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STRATIGRAPHY

THE AGE OF VEDI ALKALINE LAMPROPHYRE DIATREME (ARMENIA)

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The alkaline lamprophyres of Vedi diatreme are composed mostly of green globular volcanic glass and have typical mineral composition for these rocks. Vedi diatreme is located in the Mankouk anticline (Khosrov reserve), where Middle Jurassic ophiolite complex where the obduction took place during the Late Coniacian to Santonian. U-Pb age of pyroclastic rocks of the diatreme is determined 182±3 Ma (n=17) by LA-ICP MS ablation on zircon grains. Broken rims of zircon grains indicate that they are affected by explosion. Alkaline lamprophyres are formed in an extensional environment of a subduction setting.

Key words: Armenia, Early Jurassic, subduction, zircon

Introduction

Lamprophyres are alkaline rocks enriched in H_2O and CO_2 and genetically related to lamproites, kimberlites and carbonatites, representing volatile-rich magmas rapidly emplaced in crustal layer (e.g. Rock, 1991). They are classified on the basis of their mineralogy and chemistry (e.g., Rock, 1991; Tappe et al., 2005). Lamprophyres are reported from different settings from continental active margins (e.g. Carmichael et al., 1996; Lange and Carmichael, 1990 etc.) post collisional (e.g., Muller et al., 1992) orogenic (e.g., Abdelfadil et al., 2013), intraplate rifting (e.g. Satian et al., 2005, Tappe et al., 2006), continental rift and subuction zones (Rock, 1991; Karsli et al., 2014).

Alkaline lamprophyres (AL) in Erakh anticline and Vedi area (Armenia) was firstly studied by M. Satian (e.g. Satian et al., 2005 and references therein). They crop out as diatremes and dykes in the area of Jurassic ophiolitic (obducted oceanic lithosphere) units.

Two main ophiolitic zones are recognized in the Armenian Highland: 1) the Amasia-Sevan-Hagari zone, situated in the North, north-east of the Sevan Lake (S), and 2) the Vedi ophiolitic unit, in the SE of the capital city Yerevan, is considered as a folded klippe sequence thrusted on the South-Armenian microcontinent (SAM), a micro-continent detached from Gondwana during the

Late Palaeozoic – Early Mesozoic time (e.g. Knipper & Khain 1980; Barrier et al., 2018). The obduction occurred during the Late Cretaceous (Sokolov 1977; Knipper & Khain 1980) Late Coniacian – Santonian (Galoyan, 2008, Sosson et al., 2010), Cenomanian (Danelian et al., 2014). At the same time, to the north beneath the Eurasian plate, the subduction of the Tethys oceanic domain occurred until the collision between SA Microcontinent and Eurasia during latest Cretaceous to Middle Eocene (Sosson et al., 2010). This Tethyan oceanic closure is well presented in palaeogeographic maps (e.g. Barrier et al., 2018).

In this paper new U-Pb LA-ICPMS zircon geochronology data of Vedi lamprophyres is presented and discussed possible geodynamic environment of this magmatism. The aim is to shed more light on their genesis.

Geological setting of the studied sections

Lamprophyre diatremes (red circls) are situated in the Mankouk anticline which is affected by numerous faults (fig.1). The new found Khosrov diatreme (Sahakyan et al., 2022) is situated left part of the Khosrov river (fig.1), where conglomerates containing pebbles of the ophiolite complex (serpentinites, gabbro, radiolarites, basalts) are outcrops. About 500 m westward from the lamprophyre diatreme pillow lavas (most probably of OIB type) intercalated with radiolarites are exposed as well.

In the Mankouk anticline ophiolite complex of MORB type pillow lavas and picrodolerites of tholeiite composition, trachytes, and alkaline lamprophyres (dominated alkaline, calc-alkaline basalts) are outcrop. Algae and bryozoans fossils containing thin layered limestones exposed on the top of this unite. The age of crystal limestone lenses is dated by foraminifera as Middle Jurassic (Sokolov, 1977). The olistholites (up to several tens meters in diameter) of crystalline, gray organic limestones also observed. The pillow lavas of picrodolerites, dark grey picrobasalts and basalts of tholeiitic series, include lenses of calcareous radiolarites (Aslanyan & Satian, 1987). The age of these radiolarites is determined as Oxfordian - Kimmeridgian (Belov et. al., 1991). Biostratigraphic data for the sedimentary cover of the Vedi ophiolite Danelian et al. (2008) and Asatryan (2009) discovered Bajocian Radiolaria in radiolarites intercalated with MORB type of basalts, while Danelian et al. (2010) established the occurrence of Upper Jurassic radiolarites stratigraphically overlying basaltic lavas and middle Albian to early Cenomanian radiolarites intercalated with lavas Danelian et al. (2012). In addition, Rolland et al. (2010) provided a radiometric dating for an amphibole of a diorite with the $^{40}Ar/^{39}Ar$ method and found a 178.7±2.6 Ma plateau age (Toarcian).

This oceanic crust sequence is covered by variable thicknesses of pillowed OIB alkaline lavas. In previous studies, the presence of tholeiitic and alkaline volcanic rocks had been noted (Zakariadze et al., 1983; Satian et al., 2005). In the following are distinguished three geochemical magmatic rock types; basalts with MORB geochemical signature of the ophiolite formed in a back-arc basin, an alkaline volcanic series above the ophiolite sequence plus a hot-spot event with OIB-type geochemical features (Galoyan, 2008). $^{40}Ar/^{39}Ar$ dating of a single-grain amphibole phenocryst of OIB lavas provides a Lower Cretaceous age of 117.3±0.9 Ma (Rolland et al., 2009).

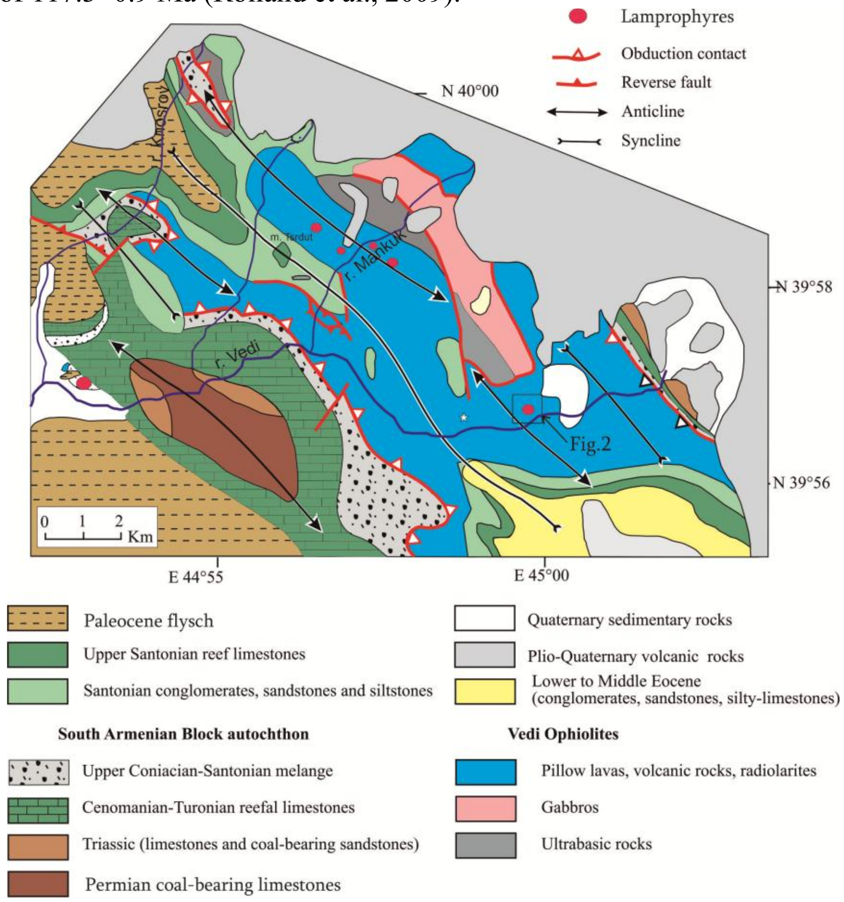

Fig.1. Geological map of the Vedi area (modified after Galoyan, 2008;). Fig.2 - Vedi lamprophyre diatreme.

In Vedi area Santonian limestones cover the ophiolite sequence. In some areas it is a conglomerate containing clasts of ophiolitic rocks (gabbros, serpentinites and basalts) that covers the ophiolitic lavas. This conglomerate evolves laterally to the above mentioned reefal limestones, built essentially of late Coniacian Hippurites. This sedimentary sequence lies over the ophiolitic rocks, ophiolitic melange, lamprophyres and the Cenomanian-Turonian shallow-water carbonates of the SAM.

AL diatreme situated in upper stream of Vedi river (39.944819° N; 44.988182° E; fig.1). Ellipse shape diatreme has a 55m length, where picro-basalt dyke cut the lamprophyres on the northern part (fig.2 A,B).

Xenolites in lamprophyres are mainly fine-grained limestones, high-Al amygdaloidal basalts of Na alkalinity, basanites, gabbro, rarely serpentinitized ultrabasites. Radiolarite xenolites in lamprophyres are absent (Sahakyan, 2007). In the lower part of diatreme reddish and tobacco-yellow ferriferous silicites

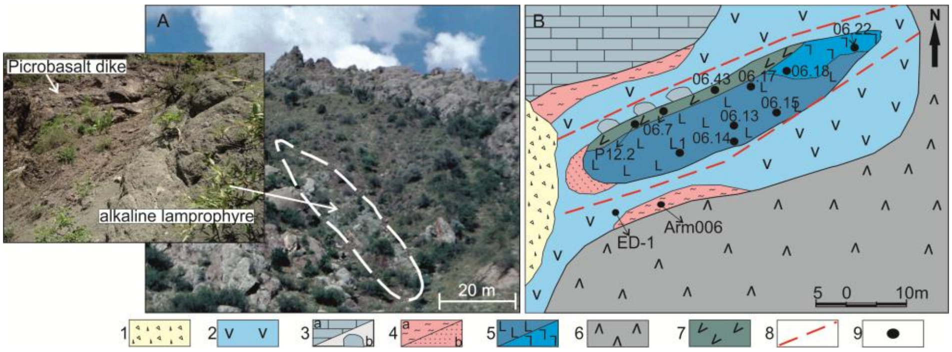

Fig.2. A-field photo and B-schematic map of the Vedi lamprophyre diatreme in the upper stream of r. Vedi. 1. Quaternary alluvial and deluvial deposits; 2. Ophiolitic volcanic rocks; 3. Middle Jurassic a) olistolite of crystalline limestone, b) crystalline limestone blocks; 4. a) middle Oxfordian early Tithonian radiolarite cherts, b) hydrothermal silicite stocks; 5. a) alkaline lamprophyres, b) alkaline basaltic tuffs; 6. Andesites; 7. Picrobasalt dyke; 8. Fault; 9. Samples.

with globular structure are exposed (sample Arm-006 in fig.2) where radiolarians of *Archaeodictyomitra apiarium* Rüst, *Cinguloturris carpatica* Dumitrica, *Eucyrtidiellum ptyctum* Riedel and Sanfilippo, *Eucyrtidiellum pyramis* AITA, *Podocapsa amphitreptera* Foreman, *Protunuma japonicas* Matsuoka & Yao, *Stichomitra sp.* A, *Stichocapsa ulivii*, *Transhsuum brevicostatum* gr. Ozvoldova, *Zhamoidellum ovum* Dumitrica, *Z. ventricosum* Dumitrica are determined and have been dated as of middle Oxfordian early Tithonian ages (U.A.Z. 9-11, Danelian et al., 2008; Asatryan, 2009).

Material and methods

LA-ICP-MS U-Th-Pb zircon analyses were performed in situ. Analyses were carried out using a Lambda Physik CompEx 102 excimer laser generating 15ns duration pulses of radiation at a wavelength of 193 nm. For analyses, the laser was coupled to an Element XR sector field ICP-MS (AETE-ISO regional facility of the OSU OREME, University of Montpellier). Analytical conditions are identical to those reported in previous studies (e.g., Bosch et al., 2011; Bruguier et al., 2017) where ablation experiments were performed under helium, which enhances sensitivity and reduces inter-element fractionation (Gunther and Heinrich, 1999). The helium stream and particles ablated from the sample were mixed with Ar before entering the plasma. Laser spot size was 51 µm. The laser was operated at a repetition rate of 4Hz using a 12 J/cm2 energy density. Total analysis time was 60s with the first 15s used for background measurement (laser disabled) which was substracted from the sample signal. Before each analysis, the surface of the targeted zone was cleaned with 10 pulses using a spot size twice larger than the size used for U-Pb analyses.

U-Pb dating

In order to determine the precise timing of AL, zircon grains were separated for U–Pb geochronology.

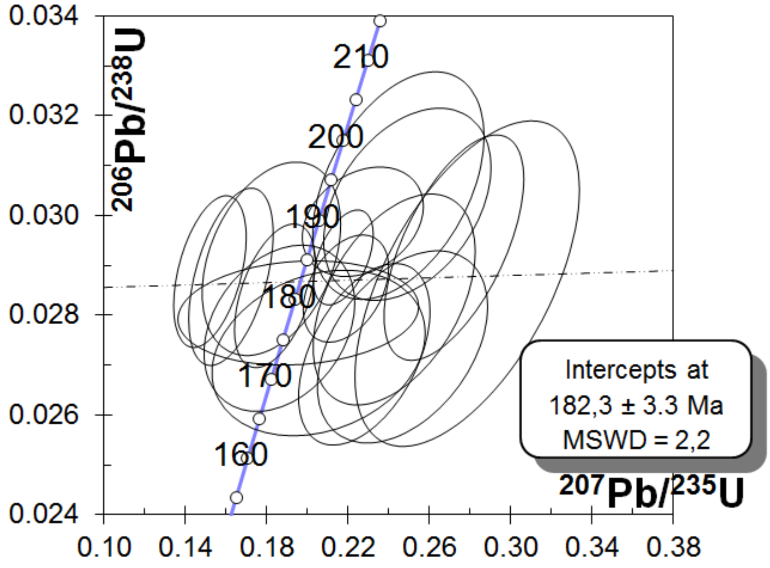

Fig.3. U-Pb Concordia diagram for the analyzed zircons from alkaline lamprophyre (L1).

The analytical results are plotted in fig.3. U–Pb analyses of 13 zircons grains from the alkaline lamprophyres (L1 from Vedi alkaline lamprophyres) yielded a mean ^{206}Pb/^{238}U age of 182±3 My (n=17).

Cathodoluminescence (CL) imaging revealed that all grains show broken rimes which suggest that they are affected by explosion (Fig.4). The zircons in

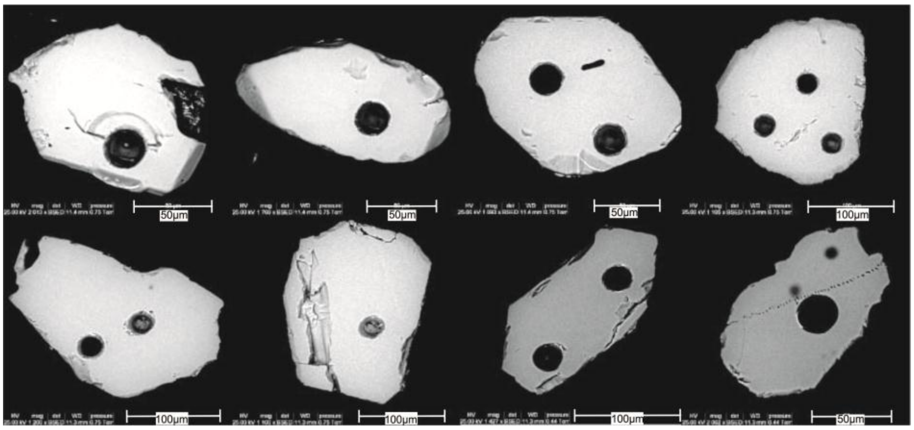

Fig.4. Cathodoluminescence (CL) images of euhedral zircons in alkaline lamprophyre.

these rocks are relatively large (generally 50-100 µm) and most of them show euhedral crystal shapes of colorless or pale pink color. They show high Th/U ratios (0.39 to 1.02) which confirm their magmatic origin (Rubatto, 2002).

Trace element geochemistry

The explanation of whole rock major- and trace-element analyses (chondrite-normalized rare earth element and primitive mantle–normalized trace element) is presented in (Sahakyan, 2007, Satian et al., 2009). The chondrite-normalized rare earth element and primitive mantle–normalized trace element (fig.5,a) patterns are shown (normalizations are from Sun & McDonough 1989). Chondrite-normalized REE patterns of lamprophyres are enriched in light REEs (LREEs) relative to heavy REEs (HREEs), with (La/Yb)N= 14.7-52.7 ratios, 5.8 for ophiolitic alkaline basalt, and 3.49 for picrobasalt dyke (Vedi diatreme). Primitive mantle-normalised element abundance patterns (fig.5,b) are characterized by enrichments in large ion lithophile elements (LILE, such as Ba, Rb, Th) relative to high-field strength elements (HFSE) with depletion in Ta and strong enrichment in U (fig.5,b). All alkaline lamprophyres show negative Zr anomalies (relative to Sm).

Table 1

Whole rock major- and trace-element analyses of studied rocks from Vedi diatreme

	alkaline lamprophyres					alkaline basaltic tuffs		basalt	picrobasalt
Samples	**L1**	**6.13**	**6.14**	**6.15**	**6.17**	**6.18**	**6.22**	**ED1**	**P12.2**
SiO_2	31.1	29.78	31.3	30.92	26.6	39.82	31.79	45.54	44.28
Al_2O_3	10.2	12	10.52	11.66	9.41	16.1	13.48	17.37	18.98
Fe_2O_3	4.39	3.88	4.07	4.6	3.51	5.37	4.11	9.23	8.22
FeO	3.33	3.25	3.44	2.13	3.02	4.03	3.71		4.08
MnO	0.11	0.1	0.12	0.21	0.13	0.11	0.08	0.34	-
MgO	2.6	7.3	7.7	3.9	7.4	8	9.52	8.67	9.95
CaO	25.65	18.26	17.32	19.78	21.7	7.04	14.8	7.16	3.97
Na_2O	1.4	1.7	1.1	1.1	1.8	1	1.3	2.9	3
K_2O	1.1	0.7	1.5	1.8	0.9	2.9	0.8	0.77	0.13
TiO_2	0.24	0.18	1.51	1.2	1.68	0.75	0.31	1.73	0.97
P_2O_5	0.26	0.62	0.61	0.14	0.58	0.38	0.23	0.32	0.19
H_2O	0.09	0.06	0.09	0.31	0.07	0.08	0.11	-	0.01
LOI	0.16	0.68	0.4	1.1	0.08	0.05	2.8	6.79	0.05
CO_2	19.37	21.49	20.32	20.74	22.94	14.37	16.96	-	6.08
Total	100	100	100	99.59	99.82	100	100	100.82	99.91
Na_2O+K_2O	2.5	2.4	2.6	2.9	2.7	3.9	2.1	3.67	3.13
Rb	21.8	-	92.7	13.6	-	90	-	7,978	3.903

Sr	2005	115	1580	300	-	830	680	304.3	207.473
Y	32	42	30	10	75	20	42	23.78	25.192
Zr	70	30	70	23	30	24	70	134.3	88.698
Ba	485	95	190	180	320	285	330	246.3	134.192
La	38.1	51.4	38.7	16.6	41.6	52.9	112	18.01	7.651
Ce	62.9	88	65	27.6	69.7	90.2	171.5	37.24	17.497
Pr	6.06	7.96	6.14	2.59	6.7	8.92	17.5	4.629	2.300
Nd	20.6	25.3	20.4	8.72	22.2	30.7	60.2	18.86	11.054
Sm	4.73	5.45	4.45	1.97	4.78	6.99	13.8	4.28	2.880
Eu	1.96	1.46	1.19	0.55	3.11	2.23	2.65	1.539	1.173
Gd	4.8	5.9	4.71	1.82	5.53	5.99	12.5	4.462	3.799
Tb	0.66	0.86	0.64	0.23	0.84	0.73	1.64	0.71	0.653
Dy	3.5	4.77	3.47	1.21	4.88	3.65	8.02	4.296	4.253
Ho	0.69	1.02	0.69	0.23	1.08	0.64	1.53	0.85	0.875
Er	1.74	2.63	1.72	0.55	2.81	1.4	3.6	2.292	2.471
Tm	0.23	0.37	0.23	0.069	0.42	0.17	0.45	0.341	0.349
Yb	1.13	1.77	1.04	0.33	2.03	0.72	1.95	2.232	2.189
Lu	0.17	0.29	0.17	0.048	0.35	0.095	0.28	0.337	0.367
Hf	2.75	2.49	4.13	2.79	3.42	3.88	0.55	3.208	2.056
Ta	0.26	0.51	0.27	0.74	0.46	2.63	-	1.571	0.482
Th	4.12	3.78	6.1	2.01	6.1	6.67	6.11	2.146	0.883
U	44.97	44.4	23.8	8.88	3.7	1.47	17.7	0.624	0.191
(La/Yb)N	24.2	20.8	26.7	36.1	14.7	52.7	41.2	5.8	3.49
Th/Yb	3.65	2.14	5.87	6.09	3	9.26	3.13	0.96	0.4
Ta/Yb	0.2	0.3	0.3	2.2	0.2	3.7		0.7	0.22
Zr/Y	2.19	0.71	2.33	2.3	0.4	1.2	1.67	5.65	3.52
Tb/Yb	0.58	0.49	0.62	0.70	0.41	1.01	0.84	0.32	0.30
Th/La	0.11	0.07	0.16	0.12	0.15	0.13	0.05	0.12	0.12
Ce/Yb	55.66	4.78	4.52	4.78	4.83	4.24	4.33	6.55	0.17
La/Sm	8.05	9.43	8.70	8.43	8.70	7.57	8.12	4.21	2.66
Ba/Th	117.72	25.13	31.15	89.55	52.46	42.73	54.01	114.8	151.90

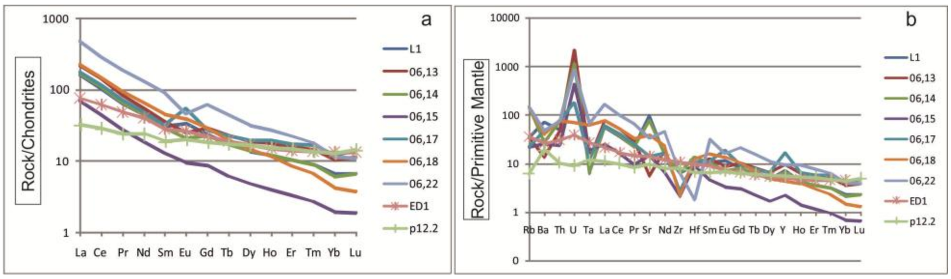

Fig.5. (a) Chondrite-normalized REE patterns and **(b)** primitive mantle-normalized spidergrams for the Vedi lamprophyres (Sun and McDonough 1989).

The Th/Yb ratio vs. Ta/Yb diagram is used to display source variation and crustal contamination (fig.6, a). The melting histories of the AL, dyke and basalt rocks are evidenced by the modeling of Tb/Yb versus Ce/Yb ratios (fig.6,b). Ba/Th vs La/Sm diagram highlights mixture between variable depleted mantle and material released from the subducted crust (fig.6,c).

Zr/Y values shown by the studied lamprophyres are > 1.0 besides samples (06.13) and (06.17) suggesting residual clinopyroxene in the protolith and low degrees of partial melting. Basalt ED1 and picrobasalt (P12.2) have 5.65 and 3.52 ratios respectively (table 1). Th/La values ranges from 0.05 to 0.16.

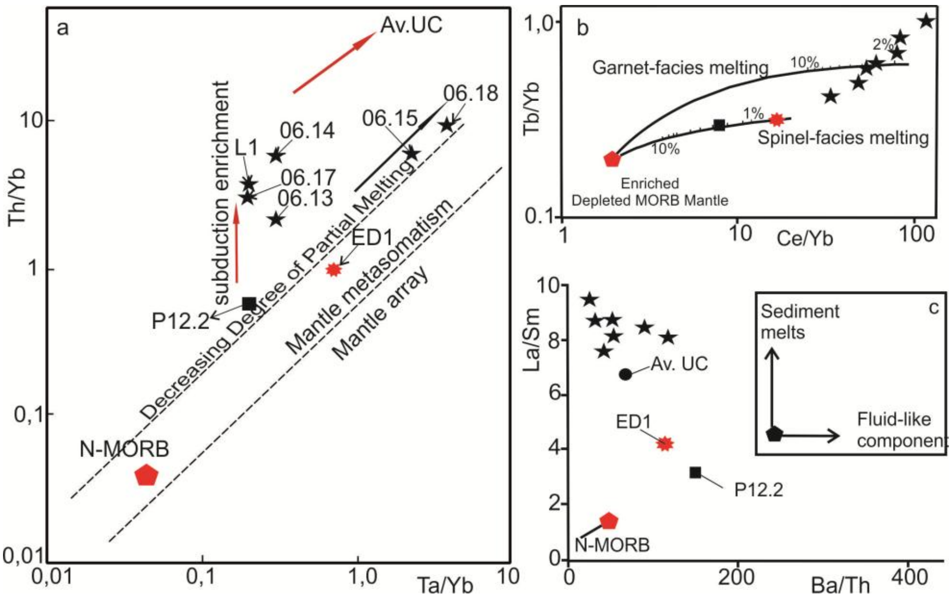

Fig.6. a) Th/Yb v. Ta/Yb log–log diagram (Pearce 2008); b) Partial melting model for the rocks from the Vedi diatreme (Tb/Yb vs Ce/Yb plot), Starting composition is enriched–depleted MORB mantle (E-DMM; Workman and Hart, 2005); Garnet- and spinel-facies melting curves use mineral assemblages from (Walter, 1998) and (Kinzler, 1997) respectively; c) Ba/Th vs La/Sm log–log diagram (Plank, 2005). Av.UC- average upper crust.

Discussion and conclusion

Several lamprophyre diatremes have outcrops in southern part of Armenia. Based on the mineral paragenesis (diopside, augite, Ti-augite, garnet, zircon and other minerals) and geochemical compositions the rocks from Vedi diatreme are classified as lamprophyres (e.g. Satian et al., 2005, 2009; Sahakyan, 2007). Diatremes are easily distinctive from the surrounding deposits by their colour and oval shape structure, composed also by dykes. The material of diatreme (or pipe of explosion) is ocherous green crumbly tuffic rocks which contain 60–70% fragments of volcanic glass with numerous globules.

AL are highly enriched in LREE (>100 times chondrite) relative to HREE (~10 times chondrite), also have high LILE, and low HFSE, which reflect either a LILE and LREE-enriched mantle source, or continental crust contamination (fig.5a,b).

In the Th/Yb v. Ta/Yb diagram (Pearce et al. 2008; fig.6,a) the AL slightly shifted to higher Th/Yb ratios. Their enrichment in Th, compared with the midocean ridge basalt (MORB) mantle, suggests the influence of subduction-zone fluids. In the plot Tb/Yb vs. Ce/Yb ratios a dynamic melting equation (Zou, 1998) is applied to an enriched depleted MORB mantle source composition (E-DMM; Workman and Hart, 2005). The modeling results show that up to ~10% (~4% for dyke and basalt) partial melting of the E-DMM source may explain the LREE and HREE levels in the AL samples and in the dyke and basalt respectively. These suggest that the source of the AL was enriched by LILEs, which can only be supplied by fluids or sediments derived from a subduction zone (Pearce, 1982). In a diagram of Ba/Th vs La/Sm highlights that mental source enrichment of the lamprophyres is dominated by melts from subducted sediment rather than by aqueous fluids (fig.6,b).

Low Ba/Th and high La/Sm ratios suggesting that the LILE and LREE- Th-U budgets of these magmas are dominated by melts from suducted sediments.

The average global subducting sediment has a Th/La ratio of 0.24 (Plank & Langmuir, 1998; Plank, 2005) while the values of the bulk and the upper continental crust are estimated to 0.27±0.05 and 0.33±0.05 respectively (Rudnick & Gao, 2003). Th/La values ranges from 0.05 to 0.16 (table 1), with values of < 0.12 indicating insignificant crustal contamination.

Some samples (e.g. 06.15, 06.18) display a HREE depletion combined with very low Y and Yb contents indicate that melting occurred in the field of a garnet-bearing source where garnet was present as a residue (e.g. Martin, 1999).

We suggest that the Early Jurassic AL could form in an extensional environment in a subduction zone setting (fore- or back-arc). A subduction related setting for the alkaline lamprophyres is evidenced by their enriched LILE and depleted HFSE (Ta) compositions and partial melting of the E-DMM source may explain the LREE and HREE levels in the AL samples.

Mental source enrichment of the lamprophyres is dominated by melts from subducted sediments. The differences in normalized element patterns support that AL and alkaline basalt (ED1) of ophiolite complex are not petrogenetically related and most likely derived from melts formed in different tectonic settings. However, it is still difficult to relate these alkaline events due to the paucity of Sr, Nd, Pb isotopic data.

Based on U-Pb dating on zircon minerals the AL of Vedi diatreme were emplaced during the Early Jurassic (182±3 My) and according previous results their mineral composition and chemistry are typical for alkaline lamprophyres.

Trace element concentrations, such as enrichment in large ion lithophile and strong depletion of some high field strength elements, indicate a mantle source that was partially modified by a subduction event. Alkaline lamprophyre diatremes were emplaced in a subduction zone setting, where the slab presumably was rolled back initiated asthenospheric upwelling.

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Վեդու ալկալա-լամպրոֆիրային դիատրեմայի հասակը (Հայաստան)

Սահակյան Լ.

Ամփոփում

Վեդու դիատրեմայի ալկալային լամպրոֆիրները կազմված են հիմնականում կանաչ օղակաձև հրաբխային ապակուց և ունեն այս ապարների համար բնորոշ միներալային կազմ: Վեդի դիատրեման տեղակայված է Մանկունկի անտիկլինալում (Խոսրովի արգելոց), որտեղ միջին յուրայի օֆիոլիթային համալիրը օբդուկցվել է վերին կոնյակ- սանտոն ժամանակահատվածում: Դիատրեմայի պիրոկլաս-տիկ ապարների U-Pb հասակը որոշվել է 182±3 միլ. տարի (n=17) ըստ ցիրկոն միներալների LA-ICP MS քայքայման: Ցիրկոն միներալների

եզրային հատվածների կոտրված լինելը փաստում է, որ միներալները վնասվել են ժայթքման արդյունքում: Ալկալային լամպրոֆիրները ձևավորվել են սուբդուկցիոն զոնայի ընդարձակման միջավայրում:

ВОЗРАСТ ВЕДИСКОЙ ЩЕЛОЧНО-ЛАМПРОФИРОВОЙ ДИАТРЕМЫ (АРМЕНИЯ)

Саакян Л.

Резюме

Щелочные лампрофиры диатремы Веди состоят в основном из зеленого шаровидного вулканического стекла и имеют типичный для этих пород минеральный состав. Диатрема Веди расположена в Манкукской антиклинали (Хосровский заповедник), где обдукция среднеюрского офиолитового комплекса произошла в позднем коньяке-сантоне. U-Pb возраст пирокластических пород диатремы определен 182±3 млн. лет (n=17) методом LA-ICP MS абляции по зернам циркона. Сломанные каймы зерен циркона указывают на то, что они задеты взрывом. Щелочные лампрофиры формиравались в условиях растяжения в субдукционной обстановке.