Mineralogical Criteria for Genetic Relationship of Igneous and Carbonatite Rocks of the Tomtor Massif (Siberian Platform)

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Abstract. The Tomtor massif, located in the north-east of the Siberian Platform, is a polychromous zonal-ring complex of alkaline ultrabasic rocks and carbonatites containing a unique deposit of Nb and REE. A comparative analysis of the typomorphic features of minerals of different types of silicate rocks and carbonatites of the Tomtor massif is given in order to establish their convergent features. In order to exclude the mutual influence of rocks formed at different times on each other, samples were taken from different dispersed independent pipe-like bodies of melteigites, a sheet body of alkaline picrites and a transverse dike of carbonatite located south of the Tomtor massif, as well as from alkaline syenites from the southern margin of the massif. It is shown that interesting convergent features are identified in the rock-forming and accessory minerals, including rare-metal ore minerals of different silicate igneous rocks and carbonatite formations. Rock-forming minerals - pyroxenes, micas, feldspars, feldspathoids, garnets, as well as basic and rare carbonates, oxide ore minerals, including Cr-containing spinelides, and sulfide and other exotic phases have such features. The confirmation of the convergence of a group of obvious high-temperature early magmatic elements MgO, Cr, and Ni - with a group of CaO, CO₂, H₂O, P₂O₅, and Y components forming carbonatite derivatives was the most interesting nuance in this regard. Existence of such polychromous complicated ore-magmatic ring complexes as Tomtor massif indicates occurrence of intraplate deep large magma-generating hearths in lithosphere mantle. Such easily fusible hearths, conserved in lithosphere mantle of residual melts of kimberlite, alkali-picrites, carbonatite compositions, under the subsequent favorable geodynamic settings, are subject to rapid flotation, undergoing decompression melting and forming concentric-zonal platform complexes of alkali ultrabasic rocks with carbonatites.

1. Introduction
The Tomtor massif is not only a uniquely rich rare metal deposit of great strategic interest, but also belongs, in its geological and petrographic structure, to one of the complex objects that require detailed scientific research [1-5 et al.]. Such ore-magmatic complexes can be sources not only of deposits of rare elements, but also of precious metals, forming, in our opinion, areal complex gold-platinum placer occurrences that are widespread in this area [6]. This article is a continuation of our work and is concerned with a comparative review of the mineralogical features of typical silicate magmatites and carbonatite rocks of the Tomtor massif in order to identify convergent traits in these two different petrotype rocks, but genetically related rocks.
2. Research methodology
When classifying alkaline ultrabasic rocks, kimberlites and carbonatites of the Siberian Platform, many variants of separation of these petrogeochemically and mineralogically related rocks are proposed: from the traditional distinguishing of two autonomous formations (alkaline-ultrabasic rocks with carbonatites and kimberlites) to their division into many formations according to different facies, material and other characteristics. Without discussing this complex problem, we still adhere to the point of view of [5] on the threefold division of the carbonatite-kimberlite formational rock assemblage into: 1 – diamondiferous kimberlites; 2 – kimberlite-like picrites- alnöite rocks (alpicrites) associated with rare metal carbonatites and 3 – non-diamond-bearing and poor-diamond-bearing kimberlites, often called picrites or "cimpicrites". Therefore, the improvement of petrochemical and mineralogical criteria for the separation of potentially diamondiferous kimberlites from cimpicrites, alpicrites, and other non-diamond-bearing rocks convergent to kimberlites, it is one of the most urgent tasks in the field of research of platform alkaline-ultrabasic magmatism, including both diamond-bearing and rare-metal-bearing formations. This will allow us to find a certain place for the Tomtor massif that fully characterizes it as a single whole object with a rare metal-bearing specialization.

The chemical composition of minerals from the rocks of the Tomtor massif studied by us was determined on the “ Cameca” Camebax-Micro microprobe analyzer (France), and their microstructural relationships were studied on the JEOL scanning microscope JSM-6480LV (Japan) in the laboratory of X-ray spectral analysis methods at DPMGI SB RAS, analysts: Khristoforova N.V., Zhuravlev A.I. Standardized minerals, pure metals, and their alloys were used as standards. Chemical analysis of silicate rocks was performed in the Department of Physical and chemical methods of Analysis at DPMGI SB RAS under the direction of Galenchikova L.T. Due to the strong variability of some silicate rocks and carbonatites of the Tomtor massif, their X-ray phase analysis was performed on a diffractometer “Bruker” D2 PHASER (Germany), analysts Yemelyanova N.N. and Tronina T.F. Identification of mineral phases was performed by N. V. Zayakina using the PDF 2 database.

3. Mineralogical and petrographic features of the Tomtor massif rocks
Data on the geological structure and composition of rocks, especially carbonatite formations of the Tomtor massif are given in the works of many researchers [1-5 et al.]. Here we present some convergent mineralogical features of silicate igneous rocks and carbonatite formations, which can serve as a criterion for assessing the genetic relationship between typical silicate magmas and carbonate magmatic melts. In this regard, for the purity of the experiment, in order to exclude traces of the interaction of silicate and carbonatite melts, manifested intensively in the central part of the massif, we limited ourselves to the study of independent small cross-cutting bodies located in the immediate vicinity of the massif itself (figure 1).

The studied tube bodies (To-1 and To-2) of melteigites-melanocratic malinites, intrude the Riphean deposits in the immediate vicinity (200-500 m) of the southern contact of the massif. The age of the To-2 pipe determined by \(^{40}\text{Ar}/^{39}\text{Ar}\) method on phlogopite is 379,4±3 Ma [6], while the formation of the Tomtor massif itself and carbonatites mainly covered the Wendian-Late Riphean and Middle Devonian time [1, 3, 7]. 0.5 km to the north of these bodies, a sample of fresh nepheline syenites was taken from the southern edge of the massif for study (To-3-1). Sheet body of alkaline picrites (To-4) was studied in the cliff of the right bank of the Chimara river 2 km southwest of the massif, and not far from this body on the left bank, a vertical dike-like (?) transverse body (To-5) of carbonatites is partially exposed (figure 1). The presence of vein carbonatites with a thickness of 1-4.5 m along the Chimara river and followed dikes of carbonitized alnöites of older age was identified in the 60s, 5-30 km south of the Tomtor massif, they mark the deep fault of the submeridional strike that controls the Tomtor and Bogdo massifs and, accordingly, expand the possibility of predicting other satellite bodies here. [4]. Compositions of the studied samples are shown in the table 1. There are no traces of secondary superimposed processes in the described bodies, this allows us to determine some
interesting convergent mineralogical features between silicate igneous and carbonatite rocks, indicating their deep genetic relationship.

Figure 1. Schematic geological map of the Tomtor massif [5]. 1 – lower Triassic tuffs, lavas of plateau basalt; 2 – Permian conglomerates, gravelites, sandstones, silt-shales, coals; 3 – Vendian sandstones, gravelites, silt-shales; 4 – dolomites, shales, silt-shales, sandstones of Ulakhan-Kurug formation of Vendian; 5–7 – carbonatite complex: 5a – rare-metal carbonatites (ankerite), 5b – ankerite-chamosite rocks, 6a– rare-metal carbonatites, 6b – calcite-microcline-mica rocks, 7a – calcite and dolomite-calcite carbonate, 7b – calcite-microcline-mica rocks; 8 – carbonatite breccias, 9 – kamaforites; 10 – small cross bodies of alkaline-ultrabasic rocks; 11 – foidolites; 12 – alkaline and nepheline syenites; 13 – fault; 14 – sampling sites. In the inset, the Tomtor massif is marked a red circle.

Table 1. Compositions of studied samples from rocks of Tomtor massif, wt. %.

| Sample | SiO₂ | TiO₂ | Al₂O₃ | Fe₂O₃ | FeO  | MnO | MgO | CaO | Na₂O | K₂O | P₂O₅ | H₂O | CO₂ | LOI | Total |
|--------|------|------|-------|-------|------|-----|-----|-----|------|-----|------|-----|-----|-----|-------|
| To-1-2 | 33,72 | 3,23 | 11,36 | 7,86  | 3,37 | 0,23 | 7,44 | 16,75 | 3,40 | 2,33 | 0,89 | 4,54 | 3,76 | 0,69 | 99,57 |
| To-2-1 | 31,70 | 2,73 | 11,79 | 5,19  | 4,83 | 0,32 | 5,75 | 15,65 | 4,84 | 2,91 | 1,26 | 5,71 | 5,95 | 0,46 | 99,09 |
| To-3-1 | 55,59 | 0,35 | 21,13 | 2,22  | 3,26 | 0,09 | 0,31 | 3,52 | 3,03 | 7,83 | 0,20 | 2,07 | 0,20 | 0,56 | 100,18 |
| To-4-2 | 31,25 | 2,87 | 8,38  | 10,29 | 5,82 | 0,18 | 15,18 | 11,12 | 0,63 | 2,57 | 1,22 | 4,45 | 5,37 | 0,65 | 99,98 |
| To-5-1 | 14,12 | 1,86 | 5,17  | 6,71  | 7,18 | 0,34 | 4,99 | 29,23 | 0,21 | 0,82 | 1,25 | 2,60 | 24,96 | 0,50 | 99,94 |
For a comparative analysis of composition of alkaline ultrabasic rocks, kimberlites, and carbonatites, we propose the following M–S–C–H₂O diagram (figure 2). Its triple system is constructed in the coordinates: M – mafic components (MgO+FeO<sub>tot</sub>+MnO+TiO₂+P₂O₅); S – alkaline-sialic components (SiO₂+Al₂O₃+Na₂O+K₂O) and C – volatile components (CO₂+H₂O) and CaO. It resembles Holmes diagram [8], but we moved the CaO from the cafmec top to the volatile components in order to more distinguish the carbonatite trend (C) from the mafic (M) and alkaline-sialic (A).

**Figure 2.** Compositions of rocks from alkaline, ultrabasic, kimberlite and carbonatite complexes in the north of the Siberian platform on the M - S - C - H₂O diagram (wt. %). 1-3 Tomtor massif: 1 - small cross-cutting bodies of alkaline picrites (a - authors data, b - according to [9]); 2 - carbonatites, numerals 1-5 on larger badges correspond to numbers of the studied samples To-(1, 2, 3, 4 and 5); 3 - nepheline and alkaline syenites; 4 - carbonatite breccias (n = 72); 5 - intrusive carbonatites (n = 7) according to [10] and 6 - intrusive kimberlites (n = 52) according to [11]; 7-11 - Maymecha-Kotuyskaya province: 7 - melilite rocks (n = 16) according to [12]; 8 - effusives of picrites and alkaline basaltoids (n = 4) according to [13]; 9 - picrite porphyrites (n = 8); 10 - meimechites (n = 26); 11 - dunites - peridotites (n = 19) of Guli massif and 12 - olivinites (n = 14) alkaline-ultrabasic massifs according to [14]. Curved lines with arrows - trends of changes of initial composition of picrite magma (I) to ultramafic (M), alkaline-sialic (A) and carbonatite (C) differentiates.

The lower double system (CaO+CO₂+H₂O) – H₂O shows the role of water in the composition of volatiles. With CaO increase in carbonatites, the water content gradually decreases and closer to the top (C), its amount is practically reduced to zero, i.e., in essentially calcite carbonatites, the role of
water is negligible. With an increase in the proportion of other petrogenic oxides in intrusive carbonatites, the water content gradually increases and the fields of carbonatite compositions are adjacent to kimberlites. We assume [6] that the parent melt of the Tomtor massif magmatites was close to the picrite porphyrites of the Guli massif, which fractional differentiation during the deposition of olivine and chromespineloid according to [14] leads to the appearance of meimechites, and then dunites (figure 2, trend M). This original composition of the Tomtor massif magmatites corresponds to alkaline picrites To-4, and melteigites To - (1, 2) and nepheline syenites To-3 are, apparently, light alkaline-sialic differentiates (trend A). Figure 2 shows that, the Tomtor massif rocks form a second pronounced carbonatite trend (C) as a result of CaO and CO₂ gradual increase in them. To-5 rocks are a transitional variety from ordinary silicate magmatites to typical carbonatites, usually containing more than 50 wt. % carbonate and less than 20-15 % silica.

The essential minerals of the melteigites of the To-1 and To-2 pipe bodies are pyroxene of diopside-augite composition (Wo₃₅-₅₂En₂₄-₄₁Fs₉-₂₅), less often, aegirine-augite, and mica of the phlogopite-annite series (table 2). They form porphyry particles in the fine-grained calcite-natrolite-mesolite groundmass. Natrolite-mesolite zeolites are typical products of nepheline alteration, that is, according to the chemical composition and mineral associations, these rocks belong to the alkaline (non-plagioclase) rocks that are unsaturated with silica, corresponding to melteigites. There are inclusions of apatite, titanomagnetite in association with leucoxene, titanite, perovskite and garnet of andradite-schorlomolite composition. Sometimes there are small inclusions (figure 3A) of rare earth element carbonates (REE) - calcinskite, ambatoarinite and carbocernaite (table 3). In some grains of REE carbonates, a WO₃ content of up to 20% is recorded, indicating a high proportion of the Ce-tungustite mineral – (Ce, Nd, Y)₂W₂O₉(OH)₃.

**Figure 3.** Rock-forming and ore minerals from rocks of Tomtor massif. A - melteigites (samp. To-1-2): small particles of REE carbonates (TR) in association with apatite (Ap) in calcite (Ca) - mesolite (Me) symplectite mass; B - alkaline syenites (samp. To-3-1): "amoeba-shaped" inclusions of wöhlerite (Wöl) in nepheline (Ne) - albite (Ab) - orthoclase (Or) symplectite matrix; C-D - carbonatites (samp. To-5-1): C - euhedral crystals of apatites (Ap) and "case-shaped" zoned substance of leucoxene (Lk) with small inclusions Ce-monazite (Ce-M) in clay-siderite-calcite (Ca) groundmass; D - zoned grain magnetite (Mgt) with a relict core of chromium spinellid (Crt) in intergrowth with phlogopite (Phi) and calcite (Ca). The image was taken in back-scattered electrons.
Table 2. Representative analyzes of silicate minerals.

| Sample | N | SiO$_2$ | TiO$_2$ | AlO$_2$ | FeO$_3$ | FeO | MnO | MgO | CaO | Na$_2$O | K$_2$O | Total |
|--------|---|---------|--------|---------|--------|-----|-----|-----|-----|--------|--------|-------|
|        |   |         |        |         |        |     |     |     |     |        |        |       |
| Diopside (N 1; 5), augite (N 2; 4; 6), aegirine (N 3; 7) |
| To-1-2 | 1 | 44.93 | 2.74 | 6.57 | 1.23 | 6.09 | 0.09 | 13.02 | 24.43 | 0.48 | 99.58 |
| To-1-2 | 2 | 46.78 | 2.64 | 2.66 | 4.70 | 13.11 | 0.10 | 8.51 | 20.18 | 1.82 | 100.50 |
| To-1-2 | 3 | 49.91 | 1.72 | 1.66 | 30.08 | 0.00 | 0.08 | 1.76 | 2.71 | 12.41 | 100.32 |
| To-2-1 | 4 | 49.59 | 1.76 | 2.05 | 0.00 | 15.83 | 0.52 | 9.58 | 21.09 | 0.10 | 100.52 |
| To-4-2 | 5 | 51.74 | 0.89 | 0.65 | 2.31 | 6.01 | 0.30 | 12.76 | 24.09 | 0.90 | 99.64 |
| To-4-2 | 6 | 50.49 | 1.62 | 2.65 | 2.59 | 5.43 | 0.21 | 13.79 | 20.62 | 1.22 | 98.63 |
| To-3-1 | 7 | 51.41 | 0.23 | 0.40 | 17.70 | 8.75 | 0.12 | 2.21 | 1.62 | 6.86 | 100.33 |
| Phlogopite (N 8; 10; 12), annite (N 9; 11), muscovite (N 13) |
| To-1-2 | 8 | 39.34 | 11.40 | 1.68** | 12.28 | 20.16 | 10.44 | 95.22 |
| To-1-2 | 9 | 37.73 | 11.04 | 28.38 | 9.95 | 9.80 | 96.90 |
| To-4-2 | 10 | 37.13 | 6.32 | 15.12 | 8.52 | 19.80 | 9.18 | 96.07 |
| To-4-2 | 11 | 40.80 | 0.93 | 11.03 | 20.25 | 0.35 | 12.21 | 0.54 | 0.34 | 8.86 | 95.30 |
| To-5-1 | 12 | 37.25 | 5.08 | 16.72 | 9.78 | 19.59 | 8.98 | 97.40 |
| To-3-1 | 13 | 45.90 | 36.02 | 3.89 | 7.30 | 93.11 |
| Mesolite (N 14), natrolite (N 15; 16), chlorite (N 17), montmorillonite (N 18) |
| To-1-2 | 14 | 41.65 | 31.19 | 5.19 | 11.31 | 89.33 |
| To-1-2 | 15 | 46.62 | 27.78 | 1.95 | 14.71 | 91.06 |
| To-4-2 | 16 | 47.52 | 27.34 | 0.32 | 16.42 | 91.60 |
| To-5-1 | 17 | 33.91 | 15.61 | 13.42 | 22.59 | 1.63 | 87.16 |
| To-5-1 | 18 | 54.69 | 18.12 | 9.76 | 3.62 | 1.55 | 0.88 | 88.62 |
| Nepheline (N 19), orthoclase (N 20), albite (N 21), hyalophane (N 22; 23) |
| To-3-1 | 19 | 43.29 | 32.84 | 15.54 | 5.97 | 97.64 |
| To-3-1 | 20 | 64.25 | 19.81 | 1.29 | 14.75 | 100.10 |
| To-3-1 | 21 | 68.51 | 20.20 | 11.67 | 0.28 | 100.66 |
| To-3-1 | 22 | 47.31 | 30.73 | 10.9BaO | 1.18 | 7.52 | 1.08 | 98.77 |
| To-3-1 | 23 | 43.81 | 28.27 | 19.8BaO | 4.05 | 2.20 | 98.17 |
| Andradite (N 24; 26), schorlomite (N 25; 27) |
| To-1-2 | 24 | 34.86 | 3.24 | 2.23 | 26.21 | 34.37 | 100.91 |
| To-1-2 | 25 | 33.36 | 12.56 | 2.21 | 18.29 | 33.17 | 99.59 |
| To-4-2 | 26 | 34.16 | 2.95 | 14.01 | 12.17 | 1.84 | 35.01 | 100.14 |
| To-4-2 | 27 | 34.29 | 6.20 | 26.01 | 33.50 | 100.00 |

Note. * - the FeO$_3$ content is calculated using the stoichiometric formula of the mineral, ** - content of other element (F and BaO). Empty cells in tables 2-3 indicate that the element was not detected within sensitivity of microprobe analysis.

The rocks of the To-4 formation body differ from the melteigite bodies considered above by their greater magnesia content, but by a lower content of aluminum, calcium, and sodium (table 1), which is reflected in their mineral composition. Pyroxene is characterized by an increased proportion of enstatite minal (Wo$_{10.9}$En$_{55.46}$ Fs$_{35.13}$), phlogopite in general has a more magnesian composition, serpentinized olivine appears. The carbonate in them is represented by dolomite (figure 4A), mesolite typical for melteigites is replaced by a less calcic natrolite. Along with chromium (Cr$_2$O$_3$ up to 20%) titanomagnetites (5-13% TiO$_2$) there are also significantly titaniferous (0.5-7.5% TiO$_2$) chromespinelids (Cr$_2$O$_3$ 20-46%). All these chemical and mineral features bring these rocks closer to the picrites of alkaline grade and meimechites.

In alkaline syenites To-3-1, along with nepheline (figure 3B), orthoclase with microperthite ingrowths of albite and hyalophane containing up to 10-20% BaO is widely developed. Pyroxene is represented by aegirine, and rare small mica particles are represented by muscovite. Small (up to 10-
20 microns) inclusions of REE carbonate, similar in composition to calcinsite, are observed in the fresh nepheline-K-Na-FS of the groundmass of syenites. Also, larger (up to 150 microns) amoeba-shaped interstitial particles of wohlerite consisting of 30-32% SiO$_2$, 1-3.5 TiO$_2$, 25-27 CaO, 7-8 Na$_2$O, 14-17 ZrO$_2$ and 12-16 Nb$_2$O$_5$ were found.

### Table 3. Composition of REE carbonate.

| Sample  | N  | CaO | SrO |WO$_3$ | CeO$_3$ | La$_2$O$_3$ | Nd$_2$O$_3$ | Total | Mineral          |
|---------|----|-----|-----|-------|---------|-------------|-------------|-------|------------------|
| To-1-2  | 29-2 | 3,66 |     | 29,17 | 20,25   | 7,84        | 60,92      | calcinsite     |
| To-1-2  | 20-2 | 6,43 | 11,75| 20,84 | 12,62   | 4,70        | 56,34      | ambatoarinite  |
| To-1-2  | 27-2 | 5,62 | 18,01| 21,51 | 12,36   | 7,61        | 65,11      | ambatoarinite  |
| To-1-2  | 22-6 | 5,60 |     | 20,00 | 20,90   | 10,96       | 54,7        | La-Ce-tungustite|
| To-1-2  | 23-8 | 6,44 |     | 18,70 | 22,31   | 13,80       | 5,38        | La-Ce-tungustite|
| To-2-1  | 2-2  | 20,32| 9,06 | 19,25 | 8,71    | 57,34       |             | carbocernaite  |
| To-2-1  | 3-4  | 6,17 | 16,79| 27,84 | 13,31   | 64,11       |             | ambatoarinite  |
| To-2-1  | 20-7 | 3,17 | 19,57| 19,01 | 10,21   | 60,75       |             | ambatoarinite  |
| To-3-1  | 15-3 | 1,78 |     | 31,33 | 17,96   | 6,96        | 58,03      | calcinsite     |
| To-3-1  | 20-7 | 3,26 |     | 28,78 | 13,86   | 5,69        | 51,59      | calcinsite     |

**Figure. 4.** Compositions of main carbonate minerals (A) and rare carbonates of Sr and REE (B). 1 - from melteigites To-1-2; 2 - same with significant admixture Ce-itririumtungusite minal Ce, Nd, Y)W$_2$O$_6$(OH)$_2$; 3 - melteigites To-2-1; 4 - nepheline syenites To-3-1; 5 - pircites To-4-2; 6 - carbonatites To-5-1; 7 - apofoidolites and kamaforites of the Tomtor massif; 8 - stoichiometric compositions of carbonate minerals.

Apatite in the melteigites of the pipe bodies To-1 and To-2 occurs mainly in the form of idiomorphic elongated crystals of hexagonal cross-section in the groundmass of the rock, usually closely associated with ilmenite-titanomagnetite aggregates, as well as small (1-50 microns) sulfide minerals - pyrite and galena. The composition of the mineral corresponds to the fluorine-containing (F up to 2-2.4%) variety of apatite. In some analyses, the P$_2$O$_5$ content is reduced to 35-38% instead of the usual 40-42%, that is probably due to an increase in the amount of CO$_2$ and the appearance of carbonat-apatite or francolite in the presence of F >1%. In such cases, due to the inability to determine
the CO$_2$ content with the microprobe, the amount of analyses of carbonate apatites is steadily reduced to 90-88%. In the picrites of the To-4 sheet body and carbonatite of the To-5 dike, all apatites have a low content P$_2$O$_5$ 34-39% with a low amount 90-93%.

Carbonatite of the To-5 dike mainly consists of calcite with an increased admixture of FeO and MgO up to 4% of each oxide. Calcite is also in close intergrowth with chlorite and montmorillonite (table 2), which often record boxy zonal particles of leucoxene with a calcite core (figure 3C). Within the leucoxene shell, the smallest xenomorphic light inclusions enriched with TiO$_2$ up to ~40%, Ce$_2$O$_3$ up to ~20% and P$_2$O$_5$ up to ~10% are often observed. If we assume that due to the small size of the bright-light inclusions, the leucoxene matrix is partially captured by the microprobe beam, then the true composition of the inclusions themselves may correspond to Ce-monazite.

A remarkable characteristic feature of the alkaline picrites To-4 and carbonatites To-5 is the similarity in their compositions of chromium-titanium spinelides. In relic spinel cores in To-5 carbonatite (figure 3D), the content of Cr$_2$O$_3$ reaches 43% with the amount of TiO$_2$ 2-5%, and edges of the grains, with a decrease in the Cr$_2$O$_3$ content (up to 5-1%) of spinel, its TiO$_2$ content (up to 10-12%). The trends of changes in the spinelids of the Tomtor massif (figure 5) are similar to those of spinelids from the alkaline-ultrabasic rocks of the Guli massif [15], picrite gabbro-dolerites of the Norilsk region [16, 17] and the poor-diamond-bearing Malokuonamskaya kimberlite pipe [18] and other high-titaniferous alkaline picrite rocks of the Anabar region [6].
4. Conclusions
As a result of our research, we obtained new data on the typomorphic features of rock-forming, secondary, accessory and ore minerals of silicate igneous rocks of the Tomtor massif, and associated carbonatite formations. The multiphase formation of different petrogeochemical types of magmatites and carbonatites with different degrees of mineralization complicates the development of petrogenetic predictive-exploring criteria for evaluating different types of mineralization. At the same time, the presence of similar mineral series that are contained in all different rocks and ores, for example, Cr-Ti-spinelides, rare metal and other ore phases with similar trends in composition changes, has been established. The identification of mineralogical criteria for the genetic relationship between silicate melts and related carbonatite derivatives in the future will allow us to adequately assess the scale of different types of mineralization of the complicate Tomtor complex.

According to V. S. Shkodzinsky's model of fractionation of the Earth's global magmatic ocean [20], alkaline-ultrabasic, kimberlite, carbonatite, and lamproite magmas are residual melts that occur during the solidification of the lower picrite and peridotite layers of the magmatic ocean. Thus, during multiple tectonic-magmatic movements in the north of the Siberian Platform, a unique combination of alkaline-ultrabasic, kimberlite, carbonatite, high-Ti alkaline and tholeiitic basites of different ages occurred. They are generated in the lithosphere and therefore form complex aggregates of different ages, but spatially combined, similar to the Tomtor massif. Their formation began, in our opinion, with the disintegration of the Rodinia supercontinent, which began in the Neoproterozoic [21] and continued in the Middle Paleozoic and Permian-Triassic.

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Table 4. Representative analyzes of Cr-Ti-spinels and magnetites.

| Sample | N   | TiO₂ | Al₂O₃ | Cr₂O₃ | Fe₂O₃ | FeO  | MnO | MgO | Total |
|--------|-----|------|-------|-------|-------|------|-----|-----|-------|
| To-4-1 | 9-116 | 3,54 | 6,03  | 45,76 | 11,58 | 24,86 | 0,40 | 6,86 | 99,03 |
| To-4-1 | 16-116 | 0,55 | 11,71 | 35,46 | 21,47 | 20,00 | 0,36 | 8,60 | 98,15 |
| To-4-1 | 18-116 | 7,45 | 5,36  | 30,58 | 19,67 | 28,31 | 0,49 | 6,58 | 98,44 |
| To-4-1 | 22-116 | 6,89 | 7,79  | 18,64 | 33,13 | 18,86 | 0,48 | 12,51 | 98,30 |
| To-4-1 | 285-183 | 9,19 | 6,36  | 7,56  | 36,86 | 31,97 | 0,94 | 4,66 | 97,54 |
| To-4-1 | 283-183 | 7,35 | 0,22  | 1,31  | 54,10 | 28,61 | 0,80 | 5,03 | 97,42 |
| To-5-1 | 9-179 | 2,12 | 14,68 | 43,26 | 9,00  | 16,97 | 0,44 | 11,94 | 98,41 |
| To-5-1 | 20-1 | 2,28 | 23,67 | 31,91 | 10,71 | 16,25 | 0,32 | 13,74 | 98,88 |
| To-5-1 | 23-4 | 5,31 | 21,72 | 23,84 | 14,68 | 21,62 | 0,55 | 11,88 | 99,60 |
| To-5-1 | 4-5  | 5,38 | 5,04  | 17,12 | 36,14 | 29,85 | 1,12 | 4,35 | 98,97 |
| To-5-1 | 20-9 | 12,03 | 0,37 | 1,11 | 45,80 | 35,92 | 1,55 | 2,99 | 99,77 |
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