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Original article

Petrology and mineralogy of the Ulaan Del Zr-Nb-REE deposit, Lake Zone, Western Mongolia

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ABSTRACT

The Ulaan Del deposit is located in the Lake Zone, Western Mongolia. In the area, middle-late Devonian alkali dykes of the Khalzan Complex are hosted in the middle-late Cambrian granodiorite-tonalite of the Togthohiinshil Complex. The alkali dykes of the Khalzan complex comprise medium- to fine-grained syenite, microsyenite, syenite-porphyry and trachyte, trachyrhyolite, and trachyandesite. The dykes are replaced to silica, sericite, albite, fluorite and are brecciated. They crosscut by quartz and quartz-carbonate veinlets. The dykes contain zircon (>0.19% Zr) with a total of rare earth elements oxides >0.1%. The host rocks of the Togtokhiinshil complex are mid-K, metaluminous, I- type granite, depleted in HFSE. Based on geochemical and mineralogical data, economic REE mineralization is concentrated in syenite and syenite porphyry of calc-alkaline high K to shoshonite series of A-type granite, emplaced at within a plate setting. Syenite dykes are enriched in REE. Ore minerals are zircon, apatite, sphene, monazite, xenotime, synchysite, parisite, fluorite and REE complex minerals, pyrite, rutile and limonite. Magmatic, metasomatic and hydrothermal processes significantly contributed to the formation of Zr, Nb, REE and Y mineralization at the Ulaan Del deposit.

Keywords: albite, feldspar, metasomatite, xenotime, alkali dykes

INTRODUCTION

The Ulaan Del deposit is located southwest of Khyargas Lake within the Lake Island arc terrane (Lake Zone) of the Northern Mongolian domain (Fig. 1). The Lake terrane contains several intact ophiolites (Khantaishir, Bayannuur, Geriin Nuruu and Agardagh), calc-alkaline basalt, andesite (522 ± 13 Ma, Sm-Nd; Kovalenko et al., 1995, 1996), rhyolite, volcanoclastic rocks intruded by Late Cambrian -Ordovician syn-and post-tectonic diorite, granodiorite and granite (497 Ma, Kroener et al., 2007) covered by clastic sediments.

Geological investigation of the region, including the Ulaan Del deposit area started in the early 1980's by 1:200000 scale geological mapping (Samozvantsev et al., 1982) and an airborne geophysical survey on the scale of 1:50000 (Gavrilov et al., 1987, 1989 and 1990). In the early 1990's Minin et al. discovered anomaly A-657 (later named Shar Tolgoi) during an airborne geophysical survey on the scale of

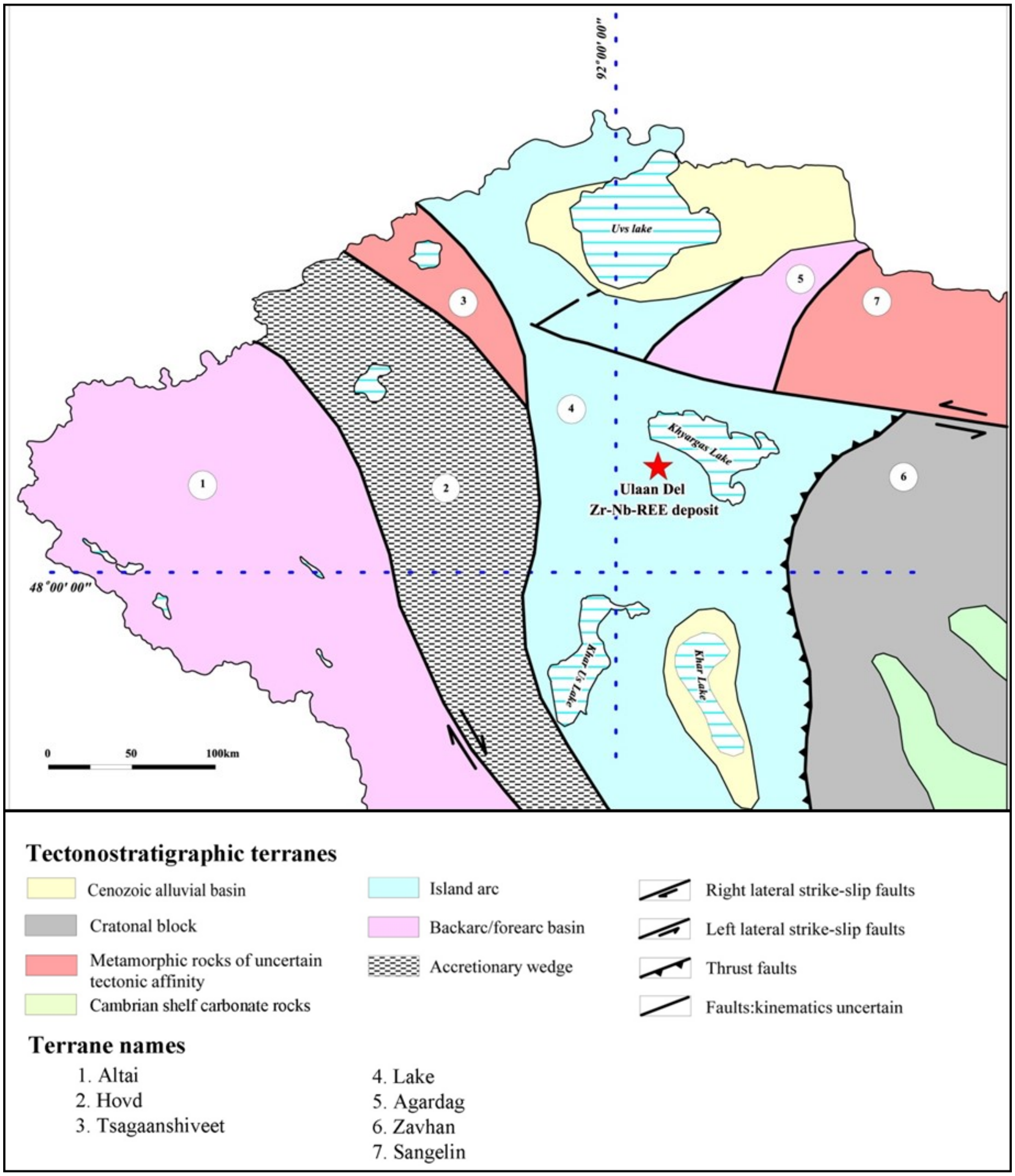

Fig. 1. Location of the Ulaan Del deposit in the terrane-tectonic map (Badarch et al., 2002)

1:50000 and explored it with a few drill holes and trenching (Fig. 2). From the exploration, the geological probable reserves were assessed at REE bearing ore of 19,900 tonnes of Ta_2O_5, 19,000 tonnes of Nb_2O_5 and 1.4 Mt of ZrO_2 (Minin et al., 1991).

Since 2009, geological prospecting and exploration works in the Ulaan Del deposit area (Fig. 2) were carried out by Geo-Info LLC, Mongolia, As a result, inferred and probable (C+P) reserves estimated 6.1 Mt of ore at 0.16% $\sum$TREO, 0.33% ZrO_2, 0.05% Nb_2O_5 and proved by the Mineral Resources Professional Council of Mongolia in 2018 (Oyunbat et al., 2018).

The Ulaan Del deposit comprises swarm stockwork-like alkaline dykes with Zr-Nb-REE mineralization (Fig. 2). This study discusses geology, petrography and geochemistry of the mineralized alkaline dykes at the Ulaan Del and includes a mineralogical study of REE bearing minerals.

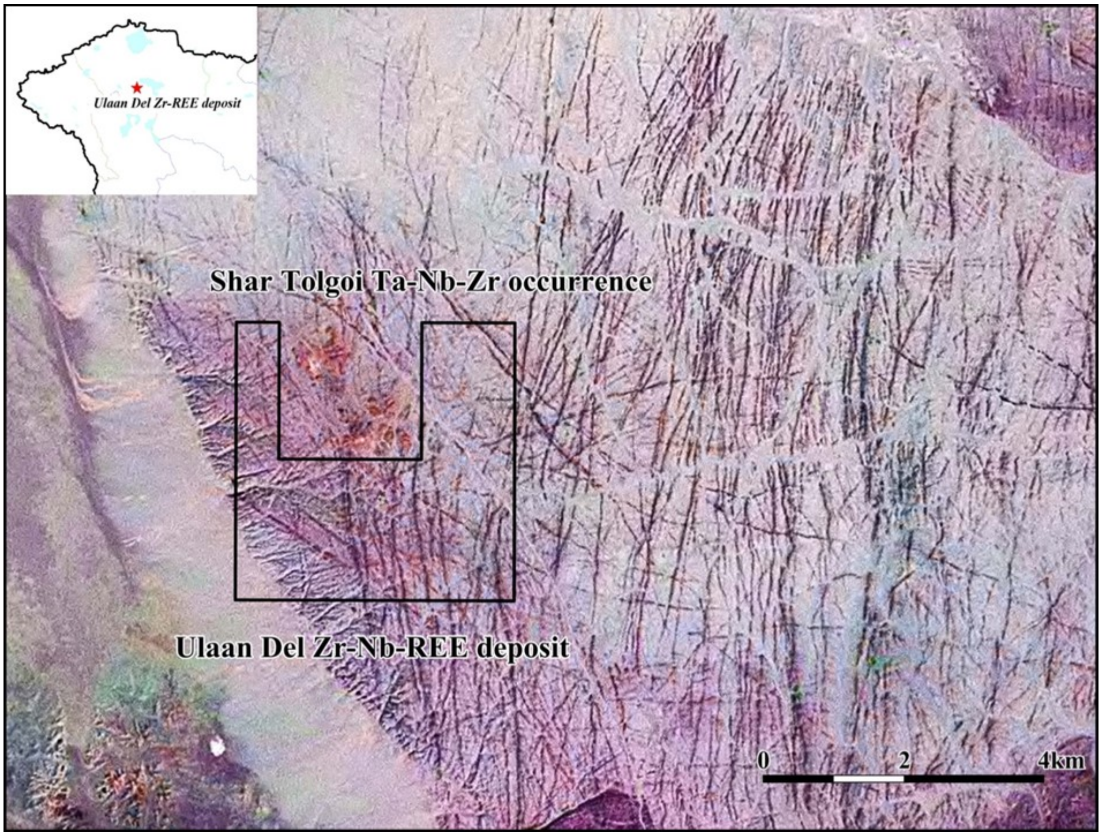

Fig. 2. Landsat image of the Ulaan Del Zr-Nb-REE deposit area. Location of the Shar Tolgoi Ta-Nb-Zr occurrence and the distribution of the ore-bearing alkaline dykes in the area

REGIONAL GEOLOGY OF THE LAKE ZONE

The Lake Zone represents one of the main tectonic domains of the Central Asian Orogenic Belt (CAOB) (Badarch et al., 2002). A number of the arc-related magmatic complexes distributed in the Lake Zone, Western Mongolia, which are considered as a result of exclusively oceanic crust subduction (Badarch et al, 2002, Kovalenko et al., 2004, Rudnev et al. 2012). This magmatism recorded the whole history from Late Proterozoic to Early Paleozoic including the formation of oceanic crust, subduction processes and arc-related magmatic activity (Sojeono et al., 2016, Rudnev et al., 2009) and post-orogenic magmatism (Yashina, 1982).

In the Lake Zone, two separate Early Paleozoic magmatic events were recognized (Sojeono et al, 2016), Middle Ordovician (460 Ma) and Late Devonian (376 Ma). Middle Ordovician magmatism produced gabbro to gabbro-diorite with mostly low to normal K- calc alkaline series plutonic rocks emplaced into the volcano-sedimentary sequences. The Late Devonian granite suite with calc-alkaline high K to shoshonitic character intruded the gabbro-diorite and volcano-sedimentary sequences. The alkaline magmatism penetrating or crosscutting the hosting rocks as dykes, stocks, bodies chains of alkaline granite bodies, alkaline syenite and gabbroids developed along deep faults and their branches and along margins of the Caledonian uplifts, within the Lake Zone (Sojeono et al, 2016).

LOCAL GEOLOGY OF THE ULAAN DEL DEPOSIT

Geology of the Ulaan Del area is dominated by alkaline dykes of the Middle-Late Devonian Khalzan complex that is hosted in the Middle-Late Cambrian Togtokhiinshil granitoids complex.

Alkaline dykes at the Ulaan Del deposit area extend over 300-500 m along the strike with variable widths (0.5-2 m). The dykes show diverse composition from andesite to granite and syenite with micro to porphyritic texture. The dykes sometimes brecciated along strike and small breccia pipes can found within the area (Fig. 3).

A geological map of the "Central" mineralized area of the Ulaan Del deposit shown as an example (Fig. 4). The dykes are brecciated, oxidized, silicified and albitized with pyrite, fluorite, muscovite, chlorite, epidote and

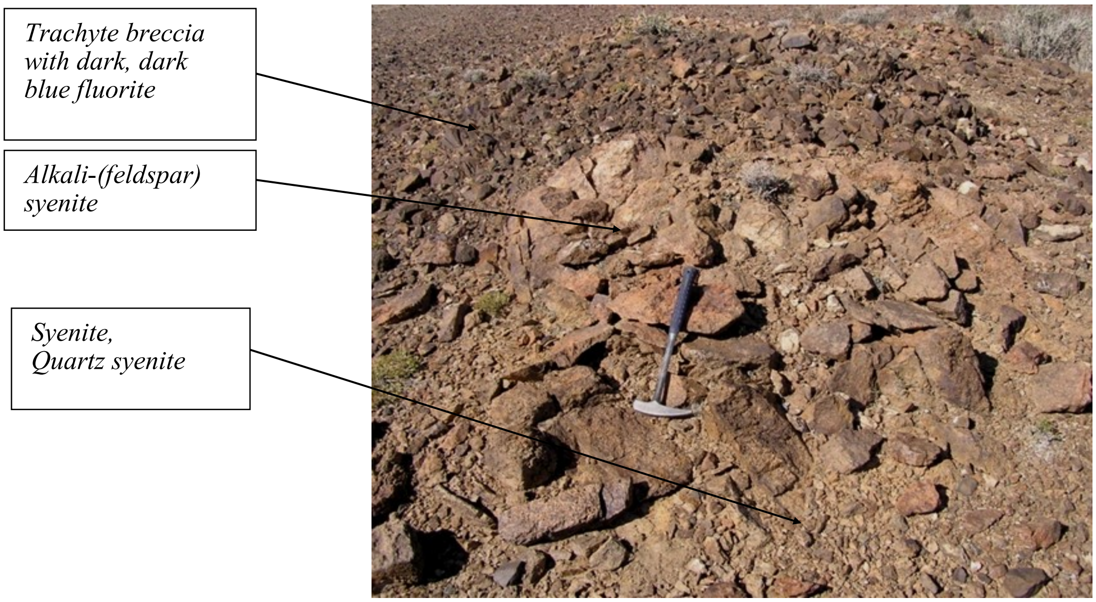

Fig. 3. Outcrop view of the breccia pipe (8.5 x 17 m)

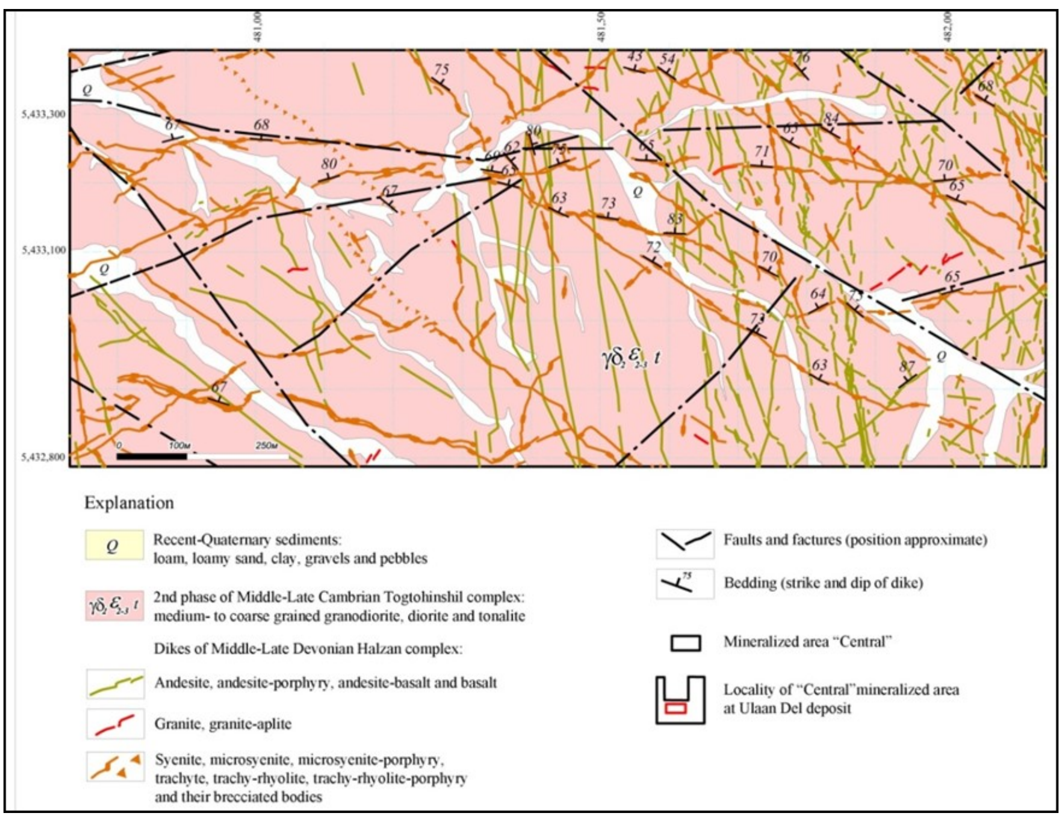

Fig. 4. Geological map of the Central area of the Ulaan Del deposit

crosscut with quartz-carbonate-iron oxide thin veinlets. Medium to coarse-grained granodiorite -tonalite, diorite and quartz monzonite of the Togtokhiinshil complex commonly distributed in the Ulaan Del area, represent the second phase of the Complex.

REE mineralization associated with alkaline dykes of the Khalzan complex. The high-grade Zr-REE mineralization associated with potassium feldspar enriched or albititic rocks with iron oxide, fluorite-(carbonate) alteration. The main minerals of the REE are xenotime, zircon and parisite-synchysite, complex REE-bearing minerals, monazite and apatite.

METHODS AND MATERIALS

More than 1000 rock samples collected, including channel and core samples. The sampling interval was about 25-40 m, but near the mineralized, more fractured and altered parts, the sampling interval narrowed. Samples designated with their drill hole identifier followed by the depth in meters.

The mineralogical and chemical composition of the rocks, alteration, REE-bearing minerals and their spatial and temporal distributions where determined by various laboratory methods.

About 65 selected samples from various dykes investigated for their texture and mineral composition. Petrographic and mineralogical microscopic studies carried out at the Geoscience Center, Mongolian University of Science and Technology.

Totally 12 drill core and rock samples from metasomatically altered alkaline dykes and host quartz diorite selected for whole rock geochemistry. Major oxides of SiO_2, TiO_2, Al_2O_3, FeO, Fe_2O_3, CaO, MgO, Na_2O, K_2O, MnO, P_2O_5, CO_2 (in wt.%), and trace elements of Ba, Nb, Sr, Ta and Zr (in ppm) determined by using XRF and rare earth elements La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu (in ppm) analyzed by ICP-MS at the Central Geological Laboratory of Mongolia.

Mineral identification using an X-ray diffraction (XRD) instrument has done at the laboratory of the Physics Department, Mongolian Academy of Sciences, and Tomsk University, Russia. The instruments operated at 40 kV voltage and a current 30 mA. The data measured in the 2σ range from five to 80° step width of 0.02° and measuring time 0.60 sec per step.

The relationship of zircon and xenotime was determined using an electron probe micro-analyzer (EPMA), with mineral liberation analysis (MLA) and alteration and REE minerals by energy-dispersive spectra (EDS) analysis and microscopic studies carried out in GTK, Finland.

RESULTS

Petrography

The Khalzan complex alkali dykes mostly represented by quartz syenite and microsyenite are fine to medium-grained pinkish, ranging from pale to reddish in color. Sometimes they are weakly brecciated and mainly replaced by albite, sericite-muscovite, carbonate, iron oxides and pyrite. The main rock forming minerals are plagioclase, K-feldspar, altered dark minerals and quartz. Phenocrysts are 0.1-0.8 mm, and groundmass is 0.05-0.6 mm in size (Fig. 5).

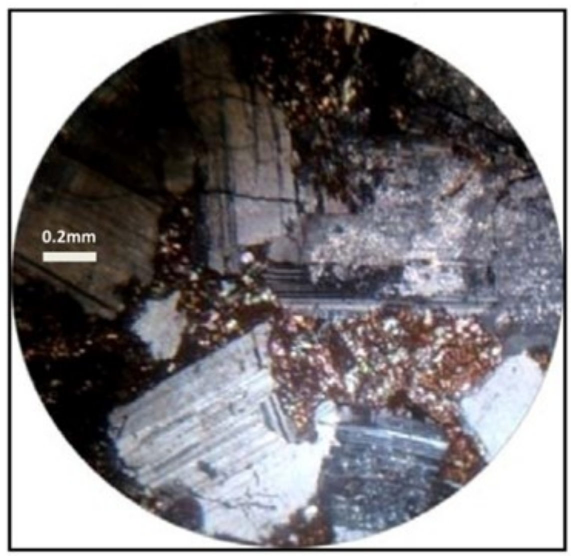

Fig. 5. Brecciated microsyenite (UD010). Phenocrysts interstitial spaces filled with muscovite-sericite

Syenite-porphyry composed of K-feldspar (from 70-75% to 85-90%) or albite (70-75%), goethite, hydrogoethite (10-15%), few quartz grains, carbonate (5-10%), pseudomorphs of chlorite with rutile (3-5%) and sericite-muscovite (5%), a minor amount of fluorite (3-5%) and apatite (3

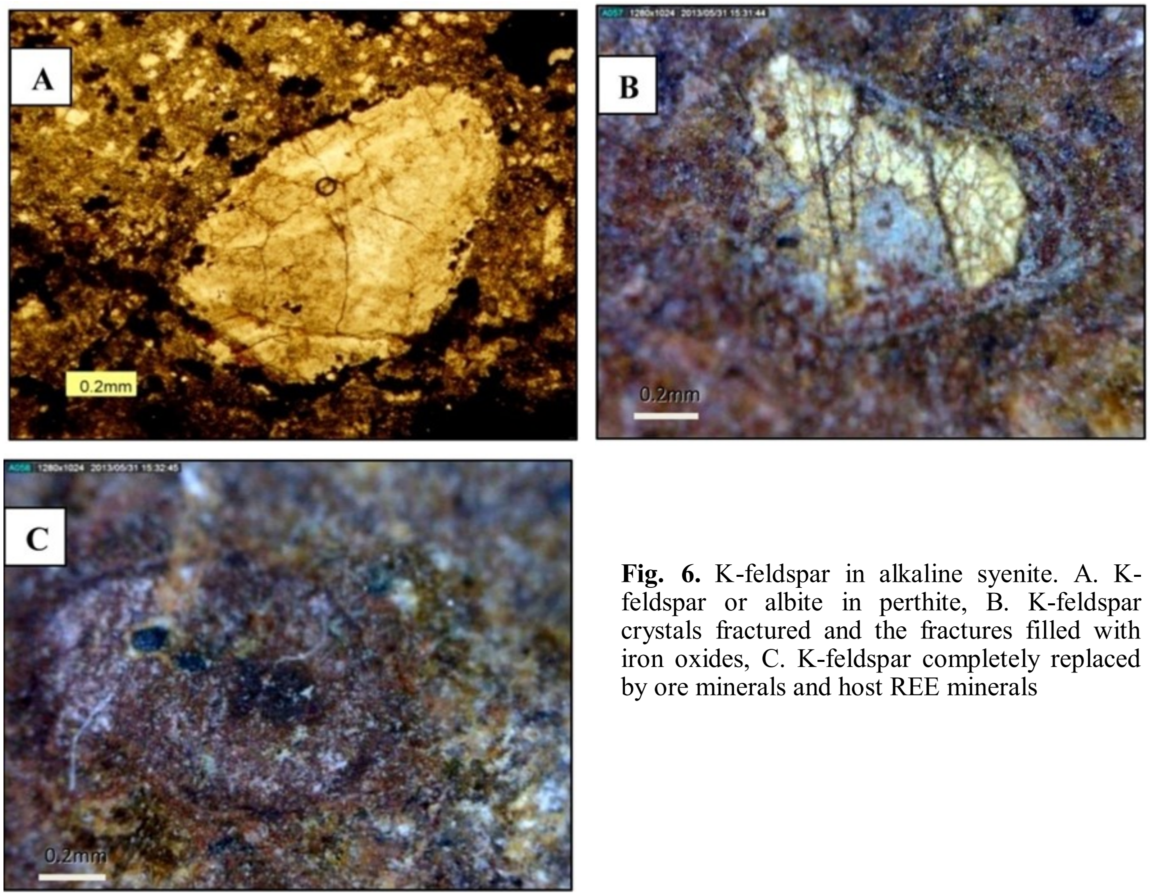

Fig. 6. K-feldspar in alkaline syenite. A. K-feldspar or albite in perthite, B. K-feldspar crystals fractured and the fractures filled with iron oxides, C. K-feldspar completely replaced by ore minerals and host REE minerals

-5%). Accessory minerals are zircon, limonite, sphene and xenotime. K-feldspar phenocrysts are mainly replaced by albite and are reddish brown due to iron oxide dust. Sometimes the syenite-porphyry is brecciated with fragments enriched in oxide and cemented by carbonate and ore minerals. The sericite-muscovite and chlorite pseudomorphs filled the interstitial spaces between K-feldspar grains (Fig. 5). Some porphyritic textures formed by large, euhedral to anhedral perthitic aggregates of feldspar with quartz and muscovite-sericite.

Plagioclase grains are 0.01x0.02 mm in size or small grains in interstitial spaces, and it associated with muscovite and sericite in volcanoclastic rocks. Plagioclase is mostly fresh and zoned, sometimes weakly replaced by secondary sericite and brecciated.

K-feldspar grains are 0.1-0.8 mm, sometimes up to 5 mm in size. Perthitic feldspar grains are 1-2 mm and are forming plate-like crystals. Twinning is very common with albite micro-growths (Fig. 6). Albite is fresh, prism-like, with muscovite micro-flakes and contains apatite, zircon and fluorite as inclusion.

One of the distinguishable features is the abundance of highly ordered microcline and albite established by XRD analysis and verified by optical microscopy. The highly ordered microcline forms the main part of perthitic alkali feldspar grains in trachytic or alkaline syenite (Fig. 7).

Goethite is pale gray, zoned and replaced with hydrogoethite from the edge and enveloped by muscovite flakes (Fig. 8).

Nests and lenses of iron-oxidized carbonates developed evenly within the dykes and host rutile, fine grains of zircon and apatite. Apatite grains as fine, prism like, irregular, isometric are observed as aggregates along microfractures, mostly along the edge of potassium feldspar

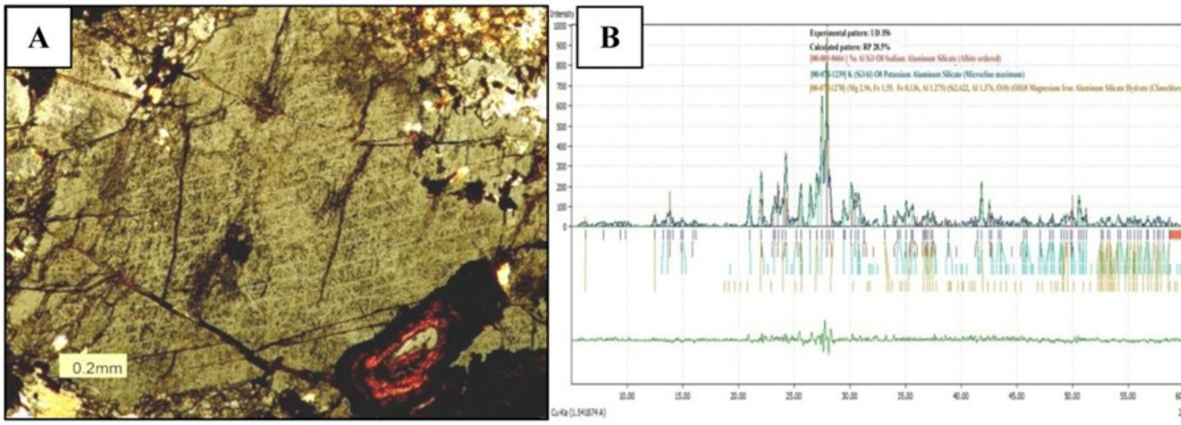

Fig. 7. Highly ordered cross-hatching microcline in alkaline rocks. A. Microcline and zoned goethite (cross polarized transmitted light). B. Quantitative XRD analysis of metasomatic rocks (albite, microcline)

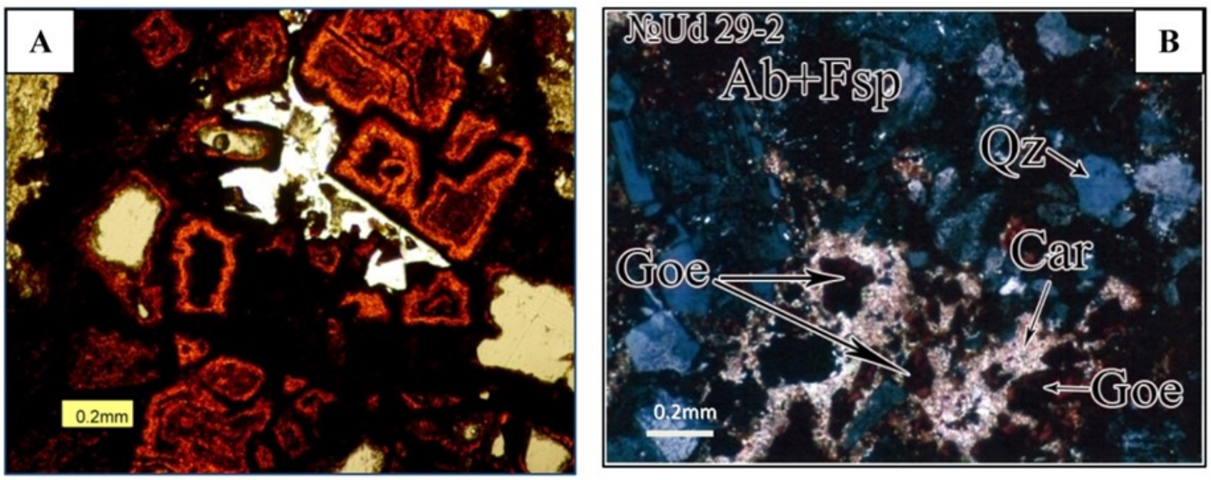

Fig. 8. A. Goethite zoned and replaced with hydrogoethite from the edge. B. Iron oxide lenses (Goe) with carbonate (Car) on albite-feldspar matrix (Ab+Fsp), Qz -quartz grains

grains. Moreover, apatite is associated with clear rutile micrograins. Some carbonaceous aggregates are synchysite-parisite or REE carbonate minerals. Relatively larger lenses of carbonate minerals tinted by iron oxides and often show red or reddish-brown color. They include apatite, zircon, monazite and xenotime (0.001-0.01 mm) grains as inclusion. Fluorite, carbonate slender veinlets and lenses are often noted along fractures.

Accessory minerals. Sphene grains have prolonged shape, 0.01-0.06 mm in size, show dark brown color and occur very often. Zircon (0.03-0.05 mm) dipyramidal, occurs as nests and micrograins. Monazite is (0.01-0.1 mm) pale, rectangle or plate like grains with a dark frame. Apatite is (0.02-0.125 mm) clear, forming hexagonal, short prism like grains. Synchysite is (0.02-0.06 mm) clear, pale to creamy brown, thick and short prism like grains and associated with dark framed grains or ore minerals. Fluorite (0.5 mm) is sometimes clear with a purple tint, filling the veinlets, spaces and fractures in the rocks. Typical fluorite crystals and xenomorth grains are associated with zircon, synchysite and xenotime (Fig. 9).

Geochemistry

Whole rock geochemical data are in Table 1, and REE data are summarized in Table 2.

The alkali dykes are fine- to medium grained, often porphyritic, weakly brecciated and affected by metasomatic alteration followed by mineralization. In the TAS diagram (Fig. 10) the Khalzan Complex rocks range from sublalkaline

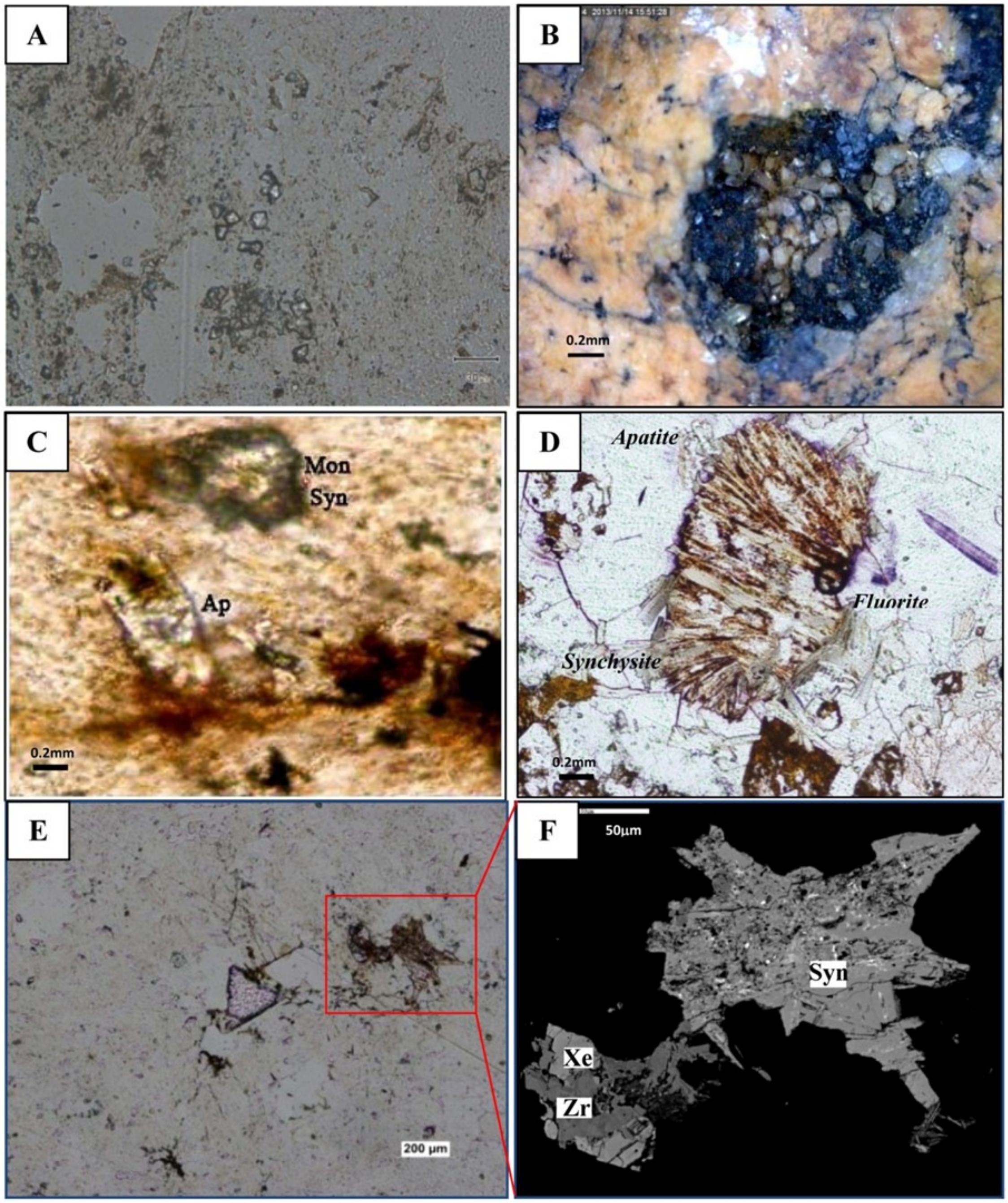

Fig. 9. Accessory minerals in alkaline dykes of the Khalzan complex. A. zircon grains, B. nests of zircon, C. apatite (Ap), monazite (Mon), synchysite (Syn), D. synchysite (Syn), fluorite, E. Goethite replaced by ore minerals with purple fluorite crystals, F. synchysite (Syn), zircon (Zr), Xenotime (Xe).

gabbro to monzonite and syenite, whereas the Togtokhiinshil Complex represented by diorite to granodiorite (Fig. 10).

The Khalzan Complex rocks are high-K to shoshonite series (Fig. 11), with high Al_2O_3 (Table 1) and ASI of <1.1, whilst the Togtokhiinshil Complex rocks plot in the low to medium-K field (Fig. 11).

The REE patterns show that the Khalzan alkali syenite and monzonite are rich in LREE, and slightly depleted in HREE, where the host diorite of the Togtokhiinshil Complex shows a similar pattern, but with a low La, Ce and HREE composition in comparison to the monzonites

Table 1. Whole rock geochemical analysis of rocks from the Ulaan Del deposit, by XRF

Complex	Khalzan complex											Togtokhi-inshilcomplex
Samples	UD562	UD323	UD2067/2	UD501	UD2083/3	UD354	UD2056	UD2085/4	UD2095/3	UD729	UD758/1	UD803
	Syenite, alkaline syenite				Syenitic breccias, syenite-porphyry breccias, monzonite					Diorite	Gabbro	Quartz diorite
Major oxides by wt.%												
SiO_2	60.75	60.99	60.15	64.36	59.98	57.0	59.88	57.13	54.88	60.08	46.64	62.35
TiO_2	0.038	0.05	0.358	0.078	0.11	0.57	0.183	0.476	0.58	0.658	1.638	0.534
Al_2O_3	21.46	19.87	18.02	17.80	19.32	17.58	19.28	17.39	18.0	17.61	16.69	16.36
tFe_2O_3	0.87	3.98	3.05	2.25	4.41	1.78	2.31	4.15	7.40	5.48	11.20	3.89
CaO	2.01	1.50	3.81	1.09	2.35	5.42	3.72	4.38	4.99	5.08	6.83	4.75
MgO	0.04	0.18	0.19	0.08	0.20	0.30	0.20	0.27	2.74	2.26	5.53	2.08
Na_2O	7.51	7.48	5.32	5.68	6.31	3.32	4.65	3.05	4.15	5.05	1.71	5.20
K_2O	3.80	3.19	4.88	6.38	3.62	7.92	5.39	8.08	3.75	0.93	4.26	1.40
MnO	0.057	0.037	0.044	0.052	0.08	0.06	0.072	0.146	0.11	0.086	0.267	0.060
P_2O_5	0.022	0.024	0.104	0.047	0.04	0.25	0.064	0.181	0.13	0.185	1.392	0.146
FeO	<0.25	<0.25	1.00	<0.25	<0.25	<0.25	0.43	0.71	2.75	1.85	4.64	1.64
CO_2	1.08	1.03	0.76	0.60	0.82	4.68	0.87	2.61	0.92	0.76	0.99	0.92
Total	97.64	98.33	97.69	98.42	97.24	98.88	97.05	98.57	100.40	100.03	101.79	99.33
Trace elements by ppm												
Ba	82	239	116	99	212	307	135	362	313	254	3019	344
Nb	293	187	139	231	243	124	153	133	131	8	20	6
Sr	42	91	77	57	178	103	107	113	428	761	1983	660
Ta	18	11	<10	29	21	11	12	12	<10	<10	<10	<10
Zr	2439	1994	807	1726	1806	196	1358	410	940	91	336	112

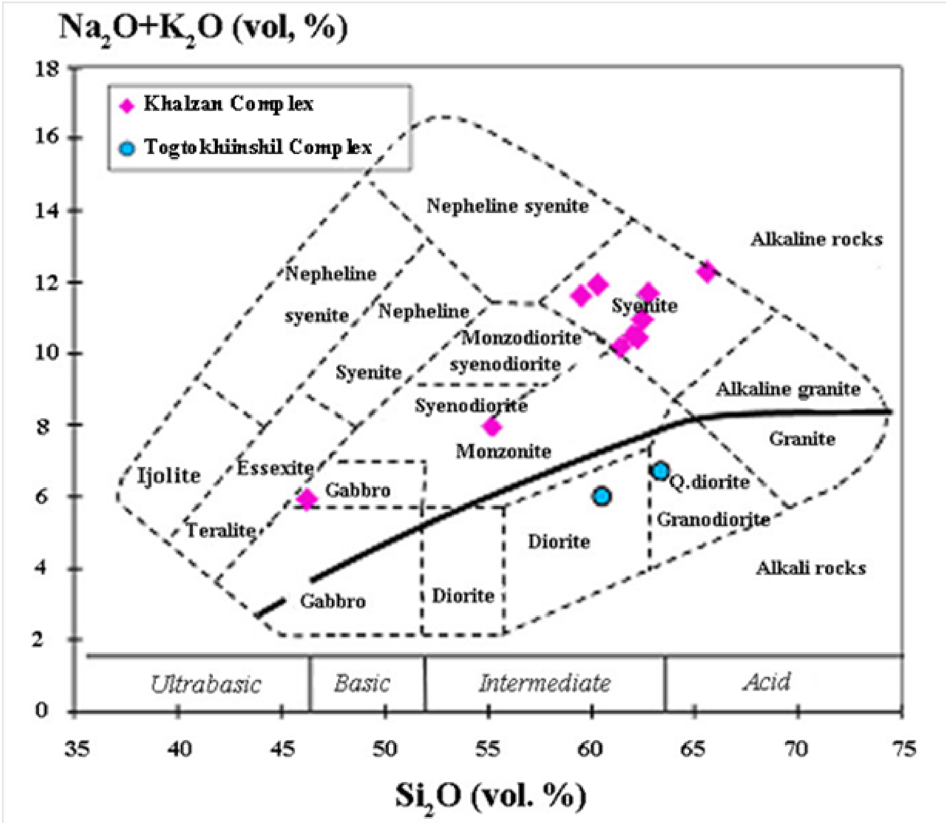

Fig. 10. TAS classification diagram (Le Maitre, 1989) for the Khalzan and Togtokhiinshil complex rocks in the Ulaan Del deposit area

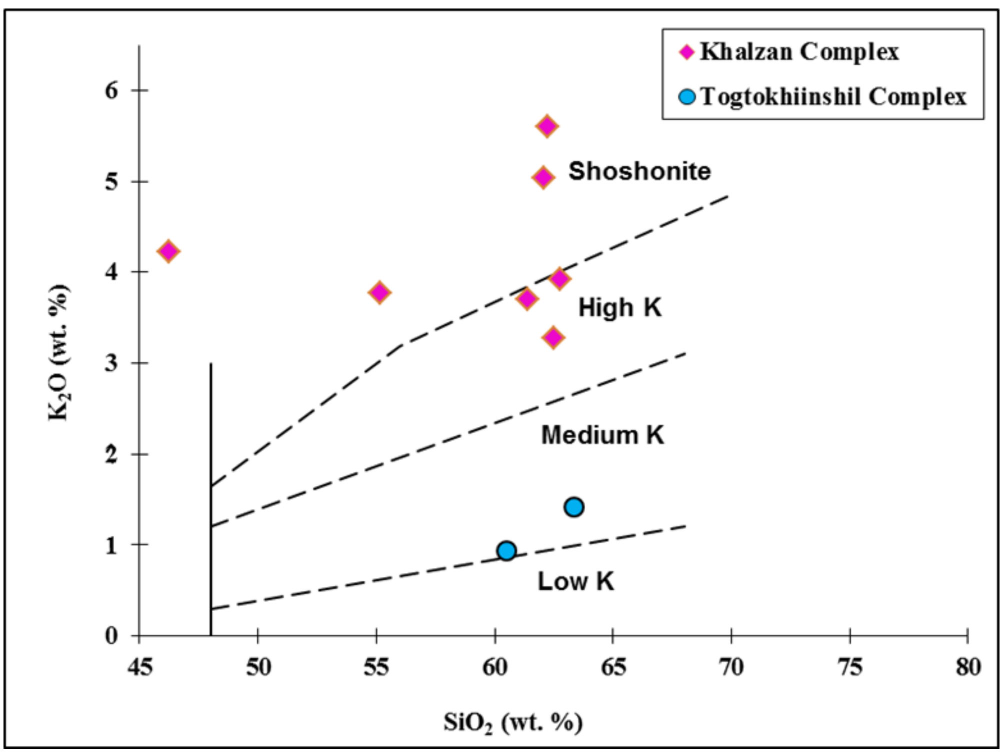

Fig. 11. K_2O vs SiO_2 variation diagram with subdivisions of Le Maitre (1989) for the Khalzan and the Togtokhiinshil complex rocks in the Ulaan Del deposit area

and syenites (Table 2 and Fig. 12).

Mineralogy

Detailed EDS, EPMA and MLA analyses carried out to investigate the alteration and REE bearing minerals. Selected parts of the altered rocks and accessory minerals were analyzed for their chemical composition by the REE spectrum distribution method.

REE distribution pattern of minerals

The analyzed metasomatic rocks are enriched in

Table 2. REE composition of alkaline dykes in the Ulaan Del

Sample ppm	UD323	UD501	UD729	UD2056	UD2095/3	UD2067/2	UD2085/4
La	128	140	30	117	78	98	60
Ce	212	326	37	212	183	213	146
Pr	52	75	30	18.08	17.96	18.08	13.12
Nd	117	115	50	58.98	59.4	62.94	57.49
Sm	30	30	30	11.28	13.32	12.19	14.22
Eu				0.97	1.25	1.13	2.02
Gd	6.95	22,57	3.1	13.33	14.19	15.08	14.39
Tb	0.98	3,73	0.42	2.16	2.44	2.06	2.41
Dy	6.03	24,52	2.05	11.56	13.26	10.47	13.97
Ho	1.13	4,44	0.35	2.42	2.64	2.03	2.61
Er	3.57	14,35	0.99	7.77	8.38	8.94	8.17
Tm	0.51	2	0.12	1.13	1.22	0.89	1.14
Yb	3.65	14,82	0.82	7.77	8.1	6.26	7.6
Lu	0.53	2,04	0.11	1.1	1.17	0.91	1.1

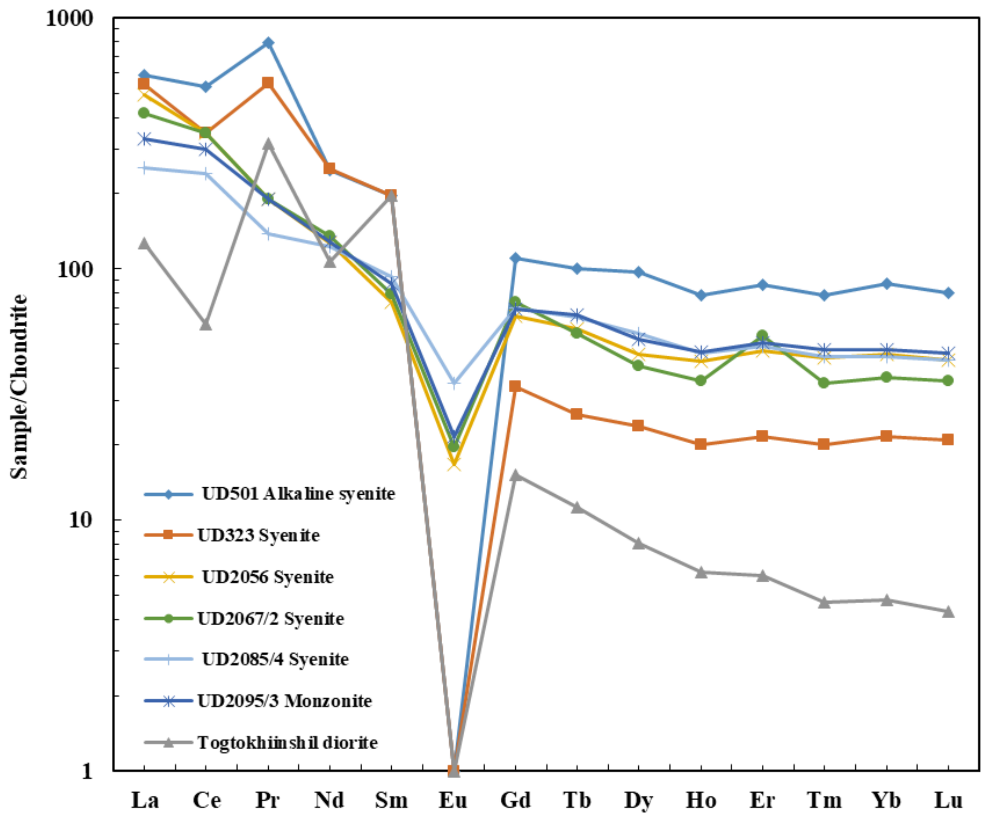

Fig. 12. Chondrite normalized REE distribution pattern of rocks from the Ulaan Del area. (C1 chondrite normalization by Sun and McDonough, 1989)

K and Na, silicified and iron oxidized (Fig. 13). Yttrium detected in different grains together with phosphorus spectra that indicate xenotime. Zircon is associated with xenotime and it is edging or framing xenotime in the same grains (Fig. 14). The REE distribution patterns showed the Ce, La, F, Y, P and Zr spectra. The La-Ce-F spectra are in the same grains that may indicate the composition of synchysite and parisite (Fig. 15).

REE distribution patterns are a responsive indicator for the formation of magmatic and metasomatic rocks. Three types of REE distribution patterns can identified within the studied samples:

- Low or primitive REE distribution patterns in medium-grained quartz monzodiorite, monzodiorite with rare pyrite phenocrysts indicate a moderate enrichment of both LREE and HREE.
- Silicified alkaline trachytic rocks show the highest grade of Zr. The general trend shows a higher amount of LREE (La-Ce group) and moderate or low HREE.
- Silicified and albitized alkaline syenite, microsyenite rocks with HREE or yttrium. The third type of REE distribution pattern unrelated to rock type, whether syenite or alkaline (albitized) syenite. This REE distribution may refer to "enriched type", due to its higher grade for HREE.

REE- bearing minerals and assemblages

Zircon is pure, less polluted. Zircon content is zirconium 35.35-46.07%, oxygen 28-34.31%, silica 12.17-14.73% and others 11.2-18.17%.

Synchysite-parisite constituent Ce 16.37%, La 9.40%, O 43.85%, C 15.5%, Ca 8.38% and

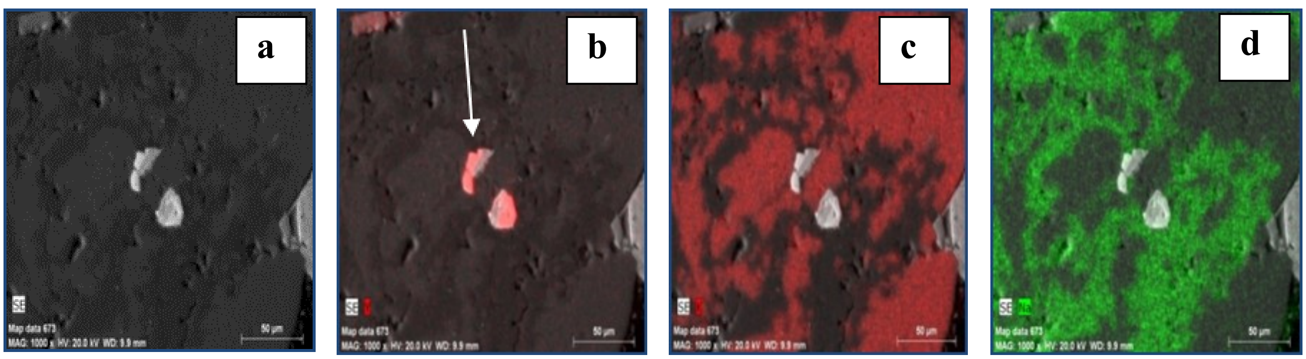

Fig. 13. Yttrium and Na-K distribution patterns. a. General view, b. yttrium, c. potassium, d. sodium distribution patterns

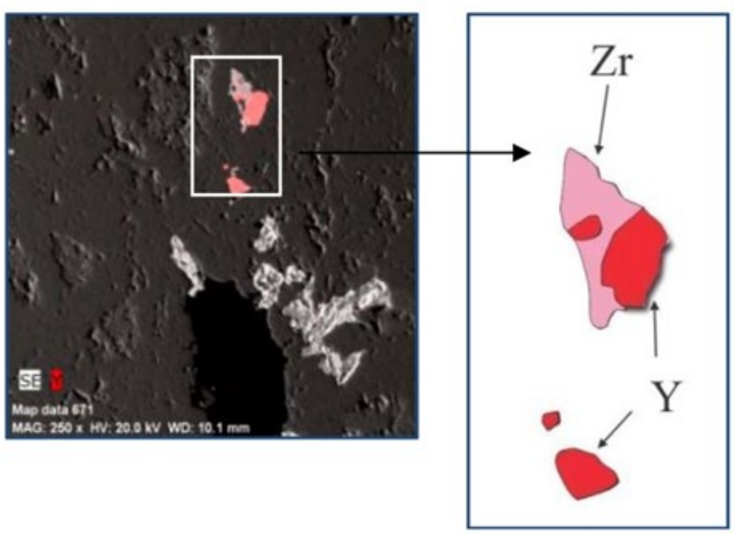

Fig. 14. Xenotime-zircon grain (Zoom 250X, HV 20.0, WD 10.1 mm)

others 6.5% in trachytic syenite rocks.

Xenotime – its elemental composition is complex, containing HREE's. Y 30.11%, Yb 2.11%, Gd 2.31%, Dy 5.37%, Er 3.17%, Lu 0.38%, and others 56.55%.

There are two types of REE minerals that are contained complex HREE and LREE. The HREE (yttrium group) consists of Y 28.65%, Gd 2.48%, Dy 8.22%, Er 4.29%, Yb 3.52%, and other elements 52.84%. The LREE (La-Ce group) consists of La 10.29%, Ce 10.21%, and also Nd 4.23%, Th 3.92%, F 18.43% and other elements of 52.93%.

A representative sample of metasomatic rocks (UD398) was analyzed using MLA. The sample crushed into 215 571 grains, then 258 477 times attacked by X-ray beam (Fig. 16), and mineral composition is shown in Table 3. The analysis showed a close relationship between xenotime and zircon.

Analyzed rock sample consists of potassium feldspar (81.67%), muscovite (8.07%), quartz (4.2%) and goethite (1.9%). REE minerals are parisite-synchysite, xenotime (0.84%) and apatite. Zircon (0.86%) is almost the same amount of that for xenotime (0.84%).

Dykes at the Ulaan Del deposit entirely silicificated, albitized and microclinized. The main REE-bearing minerals are xenotime, parisite, synchysite, monazite, apatite and zircon. The complex HREE and LREE-bearing carbonate and phosphate minerals were identified. Xenotime and zircon are closely associated.

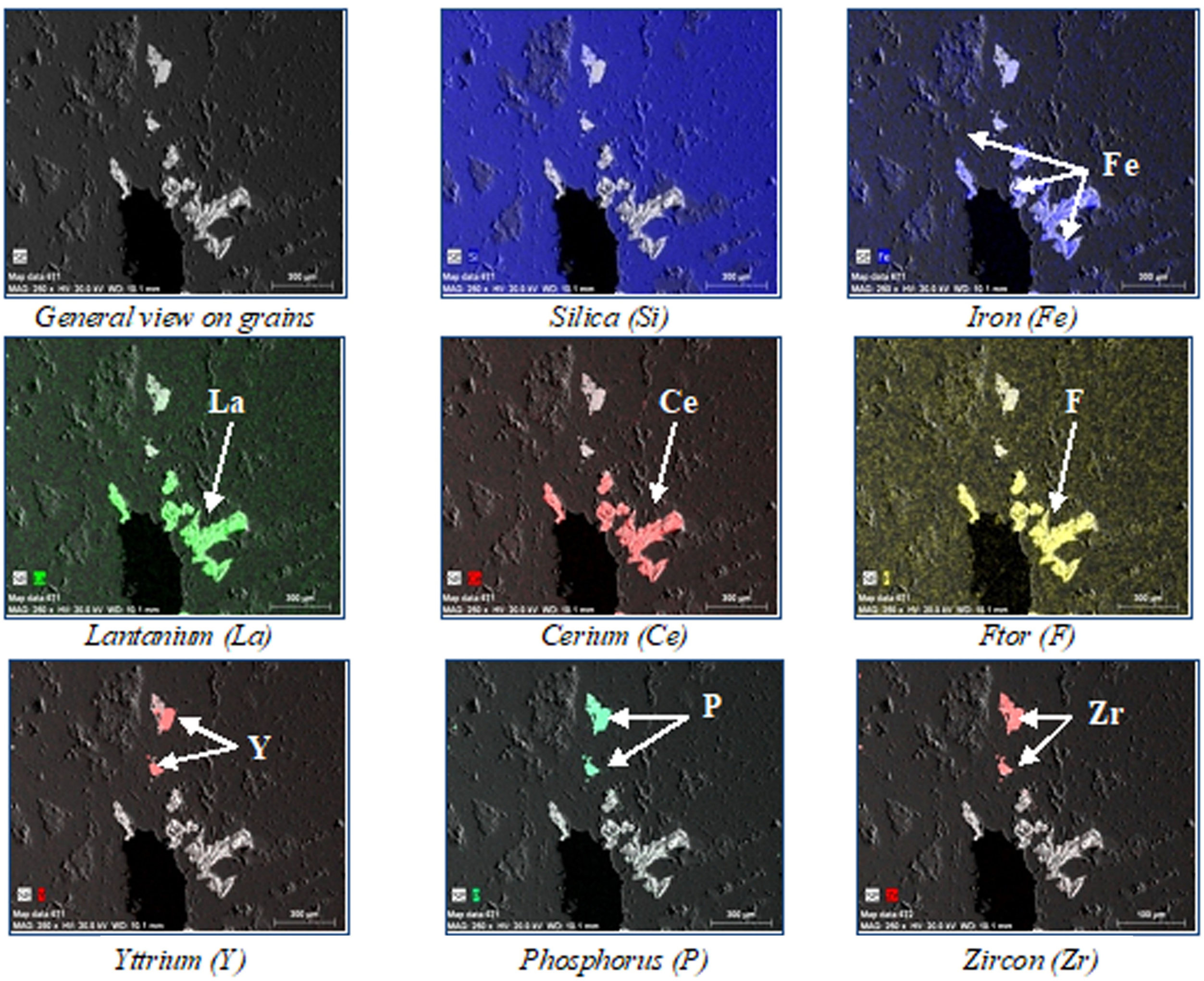

Fig. 15. REE distribution patterns in metasomatic rocks *(Zoom 250X)*

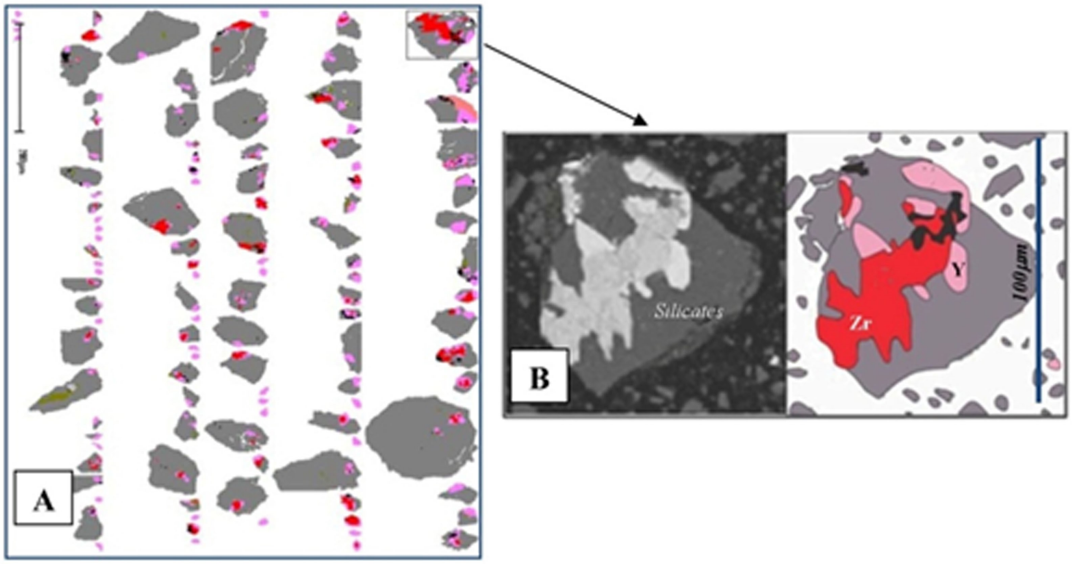

Fig. 16. Xenotime and zircon distribution, A. General view on grains attacked by X-ray beam, B.Xenotime (Y) and zircon (Zr)

Table 3. Mineral composition of selected rocks sample UD398

Mineral	Chemical composition	Vol, %	Number of grains	Density g/cm^3
Quartz	SiO_2	4.20	2105	2.65
Plagioclase	$NaAlSi_3O_8$ - $CaAl_2Si_2O_8$	0.06	142	2.62-2.76
Potassium feldspar	(KAlSi3O8)	81.67	170777	2.54-2.75
Muscovite	$KAl_2[AlSi_3O_{10}]$ $[OH]_2$	8.07	19125	2.76-3.1
Biotite	$K(Mg,Fe^{2+})_3(Si_3Al)O_{10}(OH,F)_2$	0.02	120	2.7-3.3
Chlorite	$Mg_3Si_4O_{10}$ $(OH)_2$ • $Mg_3(OH)_6$	0.66	8219	2.6-3.3
Zircon	Zr $[SiO_4]$ ZrO_2— 67,1; SiO_2—32,9	0.86	1861	4.68-4.71
Parisite	Ca (Ce,La) $(CO_3)_3F_2$: CaO - 3-10; Ce_2O_3- 22-31; La_2O_3- 27,3-33,1; CO_3 - 22,9 - 24,6; F- 6 - 7.	0.06	141	4.36
Xenotime	$Y[PO_4]$, xenotime group of minerals YVO_4 –Ce	0.84	2551	4.8
Apatite	$Ca_{10}(PO_4)_6(OH,F,Cl)_2$ (CaO): 53-56 %; P_2O_5: 41 %	0.03	62	3.2-3.4
Calcite	$CaCO_3$	0.05	140	2.71
Fluorite	CaF_2. Yttrium and cerium presented	0.05	88	3.18 Y, If Ce present-ed 3.3-3.6
Chalcopy-rite	$CuFeS_2$	0.06	39	4.3
Sphalerite	ZnS, Fe up to 26%	0.00	2	4.08-4.1
Pyrite	FeS_2	0.03	27	4.9-5.2
Psylomelan	$mMnO{\cdot}MnO_2{\cdot}nH_2O$	0.03	41	4.0-4.7
Ferrum oxides		0.25	238	
Chromite	$FeCr_2O_4$	0.33	603	4.5-4.8
Goethite	a-FeOOH	1.93	4799	
Iron		0.34	305	
Unclassified		0.45	4186	
Total		100.00	215571	

DISCUSSION

The genesis of REE-bearing rocks in the Ulaan Del area

The results of the petrographical, geochemical, and mineralogical investigations show that the REE mineralization bearing rocks of the Ulaan Del deposit is metasomatically altered syenite and syenite porphyries of the Khalzan Complex. There is a tendency that REE-bearing quartz-albite metasomatism was generated "selectively". It means that metasomatic alteration has not developed in all rock types in the area. Primarily, it was affecting only syenitic rocks in the outer contact zones.

There are many hypotheses on syenite genesis like partial melting of the metasomatic altered mantle (Lynch et al., 1993; Platt, 1996), alkali and alkaline basaltic magma differentiation (Thorpe and Tindle, 1992; Civetta et al., 1998; Ronga et al., 2010), melting of floor basalts (Sisson et al., 2005; Bonin, 2007; Jahn et al., 2009), and magma mixing with crusts (Marks and Markl, 2001).

The Togtokhiinshil Complex rocks are formed from depleted LIL and HFS sources. Therefore, it has no relation to the REE mineralization. However, it has noted that the Togtokhiinshil Complex includes an alkaline gabbro. Another proposition is that syenitic rocks may have generated from a primary enriched magma source and REE enrichment was due to subsequent metasomatism.

Origin of mineralization

The genesis of HFSE and REE mineralization associated with the peralkaline rocks is not well understood whether the mineralization is magmatic, hydrothermal, or a combination of the two (Dostal, 2016). The extensive fractional crystallization played a significant role for rare metal enrichment.

However, the mineralization is typically associated with altered alkaline intrusions and the enrichment is related to hydrothermal activities. Volatiles played an important role in the evolution of highly evolved peralkaline rocks. The parent melts of the peralkaline rocks were generated under relatively dry and reduced conditions when these magmas undergo extensive fractionation accompanied by aqueous fluids in very late crystallization history (Dostal, 2016). At these advanced stages of fractionation, the aqueous fluids escape from a magma highly enriched in incompatible elements such as REE, HFSE, Th and U containing significant amounts of halogens, particularly fluorine (Dostal, 2016). Thus the hydrothermal fluids, which are enriched in all these elements, can play an important role in concentrating HFSE, REE, Th, and U as well as during autometasomatism. It appears that both magmatic and hydrothermal processes are likely to have contributed to the formation of the rare metal deposits of peralkaline rocks.

The deposits related to layered silica-undersaturated syenite complexes display various indications of crystal accumulation associated with layers rich in REE-bearing minerals (Ilimaussaq Complex). On the other hand, in pegmatites like at Strange Lake, intrusions at Khalzan Buregtei, and felsic dikes at Bokan Mountain, there are no obvious indications of crystal accumulation. The primary magmatic mineralization is probably related to the crystallization of highly fractionated, late-stage, fluorine-rich peralkaline magma in pegmatites, minor intrusions, and dikes. At the Bokan Mountain deposit the mineralization is associated with altered zones and composed of secondary minerals, which pseudomorphically replaced primary minerals. The secondary hydrothermal processes played an important role.

All these deposits typically show imprints of hydrothermal processes that led to the remobilization of REE, HFSE, U, and Th and their redeposition in the nearby mineralized sites as secondary phases. The secondary processes not only redistributed but also enriched REE in the mineralized zones. During remobilization, LREE moved greater distances than HREE inferred that the remobilization took place at low temperatures (<350°C).

The metasomatism at the Ulaan Del area expressed in albititization of syenite and microsyenite (trachyte, trachyrhyolite). The albititized rocks have elevated by REE mineralization.

Magmatic- metasomatic -hydrothermal processes played significant role in formation of REE mineralization at the Ulaan Del deposit

The Ulaan Del REE deposit is located within the Lake Zone, where the well-studied Khalzan Buregtei Nb-ZR-REE deposit is also located. The genesis and ore formation of both Ulaan Del and Khalzan Buregtei deposits may be similar, regarding their spatial and close locality and the Zr-REE mineralization type.

According to the research works conducted at the Khalzan Buregtei deposit, enrichment in Zr, Hf, Nb, Ta, REE, Y-HFSE was related to both magmatic and hydrothermal processes (Kempe et al., 2014). But, the magmatic and hydrothermal processes developed during different and distinct events. Several distinct hydrothermal processes resulted in the formation of heterogeneous metasomatic rocks strongly enriched in HFSE. For example, a fluid, rich in carbonate and silica caused the development of Zr, Nb, and LREE rich ores in calcite-bearing alteration assemblages (Kempe et al., 1995, 1996, 1997, 1999 and 2014). Late alteration by F-rich fluids resulted in some remobilization of HFSE and significant local enrichments of HREE and Y in the ores. The interplay of all processes resulted in the formation of a complex, economic Zr-Nb-REE mineralization at the Khalzan Buregtei (Kempe et al., 2014).

Petrographical, mineralogical and geochemical data and a comparison with the Khalzan Buregtei deposit suggested that Zr-Nb-REE mineralization of the Ulaan Del deposit may have been related to magmatic-metasomatic-hydrothermal processes during multiple events of alkaline magmatism.

CONCLUSION

REE-bearing dykes at the Ulaan Del deposit are silicified and albititized syenite and microsyenite (trachyte, trachyrhyolite).

Geochemically the dykes of the Khalzan Complex are presenting calc-alkaline high-K to shoshonite series, with ASI 0.6-1.1, related to A -type rocks formed within plate setting. Syenitic rocks are REE enriched and contain HREE and LREE mineralization.

REE ore bearing minerals at the Ulaan Del deposit are zircon, apatite, sphene, monazite, xenotime, synchysite, parisite, fluorite, REE complex minerals and also pyrite, rutile and limonite. REE grades are not even but with constant >0.19% Zr and REE >0.1%.

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