

Ultrapotassic Aluminosilicate Melts: Specifics of Formation by the Example of Synnyrites from the Synnyr Massif

L.I. Panina , E.Yu. Rokosova, M.A. Ryabukha

*V.S. Sobolev Institute of Geology and Mineralogy, Siberian Branch of the Russian Academy of Sciences,
pr. Akademika Koptyuga 3, Novosibirsk, 630090, Russia*

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Abstract—To reveal the formation conditions of synnyrites in the Synnyr alkaline pluton, we studied melt inclusions in the minerals of shonkinites and pseudoleucite syenites, in apatite segregations in pyroxenites, shonkinites, and synnyrites, and in the minerals of later monchiquite–camptonite dikes. Based on the obtained and earlier published data, a conclusion has been drawn that all plutonic rocks of the massif formed from the same parental alkali-basaltic magma during long-term crystallization differentiation and fractionation in a closed system excluding a release of volatile components. Similar minerals in the rocks crystallized at similar temperatures in the same sequence: clinopyroxene (1280–1150 °C) → leucite (1250–1200 °C) → K-feldspar (1200–1180 °C) ↔ apatite (above 1180–1050 °C) → nepheline and kalsilite. The composition of the parental magma during crystallization evolved toward an increase in Si, Al, and K contents and a decrease in Fe, Mg, and Ca contents, i.e., toward melaphonolite and phonolite melts. The differentiation and fractionation processes led to the separation of minerals according to their specific gravity: Heavy minerals (clinopyroxene, ore minerals, and apatite) descended to the bottom of the magma chamber, forming the lower melanocratic series, and light minerals (leucite, K-feldspar, and foids), together with the residual melt, accumulated in the upper horizons of the chamber, forming the upper leucocratic series of rocks. During crystallization, the amount of fluids increased. At 920–830 °C, the fluids contained 3033–4051 mg/kg CO₂, 397–644 mg/kg H₂O, and 42.7–83.7 mg/kg CO. At the early high-temperature stage, when the amount of fluids was insignificant, the trend of magma transformation coincided with the trend of basaltoid crystallization. This fact is evidenced by the homogenization temperatures and chemical composition of inclusions in the minerals of monchiquite–camptonites and alkali basaltoids, similar to those in the plutonic rocks of the massif. Clinopyroxene crystallized in dike rocks at 4.58 kbar at a depth of 10–12 km. At the stage of crystallization of feldspars, when the amount of fluids in melts significantly increased during the formation of plutonic rocks and drastically decreased during the formation of basaltoids, the formation trends of these rocks became different. The trend of basaltoid crystallization was directed toward trachyte melts with an increase in Si contents and a decrease in Fe, Mg, Al, and alkali contents. During the formation of plutonic rocks of the massif, the high water pressure prevented the formation of plagioclase, and the melts became more enriched in Al and K and acquired a high-alumina ultrapotassic composition, forming kalsilite–nepheline–K-feldspar synnyrites at the final stages of transformation. A conclusion has been drawn that synnyrites crystallized from the residual products of differentiation and fractionation of alkali-basaltic magma in the temperature range slightly above 1050–1180 °C in a closed system excluding a release of volatiles. The occasional occurrence of synnyrites is due to the limited natural occurrence of closed magma chambers, macroanalogs of inclusions of mineral-forming media in minerals.

Keywords: synnyrite; melanocratic rocks; apatite segregations; melt inclusions; alkali-basaltic magma; volatile components; water; closed chamber

INTRODUCTION

Synnyrites are rare ore rocks, hololeucocratic and dense, consisting of K-feldspar (55–85 vol.%), kalsilite (up to 35 vol.%), nepheline (up to 10 vol.%), and scarce biotite grains (1–2 vol.%). The chemical composition of synnyrites includes up to 22–23 wt.% Al₂O₃ and 16.5–21.0 wt.% K₂O, which makes it possible to use these rocks as a raw material in the production of alumina and chlorine-free potassium fertilizers. As a part of ultrapotassic complex plutons, synnyrites make up the upper leucocratic series of rocks together

with pseudoleucite and nepheline syenites. Such massifs also contain lower meso- and melanocratic series made up of micaceous pyroxenites, shonkinites, and, less frequently, olivine–monticellite–pyroxene rocks (Malyi Murun massif). Ultrapotassic complex massifs occur mainly in the territory of Russia, mostly in the Baikal–Stanovoi rift system of the Siberian craton (Kostyuk, 1990; Kostyuk et al., 1990). Here they are represented by the Synnyr, Yaksha, and Sakun high-potassium alkaline massifs, formed at the stage of Paleozoic magmatism. In smaller amounts synnyrites are observed in the Malyi Murun, Lomamskii, and Dezhnev volcanoplutons, formed in the Mesozoic Era. In other countries, synnyrites are known in Greenland (Brooks et al., 1981) and the Reguibat Rise of the West African Craton, located in southern Morocco and Mauritania (Bea et al., 2014). The

 Corresponding author.

E-mail address: panina@igm.nsc.ru (L.I. Panina)

latter are the oldest formations (Archean–Proterozoic Eons) and are comparable in size to the Synnyr massif.

As for the genesis of synnyrites, opinions differ. Their unique chemical composition, which is similar to the composition of leucite, gave origin to contradictory hypotheses. The origin of synnyrites in the Reguibat Rise of the West African Craton was explained by the researchers (Bea et al., 2014) in the following way. They think that initially, water-poor mafic ultrapotassic magma crystallized beneath the already stabilized Archean crust of the Awsard–Tichla zone at 10–16 kbar. From this magma, at 1100 °C, leucite started to crystallize and ascended to the upper part of the magma chamber. Later this chamber was intruded by the water-rich and more sodic magma that appeared in the same part of the metasomatized mantle source. At the final crystallization stages, the aqueous vapor phase separated from it melted the leucite cap, turning it into low-dense hydrous leucite-like magma. Crystallization of this magma led to the formation of synnyrites and nepheline syenites. At the same time, there exist other opinions as to the origin of synnyrites in ultrapotassic massifs of Russia. Zhidkov (1980, 1986) admits the possibility of the occurrence of ultrapotassic melts in nature from which synnyrites could crystallize. Andreev (1965) thinks that such melts could be the result of the melting of leucite accumulated in the upper parts of the magma chamber during the slow cooling of the initial melt. More reasonable is the hypothesis of the formation of synnyrites from potassium alkali-basaltic magma as a result of long-term processes of its differentiation and fractionation in specific conditions that are similar to those of closed systems excluding a release of volatiles (first of all, H₂O) (Panina, 1983; Kostyuk et al., 1986, 1990). The closed nature of the system and the enrichment of melts with water during the formation of ultrapotassic plutons are indicated by the presence of biotite and hornblende in melanocratic rocks and among the daughter melts in minerals. The main evidence of the alkali-basaltic composition of initial melts is the fact that partially crystallized inclusions in pyroxenes contain potassium alkaline basaltoids of residual glasses of different ages and localizations, which are similar in composition to high-alumina potassium-rich syenites and synnyrites (Chepurov et al., 1974; Bazarova et al., 1981). An assumption was made that melts of this composition might be a result of crystallization differentiation of alkali-basaltic magma under the conditions of magma chambers, which are macroanalogs of melt inclusions in minerals.

Researchers generally agree that many facts indicate a genetic relationship between alkali-basaltic magma and ultrapotassic synnyrite massifs: (a) the same set of high-temperature minerals, ruling out feldspars, which are represented by plagioclase in basaltoids and by potassium feldspar in plutonic rocks; (b) similar temperatures and crystallization sequence of the same-name minerals; (c) the same trend of transformation of high-temperature melts conserved in minerals, which is in all cases directed toward an increase in the contents of Si, Al, and alkalis and a decrease in Mg, Fe,

and Ca contents; and (d) the similarity of the chemical composition of residual glasses in partially crystallized inclusions in clinopyroxene of alkaline basaltoids to the composition of high-alumina potassium-rich syenites and synnyrites.

There was no direct evidence of the presence of a large number of volatile components (especially water) during the formation of synnyrites. It was also necessary to find direct evidence of the formation of melts of synnyrite composition during the evolution of alkali-basaltic magma. To obtain this information, we made an attempt to study inclusions in the minerals of melanocratic rocks of the lower meso- and melanocratic series from the Synnyr massif in the form of large blocks of shonkinites and micaceous pyroxenites and to analyze inclusions in potassium feldspar of pseudoleucite syenites as well as in apatite from pyroxene–biotite–magnetite–apatite segregations in micaceous pyroxenites, shonkinites, and synnyrites. All the above-listed plutonic rocks and segregations, according to (Kostyuk, 1983; Kostyuk et al., 1986; Panina et al., 1991; Sharygin and Panina, 1993), are genetically related to each other and are derivatives of parental alkali-basaltic magma crystallized in closed conditions. Hence, the obtained information must reflect the evolutionary transformation of this magma and clarify, as it was assumed earlier (Panina, 1983; Kostyuk et al., 1990), the occurrence of ultrapotassic high-alumina melts at the final stages of crystallization.

In addition, we studied younger dikes of monchiquite–camptonites from the massif, which, by definition, belong to the derivatives of alkali-basaltic magmas. We think that the study of dikes will help us to reveal the specific features of transformation of alkali-basaltic magma during the crystallization in a more open magmatic system and to compare the obtained results with those during the formation of plutonic rocks of the massif.

To determine the composition and amount of fluids contained in ultrapotassic melts, we also conducted a chromatographic analysis of synnyrites.

GEOLOGY OF THE SYNNYR MASSIF

The Synnyr pluton is part of the North Baikal alkaline province, and it occurs in the Baikal rift zone, served as the intrusion ways of alkaline melts, among which potassium-rich magmas played the leading part. The Synnyr massif occupies the high-mountain part of the Synnyr Ridge. The massif is of isometric shape with a cross section of up to 25 km (Fig. 1). According to geophysical and geological concepts (Zhidkov, 1978, 1980; Kostyuk et al., 1990; Orlova et al., 1993), it has a laccolith, mushroom shape. The massif formed as a result of intrusion of two phases: early laccolith intrusion of high-potassium foidite syenites, covering an area of about 500 km², and later diapir stock of pulaskite–hedrumites with an area of about 90 km². The stock is localized inside the laccolith and is noticeably shifted to the southwest relative to the center of the massif. The lac-

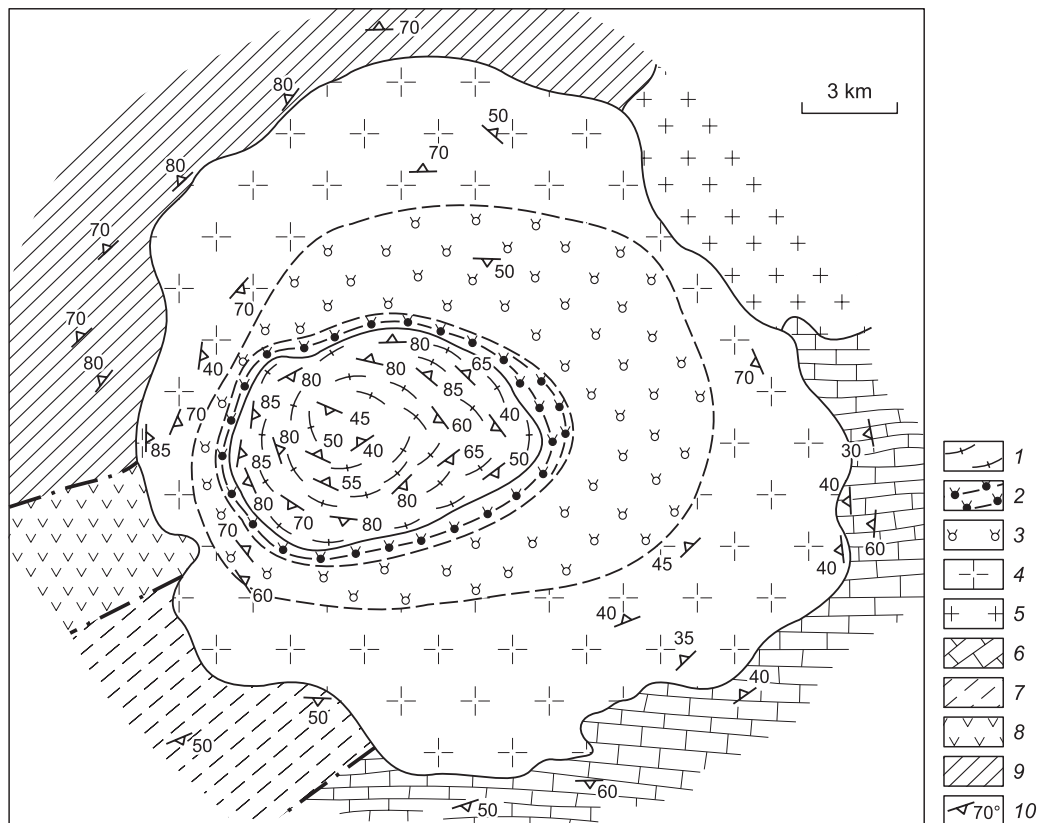


Fig. 1. Geologic scheme of the Synnyr massif (Kostyuk et al., 1990). 1, pulaskite and hedrumite of the second intrusive phase; 2–4, nepheline-kalsilite syenite of the first intrusive phase: 2, synnyrite of the inner zone; 3, synnyrite of the intermediate zone; 4, nepheline syenite, foyaite, and porphyry pseudoleucite syenite of the outer zone; 5, granitoid of the Vitimkan complex; 6, limestone of the Kookta Formation; 7, sandstone, siltstone, and conglomerate of the Kholodnaya Formation; 8, effusive rocks of basic composition from the Synnyr Formation; 9, effusive rocks of intermediate composition from the Synnyr Formation; 10, bedding attitude.

colith of the intrusive phase is a zonal–annular body. It is divided into three petrographic–petrochemical zones: outer, intermediate, and inner, which is in contact with the pulaskite–hedrumite stock. The outer zone is made up of mainly nepheline syenites (foyaite, itsindrite¹, i.e., veined biotite–aegirine nepheline syenite, and ditroites¹) with high contents of Al_2O_3 (17.5–20.0 wt.%) and alkalis (11–16 wt.%) and predominance of potassium over sodium. Near the northern endocontact (Kuikipuri Creek), there is a small body of pseudoleucite syenites with K_2O content about 15 wt.%. The inner annular zone of the laccolith consists mainly of synnyrites containing 16–21 wt.% K_2O and 22–23 wt.% Al_2O_3 . The intermediate zone of the laccolith has an asymmetric structure with the thickness varying from 2 to 7–8 km. Among these rocks, both ditroites and pseudoleucite syenites and synnyrites occur.

In the rocks of the early intrusive phase (mainly in synnyrites), occasionally ultrabasic–basic melanocratic varieties

occur in the form of bodies of different shapes (schlieren, beds, lenses, and layers) and sizes: from tens of centimeters to several meters in thickness and from tens of meters to 1–2 km in length.

Melanocratic rocks are represented mainly by shonkinites, more frequently by micaceous pyroxenites. Most of the shonkinites are concentrated in the northeastern part of the intrusion, in the Kalyumnyi area. The bodies of shonkinites occur concordantly with the common dip of the annular structure of synnyrites, which is directed toward the center of the massif. The studies of V.V. Sharygin and L.I. Panina (1993) show that the small bodies of shonkinites are homogeneous. In the largest bodies, the central zones are made up of micaceous pyroxenites up to 0.5–3.0 m in thickness, which are replaced toward host synnyrites by shonkinites turning into melapulaskites and pulaskites. From top to bottom of the section, the relative thickness of the layers enriched in salic minerals decreases, whereas that of the layers enriched in femic minerals increases. Geophysical data from (Kostyuk et al., 1990; Panina et al., 1991) show that melanocratic rocks make up the near-bottom part of the magma chamber and, at both the Sakun and Malyi Murun massifs, form lower meso- and melanocratic rock

¹ As all the works on synnyrites in Russia were carried out in the 1960s–1990s, the classification of rocks adopted at that time (Andreeva et al., 1984) was used for their description, and for the adequate perception of the literature published at that time we kept the same names of rocks.

Table 1. Chemical composition of rocks of the Synnyr massif (wt.%)

No.	Rock	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	BaO	Total
1	Micaceous pyroxenite	43.49	1.88	9.28	15.01	0.30	9.20	12.60	0.81	3.65	1.30	0.41	97.93
2	Shonkinite	50.00	0.95	12.00	10.05	0.23	7.00	9.50	1.50	7.00	0.55	0.00	98.78
3	Pulaskite	55.43	0.98	15.02	7.07	0.12	2.95	4.98	3.25	7.32	0.29	0.72	98.43
4	Foyaite	54.50	1.20	17.50	8.75	0.11	0.25	5.00	4.50	6.00	0.23	0.00	98.04
5	Itsindrite	55.58	0.50	22.13	2.73	0.04	0.59	0.91	5.89	10.12	0.07	0.00	98.66
6	Ditroite	55.43	0.30	22.11	1.23	0.02	0.50	1.02	2.65	13.57	0.15	0.00	99.89
7	Pseudoleucite syenite	54.92	0.14	22.89	1.82	0.01	0.21	0.62	1.27	16.52	0.07	0.03	98.50
8	Synnyrite	54.82	0.16	22.52	1.57	0.01	0.58	0.72	1.57	16.50	0.06	0.17	98.68
9	Synnyrite	54.88	0.05	23.20	1.02	0.02	0.24	0.27	0.72	18.38	0.03	0.00	98.81

Note. Including (wt.%) No. 3 – 0.35 F; No. 5 – 0.19 F; No. 7 – 0.24 F.

series. In shonkinites and micaceous pyroxenites, apatite associated with clinopyroxene, biotite, potassium feldspar, and magnetite is found in the form of patches, schlieren, and streaky impregnations. Apatite builds up diverse bodies, frequently of irregular shape, with a thickness of up to a few meters and a length of a few tens of meters. Similar accumulations but significantly smaller in number and size are also observed in pseudoleucite syenites and synnyrites.

The geologic age of the nepheline syenites and synnyrites determined by Rb–Sr dating is 330 ± 4 – 311 ± 1 Ma. The age of pulaskites of the second intrusive phase obtained from K–Ar dating is 305 ± 12 Ma (Kostyuk et al., 1990).

The massif also includes a late dike series of potassium basaltoid rocks consisting of monchiquite–camptonites, which occur along the zones of long-lived deep faults of northwestern strike (Gorstka and Krapivin, 1969). Their shape is platelike with distinct sharp contours 0.3–2.0 m thick and 50–300 m long and the age of 170–190 Ma.

The chemical composition of the main types of rocks from the Synnyr massif is given in Table 1, based on the data from (Yashina, 1982; Kostyuk et al., 1990; Sharygin and Panina, 1993).

BRIEF MINERALOGIC AND PETROGRAPHIC CHARACTERISTICS OF THE STUDIED ROCKS

Micaceous pyroxenites are medium-grained rocks consisting of 65–70 vol.% idiomorphic grains of clinopyroxene, 20–25 vol.% biotite, 3–5 vol.% grains and chadacrysts of apatite, and about 1% faceted grains of magnetite and rare xenomorphic grains of potassium feldspar. Chadacrysts of apatite are contained in the grains of clinopyroxene and biotite.

Shonkinites have a medium-, fine-grained, and, more rarely, porphyric texture owing to the presence of poikilocrystals of potassium feldspar and amphibole. Their composition is as follows: 40–50 vol.% idiomorphic grains of clinopyroxene, 15–20 vol.% biotite, 20–30 vol.% xenomorphic potassium feldspar, about 1 vol.% nepheline, and up to 2 vol.% hypidiomorphic grains of apatite and magnetite. Occasionally garnet (up to 5 vol.%) is also present.

The magnetite–biotite–apatite rocks forming schlieren-like bodies in pyroxenites, shonkinites, and synnyrites have a variable mineral composition. The central parts of the body consist of apatite or a biminerals biotite–apatite aggregate. The peripheral parts commonly contain up to 50 vol.% apatite, 25 vol.% biotite, and 20–25 vol.% magnetite. In the central and peripheral parts of the apatite bodies, about 1–3 vol.% titanite and 1 vol.% potassium feldspar are occasionally present. Apatite occurs in the form of large grains and grains of different sizes among which biotite, magnetite, potassium feldspar, and titanite are observed.

The data of V.V. Sharygin and L.I. Panina (1993) show that the chemical composition of the same-named minerals in micaceous pyroxenites, shonkinites, and magnetite–biotite–apatite ores is similar. *Clinopyroxene* composition corresponds to the composition of diopside–salite and contains a minor amount of aegirine endmember. In micaceous pyroxenites, the mineral has a lower iron content than that in shonkinites: $100\text{Fe}/\text{Fe} + \text{Mg} + \text{Mn} = 23$ – 35 mol.% versus 39 – 56 mol.%. *Biotite* is enriched in TiO₂ (1.6–3.6 wt.%) and BaO (0.5–2.1 wt.%). Its iron content insignificantly increases from pyroxenites to shonkinites ($100\text{Fe}/\text{Fe} + \text{Mg} + \text{Mn} = 59.4$ – 62.4 mol.%). In *potassium feldspar* the ratio of orthoclase to albite varies from 74 : 26 to 90 : 10. The mineral contains up to 1.5–3.0 wt.% BaO and 0.2–0.9 wt.% SrO. *Garnet* is represented by titanian andradite–melanite. *Apatite* refers to F-apatite and contains 0.5–2.9 wt.% SrO.

Pseudoleucite syenites are dense fine-grained rocks with pseudoleucite phenocrysts, occasionally partially faceted (Kostyuk et al., 1990). The number of phenocrysts varies from 10–15 to 20–60 vol.%, with sizes varying from 5 to 20 mm. The main mineral of the rock is hypidiomorphic potassium feldspar (90–95%), which is to a varying degree intergrown with kalsilite and nepheline. More or less idiomorphic grains of nepheline were found in a minor (1–2%) amount. The rock contains clinopyroxene (diopside–salite) and biotite and accessory titanite, titanomagnetite, and apatite.

Camptonites consist of fine-grained groundmass and small phenocrysts of clinopyroxene, biotite, amphibole, and olivine. The groundmass contains mainly plagioclase as

well as clinopyroxene, biotite, apatite, and magnetite. **Monchiquite** is represented by the phenocrysts of clinopyroxene and amphibole, rare grains of olivine, and glassy groundmass that contains microliths of amphibole, clinopyroxene, and analcime. Gorstka and Krapivin (1969) report that *clinopyroxene* is titanian augite and *amphibole* is barkevikite in composition.

METHODS

To reconstruct the physicochemical conditions for the formation of synnyrites of the Synnyr massif, along with traditional geological, mineralogical, and petrographic methods, we widely used *melt and fluid inclusion study*. The heating and homogenization experiments with the melt inclusions were carried out using the heating stage with a silite heater equipped with a microscope, which allows inclusions to be heated up to 1350–1400 °C with a constant control of changes taking place in the inclusions. The heating stage was calibrated by clearly fixed melting temperatures of chemically pure salts and noble metals. Temperature measurement accuracy was ± 10 –15 °C. Owing to the increased decrepitation of inclusions, the cooling was conducted slowly for 5–6 h and was frequently stopped after melting of the last daughter phase and a decrease in the size of the gas bubble, and then quenched.

The chemical composition of rock-forming minerals, daughter phases, and glass in heated and unheated inclusions was determined using *microprobe analysis*. The analysis was performed on the Camebax-micro X-ray microanalyzer at the Center for Collective Use of Multielement and Isotope Research of the V.S. Sobolev Institute of Geology and Mineralogy (Novosibirsk). The probe beam diameter was no more than 2–3 μm ; accelerating voltage was 20 kV; and current was 30–40 nA. We used the international standards of minerals and glasses. The detection limits of elements were estimated as follows (wt.%): SiO₂, 0.009; TiO₂, 0.036; Al₂O₃, 0.012; FeO, 0.019; MgO, 0.013; MnO, 0.022; CaO, 0.010; Na₂O, 0.020; K₂O, 0.010; BaO, 0.105; SrO, 0.019; P₂O₅, 0.008; Cl, 0.011; SO₃, 0.011. The error rate of X-ray spectral analysis on the microanalyzer did not usually exceed $\pm 1.5\%$. To reveal the qualitative and quantitative composition of volatiles present in the crystallized melt at certain temperatures, we used the gas chromatography method developed at V.S. Sobolev Institute of Geology and Mineralogy. The procedure allows quantitative determination of CO₂, H₂O, CO, H₂, O₂ + Ar, N₂, H₂S, SO₂, and hydrocarbons from methane (CH₄) to pentane (C₅H₁₂) in the same sample. The essence of the method is to register gases released from inclusions on heating and decrepitation. During the analysis, a mineral or rock sample (200 mg, fraction 0.25–0.50 mm) was placed into a capsule and connected to the vacuum system. After pumping out the air, the sample was gradually heated up to 1000 °C. During the heating process, inclusions decrepitate and gas is released from them.

The released gas causes vacuum loss of the system, which is recorded by the sensor. The heating temperature of the sample and the temperature at which the gases enter the system are determined with a thermometer. The continuously working vacuum pump brings the incoming gas into the analyzing system consisting of three serial LKhM-80 chromatographs. Here the gases are separated on the basis of different physicochemical interaction with the sorbing agent of the chromatographic column and their qualitative and quantitative determination is performed.

MELT INCLUSIONS IN MINERALS

In clinopyroxene of shonkinites, potassium feldspar of pseudoleucite syenites, and apatite segregations in the **plutonic rocks** of the Synnyr massif, we detected silicate, salt, and gas–liquid inclusions, which most frequently occur simultaneously. The largest numbers of inclusions are contained in apatite, and the smallest number, in potassium feldspar. Silicate inclusions mainly occur in clinopyroxene, potassium feldspar, and, to a lesser degree, apatite, in which salt inclusions prevail. Silicate and salt inclusions in minerals are arranged randomly, occasionally in groups, rarely singly, and belong to primary inclusions. The gas–liquid inclusions occur in through cracks and are secondary inclusions. The aim of our study is to analyze primary silicate inclusions present in the minerals under consideration. Salt and gas–liquid inclusions were studied in the special manuscript of L.I. Panina and L.M. Usol'tseva (2003).

Before proceeding to the discussion of silicate inclusions in minerals, let us mention their specific feature: regardless of the presence of inclusions in a mineral, most of them decrepitate on heating, especially at temperatures close to those of the homogenization of the content. This made the research extremely difficult, especially in determining the chemical composition of inclusions, and significantly decreased the volume of obtained information.

In **clinopyroxenes** of *shonkinites*, silicate inclusions occur as small groups, up to 7–10 individuals in sight. Clinopyroxene is represented by salite (Table 2, analyses 1–3). The shapes of the inclusions are different: elongated, isometric, and rounded. The size varies from 3 to 15 μm . The content of the inclusions is mainly fine-crystallized. Among daughter phases of the inclusions, biotite (Table 2, analysis 10) and calcite (52.14 wt.% CaO, 2.24 wt.% FeO, and 2.01 wt.% SrO) were detected. Biotite contained about 3 wt.% TiO₂ and 0.4 wt.% BaO, and calcite, up to 2 wt.% SrO. On heating, the content of the inclusions begins to melt at about 760–780 °C, at 820 °C a gas bubble is formed, and the total melting of daughter phases takes place at 1180–1190 °C. With a further increase in temperature, the gas bubble at first starts moving but then drastically decreases in size and disappears at 1235–1280 °C. The chemical composition of homogenized inclusions is similar to the composition of melaphonolites of the potassium type of alkalinity, with 0.5–1.2 wt.% TiO₂ (Table 3, analyses 1–3).

Table 2. Chemical composition of clinopyroxene, amphibole, biotite, potassium feldspar, and apatite (wt.%)

Oxid	Clinopyroxene							Amphibole		Biotite		Potassium feldspar	Apatite		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO ₂	50.07	50.32	51.66	53.74	54.94	45.89	46.85	38.63	38.34	35.33	36.25	63.50	0.00	0.00	0.00
TiO ₂	0.64	0.53	0.31	0.08	0.12	3.03	2.35	5.94	4.71	2.94	3.45	0.08	0.00	0.00	0.00
Al ₂ O ₃	2.65	2.45	3.93	0.68	0.70	8.65	5.80	13.46	14.50	13.81	16.63	19.50	0.00	0.00	0.00
FeO	14.92	13.22	13.10	4.51	4.51	7.58	7.41	11.88	13.27	21.60	18.93	0.03	0.00	0.00	0.00
MnO	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
MgO	8.69	9.82	9.14	16.42	16.03	12.23	13.77	11.72	10.23	11.19	10.21	0.00	0.00	0.00	0.00
CaO	20.46	21.89	20.05	22.78	22.56	21.78	21.99	11.67	11.88	0.63	0.73	0.01	53.51	54.26	53.42
Na ₂ O	2.35	1.64	2.94	0.39	0.40	0.62	0.53	2.40	2.57	0.15	0.96	0.50	0.19	0.23	0.22
K ₂ O	0.01	0.01	0.01	0.00	0.00	0.01	0.00	1.53	1.50	9.17	7.88	14.01	0.01	0.04	0.00
P ₂ O ₅	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	39.47	39.93	38.91
BaO	0.00	0.00	0.00	0.00	0.00	0.15	0.05	0.27	0.16	0.42	0.00	2.46	0.07	0.00	0.00
Total	99.91	99.87	100.14	98.60	99.26	99.94	98.76	97.50	97.16	95.25	95.04	100.09	98.81*	97.86*	97.71*

Note. 1–8, 12–15, host minerals; 9–11, daughter phase in inclusion. Rocks: 1–3, 10, shonkinites; 4–9, 11, monchiquites–camptonites; 12, pseudoleucite syenites. Apatite from the segregations in 13, micaceous pyroxenite; 14, shonkinite; 15, synnyrite.

*Including (wt.%) No. 13 – 2.56 SrO, 2.86 F; No. 14 – 0.49 SrO, 2.90 F; No. 15 – 2.17 SrO, 2.93 F.

Table 3. Chemical composition of silicate melt inclusions in minerals of plutonic (1–11) and dike (12–16) rocks from the Synnyr massif (wt.%)

No.	Host mineral	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	BaO	SrO	SO ₃	Cl	F	Total
1	Cpx	52.38	1.20	9.86	10.52	3.98	14.62	2.83	3.06	0.03	0.00	0.25	0.00	0.00	0.00	98.73
2	Cpx	52.95	1.18	10.84	8.24	4.62	12.34	2.20	5.62	0.08	0.02	0.00	0.00	0.00	0.00	98.09
3	Cpx	54.54	0.47	13.06	7.90	2.77	9.33	3.92	5.09	0.03	0.00	0.10	0.00	0.00	0.00	97.27
4	Kfs	55.64	0.16	22.56	0.84	0.08	1.56	2.80	12.35	0.10	2.20	0.00	0.00	0.00	0.00	98.29
5	Ap	56.69	0.00	23.16	0.07	0.00	2.61	2.09	13.59	0.23	0.00	0.00	0.00	0.00	0.00	98.44
6	Ap	53.86	0.00	23.30	0.12	0.00	2.17	3.52	15.24	0.59	0.00	0.00	0.12	0.17	0.13	99.22
7	Ap	54.44	0.00	23.05	0.16	0.00	1.28	3.87	15.04	0.30	0.06	0.00	0.00	0.06	0.04	98.30
8	Ap	55.11	0.00	22.00	0.08	0.00	1.12	2.66	14.99	0.05	0.00	0.00	0.00	0.00	0.00	96.41
9	Ap	53.82	0.14	22.42	0.00	0.01	1.75	2.48	16.53	0.35	0.00	0.01	0.00	0.00	0.00	97.52
10	Ap	53.09	0.00	23.30	0.11	0.00	1.20	2.53	15.91	0.60	0.00	0.00	0.08	0.18	0.37	97.37
11	Ap	53.65	0.00	21.90	0.00	0.00	0.73	1.93	17.16	0.29	0.02	0.00	0.00	0.39	0.00	96.19
12	Cpx	54.75	1.00	20.15	4.76	1.90	7.41	4.57	5.34	0.00	0.03	0.00	0.00	0.00	0.00	99.91
13	Cpx	55.53	0.24	21.60	1.96	0.97	3.30	4.77	4.94	0.00	0.07	0.00	0.00	0.00	0.00	93.38
14	Cpx	55.53	0.26	21.93	1.66	1.00	3.53	4.83	5.69	0.00	0.08	0.00	0.00	0.00	0.00	94.51
15	Cpx	56.06	0.11	22.87	0.90	0.32	1.77	4.54	7.48	0.00	0.11	0.00	0.00	0.00	0.00	94.16
16	Amp	55.02	0.10	22.45	0.68	0.17	2.95	4.59	7.52	0.58	0.07	0.00	0.00	0.00	0.00	94.13

Note. Melt inclusions in minerals from 1–3, shonkinite; 4, pseudoleucite syenite; 5–11, apatite schlieren and segregations from synnyrite (5, 9, 11), pyroxenite (6, 7, 10), shonkinite (8); 12–16, monchiquite–camptonite. Melt inclusions: 1–4, homogenized, 5–11, heated up to 1050–1180 °C and quenched; 12–16, unheated (12, glassy melt inclusion; 13–16, residual glass of partially crystallized melt inclusions).

In **potassium feldspar** silicate inclusions were found in *pseudoleucite syenites*. The composition of potassium feldspar is virtually sodium-free with 2.4 wt.% BaO (Table 2, analysis 12). Inclusions in potassium feldspar are small: from 5 to 20 μm, of rounded, elongated, and irregular shapes. The content of the inclusions is finely crystallized and is represented by colorless and greenish daughter phases and ore mineral. Melting of daughter phases was observed at about 800 °C. With a further increase in temperature, the ore phase becomes rounded, and a gas bubble appears. At 1000–

1025 °C, daughter phases melt intensely; most of the inclusions decrepitate; and cracks in the minerals appear. We could homogenize only single smallest inclusions at 1180 ≤ 1215 °C. The chemical composition of quenched inclusions corresponds to that of potassium phonolites (Table 3, analysis 4) and is similar to the composition of ditroites from the Synnyr massif (Table 1, analysis 6).

In **apatite** (Table 2, analyses 13–15) from *apatite segregations* in synnyrites, shonkinites, and micaceous pyroxenites, silicate inclusions have an irregular and partially fac-

eted shape. They are mainly finely crystallized. A gas bubble is typically absent. The daughter phase in the inclusions begins to melt at about 670–830 °C. At 750–860 °C, a gas bubble is formed. At 1000–1070 °C, daughter phases melt completely, and at 1050–1180 °C, most of the inclusions decrepitate. Supposedly, the homogenization temperature of the inclusions is slightly higher than 1200 °C. Similar temperatures were earlier recorded during the homogenization of inclusions in apatite which was present in the rocks from the Sakun, Malyi Murun, and Khani massifs (Panina et al., 1991). The chemical composition of the glass of the inclusions quenched at the temperature of complete melting of daughter phases varies from leucite–phonolite (Table 3, analyses 5–8) to residual ultrapotassic high-alumina (Table 3, analyses 9–11), which is, respectively, similar to the composition of pseudoleucite syenites and synnyrites of the massif under study.

Thus, the obtained data indicate that synnyrites formed from the residual differentiated melts of ultrapotassic high-alumina composition in the temperature range slightly higher than 1050–1180 °C. The widespread decrepitation of melt inclusions in the minerals of the studied rocks suggests that the melts were significantly enriched with fluids at the early magmatic stage and their amount during crystallization did not decrease but, on the contrary, increased.

In the **dikes** of *monchiquite–camptonites*, melt inclusions were found in clinopyroxene and amphibole. All of them are silicate varieties. **Clinopyroxene** of *monchiquite–camptonites* contains glassy and partially crystallized inclusions. The composition of host clinopyroxene varies from diopside to augite (Table 2, analyses 4, 5 and 6, 7, respectively). The partially crystallized inclusions consist of glass, brown and colorless daughter phases, and a gas bubble. The brown daughter phases of the inclusions in augite are represented by amphibole, and in diopside, by biotite. Amphibole is kaersutite in composition and contains 4.7 wt.% TiO₂ and 0.16 wt.% BaO (Table 2, analysis 9). Biotite has a high (3.45 wt.%) content of TiO₂ (Table 2, analysis 11). In the inclusions, melting of the glass takes place at 730–760 °C; of colorless daughter phases, at about 800 °C; and of brown phases, at 830 °C. Intense melting of daughter phases occurs at 1000–1100 °C. At these temperatures, decrepitation of inclusions frequently occurs. We managed to homogenize only very small inclusions at 1210–1255 °C.

Glassy inclusions in clinopyroxene of *monchiquites* occasionally contain liquid and gaseous CO₂. On cooling, liquid CO₂ undergoes metastable crystallization at –100, –102 °C, and its melting is observed on heating to –56.6 °C. The homogenization of carbon dioxide into a liquid the density of which is 0.725 g/cm³ occurs at +24 °C (Vargaftik, 1972). The homogenization temperatures of glassy inclusions, which correspond to 1200–1215 °C, indicate that the pressure of melt at the moment of trapping it by clinopyroxene was 4.58 kbar (Shmonov and Shmulovich, 1975; Tomilenko et al., 1977).

As most of the inclusions decrepitate on heating and only very small inclusions were homogenized, we chemically analyzed unheated glassy inclusions (Table 3, analysis 12) and residual glasses in partially crystallized inclusions (Table 3, analyses 13–15) in the minerals of monchiquite–camptonites. Their chemical composition reflects that of differentiates remaining after the partial crystallization of trapped melt in the closed vacuole. The analyses show that the glass has a K–Na phonolite composition, in which the amount of Al₂O₃ reaches 20–22 wt.% and that of alkalis reaches 10–11 wt.% with a minor dominance of K over Na. This composition is close to the intermediate composition of foyaite–itsindrites from the Synnyr massif (Table 1, analyses 4, 5).

In *monchiquites* silicate inclusions were also detected in **amphibole kaersutite** (Table 2, analysis 8). The inclusions are single, of rounded shape, partially faceted; their content is glassy and partially crystallized. The glassy inclusions contain a gas bubble that starts to grow at 700–750 °C, attains maximum sizes at 1100 °C, and then diminishes. At 1180 °C the inclusions become dark and decrepitate. The chemical composition of residual unheated partially crystallized inclusions also corresponds to K–Na phonolite and includes up to 0.6 wt.% P₂O₅ (Table 3, analysis 16).

Thus, the composition of residual glasses in partially crystallized inclusions present in clinopyroxene and amphibole of monchiquite–camptonites was found to be similar to the composition of high-alumina high-potassium rocks—synnyrite and nepheline syenites from the Synnyr pluton,—as it was earlier revealed in alkaline basalts from different regions of the world (Panina, 1983).

CHROMATOGRAPHIC STUDIES

Chromatographic analysis was used to study synnyrites and to obtain data on the composition of fluids during their formation at certain temperature intervals, starting from 1000 °C. The analysis showed (Table 4) that the composition of the fluids was simple, with a limited amount of CO₂, CO, and H₂O gases. Minor amounts of N₂, CH₄, and hydrocarbons were also present. The highest content of fluids is present at 920–890 °C. Among volatile components were 4051.0–1751.8 mg/kg CO₂, 643.6–377.0 mg/kg H₂O, and 83.7–42.7 mg/kg CO. When the temperature dropped, the amount of fluids, especially CO₂, decreased drastically and water became dominant over carbon dioxide. The drastic decrease in the content of CO₂ was, most likely, due to carbonate–silicate liquid immiscibility, which resulted from the accumulation of a high content of carbon dioxide and other volatiles in the silicate melt. The occurrence of liquid carbonate–silicate immiscibility during the formation of the Synnyr rocks was discussed in detail in the work of L.I. Panina and L.M. Usol'tseva (2003). Indirect evidence for this also comes from the presence of carbonate–salt inclusions in the minerals of the rocks under study. For alka-

Table 4. The fluid phase composition of inclusions in synnyrite minerals

No.	Heating <i>T</i> , °C	Content, mg/kg									
		CO ₂	H ₂ O	H ₂	N ₂	CH ₄	CO	H ₂ S	SO ₂	C ₂ H ₂	NH ₃
1	920	4051.0	396.8	0.0	0.0	0.0	83.7	0.0	0.0	trace	0.0
2	900	1751.8	377.0	0.0	trace	0.0	52.8	0.0	0.0	trace	0.0
3	890	3032.9	643.6	0.0	0.0	0.0	42.7	0.0	0.0	0.0	0.0
4	870	365.5	179.6	0.0	trace	0.0	30.8	0.0	0.0	0.0	0.0
5	850	284.3	212.9	0.0	0.0	0.0	28.8	0.0	0.0	0.0	0.0
6	830	334.6	129.0	0.0	trace	0.0	60.6	0.0	0.0	0.0	0.0
7	780	78.9	173.5	0.0	0.0	0.0	11.7	0.0	0.0	0.0	0.0
8	620	56.2	105.0	0.0	trace	1.4	2.4	0.0	0.0	trace	trace
9	600	25.2	173.7	0.0	0.0	1.2	trace	0.0	0.0	0.0	0.0
10	580	33.9	81.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	440	6.5	106.7	0.0	0.0	0.0	3.3	0.0	0.0	0.0	0.0
12	350	8.9	97.0	0.0	5.6	0.0	3.6	0.0	0.0	0.0	0.0

line magmas, as it was revealed in the study of fluid inclusions in the minerals of different rocks (Solovova et al., 1996; Nielsen et al., 1997; Panina and Usol'tseva, 1999), the carbonate–silicate immiscibility is a common evolutionary process. A more uncommon feature for alkaline silicate melts is the presence of water at the high-temperature stage. The role of water and its amount during the formation of ultrapotassic high-alumina melts responsible for the formation of synnyrites will be discussed below.

DISCUSSION

The melt inclusion study showed that clinopyroxene in shonkinites from the Synnyr massif crystallized at 1280–1235 °C; potassium feldspar in pseudoleucite syenites, at 1200–1180 °C; apatite from schlieren in shonkinites and patches in micaceous pyroxenites and synnyrites, at about 1180–1050 °C. Similar crystallization temperatures of the same-name minerals were earlier revealed in some rocks from the Synnyr and other ultrapotassic massifs (Kostyuk et al., 1990; Panina et al., 1990). Crystallization of clinopyroxene in micaceous pyroxenites and ditroites from the Synnyr massif was observed at 1280–1190 and 1210–1150 °C, respectively; in pyroxenites and shonkinites from the Sakun massif, at 1310–1280 and 1280–1260 °C, respectively; in pyroxenites from the Malyi Murun massif, at 1280–1210 °C. Crystallization of apatite contained in pyroxenites from the Sakun and Malyi Murun massifs took place at 1240–1200 and 1200 °C, respectively (Panina et al., 1991). Moreover, we detected the crystallization temperature (1360–1290 °C) of olivine in pyroxene–melilite–olivine rocks of the Malyi Murun massif (Panina et al., 1989) and the temperatures of formation of leucite (1250–1200 °C) and nepheline in pseudoleucite and nepheline syenites (1100–880 °C) of the Synnyr pluton (Panina, 1978). Hence, it can be concluded that, regardless of the rock composition, the same-name minerals in these massifs crystallized at similar temperatures accord-

ing to the following scheme: olivine → clinopyroxene ↔ leucite → potassium feldspar ↔ apatite → nepheline. This indicates that all the rocks from ultrapotassic massifs crystallized from the parental magma of the same composition during its evolutionary transformation.

It was also found that clinopyroxene in monchiquite–camptonites crystallized at 1255–1210 °C and 4.58 kbar, i.e., virtually at the same temperatures as clinopyroxene in shonkinites. Similar crystallization temperatures of minerals of the same name and a similar sequence of formation were also earlier found for alkaline basaltoids from different regions of the world. Data from (Polyakov et al., 1985; Kostyuk et al., 1990) showed that minerals in potassium alkaline basaltoids are formed in the following sequence: olivine (≥1400–1280 °C) → clinopyroxene (1380–1180 °C) ↔ leucite (1350–1150 °C) → plagioclase (1220–1180 °C) → biotite ↔ apatite (1240–1200 °C).

The obtained data show that crystallization of minerals during the formation of rocks of the Synnyr massif was accompanied by a decrease in the Fe, Mg, and Ca contents and increase in the Si, Al, and K contents of the melt. It was revealed that during crystallization of clinopyroxene in shonkinites, the melts had a melaphonolite composition (Table 3, analyses 1–3). It is noteworthy that in the Sakun massif clinopyroxene in earlier pyroxenites crystallized from more mafic tephrite melt (Kostyuk et al., 1990). Potassium feldspar in the Synnyr pseudoleucite syenites formed from potassium-rich phonolite melts (Table 3, analysis 4). During crystallization of apatite, the melts became more and more differentiated, more high-alumina, ultrapotassic, and more similar in composition to pseudoleucite syenites and synnyrites (Table 3, analyses 5–11). Melts compositionally similar to synnyrites formed at temperatures slightly higher than 1050–1180 °C at the final stages of the transformation of parental magma. This was the first direct evidence that synnyrites formed from magmatic melts at the final stages of the crystallization of parental magma and the first direct data on the composition and spe-

cific features of transformation of high-alumina potassic melts during the formation of synnyrites.

It is reported in (Kostyuk et al., 1990; Panina et al., 1990; Kamenetsky et al., 1995; Cioni et al., 1998; Lima, 2000; Isakova et al., 2019) that alkali-basaltic magmas trapped in inclusions also evolved through tephrite and melaphonolite toward phonolite melts. The analyzed residual glasses in partially crystallized inclusions in clinopyroxene and amphibole of monchiquite–camptonites have a phonolite composition (Table 3, analyses 12–16).

The similar crystallization temperature of minerals with the same name, formed in the same sequence of crystallization, and similar compositions of differentiated fractions of crystallized melts during the formation of the rocks from the Synnyr massif and residual glasses of inclusions in the minerals of alkaline basaltoids proved the earlier conclusion on the similarity of composition of their parental magmas.

Based on the revealed sequence of mineral formation, we tried to trace the trend of evolution of parental magma during its crystallization and formation of rocks of the Synnyr massif (Fig. 2, Table 3). It is clearly seen in Fig. 2 that during the successive crystallization of minerals in magma, the content of FeO, MgO, and CaO decreased and the amount of SiO₂, Al₂O₃, and K₂O increased, forming a common evolutionary trend. This trend confirms again that all the studied rocks crystallized from the same parental magma during its differentiation and fractionation. Assuming its alkali-basaltic

composition, we tried to plot the compositions of residual glasses from melt inclusions hosted in the minerals of monchiquite–camptonites to confirm their comparability and unidirectional transformation during crystallization (Fig. 2). It was found that residual melts not only do not distort the transformation trend of parental magma, but even somewhat supplement it. This is strong evidence that parental magma responsible for the formation of the rocks of the Synnyr massif had an alkaline mafic composition and the formation of the synnyrites is related to its long-term evolutionary transformation in closed conditions (e.g., macrovacuoles of inclusions) that exclude loss of volatiles.

This conclusion is also confirmed by plotting the obtained results on the Al₂O₃–FeO–K₂O diagram (Fig. 3), which shows the composition of alkaline basaltoids and their residual glasses from inclusions in minerals (Panina, 1983). On the diagram, the compositions of poorly differentiated melts from inclusions in clinopyroxene of shonkinites (A–C, corresponding to Table 3, analyses 1–3) plot in field I of alkali basalt. Slightly more differentiated melts (D) conserved in glassy inclusions in clinopyroxene of monchiquite–camptonites (Table 3, analysis 12) plot between the fields of basaltoids and residual glasses of inclusions. The compositions of residual glasses from inclusions in clinopyroxene and amphibole of monchiquite–camptonites (Table 3, analyses 13–16), together with those of the melts conserved in the potassium feldspar of pseudoleucite syenites

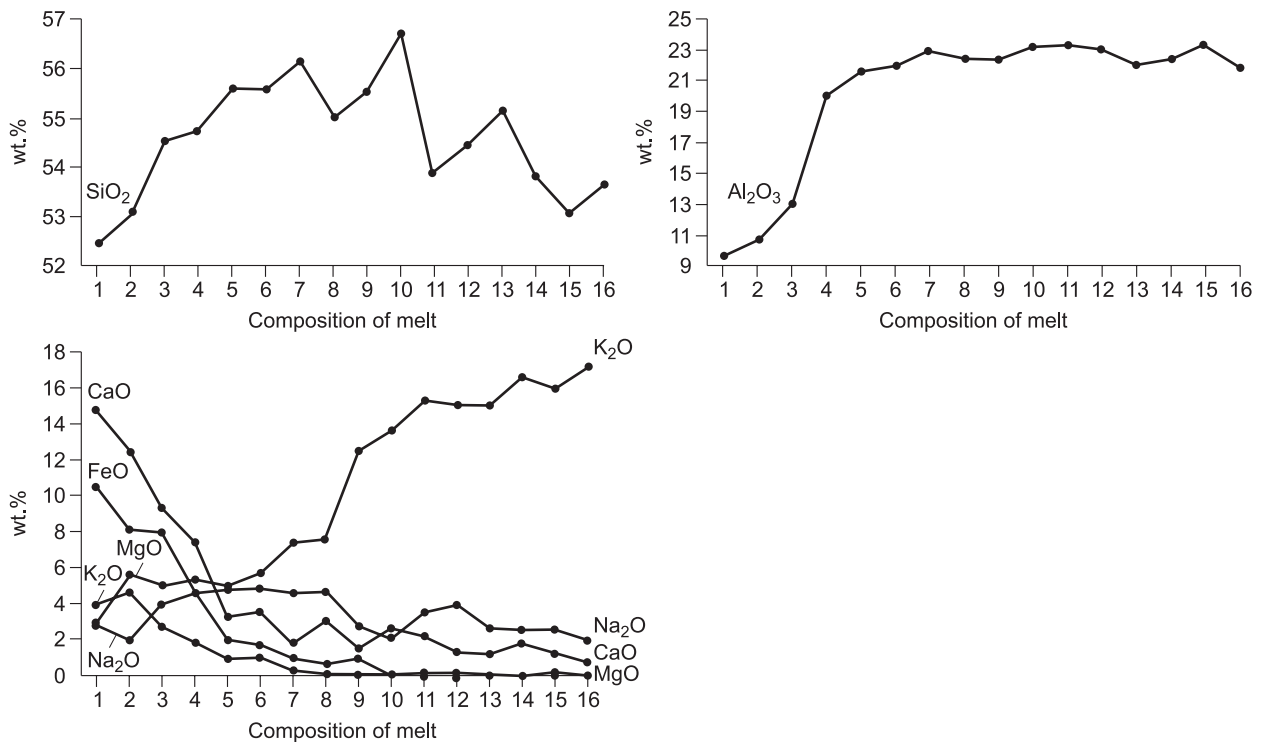


Fig. 2. Evolutionary transformation of the parental magma during the formation of the Synnyr massif rocks. The composition of melt from the melt inclusions in: 1–3, clinopyroxene of shonkinites (Table 3, analyses 1–3); 4–7, clinopyroxene of monchiquite–camptonites (Table 3, analyses 12–15); 8, amphibole of monchiquites (Table 3, analysis 16); 9, potassium feldspar of pseudoleucite syenites (Table 3, analysis 4); 10–16, apatite from apatite segregations in pyroxenites, shonkinites, and synnyrites (Table 3, analyses 5–11).

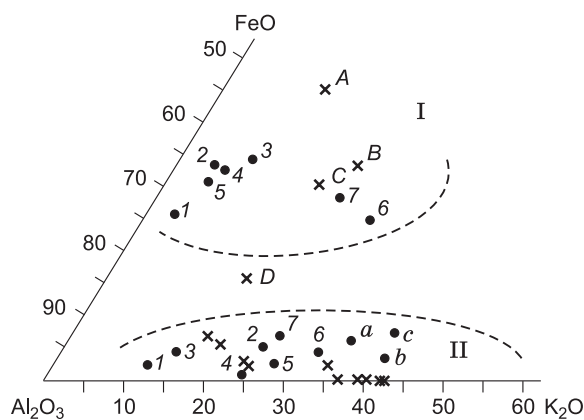


Fig. 3. Al_2O_3 – FeO – K_2O diagram for the compositions of alkaline basaltoids (I), residual glasses (II), and mineral-hosted melts of the Synnyr rocks. 1, pyrolite (Goryachegorsk massif); 2, alkali basalt (Bol'shoi Anyui); 3, olivine trachybasalt; 4, analcime tephrite; 5, analcime basalt (southern Armenia); 6, ferugite–porphyry (the Eastern Pamirs); 7, olivine pseudoleucitite (Central Aldan); a, nepheline syenite of the Synnyr massif; b, synnyrite of the Synnyr massif; c, synnyrite of the Sakun massif. Melt inclusions in the minerals of the Synnyr rocks: A–C, in clinopyroxene of shonkinites; D, glassy inclusions in clinopyroxene of monchiquites–camptonites. The cross marks the inclusions in potassium feldspar of pseudoleucite syenites, apatite from segregations in synnyrites, pyroxenites, and shonkinites, and residual glasses from inclusions in clinopyroxene and amphibole of monchiquites–camptonites.

and apatite from segregations (Table 3, analyses 4–11), plot in field II of the residual glasses of inclusions contained in the minerals of alkaline basaltoids (crosses on the diagram).

The formation of synnyrite-bearing massifs in closed systems, which exclude loss of volatiles and contribute to their accumulation during crystallization of parental alkali-basaltic magma, is indicated by the results of our chromatographic studies of synnyrites. At the final stages of formation of ultrapotassic massifs at 920–890 °C, the melts contained up to 1752–4051 mg/kg CO_2 , 42.7–83.7 mg/kg CO, and 377–644 mg/kg H_2O . Such amounts of volatiles, especially that of H_2O , which is several times higher than that in alkali-basaltic magmas (Polyakov et al., 1974, 1985), significantly influenced the trend of further transformation of crystallized melts.

During crystallization of plutonic rocks in closed conditions, the increased water pressure, according to the experiments of H.S. Yoder, Jr., and K. Tilley (1962), fostered the increase in the amount of Al in the melt and prevented the crystallization of plagioclase, instead of which potassium feldspar formed. In addition, data of experimental study of the K_2O – Na_2O – SiO_2 system (Scarfe et al., 1966) showed that the increasing water pressure also narrowed the field of formation of leucite, increasing the amount of K_2O in the melts. At $P_{\text{H}_2\text{O}} = 8.4$ kbar, instead of leucite, co-crystallization of kalsilite and potassium feldspar, which are the main components of synnyrites, took place. During crystallization of alkaline basaltoids, the evolution of magma owing to the loss of volatiles in the open magmatic system typically con-

tinues toward considerable enrichment of residual melts with Si and depletion with Mg, Fe, Ca, and alkalis. Plagioclase crystallizes from melts, and transformation of magma is mostly limited by the trachyte barrier.

One of the reasons for the scarce occurrence of synnyrites in nature is the predominant crystallization of alkali-basaltic magmas in more or less open systems, which fosters the separation of fluids containing a certain amount of water from melt. In rare cases, conditions similar to those of closed systems appear in nature when fluids are accumulated during crystallization and the processes of differentiation and fractionation of melts proceed to the end, as in microinclusions, with the enrichment of residual melts with Al and K. Only in these exceptional cases can the final products of transformation of potassium basaltoid magma acquire the composition similar to that of synnyrites.

On the basis of the obtained and earlier published data, the formation of ultrapotassic synnyrite-bearing massifs can be described as follows. All the rocks of ultrapotassic massifs formed from alkali-basaltic magmas during the intra-chamber differentiation and fractionation in closed systems that prevent loss of volatiles. Crystallization of each mineral phase led to the alteration of the chemical composition of the remaining portions of parental melt, which evolved toward an increase in Si, Al, and K contents and a decrease in Mg, Fe, and Ca contents—from tephrite to melaphonolite and phonolite compositions. Owing to the closed nature of the system, crystallized melts were enriched with fluids. High water pressure prevented the formation of plagioclase and fostered the accumulation of alumina and alkalis and crystallization of potassium feldspar. The calm tectonic environment during a long period of time allowed minerals to crystallize and to separate according to their specific gravity. As a result, heavy minerals (olivine, clinopyroxene, and apatite, as well as ore minerals) descended to the bottom of the magma chamber, forming lower meso- and melanocratic rock series from cumulative layers and lenses of pyroxenites and shonkinites containing apatite segregations. After the deposition of heavy minerals, the upper leucocratic series of rocks formed from differentiated melts accumulated in the upper horizons of the magma chamber. The continued evolutionary transformation in closed systems contributed to a further increase in Al and K contents and to the ultrapotassic high-alumina composition of residual melts, from which synnyrites crystallized. High water pressure in the magma chamber promoted the co-crystallization of kalsilite and potassium feldspar instead of leucite.

CONCLUSIONS

The whole homodromic series of rocks of ultrapotassic synnyrite massifs formed from a single alkali-basaltic magma of the potassium type of alkalinity during the long-term differentiation and fractionation in closed conditions that exclude loss of water and other volatiles.

Crystallization of magma, as in the formation of volcanic rocks, started from the separation of feric minerals at similar (about 1300 °C) temperatures, in the same sequence with an increase in Si, Al, and K contents and a decrease in Mg, Fe, and Ca contents in differentiated melts with the evolution toward tephrite, melaphonolite, and phonolite compositions.

During fractionation, heavy minerals descended to the bottom of the magma chamber, forming lower meso- and melanocratic rock series, and the upper leucocratic series of rocks formed from ascending differentiated melts.

The amount of water and other volatiles, which increased during the crystallization of magma, prevented the crystallization of plagioclase and fostered a further increase in Al and K contents in the melt up to the formation of high-alumina ultrapotassic residual melts, from which synnyrites formed, at the final stages.

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REFERENCES

- Andreev, G.V., 1965. Petrology of the Synnyr Alkaline Pluton [in Russian]. Ulan-Ude.
- Andreeva, E.D., Kononova, V.A., Sveshnikova, E.V., Yashina, R.M., 1984. Igneous Rocks, Vol. 2: Alkaline Rocks [in Russian]. Nauka, Moscow.
- Bazarova, T.Yu., Kostyuk, V.P., Khmel'nikova, O.A., 1981. Features of the formation of alkaline basalts of the Bol'shoi Anyui (tributary of the Kolyma). Dokl. Akad. Nauk SSSR 259 (5), 1192–1194.
- Bea, F., Montero, P., Haissen, F., Rjimati, E., Molina, J.F., Scarrow, J.H., 2014. Kalsilite-bearing plutonic rock: The deep-seated Archean Awasard massif of the Reguibat Rise, South Morocco, West African Craton. Earth Sci. Rev. 138, 1–24, doi: [10.1016/j.earsci-rev.2014.08.003](https://doi.org/10.1016/j.earsci-rev.2014.08.003).
- Brooks, C.K., Fawcett, J.J., Gittins, J., Rucklidge, J.C., 1981. The Babbage complex, east Greenland: a unique ultrapotassic Caledonian intrusion. Can. J. Earth Sci. 18 (2), 274–285, doi: [10.1139/e81-021](https://doi.org/10.1139/e81-021).
- Chepurov, A.I., Bazarova, T.Yu., Lavrent'ev, Yu.G., Pokachalova, O.S., 1974. Composition of magmatic melt inclusions in minerals of fergusonite-porphyr (Eastern Pamir) and pseudoleucites (Central Aldan). Dokl. Akad. Nauk SSSR 218 (5), 1185–1188.
- Cioni, R., Marianelli, P., Santacroce, R., 1998. Thermal and compositional evolution of the shallow magma chambers of Vesuvius: Evidence from pyroxene phenocrysts and melt inclusions. J. Geophys. Res. B: Solid Earth 103 (B8), 18,277–18,294.
- Gorstka, V.N., Krapivin, A.G., 1969. Vein formations, in: Geologic Structure and Apatite Content of the Synnyr Alkaline Massif [in Russian]. Nauka, Leningrad.
- Isakova, A.T., Panina, L.I., Stoppa, F., 2019. Formation conditions of leucite-bearing lavas in the Bolsena Complex (Vulsini, Italy): Research data on melt inclusions in minerals. Russ. Geol. Geophys. 60 (2), 119–132, doi: [10.15372/RGG2019009](https://doi.org/10.15372/RGG2019009).
- Kamenetsky, V., Métrich, N., Cioni, R., 1995. Potassic primary melts of Vulsini (Roman Province): evidence from mineralogy and melt inclusions. Contrib. Mineral. Petrol. 120 (2), 186–196, doi: [10.1007/BF00287116](https://doi.org/10.1007/BF00287116).
- Kostyuk, V.P., 1983. The potassic alkalic magmatism of the Baikal–Aldan belt. Sov. Geol. Geophys. 24 (5), 31–39.
- Kostyuk, V.P., 1990. The Baikal–Stanovoi riftogenic structure and the position of alkaline magmatism in it. Sov. Geol. Geophys. 31 (4), 20–25.
- Kostyuk, V.P., Bazarova, T.Yu., Panina, L.I., Vavilov, M.A., 1986. On the differentiation of alkalic basaltoid magmas and the possible formation of natural high-potassium melts. Sov. Geol. Geophys. 27 (2), 75–81.
- Kostyuk, V.P., Panina, L.I., Zhidkov, A.Ya., Orlova, M.P., Bazarova, T. Yu., 1990. Potassic Alkaline Magmatism of the Baikal–Stanovoi Rift System [in Russian]. Nauka, Novosibirsk.
- Lima, A., 2000. Experimental study on silicate-melt inclusions in clinopyroxene phenocrysts from Roccamonfina lavas (Italy). Mineral. Petrol. 70 (3–4), 199–220, doi: [10.1007/s007100070003](https://doi.org/10.1007/s007100070003).
- Nielsen, T.F.D., Solovova, I.P., Veksler, I.V., 1997. Parental melts of melilitolite and origin of alkaline carbonatite: evidence from crystallised melt inclusions, Gardiner complex. Contrib. Mineral. Petrol. 126 (4), 331–344, doi: [10.1007/s004100050254](https://doi.org/10.1007/s004100050254).
- Orlova, M.P., Zhidkov, A.Ya., Orlov, D.M., Zotova, I.F., 1993. The internal structure and formation of the Synnyr alkaline massif (northern Baikal area). Geokhimiya, No. 8, 1161–1181.
- Panina, L.I., 1978. Crystallization temperatures for pyroxene and leucite in alkaline rocks of the Synnyr pluton. Sov. Geol. Geophys. 19 (6), 42–47.
- Panina, L.I., 1983. Formation of high-potassium melts rich in aluminium. Sov. Geol. Geophys. 24 (4), 34–39.
- Panina, L.I., Usol'tseva, L.M., 1999. Alkaline high-Ca sulfate-carbonate melt inclusions in melilite-monticellite-olivine rocks of the Malomuruskii alkaline massif (Aldan). Petrologiya 7 (6), 610–625.
- Panina, L.I., Usol'tseva, L.M., 2003. The problem of carbonatite formation in the Synnyr alkaline massif (northern Baikal area), in: Proc. III Int. Workshop “Plumes and Problem of Deep Sources of Alkaline Magmatism” [in Russian]. Khabarovsk, pp. 75–87.
- Panina, L.I., Motorina, I.V., Sharygin, V.V., Vladykin, N.V., 1989. Biotite pyroxenites and melilite-monticellite-olivine rocks of the Malomurunian alkaline massif (Yakutiya). Sov. Geol. Geophys. 30 (12), 41–51.
- Panina, L.I., Sharygin, V.V., Motorina, I.V., 1990. Mica pyroxenites as products of early stages of evolution of potassium alkali magma (on the example of the Malomurun alkali massif, Aldan shield). Sov. Geol. Geophys. 31 (3), 68–75.
- Panina, L.I., Sharygin, V.V., Proshenkin, I.E., 1991. Apatite contents of potassium alkaline massifs. Sov. Geol. Geophys. 32 (1), 91–99.
- Polyakov, A.I., Naumov, V.B., Romanchev, V.P., 1974. Conditions of formation of rocks according to the data of thermometric studies, in: The East African Rift System [in Russian]. Nauka, Moscow, Vol. 3, pp. 179–183.
- Polyakov, A.I., Turkov, V.A., Murav'eva, N.S., Nesmeyanova, L.I., Ignatenko, K.I., 1985. Physicochemical conditions of processes of generation and evolution of basalt magmas of the Baikal rift zone. Geokhimiya, No. 1, 41–58.
- Scarfe, C.M., Luth, W.C., Tuttle, O.F., 1966. An experimental study bearing on the absence of leucite in the plutonic rocks. Am. Mineral. 51 (5–6), 726–735.
- Sharygin, V.V., Panina, L.I., 1993. Melanocratic rocks of the Kalyumny area (the Synnyr alkaline basin). Russ. Geol. Geophys. 34 (8), 92–100.
- Shmonov, V.M., Shmulovich, K.I., 1975. Molar volumes and equations of state for CO₂ between 100–1000 °C and 2000–10,000 bars. Dokl. Akad. Nauk SSSR 217 (4), 935–938.

- Solovova, I.P., Girmis, A.V., Ryabchikov, I.D., 1996. Inclusions of carbonate and silicate melts in minerals of alkali basaltoids from the East Pamirs. *Petrologiya* 4 (4), 319–341.
- Tomilenko, A.A., Berdnikov, N.V., Karsakov, L.P., 1977. Cryometry of inclusions in the rocks of the Chogar deep metamorphic complex (Eastern Siberia). *Dokl. AN SSSR* 234 (5), 1189–1192.
- Vargaftik, N.B., 1972. *Thermophysical Properties of Gases and Liquids, a Reference Book* [in Russian]. Nauka, Moscow.
- Yashina, R.M., 1982. *Alkaline Magmatism in Orogenic Areas* [in Russian]. Nauka, Moscow.
- Yoder, H.S., Jr., Tilley, C.E., 1962. Origin of basalt magmas: An experimental study of natural and synthetic rock systems. *J. Petrol.* 3 (3), 342–532, doi: [10.1093/petrology/3.3.342](https://doi.org/10.1093/petrology/3.3.342).
- Zhidkov, A.Ya., 1978. Typification and distribution of potassic-alumina ores at the Synnyr alkaline massif. *Dokl. Akad. Nauk SSSR* 246 (5), 1140–1143.
- Zhidkov, A.Ya., 1980. Ultrapotassic salic branch of intrusive alkaline rocks, in: *Petrology* [in Russian]. Nauka, Moscow, pp. 81–95.
- Zhidkov, A.Ya., 1986. Synnyrites—new complex raw materials. *Priroda*, No. 5, 96–101.