

# URANIUM DEPOSIT IN THE SAIMA ALKALINE MASSIF, NORTHEAST CHINA

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## ABSTRACT

The Saima uranium deposit consists of three main types of mineralization: (1) Rinkite type in grass-green-aegirine nepheline syenite, a large composite mineralization of U, Th, TR, and Nb, formed at the final stage of crystallization of residual magma when volatile components began to play an important role; (2) uranpyrochlore-betafite in alkaline skarns; and (3) pitchblende in intensively hydrothermally altered alkaline rocks with the ore containing 0.05—0.15% U. The principal factors for the formation of various types of mineralization in the Saima uranium deposit are the thorough differentiation of alkaline magma (evolving gradually from highly potassic into highly sodic) and the prolonged evolution of the post-magmatic solution. The particular geotectonic setting of the massif, the mechanism of tectonic movement, and the calcareous country rocks of the massif are also the conditions favourable for the formation of the deposit. Based on the knowledge of the general laws governing the localization of uranium mineralization in the Saima deposit, prospecting guides for finding similar deposits are presented. The discovery of the Saima uranium deposit further proves that nepheline syenite is prospective for uranium mineralization and that it is a notable object worthy of prospecting for uranium deposits.

The problem of uranium occurrence and its economic potential in alkaline rocks have attracted the attention of the uranium geological circle in recent years. So far as we know from the information available, before the end of 1950's there had been a traditional concept that alkaline rocks especially those of sodium-rich nepheline syenites were poor in uranium and rich in thorium, so exploration for uranium deposit in them was regarded as less hopeful. Up to the late 1950's there had several reports on uranium mineralization in these rocks, such as those made by Danish geologists on uranium occurrence in Greenland's nepheline syenites. At that time, however, some people still remained doubtful about the possibility of finding any valuable uranium deposits in alkaline rock province, because such uranium mineralizations were of low grade and their economic importance was not yet ascertained.

"The history of mankind is one of continuous development from the realm of necessity to the realm of freedom." People's cognizance of uranium deposits has continuously developed and abounded through plenty of uranium exploration practice since 1960's. Abandoning the traditional viewpoints, the Chinese workers and geologists who are engaged in the work of uranium geology in accordance with the principle of "independence and self-reliance" have carried out geological investigations in various ways. As early as the late 1950's geological surveys and

radiometric work were systematically made in alkaline rock province, many radioactive anomalies and occurrences were successively found, and a large uranium deposit occurring in the massif was successfully explored. The ore contains 0.05—0.15% U, and the associated Th, TR, Nb may be synthetically recovered. In order to carry out in a better way the exploration and further prospecting in the vicinity of the deposit, a research group, organized jointly by the exploration departments concerned and the Peking Institute of Uranium Geology, has conducted a systematic investigation on the massif and the deposit. The present paper is a part of the research results of the group.

## I. REGIONAL GEOLOGY AND MASSIF GEOLOGY

The uranium deposit in Northeast China is located at the conjunction part between Tianshan-Yinshan latitudinal tectonic system and the second uplifted zone of the NNE trending Neocathaysian tectonic system. Proterozoic metamorphic rocks, Sinian epimetamorphic rocks, Cambrian limestone and slate, Jurassic pyroclastic rocks and coal series are exposed in this area (Fig. 1). In the northern and southern

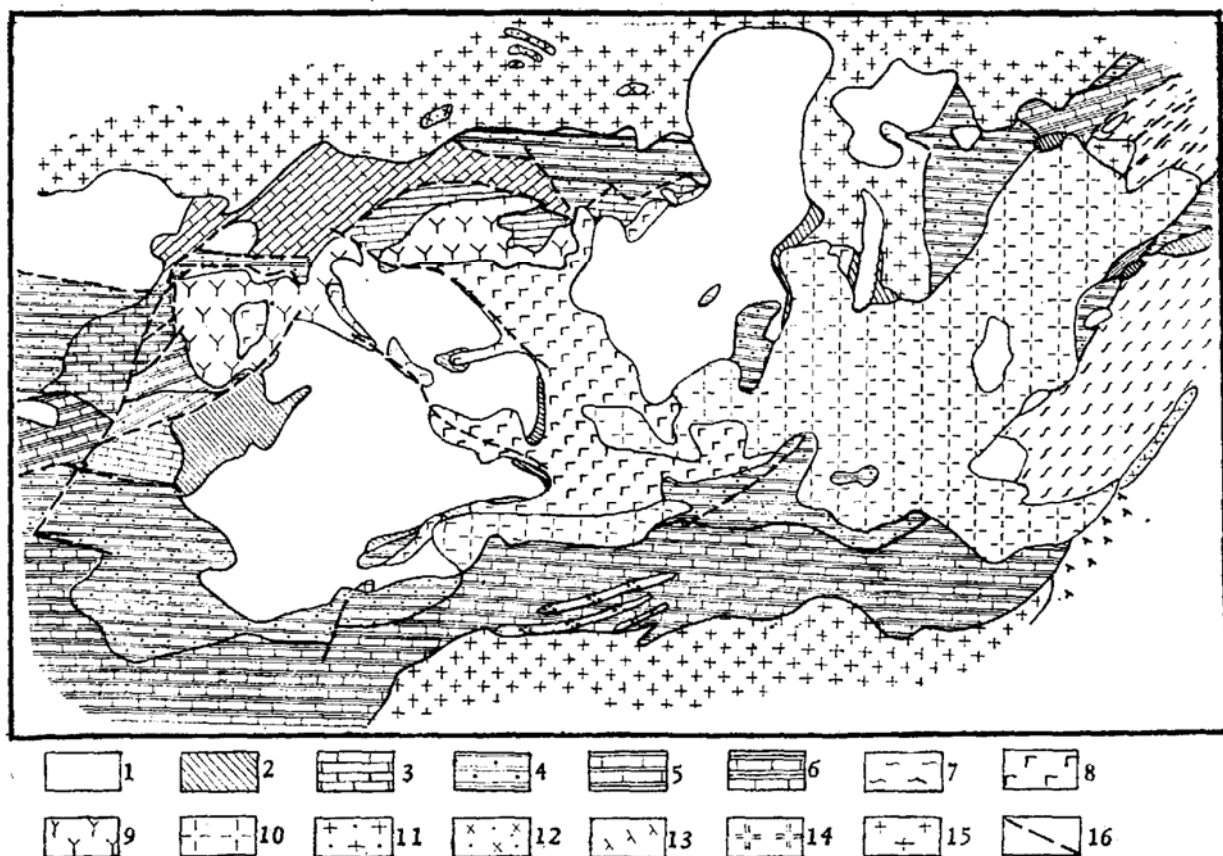


Fig. 1. Geological sketch map of the region.

- (1) Jurassic beds; (2) Peimiao Member (Lower Jurassic?); (3) Cambrian limestone; (4) Sinian quartzite; (5) Pre-Sinian marble; (6) Pre-Sinian phyllite intercalated with marble; (7) Migmatite; (8) Alkaline eruptive rock; (9) Alkaline intrusive rock mainly with nepheline syenite; (10) Alkaline intrusive rock chiefly with alkali syenite; (11) Quartz-syenite; (12) Subalkali granite; (13) Acidic eruptive rock; (14) Pegmatite; (15) Granite; (16) Fractured structure.

parts there occur the Yenshan granites, and in the central part there is a nearly E-W trending alkaline rock complex composed of four alkaline intrusive bodies and a great number of alkaline volcanic and subvolcanic rocks, covering an area of about 200 km<sup>2</sup>. In the eastern part of this rock province, the alkaline rock is made up mainly of syenite and alkali syenite; in the central part, of trachyte, pseudo-leucite phonolite, and syenite-porphry; and in the western part, of various mica nepheline syenites and aegirine nepheline syenites. The uraniferous Saima alkaline massif is located in the westernmost part of the alkaline province.

The Saima massif intruded into the core of a brachy-anticline of nearly E-W trend composed of Proterozoic and Lower Palaeozoic strata. The alkaline rock measures about 20 km<sup>2</sup> on the surface, while its depth exceeds 1,000 m as judged from drilling. The country rocks to the northern, western, and southern parts of the massif are dolomitic marble of Liaoho Group (Proterozoic); to the southwestern part, phyllites of Liaoho Group; and to the northeastern part, Sinian quartzite and Cambrian limestone. The eastern part of the massif is covered by Jurassic conglomerate, sandstone, and coal series (Fig. 2). According to the isotopic dating from

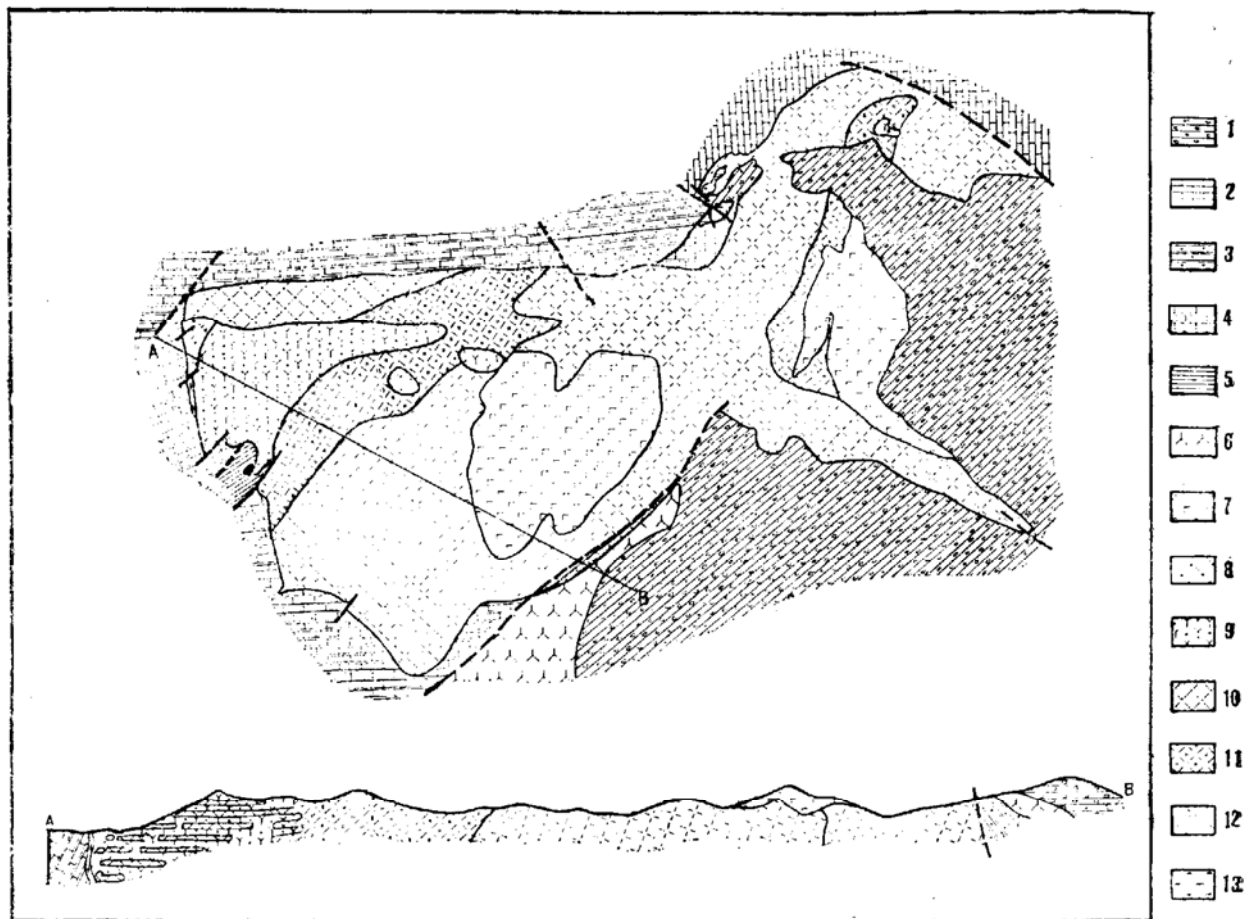


Fig. 2. Geological sketch map of the Saima alkaline massif.

(1) Jurassic conglomerate, sandstone; (2) Cambrian limestone; (3) Sinian quartzite; (4) Pre-Sinian Liaoho Group marble; (5) Pre-Sinian Liaoho Group phyllite; (6) Leucitophyre, pseudo-leucite phonolite, tuffaceous lava, tuff; (7) Phonolite, trachyte phonolite; (8) Grass-green-aegirine nepheline syenite; (9) Green-aegirine nepheline syenite; (10) Melanite mica nepheline syenite; (11) Black-aegirine nepheline syenite; (12) Mica aegirine nepheline syenite; (13) Arfvedsonite.

18 samples (including 7 different minerals) by both K-Ar and U-Th-Pb methods the ages given for rock-forming mineral (biotite) and accessory minerals (rinkite and eudialyte) vary from 240 to 220 m.y.; but for phlogopite formed in the stage of skarnization, 210–190 m.y.; for thorite and zircon formed in the hydrothermal stage, 190–170 m.y.; and for pitchblende, the latest product of hydrothermal process, only 130 m.y. These figures indicate that the formation of the massif underwent a very long process of development, the main body of which was formed in the late Hercynian movement, while the whole post-magmatic hydrothermal process persisted until the early Yenshanian Movement.

The Saima massif is composed of alkaline volcanic, intrusive and dyke rocks derived from cognate alkaline magma, with the intrusive rocks as the chief members. The main rock types, magmatic activity phases and facies are shown in Table 1.

Alkaline eruptive rocks are a suite of potassium-rich rocks mainly made up of leucitophyre and pseudo-leucite phonolite. They are present at the top and marginal part of the massif and formed prior to the intrusive rock which intruded and intersected eruptive rock. The rocks of the first intrusive phase constitute the bulk of the massif (exposed surface occupies 60% of the massif), and the main petrographic variety is the mica aegirine nepheline syenite which occurs in the central part of the massif and changes into black-aegirine nepheline syenite laterally. Owing to the assimilation of magma with the calcareous country rocks in the marginal part of the massif there often occur calcium- and magnesium-rich rocks (melanite mica aegirine syenite and mica nepheline syenite). In all these rocks, there exist nested and veined pegmatites in corresponding composition. Moreover, there occurs a kind of vein-like dark-green-aegirine nepheline syenite, which is the product of additional subphase of the first intrusive phase. The rocks of the second intrusive phase are a suite of sodium-rich aegirine nepheline syenite mainly distributed in the northwestern part of the massif. These rocks injected into the rocks of the first intrusive phase and contained a large number of its xenoliths and relics. The contact plane cuts the flow line of the first phase rocks. These rocks are generally a few scores and locally over 200 m thick. They can be divided into three petrographic varieties distinguished by the colour of aegirine. The grass-green-aegirine syenite occurring on the northwestern corner grades gradually into green-aegirine nepheline syenite towards the south-east, then both varieties change into eudialyte grass-green-aegirine nepheline syenite towards depths. Among them, the grass-green-aegirine nepheline syenite is the essential ore-bearing rock in the Saima massif, and its texture and structure vary greatly, from medium-fine-grained to pegmatoidal, but mainly coarse-grained and pegmatoidal (Photo 2). Its minerals are distributed unevenly. This rock is of gentle stratification as a result of magmatic differentiation in which the melanocratic zone rich in grass-green aegirine is interbedded with the leucocratic zone rich in feldspar and nepheline. The grass-green aegirine is rather peculiar in shape. It looks like a small needle (less than 0.05 mm wide), and often constitutes blanket-like, radiate-fibrous and irregular massive aggregates (Photo 1).

By comparing the chemical composition of the essential rock-forming minerals in rocks of the two intrusive phases (Table 2), it can be seen that the rock-forming

minerals of the second phase are characterized by relatively "purified" composition, that is to say, the molecular contents of diopside and hedenbergite (Di+Hd) in aegirine, those of albite (Ab) and anorthite (An) in alkali feldspar, and kalio-

Table 1

Main Rock Types, Phases, and Facies of the Saima Massif

|                |                             |                       |                                                                             |                                                                                                |  |
|----------------|-----------------------------|-----------------------|-----------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|--|
| Eruptive rock  | Eruptive facies             |                       |                                                                             | leucitophyre, pseudo-leucite phonolite, phonolite, trachy phonolite                            |  |
|                | Explosive facies            |                       |                                                                             | leucitophyre-tuff lava, tuff, tuff breccia                                                     |  |
| Intrusive rock | The first intrusive phase   | Marginal facies       | Assimilation series                                                         | melanite mica nepheline syenite                                                                |  |
|                |                             |                       |                                                                             | mica nepheline syenite                                                                         |  |
|                |                             | Inner facies          | Differentiation series                                                      | mica aegirine nepheline syenite                                                                |  |
|                |                             |                       |                                                                             | black-aegirine nepheline syenite                                                               |  |
|                | The second intrusive phase  | Residual magma facies |                                                                             | dark-green-aegirine nepheline syenite                                                          |  |
|                |                             |                       |                                                                             | green-aegirine nepheline syenite                                                               |  |
|                |                             |                       |                                                                             | eudialyte grass-green-aegirine nepheline syenite                                               |  |
|                |                             |                       |                                                                             | grass-green-aegirine nepheline syenite                                                         |  |
| Dyke rock      | Aplite                      |                       |                                                                             | syenite-aplite, nepheline syenite-aplite, syenite-porphyry                                     |  |
|                | Lamprophyre                 |                       |                                                                             | alkali lamprophyre (tinguaite)                                                                 |  |
| Metasomatite   | Contact metasomatite        | Skarn                 |                                                                             | calcareous skarn (tremolite, phlogopite-tremolite, phlogopite-diopsidite)                      |  |
|                |                             |                       |                                                                             | magnesian skarn (phlogopite, humite-phlogopite-spinel-forsterite skarn)                        |  |
|                |                             |                       |                                                                             | alkali skarn (arfvedsonite, phlogopite-arfvedsonite, nepheline-melanite-aegirine-augite skarn) |  |
|                |                             | Fenite                | phlogopite-aegirine-augite-albite-microcline fenite (derived from phyllite) |                                                                                                |  |
|                |                             |                       | quartz-phlogopite-microcline fenite (derived from quartzite)                |                                                                                                |  |
|                | Hydrothermally altered rock |                       |                                                                             | episyenite                                                                                     |  |
|                |                             |                       |                                                                             | aegirine episyenite                                                                            |  |

- a) Classification and nomenclature of nepheline syenites listed in the table are determined on the basis of the specificity of the Saima massif and the convenience for the practical work. The species, and characteristics of dark minerals serve as the main basis for classification and nomenclature, and traditional names of certain alkaline rocks, such as foyaite, lujavrite are not adopted.

**Table 2**  
Correlation of Chemical Composition of Main Rock-forming Minerals of the Two Intrusive Phases

| Mineral Composition        | Aegirine                  |           |              | Alkali Feldspar           |           |           |           |        |        |                 | Nepheline      |                           |           |
|----------------------------|---------------------------|-----------|--------------|---------------------------|-----------|-----------|-----------|--------|--------|-----------------|----------------|---------------------------|-----------|
|                            | Samples analysed in total | Ac mol. % | Di+Hd mol. % | Samples analysed in total | Or mol. % | Ab mol. % | An mol. % | Rb ppm | Cs ppm | K/Na mol. ratio | K/Rb wt. ratio | Samples analysed in total | Ne mol. % |
| The first intrusive phase  | 7                         | 77        | 23           | 10                        | 88.1      | 9.6       | 2.3       | 183    | 0.7    | 9               | 645            | 4                         | 74.8      |
| The second intrusive phase | 5                         | 91        | 9            | 14                        | 93.0      | 6.1       | 0.8       | 391    | 1.3    | 16              | 332            | 6                         | 77.7      |
|                            |                           |           |              |                           |           |           |           |        |        |                 |                |                           | Kp mol. % |
|                            |                           |           |              |                           |           |           |           |        |        |                 |                |                           | 25.2      |
|                            |                           |           |              |                           |           |           |           |        |        |                 |                |                           | 22.3      |

a) Aegirine composition is converted by using the data given by the total chemical analysis for monomineral fraction.

b) Feldspar and nepheline composition are converted by using the contents of K, Na, Ca determined by atomic absorption spectroscopy, and the contents of Rb and Cs are determined by using neutron activation method.

phillite (Kp) in nepheline are correspondingly lower than those of the first phase, but the contents of rubidium and cesium in feldspar are apparently higher. Generally speaking, it shows a comparatively lower temperature for forming rocks of the second intrusive phase. By referring to the correlation curve of potassium-sodium distribution in associated feldspar and nepheline with temperature presented by L.A. Berchuk (1967), it is concluded that the approximate temperature for forming rocks of the first phase of intrusion is about  $600^{\circ}$ — $630^{\circ}$ , whereas that for the second phase is about  $430^{\circ}$ — $460^{\circ}$ , the latter being about  $100^{\circ}$  higher than the critical temperature. This is very important for us to interpret the conditions under which the Saima deposit was formed.

Contact metasomatism in the Saima massif develops extensively. When the alkaline rock contacts with phyllite and quartzite, intensive fenitization often takes place, and rocks in the exomorphic zone is remodelled into various fenites composed of alkaline minerals. When the alkaline rock contacts with dolomitic marble and limestone, intensive skarnization often takes place. Skarn formed in the early stage is a suite of magnesian and calcareous-magnesian one (humite-spinel-forsterite skarn, phlogopite-tremolite skarn, etc.) The later skarns are rocks mainly of arfvedsonite and magnesian-arfvedsonite (Photo 3), and they commonly contain microcline and nepheline and are called alkaline skarn. Skarn, especially alkaline skarn is one of the important ore-bearing rocks in the Saima deposit.

A complete rock suite of hydrothermal alteration develops in the massif, from hypothermal microclinization, nephelinization to meso-epithermal abtization, natrolitization, cancrinitization, analcitization, hydromicazation, chloritization, silicification, carbonatization, fluoritization and hydrogoethitization, etc. These alterations develop predominantly along the fractures of late stage and in both endomorphic and exomorphic zones of the massif, and the most intensive alteration occurs especially in its western part. Through the meso-epithermal alteration various primary nepheline syenites are remoulded into rocks resembling alkali syenites in both appearance and composition in which all nephelines disappear, dark minerals disappear partially or wholly, and many hydrothermal minerals appear. We call it "episyenite" so as to discriminate them from the primary syenite of magmatic origin. Episyenite is also one of the ore-bearing rocks in the Saima deposit.

## II. URANIUM DEPOSIT

The Saima uranium deposit consists of three main types of mineralization: (1) The uraniferous rinkite in grass-green-aegirine nepheline syenite; (2) uranpyrochlore-betafite in skarn; and (3) pitchblende in episyenite. Among them the rinkite type is the largest in size. Besides, beyond the sphere of the deposit, in other parts of the massif, some other types of mineralization, such as uranothorite in fenite, uranthorianite in magnesian skarn, caryocerite in nepheline-acmite-augite alkaline skarn, pitchblende in altered phonolite, shachialite<sup>1)</sup> in green-aegirine nepheline syenite, etc. can also be found. But they are generally small in size.

1) Shachialite is a new mineral found from Shachia in the Saima massif. It is a silicate of Sr,  $\Sigma$  Ce, Ti, and is more or less similar to Chevkinite family in structure and in both optical and physical properties, but it contains SrO up to 22%, ZrO<sub>2</sub> 9.26%, ThO<sub>2</sub> 0.25% and U<sub>3</sub>O<sub>8</sub> 0.14%.

1. *The Rinkite Type*

The spatial distribution of the ore bodies is strictly controlled by the grass-green-aegirine nepheline syenite, which, being developed in the northwestern corner of the massif, appears in the form of a triangle narrower in the south and wider in the north in plan view and wedge-shaped in three dimensions. Almost all rinkite ore bodies are distributed within this wedge. The shape of a single ore body is stratoid or lenticular. Its dip direction is N 80°E, at an angle of 5°—25°, commonly of 10°—15°. Ore bodies are nearly parallel with each other, and are concordant with the differentiation stratification of the rocks. The ore body may reach a maximum thickness of 40 m, sporadic ore bodies can still be met with at the depth of 800 m below surface. The ore bodies are most concentrated in the central part of the wedge. Although the mineralizing boundary widens towards the north, the ore bodies are more scattered. It becomes narrow towards the south and gradually thins out (Figs. 3—6).

Table 3

Total Chemical Analysis for Rinkite and Its Altered Products

| Analytical Item                     | Rinkite |        |        | Altered Rinkite | Wudjavrite |
|-------------------------------------|---------|--------|--------|-----------------|------------|
|                                     | A       | B      | C      |                 |            |
| $\Sigma \text{TR}_2\text{O}_3$      | 16.68   | 17.04  | 14.87  | 21.80           | 36.79      |
| ThO <sub>2</sub>                    | 1.90    | 1.18   | 2.39   | 3.86            | 4.15       |
| U <sub>3</sub> O <sub>8</sub>       | 0.33    | 0.33   | 0.37   | 0.38            | 0.49       |
| (Nb+Ta) <sub>2</sub> O <sub>5</sub> | 0.80    | 0.45   | 0.41   | 0.96            | 0.74       |
| TiO <sub>2</sub>                    | 9.13    | 11.25  | 10.33  | 10.31           | 10.15      |
| ZrO <sub>2</sub>                    | 0.05    | 0.10   | 0.06   | 0.08            | 0.03       |
| SiO <sub>2</sub>                    | 34.76   | 31.73  | 34.16  | 23.58           | 17.80      |
| Al <sub>2</sub> O <sub>3</sub>      | 2.85    | 2.55   | 2.22   | 0.52            | 1.18       |
| Fe <sub>2</sub> O <sub>3</sub> +FeO | 2.40    | 0.28   | 0.60   | 1.14            | 0.81       |
| MnO                                 | 0.25    | 0.04   | 0.04   | 0.35            | 0.15       |
| MgO                                 | 0       | 0      | 0      | 0               | 0.10       |
| CaO                                 | 19.99   | 21.91  | 24.14  | 19.08           | 3.97       |
| SrO                                 | 0.70    | 0.89   | 0.64   | 2.81            | 0.72       |
| Na <sub>2</sub> O                   | 3.58    | 4.20   | 3.50   | 1.41            | 0.65       |
| K <sub>2</sub> O                    | 0.48    | 0.84   | 0.68   | 1.00            | 1.43       |
| P <sub>2</sub> O <sub>5</sub>       | 0.10    | 0.01   | 0.09   | 0               | 0          |
| F                                   | 2.95    | 4.72   | 4.03   | 0.62            | 1.19       |
| H <sub>2</sub> O <sup>-</sup>       | 0.37    | 1.43   | 0.18   | 0.80            | 9.00       |
| H <sub>2</sub> O <sup>+</sup>       | 2.69    | 2.71   | 1.77   | 3.20            | 6.40       |
| CO <sub>2</sub>                     | 1.02    | 0.51   | 1.02   | 8.31            | 5.14       |
| Total                               | 101.03  | 102.17 | 101.50 | 100.21          | 100.89     |
| —O—F <sub>2</sub>                   | 1.35    | 1.99   | 1.70   | 0.26            | 0.5        |
| Total                               | 99.68   | 100.18 | 99.80  | 99.95           | 100.39     |

The ore minerals are mainly rinkite and its altered products in different degrees (their chemical composition is given in Table 3). Their highest contents in ore may be up to over 40%. They are the main carriers of U, Th,  $\Sigma \text{Ce}$  and

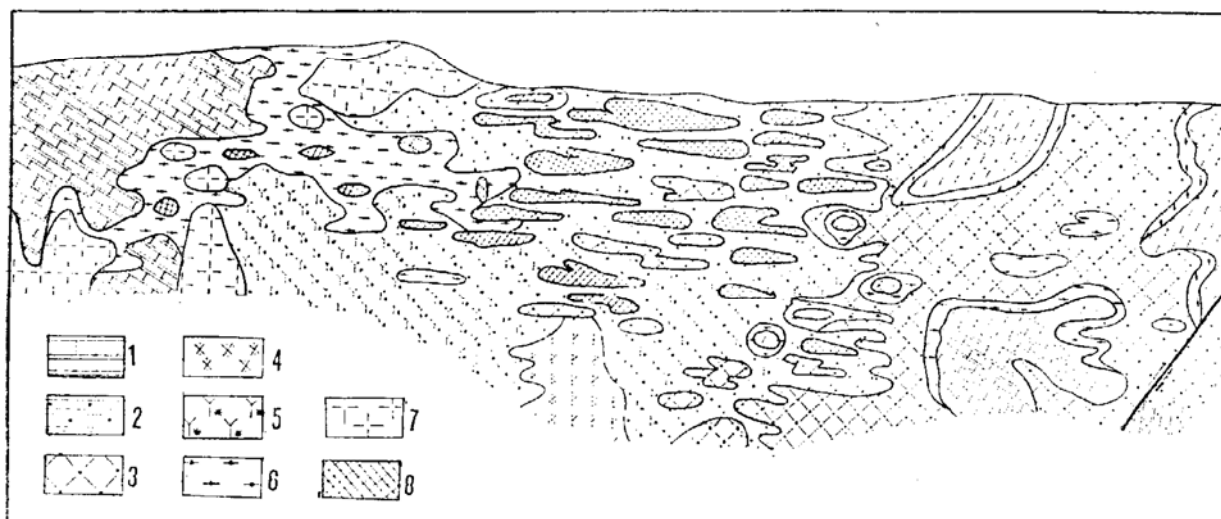


Fig. 3. Schematic longitudinal section of the deposit.

(1) Marble; (2) Quartzite; (3) Melanite mica nepheline syenite; (4) Eudialyte grass-green-aegirine nepheline syenite; (5) Grass-green-aegirine nepheline syenite; (6) Arfvedsonitite and other alkaline skarn; (7) Episyenite and aegirine episyenite; (8) Ore body.

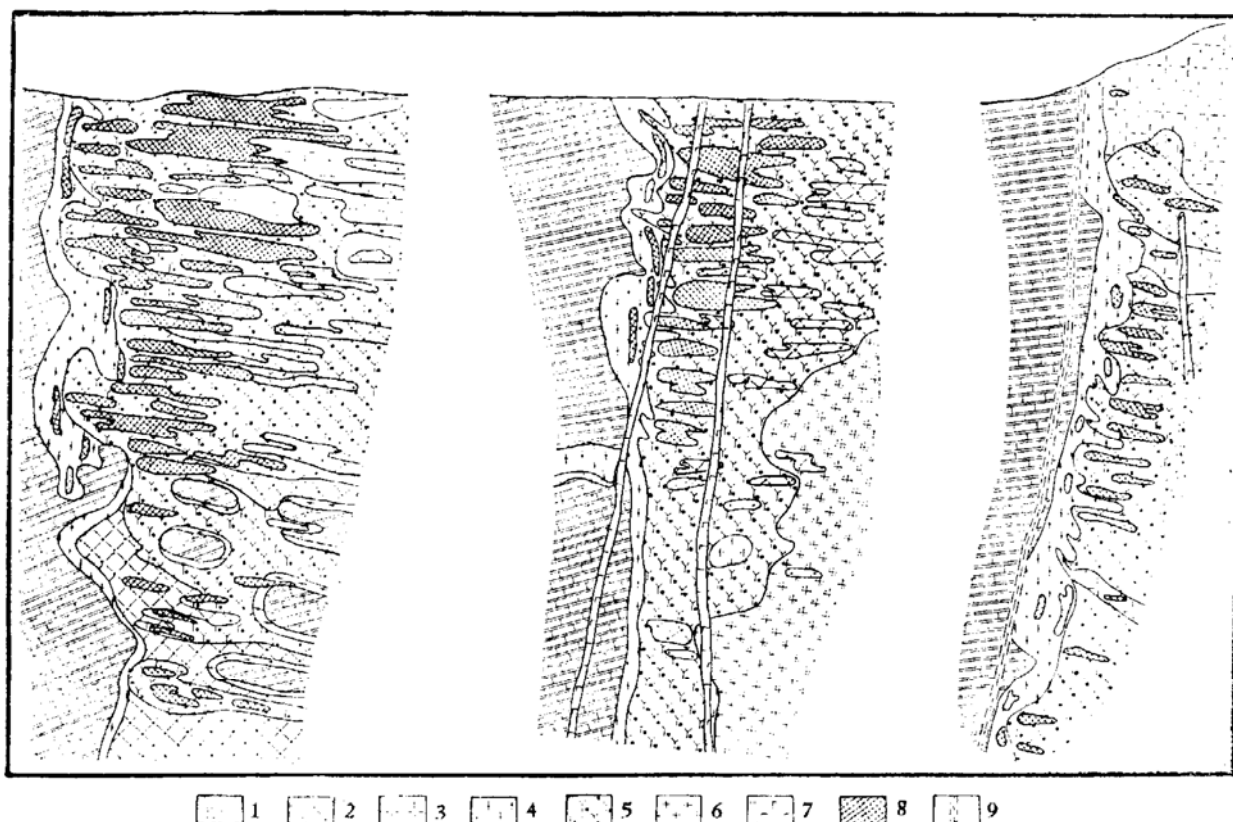


Fig. 4. Schematic transverse section of the deposit.

(1) Marble; (2) Melanite mica nepheline syenite; (3) Episyenite and aegirine episyenite; (4) Arfvedsonitite and other alkaline skarn; (5) Grass-green-aegirine nepheline syenite; (6) Eudialyte grass-green-aegirine nepheline syenite; (7) Lamprophyre dyke; (8) Ore body; (9) Fractured zone.

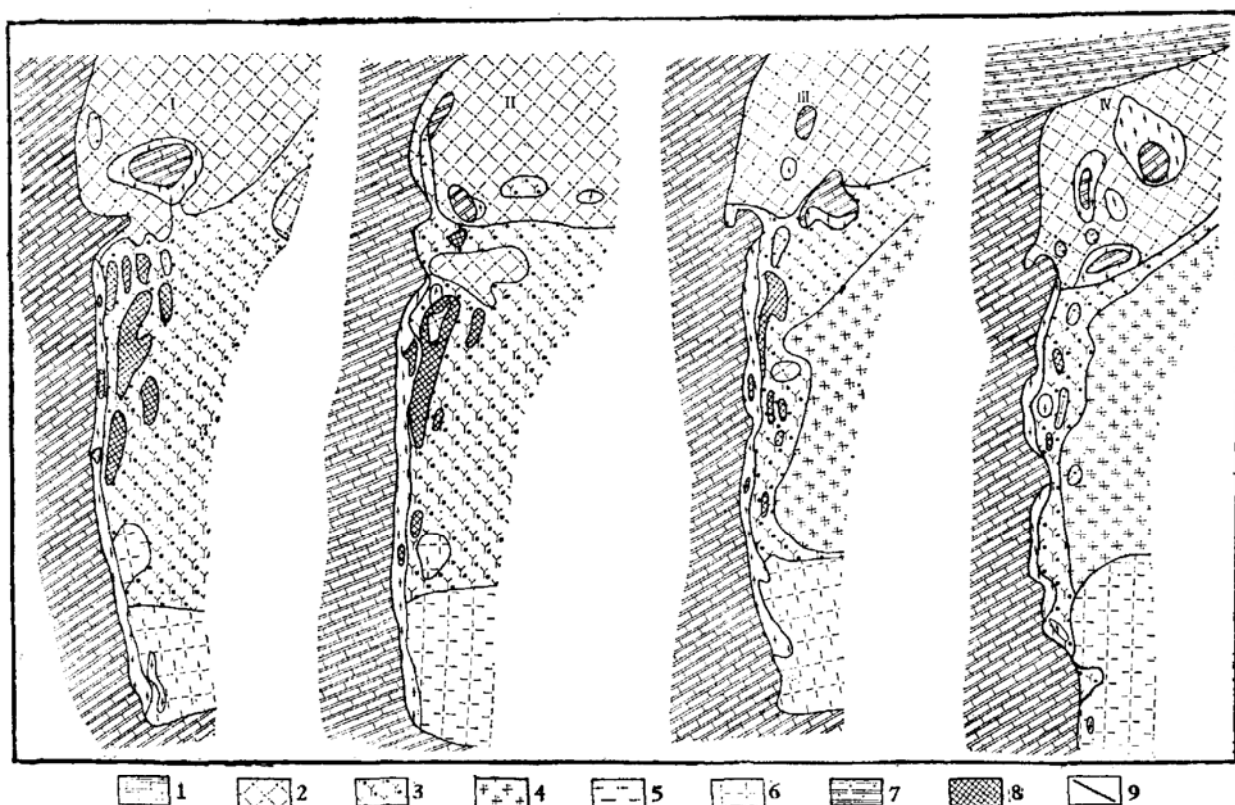


Fig. 5. Schematic horizontal section of different levels in the deposit.

(1) Marble; (2) Melanite mica nepheline syenite; (3) Grass-green-aegirine nepheline syenite; (4) Eudialyte grass-green-aegirine nepheline syenite; (5) Arfvedsonitite and other alkaline skarn; (6) Episyenite and aegirine episyenite; (7) Quartzite; (8) Ore body; (9) Fractured zone.

I—The first level; II—The second level; III—The third level; IV—The fourth level.

Nb. In addition, a small amount of radioactive minerals are present in rocks, such as lovchorrite, uranthorianite, uranothorite and nenadkevichite. The crystal of rinkite is slaty, columnar and fibrous, generally 0.2—2 cm in length, with a maximum of 10 cm. It forms frequently fan-like, radiate-fibrous and massive aggregates; sometimes it appears vein-like, replaces and intersects such rock-forming minerals as feldspar, nepheline, and aegirine (Photos 4—8).

The electron probe microanalysis reveals that such elements as U, Th, Ce, La, and Ti are distributed evenly in the fresh rinkite, and U, Th exist in the isomorphic forms (Photo 9). But most of the ores had been reformed by the late hydrothermal process, and rinkite had also been altered in different degrees until it was decomposed into mixtures of TR-carbonates, fluorite and wudjavrite. At the same time, U and Th are also distributed unevenly (Photo 10), changing their mode of existence and occurring as fine particles of uranium-thorium minerals and uranium in absorption state. The electro-dialytical coefficient of altered rinkite may reach 27% (electro-dialytical condition  $\text{pH} = 3$ ), whereas that of the fresh rinkite is only 0.1%.

Mineral composition in ores is very complicated; besides commercial minerals, it contains a large number of feldspar, nepheline, and aegirine. In addition, a small

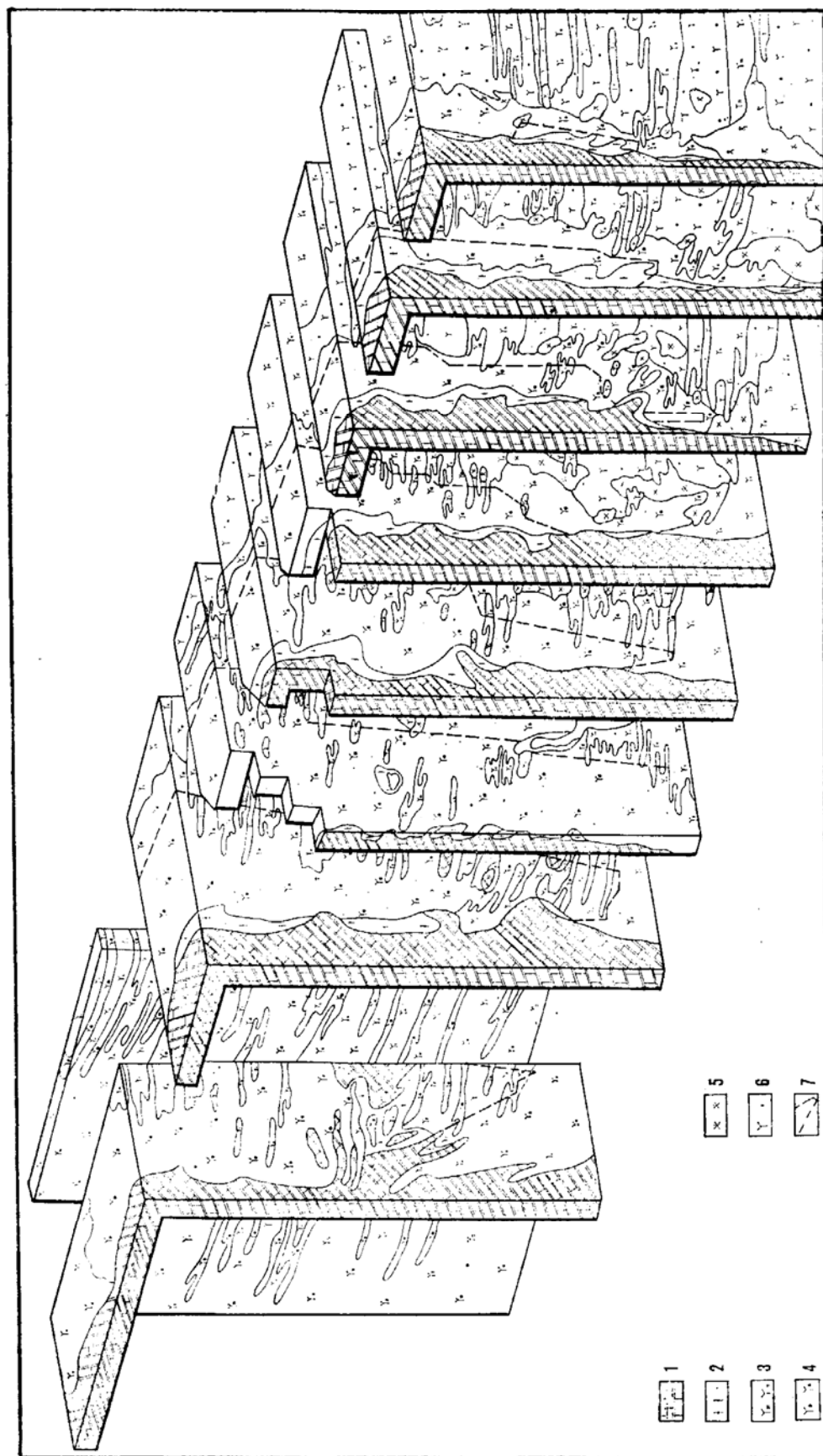


Fig. 6. Stereogram of the deposit constitution.

- (1) Pre-Sinian marble; (2) Arfvedsonite and other skarn; (3) Melanite mica nepheline syenite; (4) Grass-green-aegirine nepheline syenite; (5) Eudialyte grass-green-aegirine nepheline syenite; (6) Green-aegirine nepheline syenite; (7) Mineralization boundary delineated.

amount of eudialyte, catapleite, lamprophyllite, loparite, pektolite, and both sulfides and arsenides of Cu, Pb, Zn, Fe, Co are also present. A large amount of natrolite, chlorite, carbonate, illite, hydrogeothite, strontianite, brookite, anatase, and zircon are developed in ores hydrothermally altered. More than 70 minerals have been identified in the deposit.

### 2. *The Uranpyrochlore-Betafite Type*

Occurring in the skarn zone in the western part of the deposit, the ore-bearing rocks are mainly arfvedsonite, phlogopite; and next tremolite, carbonatized skarn, and episyenite in the endomorphic zone. The ore bodies occur as lenses and are controlled by the more steeply dipping skarn zone. Chemical compositions of minerals of uranpyrochlore and betafite are given in Table 4. They are found in inhomogeneously disseminated form (Photos 11, 12), locally striped and vein-like (Photo 13), so their formation is obviously later than that of skarn minerals. In addition to skarn minerals, feldspar, nepheline, apatite, sulfides, fluorite, zeolite, TR-carbonate, and uranothorite are also present.

### 3. *The Pitchblende Type*

It occurs in the episyenite and aegirine episyenite mainly in the upper part of the deposit and is controlled by a set of shear fractures of NE-trend with high dip angle. In general, the mineralization extends very long along the strike, but with a small thickness. The chemical composition of pitchblende (Table 5) indicates that it has a lower oxidation coefficient, and its molecular formula can be simplified as  $\text{UO}_{2.27}$  containing only 0.21%  $\text{ThO}_2$ . The pitchblende is of colloidal commonly kidney-like and spherulitic structures and contraction cracks (Photos 14, 15). Associated minerals are pyrite, sphalerite, galena, chalcopyrite, hydrogeothite, quartz, calcedony, calcite, and chlorite.

There is a close spatial relationship between the three main types of mineralization mentioned above, and certain inheritance and genetic connexion exist in mineral paragenetic association and geochemical evolution. These complex mineralizations were formed during the evolution of alkaline magma, post-magmatic solution at different stages and under different geological conditions. According to the characteristics of mineral associations, as well as the replacement and interlocking relations between minerals, six stages of the evolutionary process can be successively divided from the beginning of crystallization of grass-green-aegirine nepheline syenite to the end of mineralization. Of them 3, 5(II), and 5(IV) are the uranium ore-forming stages (Table 6).

In the area of the deposit, the intensity of meso-epithermal activities gets stronger and stronger from the deeper part towards the shallower and the types of hydrothermal alterations vary also regularly in vertical direction, thus resulting in obvious differences between ore types at the deeper part and those at the shallower part in their compositions, grades, existing forms of valuable elements, and Th/U ratio and consequently producing a certain vertical zonality for the deposit. As the hydrothermal activity is weaker at depth, the rinkite ore bodies with stable Th/U ratio are well-retained in deep level of the deposit. Rinkite underwent alteration



**Table 6**  
Ore-Forming Stages in the Saima Deposit<sup>a)</sup>

| Ore-forming Stage |                                             |     | Characteristic Mineral                                                            | Characteristic Element                                           | Evolution of Acidity and Alkalinity                                        | Remark                                                    |                                     |
|-------------------|---------------------------------------------|-----|-----------------------------------------------------------------------------------|------------------------------------------------------------------|----------------------------------------------------------------------------|-----------------------------------------------------------|-------------------------------------|
| 1                 | Early magmatic stage                        |     | nepheline, microcline                                                             | K, Al, Na                                                        | strongly alkaline                                                          | constituting the bulk of leucocratic differentiation bed  |                                     |
| 2                 | Late magmatic stage                         |     | grass-green aegirine                                                              | Fe <sup>+3</sup> , Na                                            | alkaline                                                                   | constituting the bulk of melanocratic differentiation bed |                                     |
| 3                 | Final magmatic and hydropneumatolytic stage |     | rinkite                                                                           | Ca, Ti, TR, Th<br>U, F, H <sub>2</sub> O                         | alkalinity lowered and volatile components began to play an important role | main ore-forming stage (U, Th, TR)                        |                                     |
| 4                 | Pneumatolytic hydrothermal stage            |     | pektolite, arfvedsonite, rinkite                                                  | Fe <sup>+2</sup> , Ca, Mg, H <sub>2</sub> O, F                   | alkalinity further lowered, and volatile components' role strengthened     | local development                                         |                                     |
| 5                 | Hydrothermal stage                          | I   | nephelinization<br>microclinization                                               | nepheline<br>microcline                                          | K, Na                                                                      | alkaline                                                  | mainly developed in exomorphic zone |
|                   |                                             | II  | natrolitization<br>albitization                                                   | natrolite, albite<br>uranpyrochlore, betafite                    | Na, Nb, U, H <sub>2</sub> O                                                | alkalinity lowered                                        | uranium-niobium ore-forming stage   |
|                   |                                             | III | silicification                                                                    | quartz, hydrogoethite, anatase, hydromica                        | Si, Ti, Al                                                                 | acidic                                                    |                                     |
|                   |                                             | IV  | chlorite-fluorite-carbonatization                                                 | chlorite, fluorite, calcite, TR-carbonate sulphides, pitchblende | Ca, Fe <sup>+2</sup> , U, S, CO <sub>2</sub> , F                           | weakly alkaline                                           | single uranium ore-forming stage    |
| 6                 | Hypergenetic stage                          |     | clay minerals, limonite, vitriol minerals, wudjavrite, secondary uranium minerals | H <sub>2</sub> O, CO <sub>2</sub>                                | chiefly acidic                                                             |                                                           |                                     |

a) The formation of skarn consisting of several stages is not listed in the table.

in different degrees in the middle levels of the deposit, where the predominantly isomorphous uranium changed into absorptive state and formed micromeritic uranium-thorium minerals, and Th/U ratio in the ore lowers and fluctuates more strongly. In the shallow levels of the deposit, the rinkite ore bodies were intensively destroyed, reformed, and even disappeared in a large amount. It is due to the intensive development of meso-epihydrothermal alteration that new types of mineralizations—uranpyrochlore-betafite type and pitchblende type—appear. More fluctuation in

Th/U ratio and evident domination of uranium suggest that a proportion of uranium was carried in by hydrothermal solution. The hydrothermally altered rocks (episyenite) developed over a large area in the shallow levels of the deposit are commonly enriched by 0.01–0.02% uranium, which is mostly widespread as absorptions in minerals of zeolite, hydromica, and hydrogeothite. So no remarkable concentration took place. The variation curves of Th/U ratio at different levels of the deposit, plotted according to the statistical data by gamma spectrometric logging, also reflect the vertical zonality of the deposit (Fig. 7). To master the characteristics of

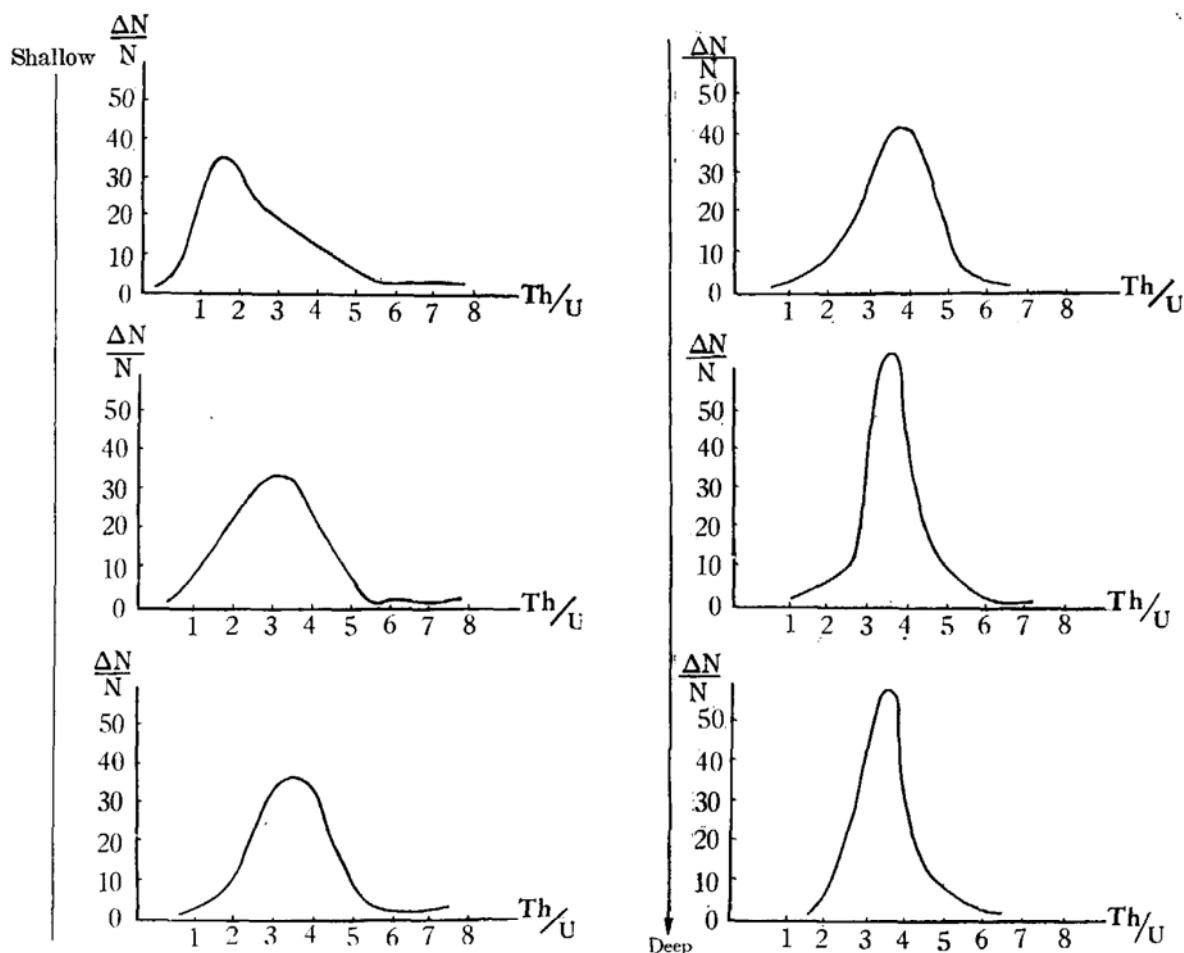


Fig. 7. Schematic diagram showing vertical variation of Th/U ratio in the Saima deposit (plotted according to the statistical data by gamma spectrometric logging).

the zonality is not only of realistic significance for mining, ore dressing, and metallurgy, but also of great importance to the minerogenetic prediction and prospecting for blind ore bodies in the light of the characteristics of hydrothermal alterations and radioactive anomalies found on the surface.

### III. THE FACTORS CONTROLLING THE FORMATION OF MINERALIZATION

As compared with some well-known alkaline massifs in the world, the size of the Saima massif is not large (20 km<sup>2</sup>) and its agpaitic coefficient (1.07) and average uranium abundance (22.4 ppm) are not very high, but it still contains so large a

valuable uranium deposit. It is evident that the Saima deposit was formed under certain special conditions and is the result of multiple favourable geological factors in mutual coordination and composite action. In the authors' opinion there exist the following three favourable factors controlling jointly the formation of various types of mineralization in the Saima uranium deposit.

### 1. Completeness of Magmatic Differentiation

Various alkaline igneous rocks in the Saima massif, from the earliest eruptive rock to the latest grass-green-aegirine nepheline syenite, are characterized petrochemically and geochemically not only by pronounced similarity and inheritance, but also by certain regular changes and differences. They are the products of differentiation of cognate alkaline magma for a long time. In particular, an extremely complete differentiations series is reflected by six phases starting from the main rock variety of the first intrusive phase—mica aegirine nepheline syenite, through black-aegirine nepheline syenite, dark-green-aegirine nepheline syenite, to rocks of the second phase—green-aegirine nepheline syenite, eudialyte grass-green-aegirine nepheline syenite, and grass-green-aegirine nepheline syenite. The average chemical composition of various igneous rocks in the massif and the average chemical composition of the whole massif calculated from the total chemical analysis data based on 56 samples are given in Table 7, and the diagram of variations of the main petrochemical parameters are shown in Fig. 8. It is clearly noted that the general trend of differentiation of magma is to evolve gradually from highly potassic to

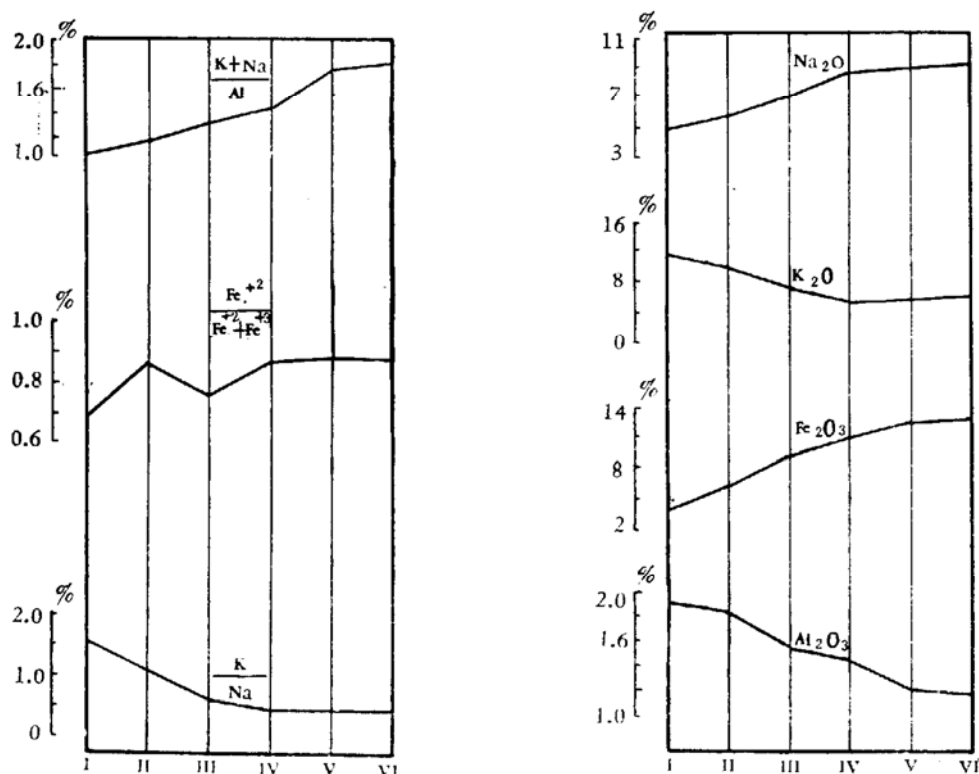


Fig. 8. A diagram showing variation in petrochemical parameters in the differentiation series.

I—Mica aegirine nepheline syenite; II—Black-aegirine nepheline syenite; III—Dark-green-aegirine nepheline syenite; IV—Green-aegirine nepheline syenite; V—Eudialyte grass-green-aegirine nepheline syenite; VI—Grass-green-aegirine nepheline syenite.

Table 7

The Average Chemical Composition and Petrochemical Parameters of Main Igneous Rock in the Saima Massif

|                          | No. | Rock Type                                            | Samples<br>in Total | Chemical Composition (%) |                  |                                |                                |      |       |      |      |                   |                  |                               |                               |                               |        | $\frac{K+Na}{Al}$ | $\frac{K}{Na}$ | $\frac{Fe^{2+}+Fe^{3+}}{Fe^{3+}}$ |
|--------------------------|-----|------------------------------------------------------|---------------------|--------------------------|------------------|--------------------------------|--------------------------------|------|-------|------|------|-------------------|------------------|-------------------------------|-------------------------------|-------------------------------|--------|-------------------|----------------|-----------------------------------|
|                          |     |                                                      |                     | SiO <sub>2</sub>         | TiO <sub>2</sub> | Al <sub>2</sub> O <sub>3</sub> | Fe <sub>2</sub> O <sub>3</sub> | FeO  | MnO   | MgO  | CaO  | Na <sub>2</sub> O | K <sub>2</sub> O | P <sub>2</sub> O <sub>5</sub> | H <sub>2</sub> O <sup>+</sup> | H <sub>2</sub> O <sup>-</sup> | total  |                   |                |                                   |
| Eruptive rock            | 1   | Leucitophyre                                         | 3                   | 53.09                    | 1.83             | 15.18                          | 5.46                           | 3.11 | 0.035 | 2.35 | 2.52 | 0.21              | 11.4             | 1.57                          | 3.74                          | 100.49                        | 40.30  | 0.61              |                |                                   |
|                          | 2   | Phonolite, Pseudoleucite<br>Phonolite                | 5                   | 54.25                    | 0.86             | 17.80                          | 4.65                           | 2.46 | 0.15  | 1.17 | 1.68 | 3.34              | 11.81            | 0.27                          | 1.15                          | 0.29                          | 99.88  | 2.31              | 0.63           |                                   |
| Phase                    | 3   | Melanite mica nepheline<br>syenite                   | 3                   | 47.31                    | 1.57             | 15.71                          | 8.79                           | 3.02 | 0.24  | 1.72 | 7.36 | 4.08              | 9.10             | 0.32                          | 1.04                          | 0.30                          | 100.56 | 1.06              | 0.72           |                                   |
|                          | 4   | Mica nepheline syenite                               | 6                   | 53.57                    | 1.04             | 17.80                          | 4.90                           | 2.77 | 0.16  | 0.82 | 2.46 | 4.71              | 10.50            | 0.15                          | 1.43                          | 0.30                          | 100.60 | 1.07              | 0.60           |                                   |
| First intrusive phase    | 5   | Mica aegirine nepheline<br>syenite                   | 9                   | 55.63                    | 0.77             | 19.03                          | 3.67                           | 1.57 | 0.09  | 0.67 | 1.13 | 4.83              | 11.37            | 0.09                          | 0.98                          | 0.27                          | 100.10 | 1.06              | 0.68           |                                   |
|                          | 6   | Black-aegirine nepheline<br>syenite                  | 7                   | 54.23                    | 0.70             | 18.29                          | 6.35                           | 0.88 | 0.09  | 0.54 | 1.08 | 5.79              | 10.23            | 0.09                          | 0.83                          | 0.43                          | 99.67  | 1.15              | 0.87           |                                   |
| First intrusive phase    | 7   | Dark-green-aegirine<br>nepheline syenite             | 2                   | 51.36                    | 1.03             | 15.13                          | 9.05                           | 2.05 | 0.24  | 0.82 | 3.48 | 7.07              | 7.11             | 0.11                          | 1.64                          | 0.12                          | 99.21  | 1.32              | 0.68           |                                   |
|                          | 8   | Green-aegirine nepheline<br>syenite                  | 7                   | 52.26                    | 1.51             | 14.30                          | 11.00                          | 1.45 | 0.28  | 0.53 | 1.76 | 8.55              | 5.58             | 0.08                          | 1.67                          | 0.29                          | 99.25  | 1.41              | 0.87           |                                   |
| Second intrusive phase   | 9   | Eudialyte grass-green-<br>aegirine nepheline syenite | 5                   | 52.32                    | 1.25             | 12.06                          | 12.56                          | 1.51 | 0.35  | 0.48 | 2.59 | 8.94              | 5.74             | 0.04                          | 1.26                          | 0.24                          | 99.29  | 1.74              | 0.88           |                                   |
|                          | 10  | Grass-green-aegirine<br>nepheline syenite            | 6                   | 52.52                    | 1.88             | 11.71                          | 12.71                          | 1.43 | 0.28  | 0.46 | 2.22 | 9.21              | 6.11             | 0.09                          | 1.44                          | 0.24                          | 100.30 | 1.85              | 0.88           |                                   |
| Dyke rock                | 11  | Syenite-aplite                                       | 1                   | 60.71                    | 0.772            | 19.46                          | 3.99                           | 0.37 | 0.022 | 0.56 | 0.31 | 5.10              | 8.00             | 0.108                         | 0.99                          | 0.21                          | 100.60 | 0.95              | 0.91           |                                   |
|                          | 12  | Nepheline syenite-aplite                             | 1                   | 52.77                    | 0.506            | 17.30                          | 4.18                           | 2.34 | 0.098 | 3.48 | 3.66 | 4.54              | 8.90             | 0.059                         | 2.11                          | 0.43                          | 100.73 | 0.98              | 0.62           |                                   |
|                          | 13  | Alkali lamprophyre                                   | 1                   | 49.40                    | 1.14             | 15.11                          | 3.80                           | 4.10 | 0.21  | 2.27 | 4.80 | 5.20              | 8.82             | 0.555                         | 1.43                          | 0.44                          | 99.70  | 1.18              | 0.46           |                                   |
| Mean Value of the Massif |     |                                                      | 56                  | 54.14                    | 1.01             | 17.32                          | 5.48                           | 2.22 | 0.13  | 0.94 | 2.66 | 4.37              | 10.64            | 0.34                          | 1.35                          | 0.34                          | 100.94 | 1.07              | 0.52           |                                   |

highly sodic, the K/Na ratio decreases gradually from 40 (leucitophyre) to 0.44 (grass-green-aegirine nepheline syenite) and agpaitic coefficient increases from 0.83 to 1.85 correspondingly, with  $\text{Na}_2\text{O}$ ,  $\text{Fe}_2\text{O}_3$  increasing and  $\text{K}_2\text{O}$ ,  $\text{Al}_2\text{O}_3$  decreasing. As regards the mineral compositions in rocks, biotite is gradually replaced by aegirine which becomes higher in percentage of the content, purer in composition (the contents of Ca, Mg, Fe tend to be dropping), and lighter in colour. The accessory minerals change from miascitic type (sphene, apatite, etc.) into agpaitic type (eudialyte, lamprophyllite, rinkite, etc.). It is very seldom to meet with such a complete differentiation within a single massif where the magma gradually evolves from high potassic to high sodic.

During the process of magmatic differentiation, the composition of potash feldspar in rocks of the differentiation series has also a regular variation (Fig. 9).  $\text{K}_2\text{O}$  and K/Na increase gradually, whereas  $\text{Na}_2\text{O}$  and CaO decrease, with Rb, Cs showing an increasing tendency and K/Rb a decreasing tendency, which also reflect the good differentiation of alkaline magmas.

The petrochemical analysis data after reduction are projected on to the schematic diagram of the ternary system of quartz-nepheline-kaliophillite, as proposed by R. Fudali (1963) (Fig. 10). The projection points show clearly a migration from the leucite field occupied by early rocks towards Na-K nepheline field, and from the high-temperature part towards the low temperature belt. The projection point of the latest differentiation phase of grass-green-aegirine nepheline syenite (10) already approaches to the ternary eutectic point, and apparently characterize residual magma. The approximate temperature for forming rocks of the second intrusive phase, as mentioned above, is about  $430^\circ\text{--}460^\circ$ , and such a low temperature is entirely coincident with the character of residual magma.

The abundance of U, Th, Nb, Zr, Hf, Ce, and La in various rocks determined by neutron activation analysis (Table 8, Fig. 11) has also reflected the characteristics of the magmatic differentiation. With the progress of the magmatic differentiation, uranium content sharply increases, whereas Th, Ce, La, and Nb/Ta correspondingly increase too; Th/U decreases, and Nb, Ta, Zr, and Hf tend to increase; but they are not harmonic with uranium. It is very interesting to note that the contents of these elements in eruptive rocks are very close to the average content of the whole massif, which not only demonstrates further that the eruptive and intrusive rocks are products of cognate magmas, but also indicates that those eruptive magmas formed at the earliest stage are probably equivalent to the original undifferentiated magmas. The grass-green-aegirine nepheline syenite, the latest product of the magmatic differentiation, is characteristic of residual magma, and contains uranium up to 122 ppm (whereas Th/U approaches 1) containing substantial amounts of Th, Nb,  $\Sigma\text{Ce}$ , Zr, and abundant volatile components (F, Cl,  $\text{H}_2\text{O}$ , and S). This agpaitic residual magma is the basic precondition for the formation of Saima rinkite ore type.

The differentiation among eruptive rocks and rocks of the first and second intrusive phases belongs to the deep differentiation, and the differentiation occurring between various petrographic facies within intrusives of the two phases belongs to differentiation *in situ*. Furthermore, in the process of crystallization of grass-green-aegirine nepheline syenite, differentiation continues uninterruptedly, forming early

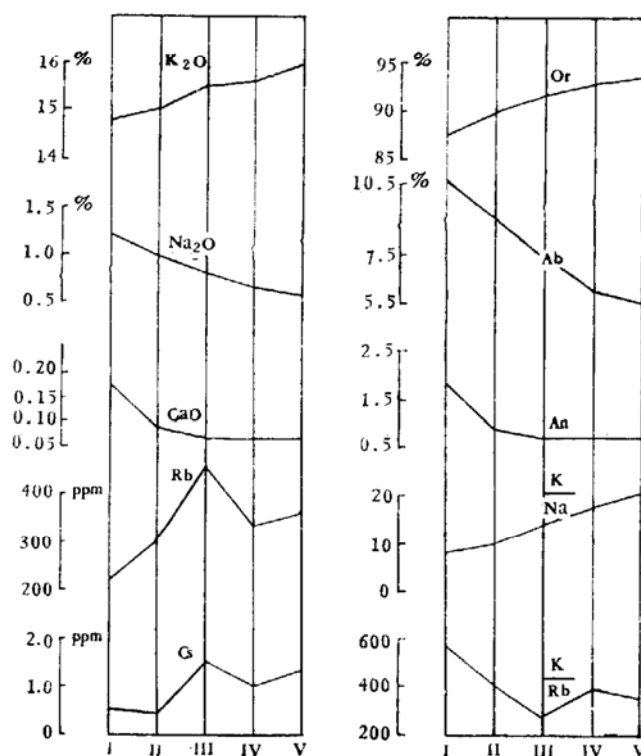


Fig. 9. A diagram showing variation in chemical composition of potash feldspar in rocks of the differentiation series.

I—Mica aegirine nepheline syenite; II—Black-aegirine nepheline syenite; III—Green-aegirine nepheline syenite; IV—Eudialyte grass-green-aegirine nepheline syenite; V—Grass-green-aegirine nepheline syenite.

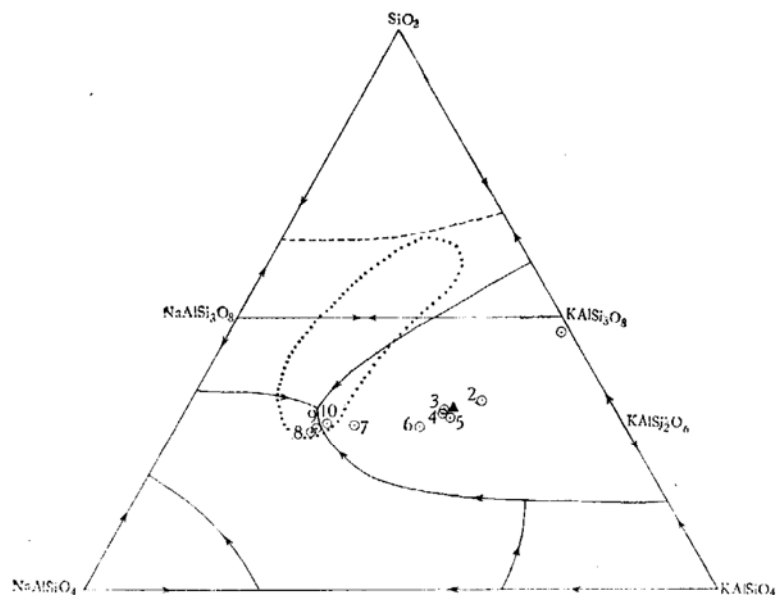


Fig. 10. Projection of main magmatic rocks in the Saima massif on the ternary system phase diagram of quartz-nepheline-kaliophilite (R. Fudali, 1963).

Numbers in order representing rock types as given in Table 7.

▲ refers to projection point of mean value in the massif.

The thin dotted line indicates the belt of low temperature.

Table 8

The Average Content of U, Th, Nb, Ta, Zr, Hf, Ce, and La in Various Rocks of the Saima Massif (ppm)<sup>a)</sup>

|                                                                                        | Rock Type                                        | U     | Th    | U/Th | Nb  | Ta  | Nb/Ta | Zr   | Hf    | Zr/Hf | Ce   | La   |
|----------------------------------------------------------------------------------------|--------------------------------------------------|-------|-------|------|-----|-----|-------|------|-------|-------|------|------|
| Eruptive Rock                                                                          | Phonolite and pseudo-leucite phonolite           | 21.9  | 58.2  | 2.2  | 123 | 3.0 | 42    | 993  | 54.9  | 18    | 355  | 140  |
| First Intrusive Phase                                                                  | Melanite mica nepheline syenite                  | 11.3  | 41.6  | 3.7  | 90  | 2.4 | 37    | 1602 | 81.2  | 22    | 294  | 103  |
|                                                                                        | Mica aegirine nepheline syenite                  | 9.5   | 38.5  | 4.0  | 59  | 2.7 | 22    | 802  | 45.9  | 20    | 354  | 237  |
|                                                                                        | Black-aegirine nepheline syenite                 | 20.2  | 67.4  | 3.3  | 90  | 2.6 | 34    | 925  | 53.1  | 17    | 424  | 210  |
| Second Intrusive Phase                                                                 | Green-aegirine nepheline syenite                 | 37.5  | 68.5  | 1.8  | 367 | 9.5 | 39    | 7889 | 482.9 | 16    | 597  | 352  |
|                                                                                        | Endialyte grass-green-aegirine nepheline syenite | 47.5  | 33.7  | 0.7  | 370 | 7.7 | 48    | 8101 | 513.9 | 16    | 586  | 274  |
|                                                                                        | Grass-green-aegirine nepheline syenite           | 122.1 | 129.6 | 1.1  | 374 | 6.3 | 59    | 7690 | 399.0 | 19    | 1005 | 469  |
| Metasomatite                                                                           | Feinite                                          | 60.0  | 240.0 | 4.0  | 133 | —   | —     | 327  | —     | —     | 700  | 352  |
|                                                                                        | Arfvedsonite                                     | 110.5 | 15.8  | 0.14 | —   | —   | —     | 766  | 12.0  | 64    | 95   | 65   |
|                                                                                        | Phlogopite                                       | 70.8  | 23.1  | 0.32 | —   | —   | —     | 188  | —     | —     | 146  | 100  |
|                                                                                        | Tremolite-arfvedsonite                           | 61.0  | 15.1  | 0.25 | —   | —   | —     | 479  | 12.5  | 38    | 262  | 207  |
|                                                                                        | Tremolite                                        | 21.8  | 11.1  | 0.51 | —   | —   | —     | 112  | 7.2   | 16    | 106  | 873  |
|                                                                                        | Weakly altered marble                            | 14.0  | 2.3   | 0.16 | —   | —   | —     | 96   | 0.5   | —     | 12   | 9    |
|                                                                                        | Aegirine episyenite                              | 101.2 | 67.5  | 0.67 | 374 | 6.4 | 58    | 6490 | 393.3 | 17    | 392  | 220  |
| Average content of the Saima massif <sup>b)</sup>                                      |                                                  | 22.4  | 56.8  | 2.5  | 119 | 3.3 | 36    | 1605 | 92.7  | 17    | 413  | 211  |
| Average abundance of the earth's crust (after Vinogradov)                              |                                                  | 3.0   | 8.0   | 2.7  | 10  | 2   | 5     | 200  | 3.2   | 63    | 45   | 18   |
| Ratio between average content of the massif and average abundance of the earth's crust |                                                  | 7.5   | 7.1   | —    | 12  | 1.7 | —     | 8    | 29    | —     | 9.2  | 11.7 |

a) All analyses were made by neutron activation method except Nb, by chemical method.

b) The average content of the massif was calculated in accordance with the proportion of exposed surface of various rock types.

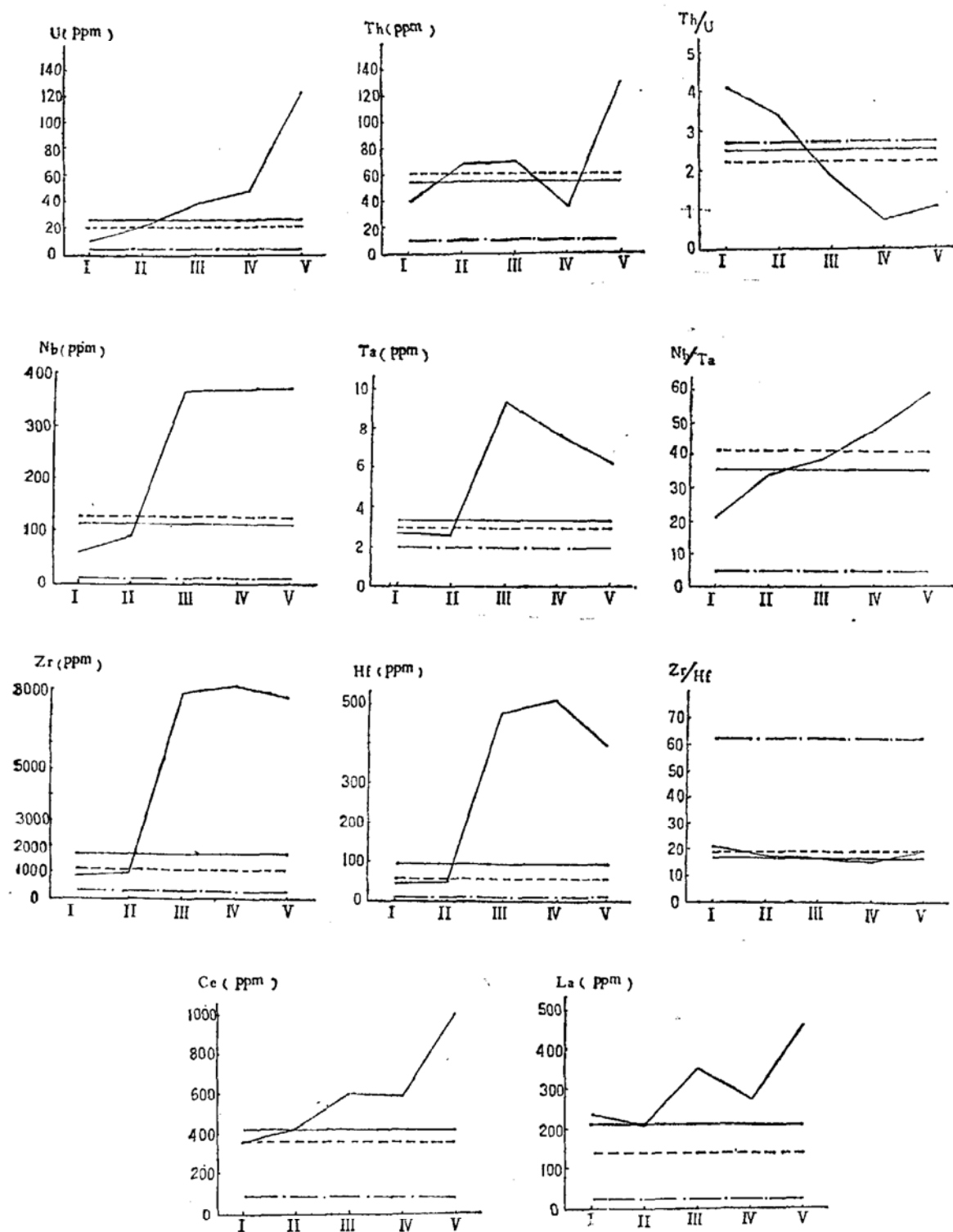


Fig. 11. A diagram showing variation in U, Th, Ce, La, Nb, Ta, Zr, and Hf contents in rocks of the differentiation series.

- Average content in the massif;
- Average content of eruptive rock in the massif;
- · - · - Average content of the earth's crust.

I—Mica aegirine nepheline syenite; II—Black-aegirine nepheline syenite; III—Green-aegirine nepheline syenite; IV—Eudialyte grass-green-aegirine nepheline syenite; V—Grass-green-aegirine nepheline syenite.

leucocratic beds and late melanocratic beds thus leading to segregation and concentration of ore-bearing residual fluids. This is also an important factor for uranium concentration. The minerogenetic mechanism of rinkite ore body may be briefly described as follows: During the process of crystallization-differentiation of residual magma, because of segregation of a good many rock-forming minerals, concentration of volatile and ore-forming components (U, Th, TR, Ti, and Nb) further increases. Volatile components carrying U, Th, etc. in the form of complex compounds migrate within grass-green-aegirine nepheline syenite body not completely consolidated along differentiation stratification towards the marginal and upper parts of the massif where the pressure and temperature are lower. In the case of further falling of temperature and pressure, rinkite substantially precipitated and replaced strongly the pre-existing rock-forming minerals. As a result of this process, the layered ore bodies in conformity with the differentiation stratification were formed. Only a small amount of ore-bearing fluids escaped to the surrounding rocks (melanite mica nepheline syenite and arfvedsonite), giving rise to small ore bodies of rinkite. This is the reason why the rinkite deposit is controlled by grass-green-aegirine nepheline syenite. In the light of the understanding of minerogenetic mechanism, the genetic type of the rinkite deposit can be termed as "residual magma-metasomatic type".

Subsequent to the crystallization of grass-green-aegirine nepheline syenite and the formation of rinkite ore bodies, the residual fluids and the post-magmatic solution constantly supplemented from the deep magmatic source rose along the contact zones and fractures, and consequently, a very complete and long evolutionary process, from hypothermal to epithermal, of the post-magmatic solutions began once more. The isotopic ages listed at the beginning of the report suggest that the process is as long as several tens of million years. As shown in Table 8, uranium contents in various metasomatites and altered rocks are universally high, in general, higher than the average U-content of the massif and that of most of the alkaline rocks. This indicates that uranium had a tendency to further concentrate in the post-magmatic process. On the other hand, Th and TR had a tendency to decrease their contents, except that only individual elements in separate metasomatites were slightly higher and they were not harmonic in concentration with uranium. It shows that in the post-magmatic stage the similarities of uranium with thorium and rare earth elements in the geochemical behaviour practically vanished. So uranium behaved more independently and actively. The rinkite ore has a Th/U ratio of about 3, and contains considerable amounts of TR, whereas the uranpyrochlore-betafite ore has a Th/U ratio of only 0.3 and practically contains no TR. The pitchblende ore formed in the epithermal stage is pure uranium ore. It seems likely that the qualitative change of geochemical behaviour is related to the transition of tetravalent uranium into the hexavalent in the post-magmatic stage.

The hypo-mesothermal solution, from which uranpyrochlore-betafite was deposited, contained more acidic volatile components; and basic skarn was just a favourable rock which gave rise to neutralization of the ore-bearing solution thus bringing about precipitation of U and Nb. Therefore, such mineralization is controlled by skarn and superimposed on the latter. In the section where pitchblende was developed, a large area of the alkaline rocks (including a part of rinkite ore bodies)

experienced strong hydrothermal alteration, and those composite rare element minerals with complicated compositions formed at the late-magmatic and hypothermal-pneumatolytic stages (rinkite, eudialyte, lamprophyllite, etc.) were decomposed into minerals of simple compositions (brookite, anatase, TR-carbonate, zircon, thorite, strontianite, etc.). During the process of decomposition, being certainly also released into the thermal solution, uranium migrated and deposited separately. Thus, at least a part of uranium forming pitchblende was derived *in situ* from the altered rocks and ore bodies. Furthermore, considering the relatively late isotopic age of pitchblende (only 130 m.y.), it may be noted that pitchblende mineralization is probably of a somewhat regenerated nature.

Summing up all described above, it may be concluded that the long and thorough differentiation and evolution of alkaline magma is the fundamental prerequisite for the formation of the Saima deposit. The petrochemical and geochemical properties of the residual magma itself are the guiding factors leading to the formation of rinkite of the residual magma-metasomatic type, and the long-term evolution of the post-magmatic solution is the main cause formation of uranpyrochlore-betafite and pitchblende types.

## 2. *Favourable Geotectonic Setting and Mechanism of Tectonic Movement*

Though the Saima massif is not big, it has produced a large uranium deposit. This is closely related to the geotectonic setting of the massif. The prolonged activities of Tianshan-Yinshan latitudinal tectonic system and its effect on the deep part of the earth's crust provided favourable conditions for facilitating the differentiation products to rise from the deep magma chamber to the upper parts. Moreover, the frequent changes of tectonic stress are also beneficial to the transportation and local concentration of ore-bearing fluids segregated in the late stage of crystallization of the residual magma. Besides, the post-diagenetic fracturing tectonic movement provided channels and ore deposition space for the post-magmatic hydrothermal mineralization. Although certain alkaline massifs in stable platform and shield cover large areas and are rich with a high average contents of uranium and volatile components, and most of the uranium and rare elements often form as accessory minerals scattering homogeneously in the massifs, or form many small-sized pegmatite dykes. The post-magmatic process mainly presents itself as autometamorphism, and in these alkaline massifs no remarkable uranium concentration has been found. The reason for this seems to be ascribed to the overstability of the tectonic environment.

Although, generally speaking, the Saima massif is located in the more active tectonic environment; the tectonic movement is always characterized by a periodicity and its intensity differs in various stages. Rinkite did form in the period of relative stability. The stratoid bodies with its inner differentiation stratification of grass-green-aegirine nepheline syenite and rinkite ore body occur rather gently. Abundant xenoliths and remnants of rocks of the first intrusive phase contained in grass-green-aegirine nepheline syenite are arranged in the same direction and in the same mode of occurrence as that just mentioned. Such a mode of occurrence corresponds right with a group of the gently dipping primary joints in the rocks of the first intrusive phase. These phenomena manifest that when grass-green-aegirine nepheline syenite

intruded, the intensity of the tectonic movement was not so great which made use mainly of the primary joint system in rocks of the early phase. This kind of relatively moderate tectonic environment not only provides conditions favourable for residual magma crystallization and differentiation, but also offers a more confining spatial condition for ore formation, preventing ore-bearing fluids and volatile components from considerable loss so as to benefit large-scale commercial concentrations. When uranpyrochlore-betafite and pitchblende were formed in the hydrothermal process, the intensity of the tectonic activities increased greatly once again, giving rise to many fractures and steeply dipping veined ore bodies, and accompanying with rock alteration in large scale. The specific mechanism and the development history of the tectonic movement are also important for the formation of multiple types of mineralization in the Saima uranium deposit.

### 3. *The Role of Calcareous Country Rock*

The existence of marble is an indispensable condition for the formation of skarn zone and uranpyrochlore-betafite mineralization, and it is favourable as well for the formation of calcium-rich commercial mineral rinkite due to the increasing CaO content in magma. In addition, so far as the alkaline rock province under study is concerned, the alkaline rock bodies occurring in calcareous country rocks are higher in alkalinity and agpaitic coefficient, while that occurring in siliceous country rocks (gneiss, quartzite, etc.) lower in alkalinity. The latter is generally composed of nepheline-free syenite, and no rinkite type of mineralization has been found. Hence, the predominant calcareous country rocks around the Saima massif played a certain favourable role in the ore formation.

## IV. CONCLUDING REMARKS

The aim for researches of natural sciences lies not only in explaining nature, but also—and this is more important—in remoulding it so as to guide practice on production. With the knowledge of ore control factors as mentioned above and the geological analysis on the Saima massif, we have conducted prospect evaluation and exploration prediction in various parts of the Saima massif. Several sections in the massif deserve further investigation.

According to the recognition of the laws governing the formation of uranium ores in the Saima deposit, in the future prospecting for similar types of mineralization special attention should be paid to the following positions favourable for the ore formation and prospecting criteria:

(1) The section where the magma has differentiated more thoroughly and agpaitic and ultraagpaitic rocks—the late products of the alkaline magmatic differentiation—are developed. The petrochemical characteristics of these rocks lie in oversaturation or high oversaturation by alkali metals, high agpaitic coefficient, high oxidation coefficient of iron and low K/Na ratio. The mineral constituents are characterized by high content of aegirine and a series of complex Na-Zr-Ti silicates (endialyte, lamprophyllite, loparite, catapleite, rinkite, etc.). In the geochemical aspect, these rocks are characterized by a high abundance of U, Th, Nb,  $\Sigma$  Ce, Zr, Ti, and Sr, with lower Th/U ratio and higher Nb/Ta ratio.

(2) The section where contact metasomatic rocks, especially those alkaline skarn and fenite associated with agpaitic rocks of the late stage are developed. It should be noted that the Na-rich alkaline skarn itself may not only produce uranium and rare elements mineralization to a certain extent, but also indicates that the existence of rocks of the late magmatic differentiation near the surface or at depth, so that it may be considered a prospecting criterion for finding the residual magma-metasomatic type of mineralization.

(3) The section where the post-magmatic hydrothermal alteration is developed, especially where albitization, natrolitization, carbonatization, silicification, and fluoritization are strongly developed. In these altered rocks the veined uranium mineralization may occur. Furthermore, as revealed by the vertical zonality of the Saima deposit, the altered rocks frequently indicate that buried residual magma-metasomatic deposit or other hypothermal deposit may probably be found at depth.

(4) The marginal and upper parts of the massif. These are often the more developed sections for the products of the late magmatic differentiation, and they are also the favourable localities for the concentration of volatile components and uranium, thorium and rare elements.

(5) The sections of developed fractures and fissures. They are as usual the places for the late hydrothermal alteration and veined uranium mineralization.

(6) The calcareous country rock is relatively more favourable than the siliceous one. What is especially worth noting is the contact zone between the rocks of the late magmatic differentiation and calcareous country rock.

(7) By taking into consideration the regional geotectonic condition, the alkaline massif in the relatively active tectonic region is more favourable than that of the long-standing stable region for the concentration of uranium.