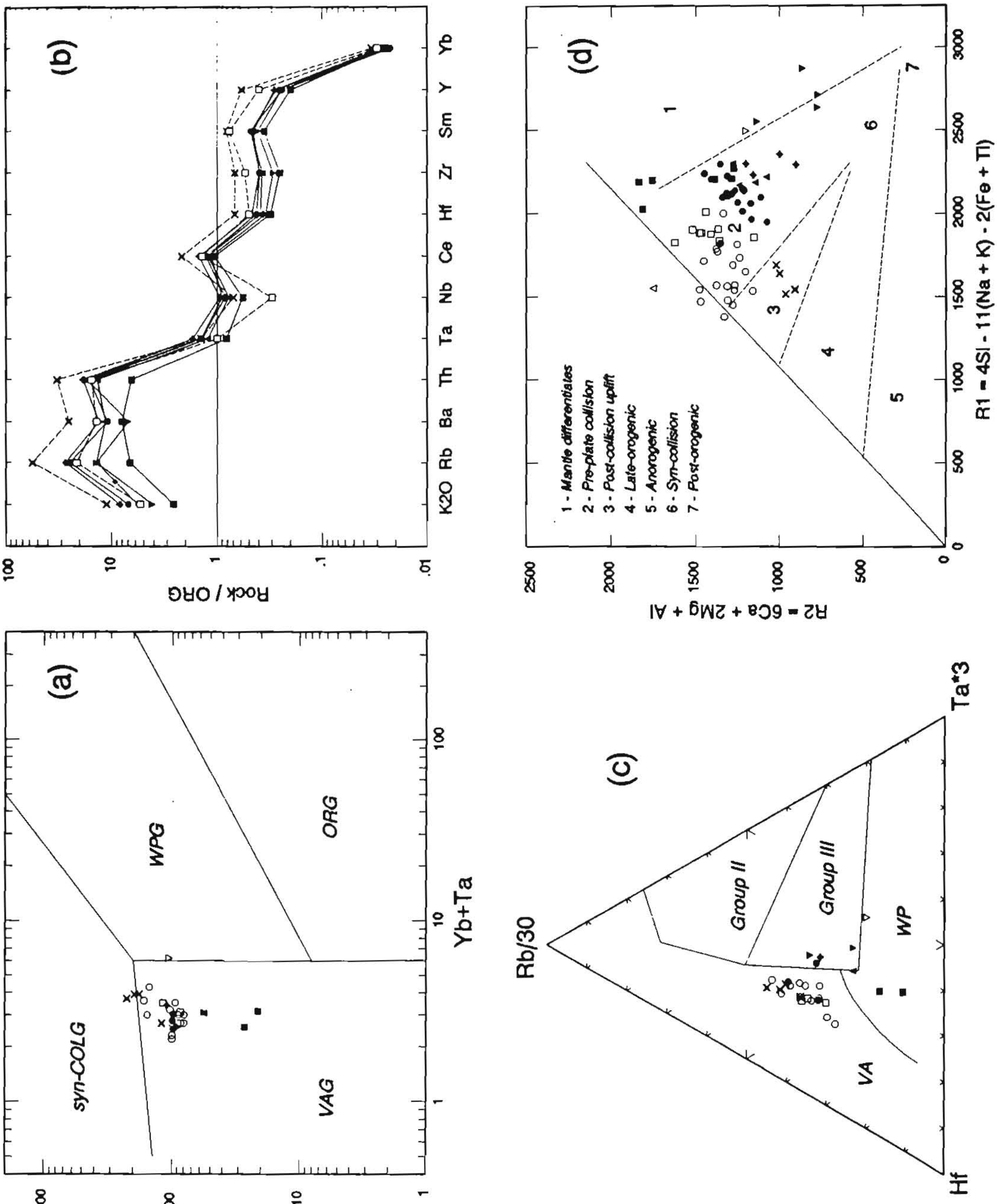

Fig. 6. Discrimination diagrams for selected samples from the Zvezdel and Leptokarya-Kirki plutonic rocks. Symbols as in Fig.2.
***(a), (b)**: after Pearce et al. (1984);*
***(c)**: after Harris et al. (1986);*
***(d)**: after Batchelor and Bowden (1985).*

rocks, strong LREE enrichment ($(La/Sm)_{cn}$=2.43-4.77) but almost unfractionated HREE ($(Tb/Yb)_{cn}$=0.96-1.59). All samples have moderate negative Eu anomalies (Eu/Sm=0.15-0.32) except one sample (qz-gabbro) which is cumulitic and shows positive Eu anomaly. Compared to those of Zvezdel the Leptokarya-Kirki rocks have lower ΣREE.

Major and trace element data were used to discriminate the tectonic setting of the Zvezdel and Leptokarya-Kirki intrusions. The Yb+Ta vs Rb diagram and the patterns of the spiderdiagrams (Pearce et al., 1984) show characters of volcanic arc or post-collision granites (Fig. 6a,b) (the two settings do not discriminate in these diagrams). However, on the triangular diagram Hf-Rb/30-Ta*3 (Harris et al., 1986), where such a discrimination is possible, the majority of the samples plot in the field of the volcanic arc granites and a few of them, mainly from Leptokarya-Kirki, in the Group III field (post-collision granites) (Fig. 6c). Similarly, on the R1 vs R2 diagram (Batchelor & Bowden, 1985) most of the samples plot in the pre-plate collision field (volcanic arc or continental margin) and only few of them, from Zvezdel, in the post-collision field (Fig. 6d).

DISCUSSION

The Leptokarya-Kirki rocks compose a well-defined belt made up of a few intrusions while the Zvezdel rocks consist part of a larger belt of plutonic intrusions. The emplacement age of the rocks in both belts is about the same (35-32 m.y. in Leptokarya-Kirki and about 33 m.y. in Zvezdel). The distribution of the intrusions is related to major basement-controlled lineaments trending NE-SW (Ivanov, 1963; Papadopoulos, 1979; Konstantinides et al., 1983). Based on mineralogical and petrological data the studied rocks show, on the whole, characteristics of orogenic belts. The orogenic affinity of the rocks is confirmed by the patterns of the spiderdiagram of the hygromagmatophile element abundances normalized to an ORG composition (Pearce et al., 1984) shown in Fig. 6b, where a distinct enrichment in LILE and a depletion in elements from Hf to Yb is obvious

An overall increase in K_2O is noted from the Greek rocks to the Bulgarian ones leading thus to the characterization of them as calc-alkaline to high-K calc-alkaline and high-K calc-alkaline to shoshonitic respectively.

Moreover, some differences between Leptokarya-Kirki and Zvezdel, regarding mineralogical composition can be observed. Hornblende for example appears mostly as a main mineral constituent in Leptokarya-Kirki but only as alteration product (uralite) in Zvezdel. Also, the zoning of plagioclase and pyroxene is more intensive in Zvezdel.

Differences in chemical composition, though not great, exist between the two areas. In Zvezdel, compositional variations lead to rocks ranging from monzogabbros to tonalites while in Leptokarya-Kirki from qz-gabbros to granodiorites. The differences in compositional variations between Zvezdel and Leptokarya-Kirki plutonic rocks are in agreement with the Ivanov's (1960) suggestion according to which a lateral variation exists regarding the chemical composition of the magmatic rocks of the Rhodope massif. This variation could be essentially explained in terms of plate tectonics.

The relatively higher K_2O content in both the volcanic (Eleftheriadis et al., 1989a) and the plutonic (present work) rocks from the Zvezdel region in relation to the corresponding rocks from the Alexandroupolis area is in accordance with the subduction of the

African plate under the European and the suggestion that the alkalinity of the erupted lavas increases away from the trench (Dickinson & Hatherton, 1967). An increase of the K_2O/Na_2O ratio is also mentioned by Sideris (1973) from west Thrace volcanics northwards which is interpreted in terms of a subduction process. However, Yanev et al. (1989) relate the high K_2O content of some basaltic rocks in the area with a collision process.

The spatial variation, which is better expressed in passing from the calc-alkaline/high-K calc-alkaline plutonics in the south (Leptokarya-Kirki) to the high-K calc-alkaline/shoshonitic ones in the north (Zvezdel), suggests a northward dipping of the subducted slab.

Other chemical differences such as the higher MgO, Cr and Ni contents in the Leptokarya-Kirki could be interpreted by more intense fractionation of olivine and pyroxene (?) in Zvezdel. The different erosion levels in Zvezdel and Leptokarya-Kirki could also explain these differences. Geological, geophysical and mineralogical data support the suggestion that the Zvezdel erosion level is higher: a) the greater dimensions of the Leptokarya-Kirki intrusions, the existence of more abundant xenoliths in Zvezdel, the thicker aplitic veins in Leptokarya-Kirki, and the geological setting of the intrusions (in Zvezdel they intrude the comagmatic stratovolcanoes - in Leptokarya-Kirki they mostly intrude the metamorphic basement); b) only a small part of the Zvezdel pluton outcrops while the rest of the body becomes larger at about 1 km in depth and continues up to about 9 km (Veltchev et al., 1974); c) the more rapid change in mineralogical composition and consequently the greater diversity of the petrographic types in Zvezdel intrusions as well as their finer grained textures compared with the Leptokarya-Kirki; d) the relatively more intensive plagioclase and pyroxene zoning in Zvezdel as well as the abundance of hornblende in Leptokarya-Kirki and the almost entire absence of it from Zvezdel.

Available data such as similar mineralogical, textural and geochemical characteristics, geotectonic environment, geological setting and age support a cogenetic relation between the Zvezdel and Leptokarya-Kirki plutonic rocks. However isotope data that would confirm this hypothesis are inadequate.

The compositional variations observed in Leptokarya-Kirki are related to differentiation by fractional crystallization (Eleftheriadis et al., 1989b). Major, trace and REE abundances along with the existence of cumulitic rocks in this area support such a process (see also Del Moro et al., 1988). A similar process was adopted for Zvezdel plutonics by Nedyalkov (1986, 1989).

Regarding source region, the relatively flat HREE patterns and the enrichment of LREE and other LILE are compatible with an "enriched" upper mantle. The genesis of the Zvezdel and Leptokarya-Kirki intrusions is subduction-related as indicated by their tectonic setting. The process, responsible for the genesis of these rocks but also for the orogenic magmatism (volcanoplutonic association) of Rhodope, is related to the subduction of the African plate under the European plate (Fytikas et al., 1985). The subduction contributed to the enrichment of mantle either by partial melts or by hydrous fluids released from the descending oceanic crust (cf. Ringwood, 1974; Best, 1975) or even by a combination of the above two mechanisms. The existence of an "enriched" upper mantle has already been suggested by Eleftheriadis et al. (1984), Eleftheriadis (1989), Eleftheriadis et al. (1989b), Del Moro et al. (1988) and Mavroudchiev (unpublished data).

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