Contents

1. Preface

The development of the Kola Peninsula took start with the study of the Lovozero and Khibiny massifs at the end of the XIX century. At the same time, the Lovozero complex is still attractive for no mere domestic, but also foreign geologists of different specialization.

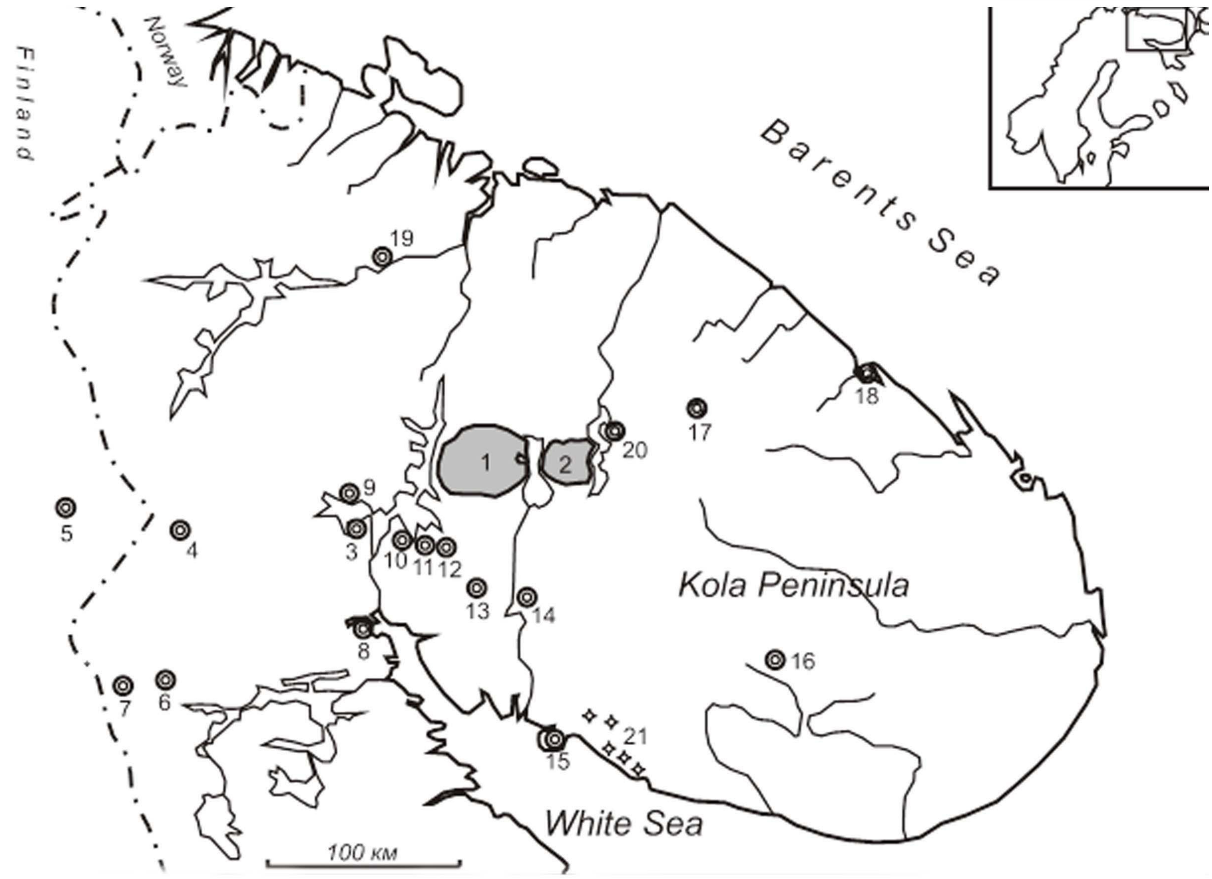

Fig. 1. Locations of the alkaline Palaeozoic complexes in the Kola Peninsula. After Arzamastsev et al. [2002]: 1 – Khibiny, 2 – Lovozero, 3 – Niva, 4 – Kovdor, 5 – Sokli, 6 – Vuoriyarvi, 7 – Sallanlatva, 8 – Kandaguba, 9 – Mavraguba, 10 – Afrikanda, 11 – Ozernaya Varaka, 12 – Lesnaya Varaka, 13 – Salmagora, 14 – Ingozero, 15 – Turiy Mys, 16 – Pesochny, 17 – Kontozero, 18 – Ivanovka, 19 – Seblyavr, 20 – Kurga.

Currently, unique and world-biggest deposits of loparite (tantalum, niobium, REE) and eudialyte (zirconium, REE) ores have been explored. However, more than one century of continuous study leaves much questions (mainly, those regarding petrogenesis) to be answered.

2. Geological setting and structure of the Lovozero complex

The Kola alkaline Province (Fig. 1) on the eastern part of the Baltic Shield includes the world-largest complexes of agpaitic feldspathoid syenites, numerous intrusions of alkaline ultramafics and carbonatites (about 20) and dyke swarms of alkaline and melilite picrites, nephelinites, kimberlites and carbonatites. Several thousand cubic kilometers of peralkaline and mafic magmas were emplaced during the Devonian.

The Lovozero (650 km^2) and Khibiny (1327 km^2) superlarge complexes of agpaitic feldspathoid syenites are located in the central part of the Kola Peninsula. They are extremely rich in volatiles (F, Cl, S) and incompatible trace elements (REE, Nb, Ta, Zr, Hf, Th, U, Sr, Ba).

The Lovozero complex lies within a NW-striking tectonic zone in which a sunken, EW-trending belt of Palaeozoic rocks has been preserved.

Peralkaline magmas are emplaced in the Archaean granite gneisses. The roof of the intrusion consists of the Lovozero Effusive Formation (picrites, trachytes, phonolites and their tuffs) of the Middle Palaeozoic age. Rocks of the Lovozero Formation occur as xenoliths within the nepheline syenites of the massif.

The intrusion (Fig. 2) has the form of a lopolith (almost rectangular with rounded angles in plane) with a broad base (Gerasimovsky et al. 1966). Geophysical data demonstrate that the gigantic magma chamber is trough shaped with a feeding channel situated in the south-western part of the intrusion (Arzamastsev et al. 1998). Geophysical work also indicates that the alkaline rocks continue to the depth of more than 20 km with no apparent lower limit (Arzamastsev et al. 1998). Rb-Sr whole rock and mineral isochrones give ages of 370.4±6.7 Ma for Lovozero and 367.5±5.5 Ma for Khibiny (Kramm and Kogarko 1994).

3. Sequence of intrusions

Eliseev and Fedorov (1953), Gerasimovsky et al. (1966), Kogarko et al. (1995) and some others investigators describe the Lovozero complex as four intrusive phases (Table 1). Rocks of Phase I comprise about 5% of the total volume; they may, however, increase in volume with depth. Phase II forms the main portion with 77% in volume and phase III amounts to about 18%. Rare dykes of phase IV are volumetrically insignificant (0.01%). Based on geological and geophysical observations, Arzamastsev et al. (1998) suggested that about 25 vol % of ultrabasic alkaline magma intruded before the first manifestation of nepheline syenites (Fig. 3).

3.1. Phase I

Phase I consists of evenly grained nepheline syenites, nepheline-nosean syenites, poikilitic nosean syenites and metamorphosed nepheline syenites. Abundant Phase I xenoliths are found throughout the complex in the later phases. The main minerals

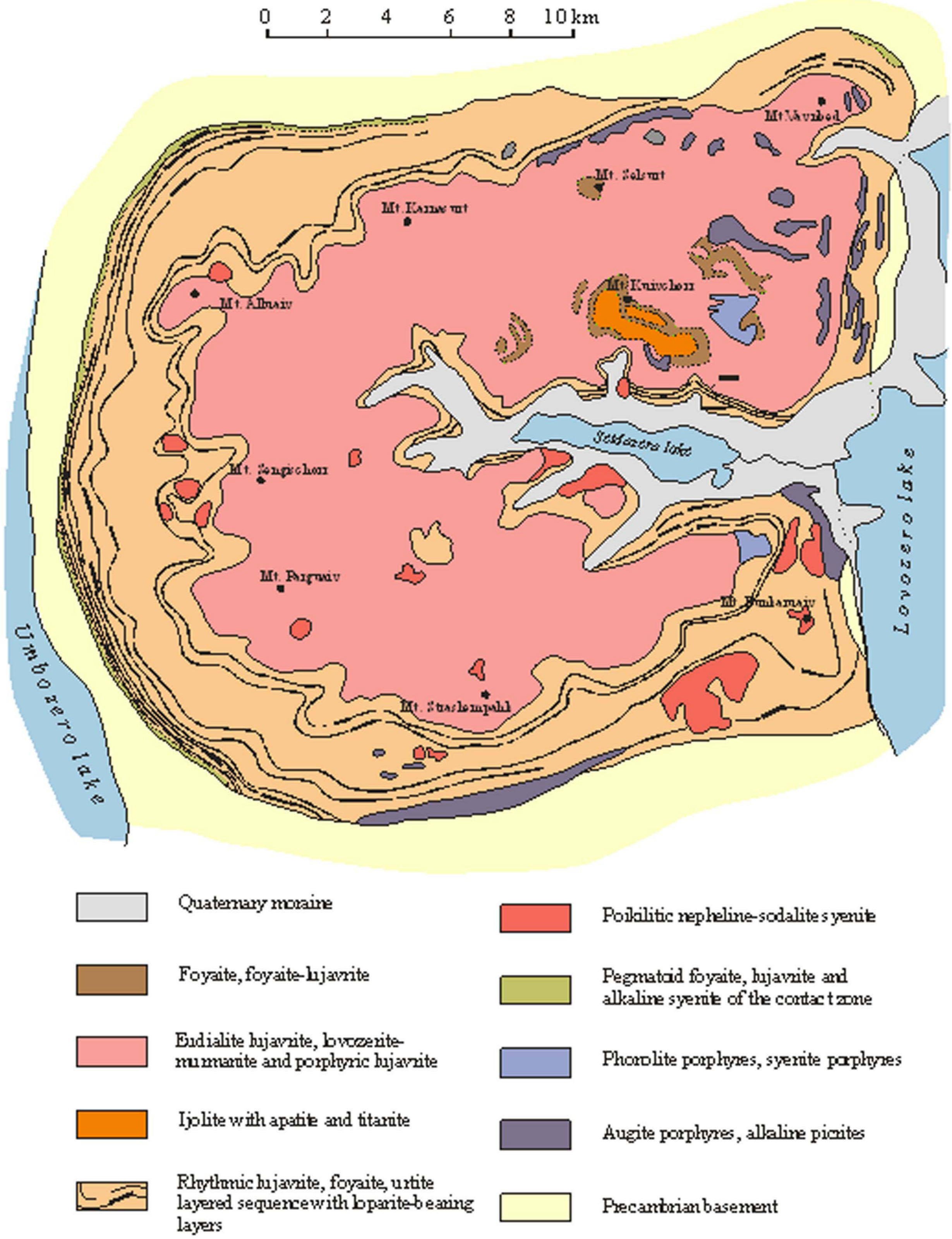

Fig. 2. Geological map of the Lovozero massif generalized from V.I. Gerasimovsky et al., 1966, I.V. Bussen and A.S. Sakharov (1972).

are K-Na feldspar, nepheline, nosean, aegirine-diopside and magnesioriebeckite with biotite, zircon, ilmenite, titanite, apatite and mosandrite group minerals as accessory phases.

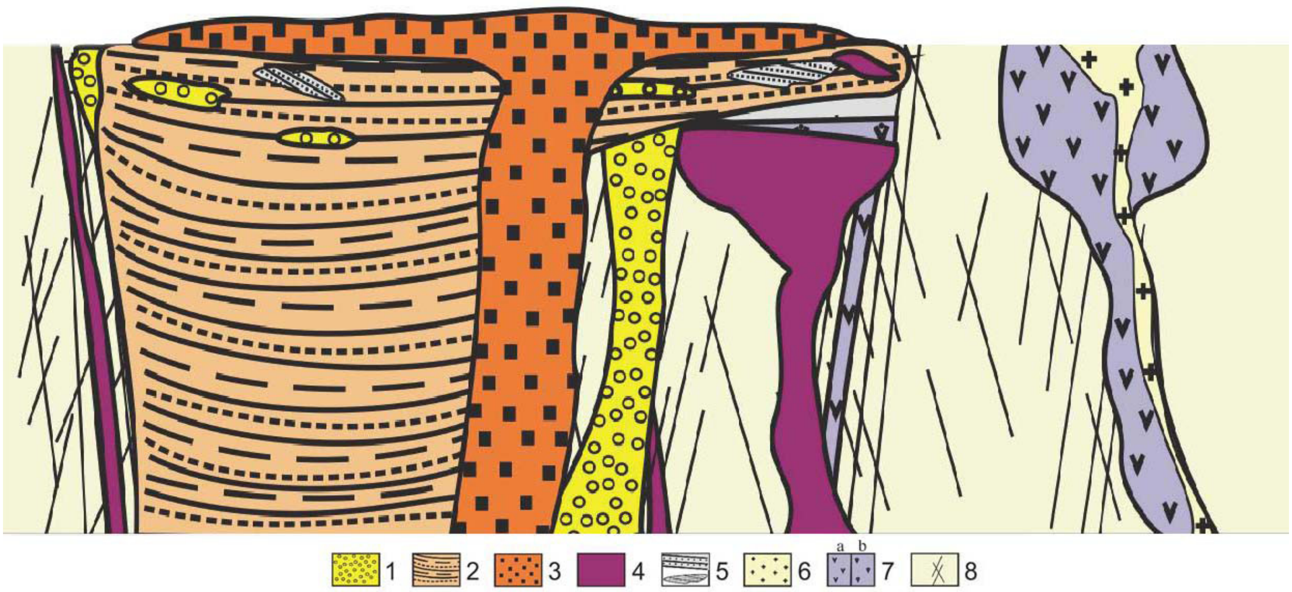

Fig. 3. Hypothetic scheme of formation of the Lovozero massif: 1 – Phase I: evenly grained nepheline syenites, poikilitic sodalite syenite and others; 2 – Phase II: The Differentiated Complex (loparite-bearing lujavrite-foyaite-urtite); 3 – Phase III: The Eudialyte Complex (eudialite lujavrite); 4 – hypothetic alkaline ultrabasic rocks; 5 – The Lovozero effusive Formation. Kurga massif: 6 – alkaline syenites, 7 – ultrabasic alkaline rocks (a – peridotite, b – pyroxenite), 8 – dykes of olivine melanephelinite and picrite.

3.2 Phase II. The Differentiated Complex

The Layered Series of phase II is a well differentiated with a rhythmic and macrorhyth-mic layering. It is also referred to as the "Differentiated Complex". The main rock-forming minerals are nepheline, KNa feldspar, aegirine and amphibole.

Four divisions ("zones") are distinguished with the lowermost division consisting mostly of alternate foyaite and lujavrite layers, intermediate in composition between agpaitic and miaskitic, and rarely of juvites. The accessory mineral assemblage is miaskitic and comprises zircon, Mn-ilmenite, apatite, titanomagnetite, titanite, minerals of the mosandrite group and rarely anhedral loparite.

The overlaying division (Fig. 4) (the so-called Lower zone of The Differentiated Complex) mostly consists of two- and threefold units of foyaite-lujavrite and juvite-foyaite-lujavrite (from bottom to the roof). The accessory minerals, both miaskitic and agpaitic, are ilmenite, titanite, parakeldyshite, loparite, eudialyte, sodalite and rarely members of the mosandrite group.

The next division (The Middle zone of The Differentiated Complex) is a weakly layered sequence of melano-, meso- and leucocratic aegirine/or amphibole-lujavrites and rare urtites and foyaites. The accessory minerals are eudialyte, titanite, lamprophyllite, murmanite-lomonosovite group, apatite and loparite.

The uppermost division (the Upper zone) consists of twofold (from bottom to the roof – foyaite-lujavrite and urtite-foyaite sequences) and threefold (urtite-foyaite-lujavrite) macrorhythmic units. The accessory paragenesis is very agpaitic and is represented by eudialyte, loparite, lamprophyllite, minerals of murmanite-lomonosovite group, villiaumite and sodalite. Euhedral loparite (Fig. 2a) occurs throughout the

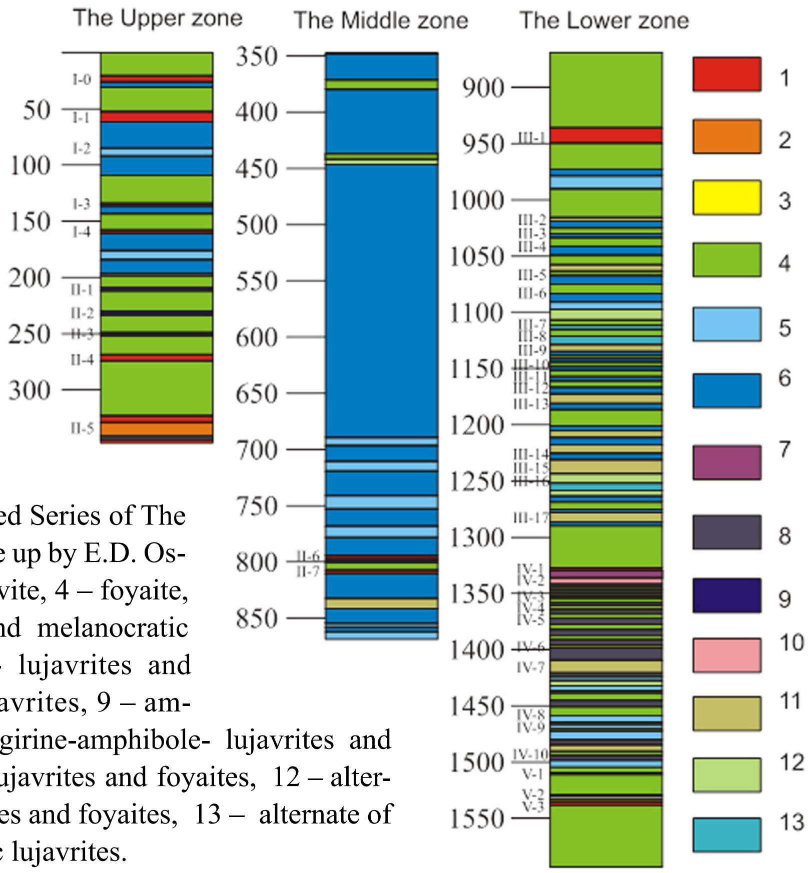

Fig. 4. Stratigraphy scale of The Layered Series of The Differentiated Complex (Phase II) made up by E.D. Osokin. 1 – urtite, 2 – ijolite-urtite, 3 – juvite, 4 – foyaite, 5 – leucocratic lujavrite, 6 – meso- and melanocratic lujavrite, 7 – alternate of amphibole- lujavrites and foyaites, 8 – aegirine-amphibole- lujavrites, 9 – amphibole-lujavrites, 10 – alternate of aegirine-amphibole- lujavrites and foyaites, 11 – alternate of leucocratic lujavrites and foyaites, 12 – alternate of meso- and melanocratic lujavrites and foyaites, 13 – alternate of leucocratic and meso- and melanocratic lujavrites.

Differentiated Complex except lowermost zone and is concentrated in seams and in ore layers, where it accumulates up to 5%.

3.3. Phase III. The Eudialyte Complex

Phase III (also known as The Eudialyte Complex) forms the summits of the mountains. It is 450 m thick in the northwest and diminishes southeastwards because of erosion. It consists of a suite of eudialyte lujavrites, eudialyte foyaites and urtites which cut and overlie the upper part of the rocks of Phase II. The lower part is more leucocratic, the upper part more melanocratic and a coarser layering is developed than in Phase II. The contact plane dips towards the centre of the complex with an angle increasing from the margins towards the centre. It is marked with bodies of porphyritic lujavrite, which are considered to be quenched rocks of Phase III. Poikilitic sodalite syenite and tawite (sodalite with some aegirine and minor nepheline, alkali feldspar and eudialyte) are found as equidimensional, sharply defined bodies within the eudialyte lujavrites. Titanite and Ca-rich amphibole are enriched in eudialyte lujavrites in the contact zone with xenoliths of the Lovozero effusive Formation. Eudialytite seams and lens like bodies are common in the upper part of Phase III. They are in places almost monomineralic with 50-85% eudialyte (with 8-10% of ZrO_2).

Up to several kilometers long dykes of porphyritic lujavrite, cut Phases I, II and III. These are rich in rare minerals like lovozerite and murmanite. The main rock-forming minerals of Phase III are nepheline, microcline, aegirine, eudialyte, lamprophyllite and arfvedsonite. Eudialyte is euhedral, (Fig. 2c) which is the principal difference to the lujavrites of Phase II. The common accessory minerals are lomonosovite-murmanite, loparite, lovozerite, pyrochlore and sodalite. The alkalinity increases in the Eudialyte Complex, the average agpaiticy index is 1.50.

3.4. Phase IV

Phase IV consists of rare dykes of alkaline lamprophyres (monchiquite, fourchite, tinguaite, etc.) which cut all the other alkaline rocks and the surrounding granite gneisses.

Loparite – the main ore mineral for niobium, tantalum and REE – has been mined for many years. Mining of eudialyte – the valuable source for zirconium and hafnium – has not commenced yet.

4. Excursion to the Raslaka 1 Cirque

The Lovozero Differentiated Complex is an excellent example of one of many well-investigated layered intrusion (such as Bushveld in South Africa, Skaergaard and intrusions of the Gardar Province in Greenland, Duluth and Stillwater in USA, Rum in GB). The whole known section of The Differentiated Complex is occupied by a layered serried (Fig. 4) with macrorhythmic layering in the upper division (zone), rhythmic and macrorythmic layering in the lower division (zone) and almost non-rhythmic and

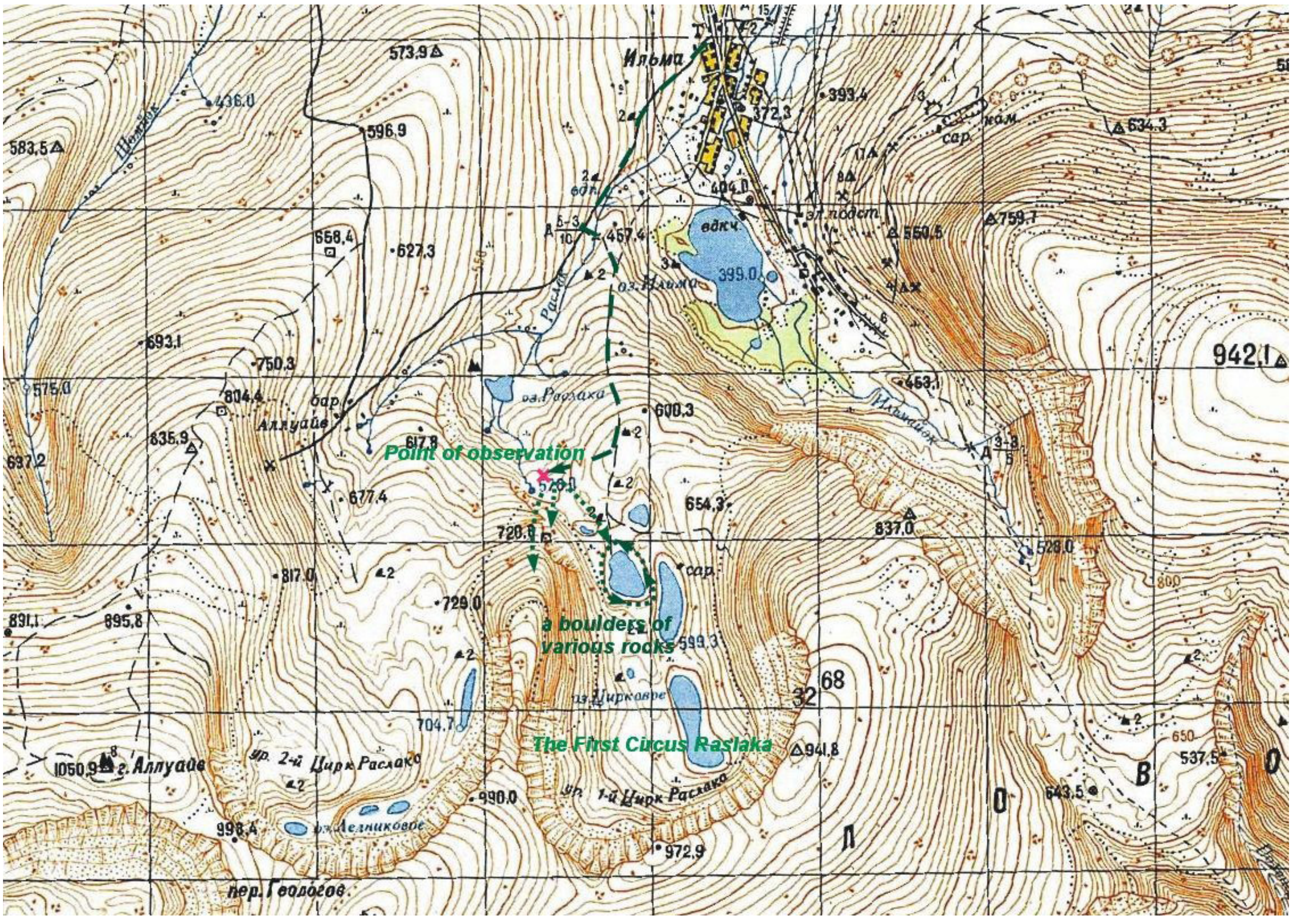

Fig. 5. Topological map of the observation pit setting. The Raslaka 1 Cirque is in the centre.

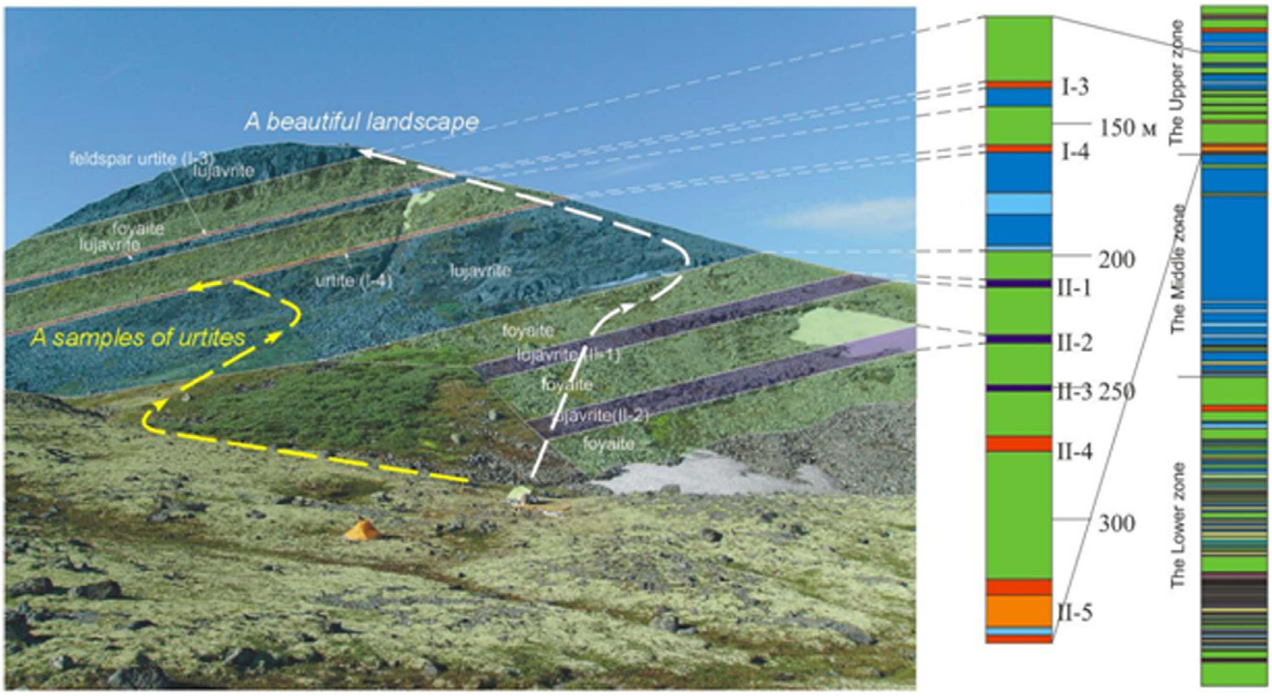

Fig. 6. Exposure of macrorhythmic layering of The Differentiated Complex on the western mountain-side of the Circus Raslaka 1.

monotonous middle division (zone). The rhythmic units of The Differentiated Complex are unique with the sequence of cumulate minerals composing them. The formation of these units cannot be explained only by gravity separation differentiation because of they have a inversion by gravity of main cumulus minerals (nepheline – 2.59 g/cm^3, K-Na feldspar – 2.59 g/cm^3, aegirine – 3.52 g/cm^3).

Point of observation: source of the Raslak brook. Position data: true altitude 605 m, N 67°52’43.3” E 34°34’41.1” (system WGS 84) (Fig. 5).

In this side we can observe the eastern slope of the Raslaka 1 Cirque, where The Upper Division of The Layered Series is partly exposed. Terraces cut the slope (Fig. 6). The rocks rich in nepheline (urtite – nepheline cumulate) have low resistance to weathering and depressions correspond with them. Foyaites (feldspar-nepheline cumulate) have better resistance to weathering. Lujavrites (feldspar-aegirine-nepheline cumulate) are best-resistant to weathering. Mainly, cliffs on the slope correspond with them.

Here, along the slope, four horizons of loparite ores occur. One of these (I-4) has been mined on the Karnasurta mine located 2 kilometers northeastwards from this observation pit. Horizons II-1 and II-2 correspond with the contacts of amphibole lujavrites with overlaying foyaites. These are examples twofold (deficient) rhythmic units. Other two horizons (I-3 and I-4) correspond with the lower part of the threefold (complete) rhythmic units, including urtite layers.

Urtites and foyaites have massive structure. Trachytoid structure (igneous lamination) of lujavrites and upper parts of foyaites is due to plane-parallel orientation of K-Na feldspar laths and needle-shaped aegirine.

Relations of rock-forming urtite minerals vary greatly and may include sodalite, zeolites, alkali amphiboles. The common mineral composition of urtite is to follow: K-Na feldspar – 5-10 %, nepheline (sometimes together with sodalite and zeolites) – 75-97%, aegirine – 5-15 %. Maximum concentrations of loparite in ore horizons are interrelated with urtites. For foyaites rock-forming minerals are K-Na feldspar – 60-75 %, nepheline – 15-25 %, aegirine – 10-15 %. Secondary minerals are albite, sodalite and zeolites. Lujavrites are more abundant type rocks. Their mineral composition is K-Na feldspar – 60-70 %, nepheline – 15-20 %, aegirine – 20-35 %.

The angle of igneous lamination dipping approximately agrees with the angle of rocks dipping (according to I.V. Bussen and A.S. Saharov (1972) there are minor differences between these angles of dipping) and they are 10-15 ° (in the point of observation they are about 10 °) towards the central part of the massif.

Now we may climb up the slope and observe urtite of horizon I-4 and other rocks. Also we may go upper to the mountain and observe the view. Then we may go to the lake in 500 meters from here and observe very interesting relations of local rocks in boulders.

5. Beautiful minerals to be found

The Lovozero complex is known to be rich in rare and picturesque minerals in natural outcrops and open pits, e.g. *eudialite*, *aegirine*, *murmanite*, *ussingite*, *elpidite*, *lamprophillite*, *lorenzenite*, *zircon*.