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Original paper

Lamprophyric rock locations in Greece

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Abstract. Twenty-four areas with lamprophyric formations have been located through a bibliographic search in Macedonia, Thrace, the islands and Attica. Most lamprophyre types have been identified including rare "alkali minette". In most localities the dikes/sills appear to be late mantle products associated with deep faulting following extensional activity in granitoids.

Key-words: lamprophyric rocks, distribution, Greece, bibliography

1. Introduction

According to the Glossary of Geology (Neuendorf et al. 2005) the term lamprophyric describes rocks with holocrystalline-porphyritic texture exhibited by lamprophyres in which mafic phenocrysts occur in a fine-grained crystalline groundmass. Picritic rocks are excluded (Woolley et al. 1996).

The word "lamprophyre", first used by von Gumbel in 1874 for certain micaceous porphyritic dikes from the Bohemian massif, comes from the Greek word "lampros" which means bright. The ending – "phyre"-, which comes from "porphyry"-, describes the rock's porphyritic nature. Lamprophyres are defined as mesocratic to melanocratic porphyritic hypabyssal rocks, containing mafic phenocrysts such as micas, amphiboles and to some extent clinopyroxene. Feldspars or foids are confined to the groundmass which may also contain any of the above mafic minerals. Geochemically, lamprophyres tend to have a higher K_2O, Na_2O, volatiles (H_2O, CO_2), S, P_2O_5 and Ba content than mineralogically similar rocks (Le Maitre 2002).

According to the I.U.G.S. the lamprophyre nomenclature includes the calc-alkaline minette, kersantite, spessartite, vogesite and the alkaline sannaite, camptonite, monchiquite (for detailed mineralogy see Streckeisen 1978 and Le Maitre 2002).

There are also ultramafic lamprophyres such as aillikite, damtjernite, ouachitite and turjite. All four types contain primary carbonate in their matrix. As the carbonate content increases they grade into carbonatites.

Alnöites, bergaliths, farrisites, luhites, modlibovites, polzenites and vesecites, on the other hand, have been classified together with melilitic rocks because they contain >10% vol. melilite (Woolley et al. 1996; Le Maitre 2002). Recently however, they were reintroduced as melilite-bearing ultramafic lamprophyres (Tappe et al. 2005; Ulrych et al. 2014). There is also a long list of local and lesser known or obscure lamprophyre types.

Despite their uniqueness and puzzling character, compared to most igneous rocks (Prelević 2010), lamprophyres hold an important role in understanding mantle processes since they are considered windows into the deep mantle. Minettes, for example, are formed at a depth of 60-190 km (O'Neill, Wyman 2006). Lamprophyres generally show high concentrations of incompatible elements (Table1), which appears to exclude any origin by partial melting of typical spinel and pyrope lherzolite mantle, as very low degrees of partial melting (<1%) would be required. They have to be derived from enriched or metasomatized mantle sources. This could take place with the transportation of small volume partial melts-fluids over time or with the input of H_2O rich fluids from subduction zones (Wilson 1989). However, many lamprophyre mineral assemblages appear to be hybrid and from diverse sources. This includes autometasomatism and 'frozen" or arrested products of various complex resorption reactions. Therefore, few inferences from natural bulk rocks (experiments or analyses) will have any relevance to those source magmas. The "liquid lamprophyre magma question" is still unresolved (Rock 1991).

The scope of this paper is to locate lamprophyric rocks in Greece, aiming to help future geologists in their studies of Greek lamprophyres. Similar surveys have taken place for example in Greece (Kamvisis 2010), in the Bohemian massif (Krmíček 2010) and Slovakia (Spišiak 2010).

2. Method and results

Lamprophyres were first discovered in Greece by the French geologist F.A.Fouque in 1879 during his geological expedition in Santorini (Thera) island. His work is still considered a valid tool for field geologists who study the caldera of Santorini. Through the years, more areas have been discovered in mainland northern and southern Greece and the Greek islands of the Aegean Sea.

After an extensive bibliographic search twenty-four areas have been identified. In relation to the main isopic zones, six areas were found in the Circum-Rhodope belt (9, 10, 11, 12, 15, 22), six within the Attic-Cycladic complex (3, 6, 16, 18, 19, 20), four within the Pelagonian zone (2, 8, 14, 24), four in the Serbo-Macedonian massif (1, 4, 13, 17), three in the Rhodope massif (7, 21, 23), and one in the Gavrovo-Tripolitza zone(5). The twenty-four areas of Greece (with indicative coordinates) are the following (Fig. 1):

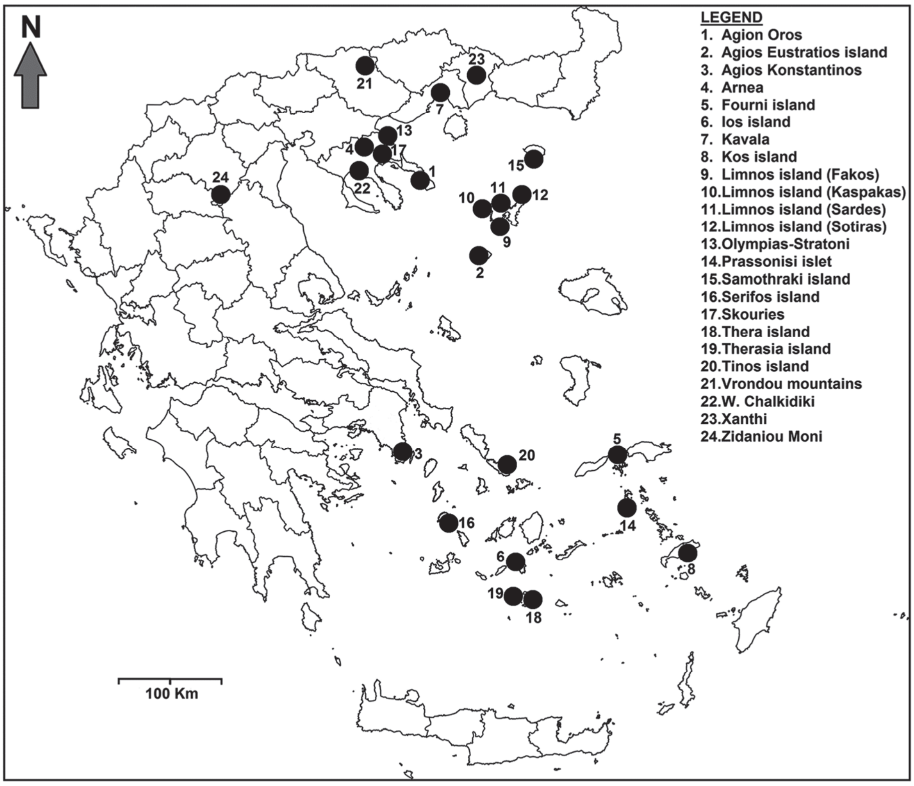

Fig. 1. Prefectural map of Greece showing the distribution of lamprophyric rocks (dots).

2.1. Agion Oros Peninsula Autonomous Region, Macedonia, northern Greece

(Georgiades 1938; Rock 1991)
N 40.186096, E 24.252068

A single kersantite dike intrudes the Osiou Gregoriou granitoid pluton in the area between Moni Osiou Gregoriou and Moni Simonos Petras (for whole-rock analysis see Table 1).

2.2. Agios Eustratios island, Prefecture of Lesvos, Aegean Sea

(Ktenas 1928; Johannsen 1938; Tröger 1969; Tomkeieff et al. 1983; Rock 1991; Le Maitre 2002; Neuendorf et al. 2005)
N 39.513865, E 24.975069

Several camptonite dikes, 4 to 5 m wide, cut the volcanic formations in Lidario in the western part of the island. This melanocratic rock has rare phenocrysts of olivine, corroded hornblende and augite in a groundmass composed of idiomorphic augite, titanomagnetite [$Fe^{2+}(Fe^{3+},Ti)_2O_4$], interstitial feldspar, mica and glass (Table1).

TABLE 1

Whole-rock major and trace element analyses of some Greek lamprophyric rocks. Analysis for area 1 are from Georgiades (1938), for 2 from Ktenas (1928), for 3 from Bonsall et al. (2011), for 8 from Wimmenauer (1977) and Soder (2017), for 13 from Kalogeropoulos et al. (1989), for 15 from Christofides et al. (2000) and Pirera (2015), for 16 from Marinos (1951), for 21 from Kolokotroni (1992), for 22 from Mussalam and Jung (1986).

Area→	1	2	3	3	8	8	8	8	13	13	15	15	16	21	21	22	Malchite(8)
SiO_2	48.82	48.84	51.34	58.13	41.8	44.7	48.3	51.5	50.88	54.76	56.26	56.27	55.82	46.89	48.04	54.08	54.1
TiO_2	1.39	1.22	0.64	0.62	1.17	1.05	1.00	0.59	0.65	0.83	1.16	1.12	0.57	1.49	1.34	0.50	1.11
Al_2O_3	14.69	13.78	16.00	15.76	16.2	14.6	14.3	17.5	12.11	13.64	10.73	11.7	17.50	14.23	12.92	15.01	18.53
Fe_2O_3	3.60	3.23	3.46	5.89	8.67	8.11	7.73	5.27	4.27	3.78	n.a.	5.64	1.40	13.59	13.44	1.75	4.60
FeO	7.02	4.35	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	5.09	n.a.	3.87	n.a.	n.a.	7.35	2.64
MnO	n.a.	0.18	0.06	0.08	0.10	0.14	0.14	0.12	0.11	0.13	0.21	0.24	0.11	0.42	0.24	0.16	0.11
MgO	10.88	8.74	3.21	4.74	5.71	9.24	7.77	2.81	4.33	5.41	7.57	9.42	5.84	5.00	5.40	5.84	2.60
CaO	8.05	9.52	7.16	7.58	11.3	10.4	9.68	6.03	7.01	6.85	5.02	5.21	7.46	9.32	9.45	10.21	5.40
Na_2O	2.08	3.88	-	2.70	2.89	2.75	2.35	3.01	0.65	2.53	0.71	0.94	3.75	2.32	1.75	1.46	4.28
K_2O	3.01	3.62	4.03	1.39	2.70	2.71	3.79	7.21	4.81	5.44	8.35	8.11	2.09	3.21	3.41	0.16	5.07
P_2O_5	-	0.93	0.14	0.13	1.25	1.18	0.73	0.54	0.41	0.38	0.84	1.06	0.18	1.45	1.81	0.03	0.62
BaO	n.a.	n.a.	n.a.	n.a.	0.38	0.20	0.26	0.49	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
SrO	n.a.	n.a.	n.a.	n.a.	0.28	0.17	0.17	0.42	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
H_2O+	0.21	1.70	12.69	2.76	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1.17	n.a.	n.a.	n.a.	0.64
H_2O-	0.31	0.36	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.29	n.a.	n.a.	n.a.	n.a.
CO_2	n.a.	-	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.28
SO_3	n.a.	n.a.	0.15	0.52	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
LOI	n.a.	n.a.	n.a.	n.a.	7.22	3.94	2.46	3.70	12.18	5.98	n.a.	n.a.	n.a.	n.a.	n.a.	3.03	n.a.
Sum	100.06	100.35	98.88	100.30	99.7	99.2	98.6	99.2	97.41	99.73	98.6	94.07	100.05	97.90	97.78	99.58	99.88
Sc	n.a.	n.a.	22	16	28	41	35	15	-	11	21	18	n.a.	40.2	44.3	52	n.a.
V	n.a.	n.a.	140	147	295	231	235	174	94.36	75	133.27	49	n.a.	355.6	369.2	300	n.a.
Cr	n.a.	n.a.	166	125	19	287	383	42	145.16	129	418.84	n.a.	n.a.	11.3	9.8	121	13

Co	n.a.	n.a.	28	58	25	34	29	16	19.21	16	n.a.	n.a.	n.a.	n.a.	n.a.	70	n.a.
Ni	n.a.	n.a.	16	26	20	111	74	16	55.43	52	292.09	n.a.	n.a.	13.1	15.5	50	<10
Rb	n.a.	n.a.	153	49	66	72	124	134	218	118	389.09	389	n.a.	n.a.	n.a.	7	186
Cs	n.a.	n.a.	n.a.	n.a.	5	3	3.1	4.4	11.2	8.6	4.32	n.a.	n.a.	n.a.	n.a.	-	n.a.
Sr	n.a.	n.a.	23	658	2400	1410	1430	3560	390	235	521.14	557	n.a.	n.a.	n.a.	88	1055
Ba	n.a.	n.a.	83	514	3420	1780	2360	4390	840	1216	1839.41	2284	n.a.	752.8	962.8	26	1760
Y	n.a.	n.a.	25	25	33	30	29	37	21.1	24	27.78	47	n.a.	n.a.	n.a.	16	n.a.
Zr	n.a.	n.a.	170	166	220	299	260	422	390	251	901.49	846	n.a.	n.a.	n.a.	20	n.a.
Nb	n.a.	n.a.	19	-	80	35	18	43	-	28	20.92	6	n.a.	n.a.	n.a.	3	n.a.
La	n.a.	n.a.	25	40	197	69	71	222	47.2	55.81	84.79	72	n.a.	46.3	49.1	16	n.a.
Ce	n.a.	n.a.	82	57	400	153	156	410	103	100	189.82	151	n.a.	122.7	99.6	9	n.a.
Pr	n.a.	n.a.	n.a.	n.a.	43	18	19	47	n.a.	n.a.	20.41	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Nd	n.a.	n.a.	35	22	160	75	76	175	<70	<40.4	89.07	84	n.a.	65.9	53.9	-	n.a.
Sm	n.a.	n.a.	n.a.	n.a.	22.2	13	13.4	26	7.7	9.16	14.33	n.a.	n.a.	n.a.	n.a.	-	n.a.
Eu	n.a.	n.a.	n.a.	n.a.	5.9	3.4	3.4	6.8	1.55	2	3.37	n.a.	n.a.	n.a.	n.a.	-	n.a.
Gd	n.a.	n.a.	n.a.	n.a.	13.2	9.1	9.2	15.2	n.a.	n.a.	10.10	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Tb	n.a.	n.a.	n.a.	n.a.	1.43	1.1	1.13	1.57	0.57	0.62	1.26	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Dy	n.a.	n.a.	n.a.	n.a.	7.1	6	6.1	7.7	n.a.	n.a.	5.81	n.a.	n.a.	n.a.	n.a.	-	n.a.
Ho	n.a.	n.a.	n.a.	n.a.	1.2	1.08	1.08	1.24	n.a.	n.a.	0.92	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Er	n.a.	n.a.	n.a.	n.a.	3	2.8	2.8	3	n.a.	n.a.	2.32	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Tm	n.a.	n.a.	n.a.	n.a.	0.42	0.37	0.37	0.43	n.a.	n.a.	0.37	n.a.	n.a.	n.a.	n.a.	-	n.a.
Yb	n.a.	n.a.	n.a.	n.a.	2.6	2.7	2.5	2.8	1.43	2.07	1.80	n.a.	n.a.	n.a.	n.a.	-	n.a.
Lu	n.a.	n.a.	n.a.	n.a.	0.37	0.38	0.36	0.39	0.26	0.34	0.26	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Hf	n.a.	n.a.	n.a.	n.a.	4.8	7.5	6.6	8.4	11.8	7.87	26.16	n.a.	n.a.	n.a.	n.a.	-	n.a.
Ta	n.a.	n.a.	n.a.	n.a.	2.7	1.6	0.9	2	1.04	1.4	1.44	n.a.	n.a.	n.a.	n.a.	-	n.a.
Pb	n.a.	n.a.	1	7	16	5	17	91	-	33	24.94	n.a.	n.a.	n.a.	n.a.	7	n.a.
Th	n.a.	n.a.	6	8	34	13	17	45	20	26	36.96	n.a.	n.a.	n.a.	n.a.	7	n.a.
U	n.a.	n.a.	4	6	7.1	2.9	3.5	8.5	10.4	10	12.63	n.a.	n.a.	n.a.	n.a.	-	n.a.

As	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	7.91	-	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Au	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	<0.02	-	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Be	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	4.6	4.5	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Cu	n.a.	n.a.	19	18	n.a.	n.a.	n.a.	n.a.	17.09	26	n.a.	n.a.	n.a.	67.5	26.3	65	n.a.
Ga	n.a.	n.a.	23	18	n.a.	n.a.	n.a.	n.a.	<19	9	n.a.	n.a.	n.a.	n.a.	n.a.	-	n.a.
Li	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	21	34	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Sb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	19.3	-	n.a.	n.a.	n.a.	n.a.	n.a.	-	n.a.
W	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	64.8	5	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zn	n.a.	n.a.	231	27	n.a.	n.a.	n.a.	n.a.	56.24	51	n.a.	129	n.a.	n.a.	n.a.	65	n.a.

2.3. Agios Konstantinos area, Prefecture of Attica, southern Greece

(Bonsall 2008; Bonsall et al. 2011)
N 37.724634, E 24.026928

Three lamprophyric dikes have been found in the North Serpieri deposit near the Agios Konstantinos settlement in the vicinity of Lavrion. Two show propylitic alteration and the other sericitic alteration (Table 1).

2.4. Arnea area, Prefecture of Chalkidiki, Macedonia, northern Greece

(Oladeji 1997; Perugini et al. 2004; Christofides et al. 2007)
N 40.546429, E 23.584956

Numerous mesocratic-melanocratic minette and vogesite dikes and sills (color index up to 75) intrude the Arnea A-type granitoid. The dikes are from a few cm to 3 m wide and 10 to 15 m long. They are found along the Arnea-Palaeochora national road, near the village of Stanos, Paliokastro and around the hills of Giagova, Milopetra and Profitis Elias NNE of Arnea. Some of the dikes are weathered and show foliation.

2.5. Fourni island, Prefecture of Samos, Aegean Sea

(Georgalas 1924)
N 37.632252, E 26.505924

A 20 cm wide and 100 m long dark green vogesitic dike cuts the mica schists in the northern part of the island, NW of the Chryssomilia settlement and up to Phanos near the sea. It is possibly connected to an underwater pluton (Katsikatsos in press).

2.6. Ios island, Prefecture of Cyclades, Aegean Sea

(Maar 1980; 1981a; 1981b; Maar, Jansen 1983; Pe-Piper, Piper 2002)
N 36.734698, E 25.275187

A couple of weakly metamorphosed oblong mafic bodies intrude the garnet-mica schist zone near the augengneiss in the basement complex of Ios. The two exposures are north of Ios town. The rocks contain sericitized relicts of brown hornblende, allanite $[(Ce,Ca,Y,La)_2(Al,Fe^{3+})_3(SiO_4)_3(OH)]$, biotite, albite and some quartz. They were identified as meta-lamprophyres.

2.7. Kavala area, Prefecture of Kavala, Macedonia, northern Greece

(Voudouris et al. 2016; Xydous 2018)
N 40.960313, E 24.438440

Several lamprophyre dikes crosscut sheeted veins and the Kavala granodiorite pluton on the highway to Thessaloniki. They have a modal composition of biotite-hornblende quartz monzodiorite. The lamprophyres originated in metasomatized upper mantle and have been associated with an intrusion-related gold deposit.

2.8. Kos island, Prefecture of Dodecanese, Aegean Sea

(Altherr et al. 1976; 1988; Wimmenauer 1977; Rock 1991; Stouraiti 1995; Kalt et al. 1998; Altherr, Siebel 2002; Pe-Piper, Piper 2002; 2007a; 2007b; Pe- Piper et al. 2005; Pe-Piper, Moulton 2008; Tsoukalas 2008; Zouzias 2011; Soder 2015; Soder et al. 2016; Pandey et al. 2017; Soder 2017; Stouraiti et al. 2018)
N 36.817775, E 27.185507

Forty-four lamprophyre dikes cut the deformed Mount Dikeos monzonite massif, the older basement series and the faulted margin of the monzonite against the country rock. The massif is located at the eastern edge of the South Aegean volcanic arc in a retreating subduction zone where melting of the metasomatized mantle wedge is taking place. Crustal contamination of the dikes here may reach 50%. The total area over which the rocks are exposed is 2.5 km^2.

The majority of the dikes, especially those NE of Rachi ridge, have been classified as kersantites. There are also spessartites 1.1 km ENE of Eleona, minettes in a small valley 1 km SE of Eleona, biotite-fourchites between Eleona and Damia (containing picotite $(Fe^{2+},Mg)(Al,Cr)_2O_4$) and finally vogesites. Biotite-malchite dikes were identified on the coast between Eleona and Damia (Table 1). The thickness of the dikes ranges from a few cm to 20 m.

Lamprophyres are well known in collision zones but rarely along volcanic arcs, which is why Kos is an unusual example of lamprophyric magmatism.

2.9. Limnos island (Fakos area), Prefecture of Lesvos, Aegean Sea

(Voudouris 2006; Voudouris 2010; Djiba et al.2018; Sutphin et al. 2013)
N 39.816331, E 25.167514

In the southern part of the island of Limnos, in the Fakos peninsula, lamprophyre dikes intrude the Fakos quartz-monzonite porphyry subvolcanic body.

2.10. Limnos island (Kaspakas area), Prefecture of Lesvos, Aegean Sea

(Djiba et al. 2018)
N 39.913500, E 25.079716

At the coastal village of Kaspakas, in the western part of the island, lamprophyre dikes crosscut a sericitically altered trachydacite porphyry.

2.11. Limnos island (Sardes area), Prefecture of Lesvos, Aegean Sea

(Djiba et al. 2018)
N 39.941606, E 25.141025

Lamprophyre dikes intrude the trachydacite porphyry near the mountain village of Sardes.

2.12. Limnos island (Sotiras area), Prefecture of Lesvos, Aegean Sea

(Roussos 1993)
N 40.007945, E 25.390676

In northeastern Limnos, in the Sotiras headland (Agios Charalambos Bay), a single 1m wide dike cuts molasse sediments. The lamprophyre is melanocratic with biotite, clinopyroxene and serpentinized olivine phenocrysts in a feldspathic groundmass which also contains the previous mafic minerals.

2.13. Olympias–Stratoni area, Prefecture of Chalkidiki, Macedonia, northern Greece

(Nicolaou 1960; Papadakis 1971; Nicolaou, Kokonis 1980; Kalogeropoulos et al. 1989; 1991; Maltezou et al. 1989; Kilias et al. 1996; Haines 1998, Christofides et al. 2007; Modis, Komnitsas 2007; Michailidis, Sofianska 2010; European Goldfields 2011; Poli et al. 2012; Nestorov 2013; Vasilatos 2013; Arvanitidis 2018)
N 40.600754, E 23.748452

Numerous lamprophyre dikes (>27) intrude the basement metamorphics of the Kerdylia Formation and the Stratoni granodiorite. The dikes are sometimes tens of meters wide and follow the direction of deep NE-SW faults. They have been characterized as highly contaminated mantle melts (containing fuchsite $K(Al,Cr)_2(AlSi_3O_{10})(OH)_2$).

More specifically, lamprophyres have been found in the Olympias mines, the Vathilakkos gorge E of Madem Lakkos, in Vagionia, Stratoni, Mavres Petres W of Madem Lakkos and in some boreholes in the broader area. Seven borehole samples showed that the predominant lamprophyres in the Olympias mines are minettes (Kalogeropoulos et al. 1991). According to six whole-rock major and trace element geochemical analyses, four of the minettes are ultrapotassic (see Table 1).

In all the other localities, including gallery 173 of the Kassandra mines, the rocks were classified as spessartites.

2.14. Prassonisi islet, Prefecture of Dodecanese, Aegean Sea

(Galeos 1993)
N 37.267724, E 26.559506

On the Prassonisi islet south of Patmos island, a dike cutting the islet's microsyenite carries lamprophyric xenoliths. These are composed exclusively of hornblende and biotite.

2.15. Samothraki island, Prefecture of Evros, Thrace, Aegean Sea

(Christofides et al. 2000; 2007; Perugini et al. 2004; Pipera 2015)
N 40.397975, E 25.570140

Several contaminated dark grey minettes intrude the southwestern Samothraki granitoid pluton. Two whole-rock geochemical analyses (see Table 1) showed that the rocks are ultrapotassic and peralkaline. Some other values are also typical of lamproitic rocks. Additionally, due to the high Mg/Fe ratio, these rocks contain phlogopite laths instead of biotite (Woolley et al. 1996).

The rocks, on the other hand, contain plagioclase in their groundmass, a mineral commonly found in lamprophyres but not lamproites. In addition to plagioclase, lamproitic rocks totally lack all Na-leucophases (Mitchell, Bergman 1991; Le Maitre 2002).

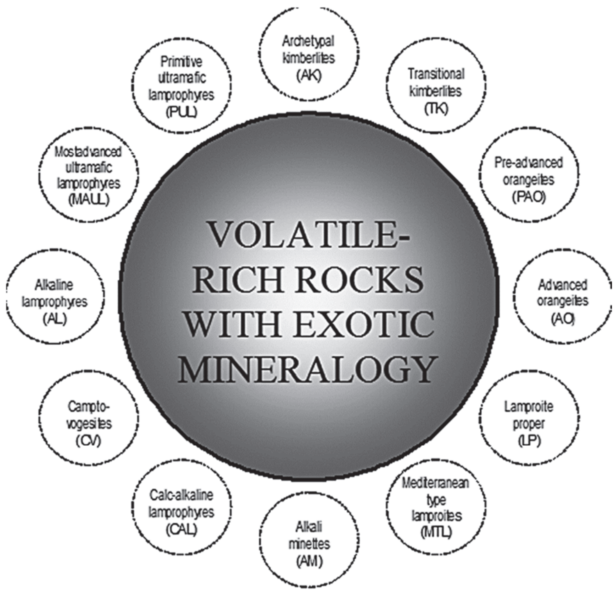

Fig. 2. Circular diagram (Kamvisis 2010) showing a possible continuum among some volatile-rich porphyritic rocks with exotic mineralogy and/or composition. Note that all groups lack plagioclase phenocrysts. AK= intracratonic basaltic kimberlites, TK= rocks petrographically and geochemically intermediate between kimberlites and orangeites, PAO= micaceous peri-cratonic kimberlites, AO= orangeites with K-richterite, groundmass sanidine and Zr-silicates like wadeite, LP= anorogenic olivine lamproites, MTL= orogenic phlogopite lamproites sometimes containing crustal plagioclase (Prelević et al. 2007), AM= ultrapotassic and peralkaline phlogopitic minettes with lamproitic characteristics, CAL= minettes, kersantites, spessartites and vogesites, CV= mafic vogesites bearing brown amphibole, AL= sannaites, camptonites and monchiquites, MAUL= melanocratic ultramafic lamprophyres having >10% felsic minerals (e.g. ouachitites), PUL= holomelanocratic damtjernites to aillikites with >15% MgO (Francis, Patterson 2009).

All these point to a rare kind of minette known as “alkali minette” (Woolley et al. 1996). “Alkali minettes” could be considered as transitional between minettes and Mediterranean-type lamproites (see Fig. 2). There are only a few examples of “alkali minettes” worldwide mainly associated, like Mediterranean-type lamproites, with major late to post-collisional igneous activity.

Three separate magmatic processes may contribute towards the formation of “alkali minettes” (Peterson et al. 1994; Prelević 2010). The first is mixing lamproitic and minette magmas. The second involves source regions that have a transitional character while in the third the composition of lamproite magma changes to minette magma when passing through the Earth’s crust. These dikes have high MgO, Cr and Ni contents together with high contents of incompatible elements which could not have originated from granitic contamination. The rock’s source is highly metasomatized lithospheric mantle.

2.16. Serifos island, Prefecture of Cyclades, southern Aegean Sea

(Marinos 1951; Petrakakis et al. in press)
N 37.127544, E 24.457196

Late lamprophyre sills and dikes intrude the Serifos granodioritic pluton in the southeastern part of the island, along with more felsic lavas such as rhyolites, dacites, porphyries and aplites. In the Halara headland camptonite veins crosscut local marbles and gneiss (see Table 1). One of them is >25 m long and 30 cm thick and has a distinct 5-10 cm thick skarn zone in contact with country rock (Ktenas 1917).

2.17. Skouries area, Prefecture of Chalkidiki, Macedonia, northern Greece

(Voudouris et al. 2016)
N 40.469631, E 23.703588

Near Neochori settlement, in eastern Chalkidiki, several lamprophyric dikes cut the Skouries porphyry. Small mela-syenite (durbachite) dikes also occur in the area (McFall et al. 2018). Durbachites are considered as the plutonic equivalents of calc-alkaline lamprophyres (Rock 1991).

2.18. Thera/Santorini island, Prefecture of Cyclades, Aegean Sea

(Fouque 1879)
N 36.406227, E 25.428519

During his journey in 1879, F.A.Fouque discovered numerous kersantitic blocks in the lowermost ash layer of the cliffs of Thera (the Caldera cliffs). Fouque concluded that the blocks must have been brought up from a granitoid (from the Basement Series). This statement proves to have been very reasonable since, nearly a century later, Puchelt (Puchelt et al. 1977) identified a granitic xenolith in the pumice of the Christiana islands, a few miles SW of Thera. Later, Skarpelis (Skarpelis et al.1992) found, through a 250 m deep borehole, that a granitoid body had indeed intruded the metamorphic basement of Santorini.

2.19. Therasia island, Prefecture of Cyclades, Aegean Sea

(Fouque 1879)
N 36.437786, E 25.349062

A very similar occurrence to that of Thera. In 1879 F.A.Fouque discovered a great number of kersantitic blocks in the volcanic ash at the bottom of the island's cliffs. The cliffs are probably those of the Therasia Shield Formation.

2.20. Tinos island, Prefecture of Cyclades, Aegean Sea

(Melidonis 1980; Pantziris 2000)
N 37.628971, E 25.194155

A few lamprophyre dikes and sills intrude the periphery of the N-NW Tinos granitoid.

2.21. Vrondou mts, Prefecture of Serres, Macedonia, northern Greece

(Kolokotroni 1992; Christofides et al. 1998; 2007; Soldatos et al.1998;
Perugini et al. 2004; Zananiri 2004; Pipera 2015)
N 41.200331, E 23.566788

In the area of the Vameno stream, between the villages of Orini and Xerotopos, three lamprophyre dikes cut the southern margins of the deformed Vrondou granitoid. They run sub-parallel to the margin. The lamprophyres are calc-alkaline (Table 1) and contain abundant coarse (up to 4 mm) green to green-brown euhedral amphibole crystals, interstitial K-feldspar, subordinate plagioclase, minor quartz and accessory titanite, apatite and opaques.

According to Kolokotroni (1992) and Soldatos (1998) these lamprophyres formed during subduction. They are the precursors of High-K MME which formed through crystal fractionation of melts from an enriched lithospheric mantle source.

2.22. W. Chalkidiki peninsula, Prefecture of Chalkidiki, Macedonia, northern Greece

(Jung et al. 1981)
N 40.283411, E 23.444179

There are two lamprophyric dike swarms. One crosscuts the diorites of the Chortiatis suite and the other the Thessaloniki ophiolites. The dikes are centimeters to meters thick. They are dark, weakly porphyritic, have chilled margins and often a fluidal texture. They have a dioritic mineralogy with light green hornblende, intermediate plagioclase, and some epidote and opaques. Their composition, especially the trace elements, is also dioritic. It should be noted that Pe-Piper and Piper(2002) mention hornblende microdiorite dikes (Table 1) occurring along the SW margin of the Gerakini and Metamorphosis mafic-ultramafic rocks. These have been related to extensional faulting (Mussallam, Jung 1986). Additionally, in the same area, there are some late porphyritic to microporphyritic sills of intermediate composition. They contain clinopyroxene and hornblende phenocrysts (40%), plagioclase, quartz, accessory biotite (2-3%) and pyrite (Mussallam, Jung 1986). These sills could be characterized as lamprophyric.

23. Xanthi area, Prefecture of Xanthi, Thrace, northern Greece

(Christofides 1977; Eleutheriadis 1986; Koukouvelas, Pe-Piper 1991; Sergi 1997; Pe-Piper, Piper 2002; Eleutheriadis, Koroneos 2004; Kokkinakis 2007; Papadopoulos 2011; Scarrow et al.. 2011; Pirera 2015)
N 41.148860, E 24.946263

Twenty-three dark green lamprophyre dikes and sills have been mapped by Koukouvelas and Pe-Piper between the city of Xanthi and the village of Filia. They follow early joints radially cutting the margin of the Xanthi pluton and earlier aplite veins. This particular subduction-related pluton is located on the Kavala-Komotini dextral strike-slip fault zone. The lamprophyres have been associated with continued regional NE-SW directed pull-apart extension at a classic locality for transtensional stress (a bend in the fault). The dikes are 0.5 to 1 m wide and can be traced up to 30 m along strike. There are also some small intrusions measuring 10x10 to 20x100 m^2. The rocks are calc-alkaline, composed of olive green amphibole phenocrysts (altered to epidote and chlorite) and a little pyroxene. Plagioclase is confined to the groundmass which also contains amphibole and sometimes K-feldspar and quartz. Occasionally they contain granodioritic inclusions.

2.24. Zidaniou Moni area, Prefecture of Kozani, Macedonia, northern Greece

(Netelbeek 1959; Anonymous 1978; Orris 1993)
N 40.084048, E 21.850717

Several lamprophyric sills and dikes intrude the southern part of the Vourinos ophiolitic complex 25 km SSE of the city of Kozani, between the villages of Mikrovalton, Tranovalton and Moni Zidaniou. This part of the complex is composed mainly of dunites and some more serpentinized rock types. The dunite is cut by a few dark lamprophyric dikes measuring up to 60 cm in width. In the more serpentinized ophiolites most lamprophyric rocks occur as brownish grey sills up to 15 m in length and sometimes as ‘sliced dikes’. Most of the rocks are altered, deformed and have a rather schistose appearance due to shearing. The area also includes the Zidani asbestos mine where small lamprophyre dikes irregularly intersect the serpentinite. Additionally, lamprophyric dikes have been found in several deep boreholes (up to 150 m in depth).

The dominant minerals are brown biotite, actinolite and albite forming a fine-grained groundmass. Accessory minerals include apatite, rutile, magnetite and ilmenite. In one locality the rocks contain globular structures filled with albite and biotite. These structures are characteristic of lamprophyres and very common among them. The petrographic type here is a kind of lamproschist (for definition see Neuendorf et al. 2005).

Although it is uncommon for lamprophyres to occur in ophiolitic complexes, there have been a few confirmed examples from well-known ophiolites such as the Bayazeh ophiolite in central Iran (Bayat, Torabi 2011), the Haybi in the Semail ophiolitic complex of Oman (Searle 1984), the north Anatolian ophiolitic mélange (Gülmez et al. 2014), Unst in Scotland (Taylor 1988; Flinn, Oglethorpe 2005), and the Vedi ophiolite in Armenia (Satian et al. 2009).

3. Discussion

It is almost certain that more calc-alkaline lamprophyres will be discovered in the granodioritic and monzonitic massifs of Greece. On the other hand, alkaline lamprophyres have been connected around the world primarily with basanites and alkali basalts. The small (75x150 m) intrusion 2 km E of Metamorphosis (Kilkis Prefecture, Macedonia) is one example. The intrusion (Melidonis 1972) contains kaersutite $NaCa_2(Mg_3Ti^{4+}Al)(Si_6Al_2)O_{22}(OH)_2$, oxyhornblende $NaCa_2(Mg,Fe^{2+},Fe^{3+},Al,Ti)_5(Si_6Al_2)O_{22}(O,OH)_2$ and Ti-biotite $K(Mg_2Ti)(Si_3AlO_{10})O_2$ phenocrysts (Fig.3). The rock has close affinities with camptonites (Le Maitre 2002). It appears to be related to the basanites found in the northern part of the Sava-Vardar-Axios suture zone. Another interesting formation, that could potentially be classified as lamprophyric, is the Achillion volcanics in central Greece (Innocenti et al. 2010).

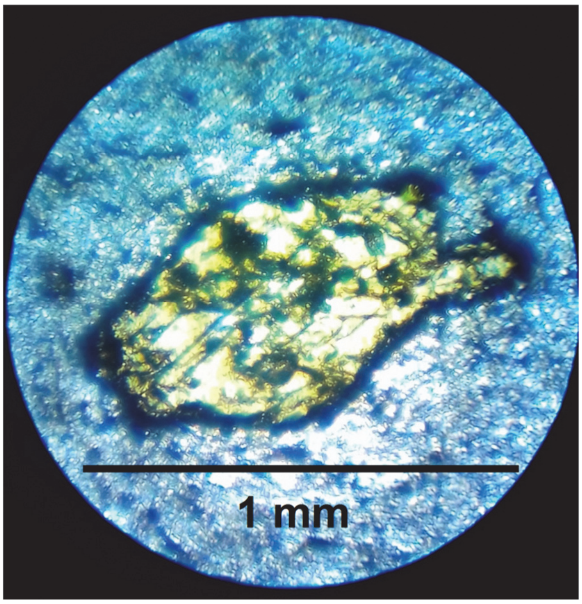

Fig. 3. Photomicrograph of a light brown amphibole phenocryst from the Kilkis intrusion. Groundmass is mainly oligoclase.

The most prominent area however, for lamprophyric rocks to occur is in Thrace, close to the Greek-Bulgarian border. This area lies to the south and at a very small distance from the Krumovgrad intraplate camptonite dikes (Marchev et al. 1998). The eastern dikes are camptonites (Marchev et al. 2006). In the Kotza Ele mountain area of Bulgaria, near the source of the Juruklerska river, a diatreme lies only 200 m from the borderline N of the Greek village of Chloi (Marchev et al. 1998). An interesting formation of the broader area, which has to be more thoroughly examined, is a subvolcanic body described as porphyritic gabbrosyenite (IGME unpublished data). It is located in Mavrohorara.

4. Conclusions

Despite the uncommon nature of lamprophyric rocks twenty-three areas have been identified through a bibliographic search. Most lamprophyre types have been identified including vogesite, the rarest of all calc-alkaline lamprophyres (see Rock 1991). Semi-lamprophyric malchite and alkali minette have also been located. Almost all the above lamprophyres occur as dikes and occasionally as sills cutting granitoid plutons. They are considered to be the latest and deepest (mantle generated) igneous products, associated with deep faulting following extension in granodiorite and monzonite massifs. Lastly, lamprophyric rocks have been recognized within ophiolite complexes in Kozani and W.Chalkidiki.

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