The Canadian Mineralogist
Vol. 34, pp. 265-280 (1996)

ALKALINE ROCKS OF THE TURIY PENINSULA, RUSSIA, INCLUDING TYPE-LOCALITY TURJAITE AND TURJITE: A REVIEW

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ABSTRACT

The Turiy Massif, emplaced during the late Devonian, forms part of the Kola Alkaline Province, Russia. It consists of five magmatic centers, with three spatially related phases of dyke activity. Rock types range from pyroxenite to SiO_2-undersaturated alkaline rocks, including melilitolite, late-stage carbonatite and phoscorite. The great diversity of rock types can be explained by crystal fractionation coupled with metasomatic activity. We present results of new electron-microprobe analyses of minerals from turjaite (a nepheline melilitolite) and turjite (an alkaline lamprophyre) from the type locality at Turiy. The turjaite contains Na-saturated and Fe^{3+}-bearing melilite, phlogopite, nepheline or cancrinite, with lesser amounts of diopside, titanian andradite, calcite, apatite, magnetite, *REE*-rich perovskite and a number of accessory phases. Mineralogical and compositional changes in the mineral assemblages noted in two samples of turjaite are interpreted as the product of a differentiating magma body, with possible additional increase in Na and volatiles during the final stages of magmatic activity. Turjite is part of the syn-massif-emplacement stage of dyke activity and may relate, compositionally, to the reaction between a late-stage ijolite – urtite and carbonatite. The modal mineralogy of turjite includes phlogopite and biotite, garnet of the schorlomite – andradite series, primary calcite, interstitial analcime and cancrinite with lesser magnetite, apatite, perovskite and aegirine and possible relict nepheline. A more SiO_2-rich sample also contains celsian, ilmenite and titanite.

Keywords: turjaite, turjite, carbonatite, alkaline rocks, electron-microprobe data, Turiy Massif, Kola Peninsula, Russia.

SOMMAIRE

Le massif de Turiy, d'âge dévonien supérieur, fait partie de la province magmatique alcaline de Kola, en Russie. Il est composé de cinq centres magmatiques et de trois phases d'activité filonnienne associées. On y trouve pyroxénite et une suite sous-saturée en silice, y compris mélilitolite, et, dans les stades tardifs, carbonatite et phoscorite. La grande diversité dans cette suite de roches s'expliquerait par cristallisation fractionnée avec les influences d'une activité métasomatique. Nous présentons des données nouvelles, obtenues par microsonde électronique, sur la composition des minéraux de la turjaïte, c'est-à-dire, mélilitolite à néphéline, et turjite, type de lamprophyre alcalin, dont c'est la localité-type. La turjaïte contient une mélilite saturée en Na qui contient Fe^{3+}, phlogopite, néphéline ou cancrinite, avec des quantités moins importantes de diopside, andradite titanifère, calcite, apatite, magnétite, pérovskite enrichie en terres rares, et plusieurs minéraux accessoires. Les variations minéralogiques et chimiques qui distinguent deux échantillons de turjaïte seraient dues à la différenciation d'un magma, avec ajout possible de Na et d'une phase volatile vers la fin de l'activité magmatique. La turjite fait partie d'un cortège d'injections filonniennes accompagnant l'intrusion du massif. Ce genre de roche pourrait être lié, dans sa composition, à une réaction entre un magma ijolitique ou urtitique tardif et une venue carbonatitique. L'assemblage de minéraux de la turjite typique comprend phlogopite et biotite, grenat de la série schorlomite–andradite, calcite primaire, analcime et cancrinite interstitielles, avec une proportion moindre de magnétite, apatite, pérovskite, et aegyrine, et peut-être des reliques de néphéline. Un échantillon plus riche en silice contient aussi celsian, ilménite et titanite.

(Traduit par la Rédaction)

Mots-clés: turjaïte, turjite, carbonatite, roches alcalines, données de microsonde électronique, massif de Turiy, péninsule de Kola, Russie.

INTRODUCTION

Of the many alkaline provinces related to continental rifting, the Kola Alkaline Province in Russia is one of the most extensive. It has been the subject of intense scrutiny by Russian geologists for more than sixty years, mainly because of the large deposits of apatite, magnetite, and phlogopite, as well as the rare-earth elements (*REE*) and Nb associated with some of the syenitic and carbonatitic complexes. The Kola peninsula, which forms part of the northeastern section of the Baltic Shield, was intruded during the Paleozoic by a series of alkaline magmas now represented by plutonic bodies from 1 to 40 km in diameter, including Khibina, the largest agpaitic body containing the largest accumulation of apatite yet found on Earth. The Paleozoic Kola province (Fig. 1) covers an area of more than 100,000 km^2 that extends westward from Finland across to the eastern part of the Kola Peninsula. The emplacement of some twenty-four ultrabasic and alkaline complexes, along with numerous dykes, was controlled by rifting perpendicular to and along the northwest–southeast-trending Proterozoic structures of the Kola Peninsula. The Kandalaksha Graben follows the Kandalaksha Deep Fracture zone (one of the most prominent structural features of the eastern Baltic Shield), and extends across the White Sea from Kandalaksha Bay to Archangelsk, a distance of about 300 km. The Kandalaksha fracture zone is considered to control the spatial distribution of the Sökli carbonatite complex in Finland and the Kovdor, Kandagubskii and Turiy complexes further to the east (Fig. 1). For a general review of the Paleozoic complexes of the Kola Peninsula, the reader is referred to the books by Kukharenko *et al.* (1965) and Kogarko *et al.* (1995) and the summary papers of Gerasimovsky *et al.* (1974) and Kogarko (1987).

Rb–Sr dates from many of these complexes are fairly restricted (360 to 380 Ma) and are considered to be close to the ages of intrusion (Kramm *et al.* 1993). Few carbonatitic and syenitic complexes are known to be of this age outside of Russia, although some found along the eastern margin of the Omineca Belt in the Canadian Cordillera (Pell 1994) are of about the same age.

The Turiy (Turi, Turii, Turij, Tur'ya, Turja) Peninsula is situated along the Terskii coast (34°44′E, 66°62′N), just to the south of the Kandalaksha deep-fracture zone on the south of the Kola Peninsula in northwestern Russia (Fig. 1). Lying approximately 20 km to the east of the port of Umba, it forms a peninsula about 80 km^2 that juts into the White Sea. The peninsula includes some of the classic alkaline rock-types; not only is Turiy the type locality for turjaite and turjite, but it is also the first place in Russia where carbonatites were discovered. The earliest investigations of these rocks were made by Betlink in 1840; several years later, Federov made trips to the coast of the White Sea between 1895 and 1905.

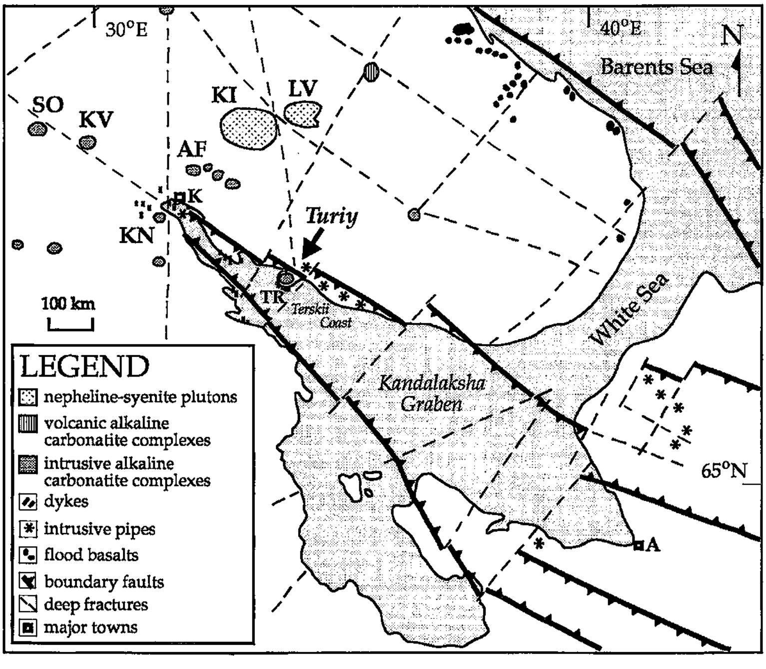

FIG. 1. Map of the Kola Peninsula showing the location of the major intrusive complexes and deep tectonic features. Igneous complexes: AF: Afrikanda, KI: Khibina, KN: Kandagubskii, KV: Kovdor, LV: Lovozero, SO: Sökli, TR: Turiy. Major towns: A: Archangelsk, K: Kandalaksha.

The peninsula was visited by Ramsay and Brenner in 1911 and later, in 1914, Sederholm and Brenner made a collection of rocks from the area. A part of this collection was presented to Brøgger, who included the first descriptions of turjaite and carbonatite in his famous monograph on the area (Brøgger 1921). Later, a more systematic description of Ramsay's collection was made by Kranck (1928). The Turiy peninsula was subjected to a preliminary investigation by the Russian geologists Beliankin and Kupletsky in 1917 (Beliankin & Kupletskii 1924). Given that so little of the extensive literature regarding the alkaline rocks of the Kola Peninsula has been translated into English, excluding, of course, the classic work by Kranck (1928), the purpose of this paper is to: (i) summarize the results of the investigations of the Turiy massif made by the Russian geologists over the last approximately 65 years, and (ii) report new electron-microprobe data characterizing the mineralogy of the two type-locality rocks mentioned above. Included among the papers in English are those of Dmitriyev *et al.* (1970), Mal'kov (1970), Bulakh *et al.* (1972), Vlodavetz (1972), Ivanikov (1973), Bulakh *et al.* (1973, 1975), Bulakh & Mazalov (1974), Panina & Podgornykh (1974), and Ronenson *et al.* (1981). The most comprehensive account of the geology and mineralogy of the rocks of the Turiy Peninsula can be found in the book "The problems of mineralogy and petrology of carbonatites" published in Russian by Bulakh & Ivanikov (1984). Although reference is made to other papers, this review is based mainly on their findings.

GEOLOGICAL SETTING

The Turiy Peninsula is located mid-way along the length of the Kandalaksha graben. Movement is considered to have been initiated in the Proterozoic and continued through to the Paleozoic, with later reactivation during the Alpine Orogeny (Barchatov *et al.* 1973). The length of the graben is uncertain, and may extend as far as Finland to the west and the Zimniy Coast to the east. Magmatic activity along the graben included the emplacement of ultrabasic alkaline rocks, plutons of undersaturated alkaline rocks with related carbonatites, and kimberlite-like eruptive breccias. Pipes bearing diamond – olivine – phlogopite, similar to Group-II kimberlites, have been found along the Terskii and Zimniy coasts (Kalinkin *et al.* 1993), close to the northern edge of the graben. A well-defined Rb–Sr isochron date of 373 ± 6 Ma based on apatite, biotite, K-feldspar, garnet and whole rock was obtained by Kramm *et al.* (1993) for the Turiy massif, and the initial $^{87}Sr/^{86}Sr$ of 0.7038 ± 0.0001 indicates a source with a time-integrated low Rb/Sr ratio (Kramm *et al.* 1993). The middle to late Devonian Rb/Sr date from Turiy is similar to additional dates obtained by Kramm *et al.* (1993) from other akaline complexes (Afrikanda, Iivaara, Khibina, Lovozero, Sökli and Ozernaya Varaka) emplaced into the northeastern Baltic Shield.

Several features of the Turiy massif impinge on

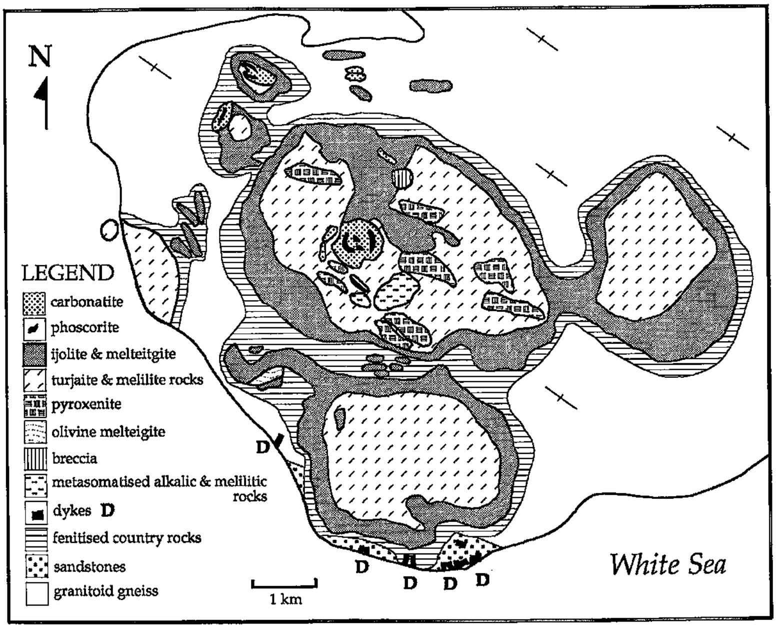

FIG. 2. Schematic diagram of the Turiy complex, showing the main rock types (after Bulakh & Ivanikov 1984).

some of the more important problems of the genesis of alkaline rocks (Bulakh & Ivanikov 1984). These are reflected in: (i) the abundance of melilite-bearing plutonic and hypabyssal rocks, (ii) the great variety of undersaturated silicate rocks and carbonatites, (iii) the presence of magnetite–apatite-rich rocks (phoscorite), and (iv) extensive and periodic metasomatic activity. The intimate association of carbonatite, phoscorite and Ca-rich silicate rocks, many of which contain calcite, provide a unique opportunity to evaluate the relationship between silicate and carbonatitic melts.

The main Turiy massif is a classic example of a hypabyssal complex. Geophysical studies suggest that a single magma chamber produced five eruptive centers along with associated dyke activity. The four main intrusive bodies (Fig. 2) are the Central Complex (28 km^2), the Southern Complex (13 km^2), the Eastern Complex (10 km^2) and the Kuznavolok Complex to the west (1.3 km^2). The complexes are intruded into early Proterozoic, high-grade metamorphic and granitoid rocks and Riphean sandstones, and all are surrounded by fenitized country-rocks, including microcline–aegirine, albite-rich, and feldspar – aegirine – nepheline fenites.

The main rock-types within the Turiy massif can be divided into five petrographic groups. From oldest to youngest, these are: (i) ultramafic rocks (jacupirangite, pyroxenite, olivinite); (ii) early alkaline rocks containing nepheline (melteigite, ijolite), (iii) melilitolite (turjaite, uncompahgrite, okaite), (iv) late alkaline rocks (ijolite, urtite, porphyritic and phaneritic ijolites, nepheline-bearing pegmatites), as well as breccias containing fragments of pyroxenite, melteigite, melilitolite and metasomatized rocks cemented by coarse-grained ijolite, and (v) phoscorite and carbonatite.

The modal mineralogy of some of these plutonic rocks is given in Table 1. We have retained some of the older names, such as turjaite and turjite, which are not recommended by the Subcommission on the Systematics of Igneous Rocks (Le Maitre 1989), as the naming of the melilite-bearing plutonic rocks is still undergoing revision. Also, note that "olivinite" is used instead of dunite to signify an association of olivine of composition close to Fo_{80} with magnetite, not chromite, as the accessory spinel phase.

TABLE 1. MODAL MINERALOGY, PLUTONIC ROCKS OF THE TURIY PENINSULA

	TUR I	TUR II	TU 119	TU 120A
phlogopite	35	6	12	25
melilite	30	65		
nepheline		10	(5)	(3)
analcime			16	25
cancrinite	16	trace	trace	
clinopyroxene	4			
monticellite		trace		
schorlomite, titanian andradite	4	2	55	30
celsian				5
pectolite		trace		
apatite	4	trace	1	trace
calcite	4	1	8	20
strontianite	trace			
magnetite	3	7	2	
ilmenite				trace
perovskite	trace	5	1	
titanite				trace
cuspidine	trace	1		
djerfisherite (?)		trace		
hillebrandite	trace			

Proportions of the rock–forming minerals are expressed in % (volume). Samples: TUR I, II: turjaite; TU 119, 120A: turjite.

Three generations of dyke rocks have been documented. Only one of these is contemporaneous with the emplacement of the main Turiy complex; the remainder are either pre- or post-emplacement relative to the age of the complex.

Although generalizations about the geology of the four centers at Turiy are difficult, each can be considered as consisting of an outer ring of ijolite–melteigite surrounding later melilite- and melilite–nepheline-bearing rocks. Blocks of ultramafic rocks, including pyroxenite, olivinite and jacupirangite, found in the Central Complex, form the earliest rocks at Turiy. One suite of ijolitic rocks within the Central Complex was intruded post-pyroxenite, pre-melilitolite, and the other after a period of metasomatism associated with the intrusion of the melilite-bearing rocks, but prior to the formation of bodies of carbonatite and phoscorite. The melilite-bearing rocks are cut by veins, dykes and eruptive pipes of ijolite and urtite. Although some of the melilite-bearing rocks may be produced by metasomatism, others are clearly magmatic, as they are equigranular, form dykes and veins, and have the same mineralogical composition throughout.

Although the Central Complex bears some similarity to the Kovdor massif that lies further to the west, ultramafic rocks are scarcer, and the melilite-bearing rocks, more abundant at Turiy. The outer zone of the Central Complex consists of ijolite–melteigite, whereas the inner zone consists of melilite-bearing rocks encompassing early pyroxenite. The center is dominated by late ijolite–urtite, phoscorite and carbonatite. At the margin of the Central Complex, a zone of fenite 500 to 700 m wide is developed.

Few massifs in the western hemisphere match the petrogenetic diversity and complexity of Turiy and some of the other massifs of the Kola Peninsula. Plutonic rocks that are melilite-bearing are comparatively rare, and the best known of these are perhaps to be found in the Gardiner intrusive complex of south-eastern Greenland, and the Oka carbonatite complex, in Quebec. Nielsen's (1994) review of the Gardiner complex includes a description of late ring-dykes that expose larnite-normative melilitolite (including turjaite), and of the five magmatic suites described from Oka (Gold *et al.* 1986), one contains okaite, a plutonic rock consisting of 60–90% melilite with variable amounts of nepheline, haüyne, apatite, magnetite, perovskite and biotite.

CARBONATITES

Calcite, calcite–dolomite and dolomite carbonatites are found at Turiy. The calcite carbonatites can be divided into forsterite-, phlogopite-, biotite-, diopside-, aegirine-, melilite- and monticellite-bearing varieties. Two varieties of calcite–dolomite carbonatite occur, one consisting mainly of carbonate minerals, the other containing, in addition, amphibole, phlogopite and magnetite. The dolomite carbonatite contains phlogopite, magnetite and apatite.

The inner part of the Central complex, a vertical pipe-like body of carbonatite and phoscorite, consists of intersecting veins of carbonatite with relics of altered ultrabasic, melilite-bearing and other alkaline rocks. Phoscorite, or so-called "ore rock", is rich in magnetite, and contains 5 to 60% apatite and from 10 to 50% calcite. Phoscorite from the Central complex may display the following associations: forsterite – magnetite with calcite and phlogopite, calcite – diopside – magnetite with phlogopite, and calcite – magnetite with phlogopite. The variants of carbonatite constitute the youngest rock-types in the complex, and the "pure" carbonatites invariably postdate the phoscorite. Both carbonatite and phoscorite are associated with Nb, Ta, Zr and *REE* mineralization, with pyrochlore concentrating the high-field-strength elements (*HFSE*), whereas the *REE* are concentrated in apatite and calcite (Anastasenko & Bulakh 1978).

METASOMATISM

Mineralogical evidence from almost all of the rock types found at Turiy point to extensive metasomatism both within the complex and throughout the surrounding country-rocks. Evdokimov (1982) recognized two broad stages of metasomatic activity, an earlier event involving the gradual fenitization of wallrocks related to the intrusion of the alkaline ultrabasic melts, and a later, lower-temperature event. Hydrothermal alkaline carbonate-bearing solutions were involved both in the metasomatic alteration and the recrystallization of phoscorite and carbonatite (Bulakh & Iskoz-Dolinina 1978, Bulakh 1979).

Although there are several periods of metasomatism, the most important phase occurred following formation of the melilite-bearing rocks. Melteigite and melilite-bearing rocks commonly show the following mineral assemblages: in melteigite: (i) calcite + hastingsite + diopside, (ii) calcite + cancrinite + diopside, and (iii) calcite + hastingsite + cancrinite; in melilitolite: (iv) calcite + titanian andradite + diopside + vesuvianite. Two periods of phlogopite and richterite formation occurred, one prior to the formation of phoscorite and carbonatite, the other contemporaneous with their emplacement.

DYKES

Seventy percent of the numerous dykes along the shores of the White Sea are concentrated in two areas, one near the town of Kandalaksha, and the other on the Turiy Peninsula. On the basis of a study of more than three hundred dykes exposed along the cliffs at Turiy, Bulakh & Ivanikov (1984) defined three groups, which are pre-, syn- and post-emplacement relative to the main complex.

Most of the early dykes are highly altered. These include dykes of alkaline picrite, melanephelinite, alnöite, calcite-bearing ultramafic lamprophyre (damkjermanite) and carbonatite, as well as a few eruptive breccias. Some of the carbonatite dykes contain amphibole, phlogopite, clinopyroxene and olivine megacrysts and have been referred to as lamprophyric carbonatite. These can grade into ultramafic lamprophyres. These silicate minerals are also found as nodules in some carbonatite and lamprophyre dykes, along with xenoliths of spinel harzburgite, eclogite and granulite (Ivanikov 1973). The textures of these ball-shaped silicate inclusions are attributed to immiscibility between carbonate and silicate liquids.

Dykes of the second series formed at the same time as the main alkaline ultrabasic massifs, and consist of several generations of micromelteigite – micro-ijolite, two generations of turjite dykes and a pipe-like body of olivine melteigite.

The youngest dykes of Turiy, listed in order of emplacement, consist of olivine nephelinite and olivine melilite melanephelinite, nepheline melilitite, melilite nephelinite and nephelinite. In the older literature, many of the dykes were referred to as monchiquite (*e.g.*, Kranck 1928, Mal'kov 1970, Borodin *et al.* 1976), but these are now known to be restricted only to the later set of dykes at Kandalaksha. In these, plagioclase occurs in the norm. Those rocks formerly considered as monchiquite are really nephelinite with olivine and melilite.

The carbonatite dykes, fourteen in all, form part of the third set of dykes, and can be grouped into two generations. The earlier generation was intruded between the olivine melilite nephelinite and the nepheline melilitite dykes, and the later generation between the melilite nephelinite and nephelinite dykes. The carbonatite dykes show little textural or mineralogical similarity to carbonatites associated with the main complex.

Dykes further to the west along the graben, near Kandalaksha and on the Kandalaksha Islands, can also be grouped into two generations on the basis of age. The early dykes are similar to those found at Turiy. Less altered, they consist of alkaline picrite, ultramafic lamprophyre, olivine melilitite, carbonatite and eruptive breccia, whereas the younger dykes consist of limburgite (the oldest), monchiquite, camptonite, and nephelinite (the youngest). The youngest period of dyke activity at Kandalaksha can be correlated with the youngest period of dyke formation at Turiy. Modal plagioclase occurs only in the later series of dyke rocks; melilite-bearing rocks and carbonatite dykes have yet to be observed. The carbonatite dykes at both Kandalaksha and Turiy make up about 5% by volume of the dyke material.

AGE OF EMPLACEMENT

The early dykes, both at Turiy and Kandalaksha, have ages between 620 and 470 Ma, suggesting a possible correlation between dyke activity and the emplacement of pipes of olivine melilitite found further to the east along the Terskii coast (Kalinkin *et al.* 1993). These events are possibly related to early Caledonian movement along the Kandalaksha rift. The youngest Turiy and Kandalaksha dykes are considered to be late Caledonian to Hercynian.

Kramm *et al.* (1993) showed that most of the intrusive complexes were emplaced in a relatively short time-interval of 380 – 360 Ma, and related the magmatism temporally to the subsidence of the Kontozero Graben in the central Kola Peninsula. Subsidence may also be related to the renewed tectonic and magmatic activity of other NW–SE-trending grabens within the Fennosarmatian Platform and Baltic Shield at this time, such as the Vyatka and Dneiper – Donets grabens further to the east and south, respectively (*e.g.*, Chekunov *et al.* 1992).

TYPE-LOCALITY ROCKS

Among the many alkaline rock-types found at Turiy, two have the Turiy Peninsula as their type-locality. Turjaite was first defined by Ramsay in 1921, who considered it to be the intrusive equivalent of a melilite nephelinite, containing ~30% of both melilite and phlogopite, ~17% nepheline, 10% apatite and lesser amounts of perovskite, ilmenite, calcite and magnetite. The type locality is Kusnavolok on the western side of the peninsula. Kranck's (1928) description of turjaite includes the identification of titanian andradite, olivine, cancrinite, cebollite, sericite, natrolite and vesuvianite, along with minor amounts of chlorite, pyrite and clinopyroxene.

Included among the rock types at Turiy that contain significant amounts of carbonate minerals is turjite, the second type-locality rock. Formed as part of the second phase of dyke activity, it was defined by Beliankin & Kupletskii (1924). They estimated the modal proportions as approximately 40% mica, 20% analcime, 20% garnet, 20% calcite and 1.5% apatite. Beliankin & Vlodavetz (1932) later included cancrinite. Celsian, with minor perovskite, titanite, magnetite, ilmenite, apatite and aegirine-augite, also have been found in this study. Le Maitre *et al.* (1989) refer to turjite as a melanocratic lamprophyre rich in analcime, biotite, calcite and titanian andradite.

ANALYTICAL TECHNIQUES

Mineral analyses were obtained using a JEOL 3600 scanning electron-microscope (SEM) with energy-dispersion system (EDS) detection operating at 15 kV, with a beam current of 0.8 nA and a beam diameter of ~2–5 µm, and a JEOL 733 electron microprobe at the Canadian Museum of Nature using four wavelength-dispersion system (WDS) spectrometers operating at 15 kV with a beam current of 20 nA and a beam diameter of 10–30 µm. A selection of natural and synthetic standards were used. Data for microprobe standards were measured for 25 s or 0.25% precision per element, whichever was obtained first; data for the samples were measured for 25 s or to 0.5% precision, whichever was attained first. Cross-calibration checks were within analytical error.

TURJAITE

Detailed petrographic and chemical studies are given by Ramsay (1921), Brøgger (1921) and Kranck (1928). The last paper gives a comprehensive account that includes petrographic observations, mineral compositions, as well as documentation of the reaction relations among the various mineral phases. We investigated two samples of turjaite from the type locality at Kusnavalok on the western side of the peninsula; their modal mineralogy is given in Table 1. Both consist primarily of melilite (30–65%), phlogopite (up to 30%), nepheline or cancrinite (or both) (17–20%), along with less abundant titanian garnet, apatite, calcite, perovskite and magnetite.

TUR II is a melilite-rich, relatively anhydrous turjaite, containing nepheline, magnetite, Al-rich phlogopite (mostly occurring as a rim around the magnetite) and at least two generations of perovskite. Coarse-grained (5–15 mm) subhedral melilite poikilitically encloses magnetite, mica and anhedral clinopyroxene. Cancrinite, monticellite and diopside form rare and minute crystals along the grain boundaries. The texture and mineral compositions possibly suggest early accumulation of melilite crystals. Of the two generations of perovskite, one consists of solitary, euhedral to subhedral, deep brown grains, whereas the second generation occurs as colorless rims around medium-grained, subhedral to anhedral magnetite. These rims are rarely found around the early dark brown perovskite. Subhedral Al-rich phlogopite appears to have crystallized at the same time as the melilite and forms a rim around some, but not all, of the magnetite crystals. Apatite and interstitial calcite are also found in small quantities.

TUR I contains less melilite than TUR II, but instead contains coarse-grained, abundant, euhedral cancrinite and subhedral brown phlogopite. Stubby needles of apatite, which cut across or are enclosed by other mineral phases, and interstitial calcite, which appears to have crystallized under equilibrium conditions with adjacent mineral phases, become increasingly abundant. Diopsidic pyroxene occurs either as anhedral grains enclosed by melilite, or as subhedral crystals associated with melilite and calcite. Subhedral deep red titanian andradite grades into thin, colorless, birefringent andradite veins, which commonly surround the melilite crystals. Two generations of perovskite occur, similar to those seen in TUR II.

Other samples of turjaite, from the south, east and central parts of the Turiy Massif, show intermediate textural and compositional variations compared to the two rather extreme samples described here (Dunworth, unpubl. data).

TABLE 2. SELECTED COMPOSITIONS OF MELILITE IN TURJAITE

	TUR I			TUR II		
SiO_2	44.50	44.01	45.11	44.09	44.41	43.94
Al_2O_3	7.25	9.71	9.08	7.74	7.69	7.59
Fe_2O_3	0.29	0.26	0.20	0.00	0.14	0.00
FeO	2.13	2.45	2.36	2.30	2.40	2.43
MnO	b.d	0.15	0.07	b.d	0.11	b.d
MgO	7.38	5.96	6.36	7.74	7.76	7.77
CaO	32.33	30.59	30.32	34.24	34.13	34.38
SrO	0.92	0.98	0.95	n.a.	n.a.	n.a.
Na_2O	4.81	5.62	5.92	3.95	4.28	3.77
TOTAL	99.61	99.74	100.37	100.06	100.91	99.88
Si	4.026	3.966	4.028	3.957	3.962	3.958
Al	0.773	1.031	0.956	0.819	0.809	0.806
Fe^{3+}	0.020	0.018	0.013		0.009	
Fe^{2+}	0.161	0.185	0.176	0.173	0.188	0.183
Mn		0.011	0.005		0.009	
Mg	0.995	0.801	0.847	1.048	1.032	1.044
Ca	3.134	2.954	2.901	3.293	3.263	3.318
Sr	0.048	0.051	0.049			
Na	0.844	0.982	1.025	0.688	0.741	0.658
TOTAL	10.00	10.00	10.00	9.98	10.00	9.97
Mg #	0.86	0.81	0.83	0.86	0.84	0.85

The structural formulae are normalized to 10 cations and 14 atoms of oxygen. The compositions are expressed in wt.% oxides. Mg # = Mg/(Mg + Fe^{2+}). b.d.: below detection. n.a.: not analyzed.

Melilite

Melilite, by far the most abundant mineral in turjaite, forms two distinct compositional varieties on the basis of the samples studied. The first, making up ~65% of TUR II and occurring rarely in TUR I, contains 60% åkermanite$_{ss}$ (Åk) ($Ca_2[Mg,Fe^{2+}]Si_2O_7$) with 40% sodian åkermanite ($CaNaAlSi_2O_7$) (NÅk); it has a birefringence of 0.008 (optically negative), whereas the second has a composition between Åk$_{54}$NÅk$_{46}$ and Åk$_{48}$NÅk$_{52}$ (Table 2, Fig. 3). The latter composition also contains up to 4.5 mol.% of $CaNaFe^{3+}Si_2O_7$. The appearance of Fe^{3+} may explain the increase in birefringence to 0.011 (optically negative), as first suggested by Kranck (1928). The Mg#, defined in this paper as molar Mg/(Mg + Fe^{2+}), is 0.84–0.86 in TUR II and 0.78–0.84 in TUR I, assuming all Fe as Fe^{2+}. If Fe^{3+} is calculated by stoichiometry, then the Mg# for TUR I increases to 0.81–0.86.

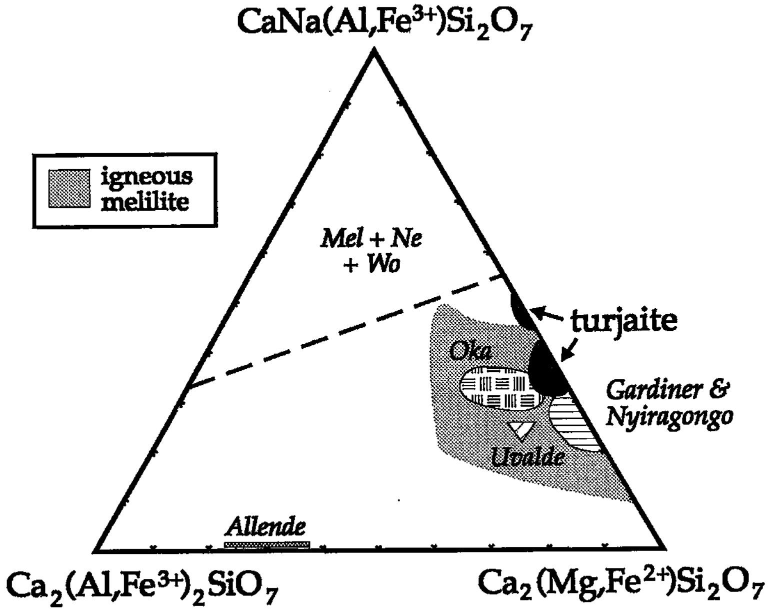

FIG. 3. Melilite composition in mol.% end members. The field of natural igneous melilite is taken from Yoder (1973a), with other data from Deer *et al.* (1986) and turjaite (this study). Data from the Allende meteorite are shown for comparison.

A basal cleavage within the melilite grains becomes increasingly common but more irregular from TUR II to TUR I. Cathodoluminescence shows the presence of rare inclusions that run perpendicular to these main fractures, possibly similar to the "peg structure" seen parallel to the *c* axis in melilite in extrusive rocks. These inclusions contain minerals of an unidentified composition. Panina & Podgornykh (1974) investigated inclusions in melilite from a variety of melilite-bearing rocks from the Turiy Massif, including several varieties of turjaite. Primary inclusions in the melilite yielded homogenization temperatures of between 1200° and 1230°C, clearly indicating a magmatic, rather than a metasomatic origin, for the melilite.

Åkermanite can dissolve between 40 and 60% $CaNaAlSi_2O_7$ (Schairer *et al.* 1967), depending on pressure (between 1 and 6 kbar) and fluid content of the magma. The extremely sodic compositions seen in the Turiy samples must therefore be close to their stability limit. Given the abundant fenitization surrounding and within the massif, the addition of Na and volatiles to the melt or even directly to the melilite itself from migrating fluids during crystallization is a process that cannot be ruled out.

The edge of the melilite crystals invariably shows a brown altered rim, consisting mostly of sieve-textured melilite, similar to that described in detail by Kranck (1928). In sample TUR I, melilite is surrounded by a late-stage rim of andradite with a relatively high Al content (Fe^{3+}:Al = 2:1), similar to that documented in okaite from Oka, Quebec, by Watkinson (1971), who attributed it to reaction between a late-stage magmatic liquid and melilite, rather than hydrothermal alteration. Seifert (1974) documented the breakdown of Fe-rich melilite to wollastonite and andradite under oxidizing conditions. The replacement of melilite by andradite can release large amounts of Na into a residual fluid, allowing further reactions to take place, and providing Na-rich vapor and fluid for possible fenitization in the surrounding rocks (Watkinson 1971).

Mica

Phlogopite occurs in both samples of turjaite. It forms an early-stage rim around magnetite in TUR II, and demonstrates a normal scheme of pleochroism from pale yellow to green. In sample TUR I, abundant, large, subhedral crystals of deep brown phlogopite with a green, (Mg,F)-rich, Ti-poor rim show resorbed edges that are common near crystals of titanian andradite. Compositions in the irregular rim suggest that the mica reacted with late-stage magmatic liquid. The normal pleochroic scheme shown by the phlogopite indicates a lack of $^{[IV]}Fe^{3+}$ found in phlogopite associated in certain alkaline rocks; here, Si and Al fully occupy the tetrahedrally coordinated sites (Table 3). The Mg# values are relatively constant in both samples (0.85–0.89 in TUR II, 0.82–0.88 in TUR I). The Al content is slightly higher in TUR II (15.5–17.8 wt% Al_2O_3) than in TUR I (14.3–15.9 wt% Al_2O_3). These compositions are compared with those of mica from alkaline volcanic rocks including carbonatite, nephelinite, leucitite, melilitite and lamproite in Figure 4. The high Mg# and Al contents documented in the mica of the turjaite are typical of Ti-poor mica commonly found in carbonate-rich rocks.

TABLE 3. SELECTED COMPOSITIONS OF PHLOGOPITE IN TURJAITE AND TURJITE

	TUR II		TUR I		TU 119		TU 120A	
SiO_2	37.39	37.86	38.28	36.54	38.27	39.02	38.40	34.78
TiO_2	2.09	0.69	1.17	2.67	2.10	1.26	1.50	3.38
Al_2O_3	16.06	17.30	15.15	15.66	13.10	10.63	12.77	14.45
Fe_2O_3					0.84	1.24		0.54
FeO	6.00	6.64	7.68	7.45	7.96	17.35	12.09	10.51
MnO	b.d.	0.13	0.15	0.08	0.20	0.57	0.55	0.31
MgO	22.36	22.45	21.96	21.28	21.23	15.13	18.82	18.34
CaO	b.d.	b.d.	b.d.	0.05	0.05	0.22	b.d.	b.d.
BaO	1.11	0.46	0.59	1.42	0.84	0.13	0.66	1.26
K_2O	9.27	10.05	9.47	9.17	9.92	9.69	10.15	9.27
Na_2O	0.86	b.d.	0.71	0.61	0.46	0.19	b.d.	b.d.
F	b.d.	b.d.	0.82	0.75	2.13	2.01	n.a.	n.a.
H_2O	4.14	4.17	3.74	3.73	3.05	2.96	4.01	3.91
O=F			–0.35	–0.32	–0.90	–0.85		
TOTAL	99.28	99.75	99.37	99.09	99.18	99.43	98.95	96.75
Si	5.418	5.443	5.564	5.364	5.643	5.948	5.747	5.361
$^{[IV]}Al$	2.742	2.931	2.595	2.710	2.273	1.910	2.252	2.582
$^{[IV]}Fe^{3+}$					0.093	0.142		0.057
[IV]	8.000	8.000	8.000	8.000	8.000	8.000	7.999	8.000
$^{[VI]}Al$	0.160	0.374	0.159	0.074				
Ti	0.227	0.075	0.128	0.295	0.232	0.144	0.169	0.389
Fe^{2+}	0.727	0.798	0.934	0.915	0.981	2.212	1.514	1.347
Mn		0.016	0.018	0.010	0.025	0.074	0.070	0.040
Mg	4.830	4.811	4.759	4.657	4.659	3.438	4.198	4.189
Ca				0.008	0.008	0.036		
Ba	0.063	0.020	0.034	0.082	0.048	0.008	0.039	0.076
K	1.713	1.847	1.756	1.717	1.863	1.894	1.937	1.812
Na	0.241		0.200	0.174	0.131	0.056		
TOTAL	15.96	15.94	15.99	15.93	15.95	15.83	15.93	15.85
Mg #	0.86	0.85	0.83	0.83	0.83	0.61	0.73	0.76

The structural formulae are normalized to 8 tetrahedrally coordinated cations and 22 oxygen equivalents. Mg # = Mg/(Mg + Fe^{2+}). b.d.: below detection. n.a.: not analyzed. The proportion of H_2O was calculated according to stoichiometry. Proportions of oxides and F are expressed in wt.%.

Pyroxene

TUR I contains about 4 modal % of green-yellow, subhedral to anhedral diopside, with 1–5% aegirine component, usually found enclosed within or associated with the Na-rich melilite or calcite. Compositionally, it is closer to diopside than the pyroxenes in the Turiy samples investigated, but not identified, by Mitchell & Platt (1982). The Mg# of the pyroxene is identical to that of the enclosing melilite, but it contains enough Al to allow for a small amount of Ca-Tschermaks component [according to the cation-allocation model of Smyth (1980)]. A comparison of these compositions with those of the enclosing Na-saturated, Fe^{3+}-rich melilite could indicate an

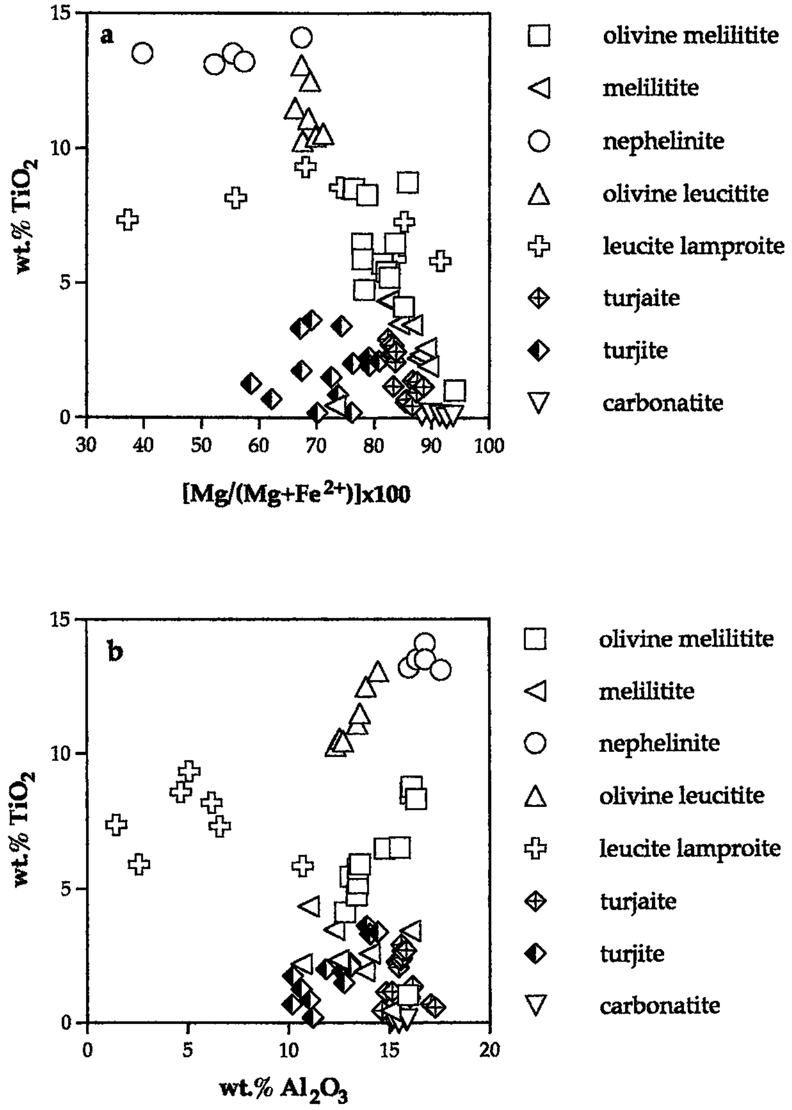

FIG. 4. Major-element compositions of phlogopite from selected alkaline extrusive and intrusive rocks. Proportion of TiO_2 (wt%) *versus* a) $[Mg/(Mg + Fe^{2+})] \times 100$, and b) proportion of Al_2O_3. Sources of data: olivine melilitite: Dunworth (1991), melilitite: Boctor & Yoder (1986), nephelinite: Mansker *et al.* (1979), olivine leucitite: Zhang *et al.* (1993), leucite lamproite: Mitchell (1981), turjaite and turjite, this study, and carbonatite: E.A. Dunworth (unpubl. data). Compositions all recalculated on the basis of 8 tetrahedrally coordinated cations and 22 atoms of oxygen.

interesting partitioning effect of Na and Fe^{3+} into the melilite, and Al into the pyroxene, rather than into the more typical sodian melilite and aegirine components. This, however, assumes that the two minerals crystallized from or reached equilibrium with the same magmatic liquid, according to their similar Mg# values. The reaction

$$CaMgSi_2O_6 + CaCO_3 \leftrightarrow Ca_2MgSi_2O_7 + CO_2$$

(Yoder 1973b) shows evidence of proceeding in both directions in TUR I; despite the anhedral pyroxene within melilite and subhedral pyroxene next to calcite, the grain boundaries show less evidence of reaction of the pyroxene within the melilite. Diopside-rich pyroxene is only found as rare, minute crystals along grain boundaries in TUR II. Thus, in the volatile-rich TUR I, which contains far more calcite and diopside than TUR II, the reaction shown above probably proceeded from right to left. However, comparison with samples from other parts of the massif suggests that the relationship is not as simple. Work is currently in progress to solve this problem, which also has significant bearing on the relationship between the melilite-bearing rocks and ijolite in the complex.

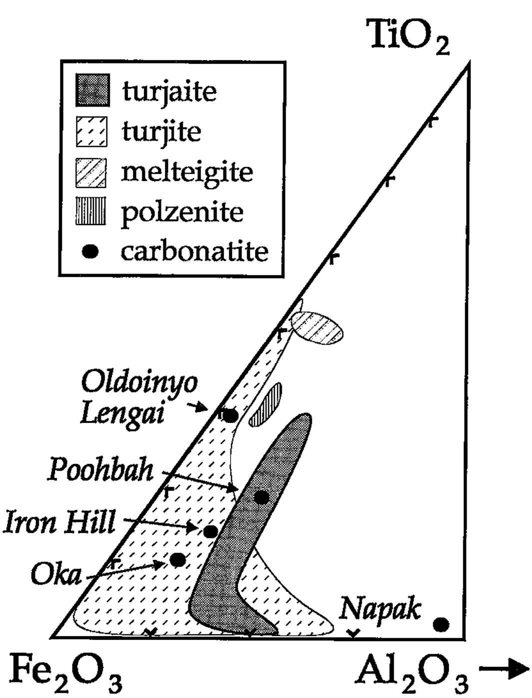

FIG. 5. Composition fields of garnet from turjaite and turjite (this study). Other data from Deer *et al.* (1982). Information on samples of polzenite from the Ohre Rift, Czech Republic, was provided by M. Wilson (unpubl. data).

Garnet

Titanian andradite is a major mineral phase in turjaite. In TUR I, it occurs as subhedral, deep red, optically unzoned crystals, up to 1 mm in diameter, that form about 3% of the rock. Pale birefringent andradite $[^{[VI]}Fe^{3+}/(Fe^{3+} + Al^{3+}) \approx 0.7]$ occurs in veins, and as an irregular rim around melilite. In TUR II, garnet occurs as rare veins $[^{[VI]}Fe^{3+}/(Fe^{3+} + Al^{3+}) \approx 0.75]$. Chemically, the andradite is zoned, with between 0.2 and 1.2 atoms per formula unit (*apfu*) of Ti (Table 4, Fig. 5), and shows an unusually Al-rich composition compared with that of garnet from other alkaline magmas. This is consistent with the suggestion of Watkinson (1971) that an andradite rim can be produced by a reaction involving sodian melilite. Although there has been much debate over the last twenty years as to the preferential coordination of Al, Fe^{3+} and Ti, microprobe results alone do not enable us to accurately allocate cations to the tetrahedrally and octahedrally coordinated sites within the garnet. We have assumed preferential Si > Al > Fe^{3+} occupancy of the tetrahedral site, which provides the following 1:1 substitution schemes:

$$^{[VI]}[Mg^{2+} + Ti^{4+}] \leftrightarrow {}^{[VI]}[Al^{3+} + Fe^{3+}]$$
$$^{[VI]}Ti^{4+} + {}^{[IV]}Al^{3+} \leftrightarrow {}^{[IV]}Si^{4+} + {}^{[VI]}(Al^{3+}, Fe^{3+}).$$

TABLE 4. SELECTED COMPOSITIONS OF GARNET IN TURJAITE AND TURJITE

	TUR II		TUR I		TU 119		TU 120A	
SiO_2	36.29	32.36	35.59	36.19	34.87	33.66	33.30	34.80
TiO_2	b.d.	8.53	3.44	0.29	1.65	6.07	7.42	3.26
Al_2O_3	5.27	3.56	4.34	5.40	0.72	1.60	1.26	0.87
Fe_2O_3	23.32	21.80	20.19	23.90	29.09	22.73	24.60	27.35
FeO			2.19			0.73		
MnO	b.d.	0.17	0.08	b.d.	0.33	0.33	0.31	0.36
MgO	0.33	1.17	0.51	b.d.	0.16	0.64	0.78	b.d.
CaO	34.75	33.11	33.15	34.14	32.94	33.27	32.60	33.07
Na_2O	n.a.	n.a.	n.a.	n.a.	0.08	0.19	n.a.	n.a.
TOTAL	99.96	100.70	99.49	99.92	99.85	99.22	100.27	99.71
Si	5.968	5.326	5.891	5.952	5.884	5.665	5.545	5.850
Ti		1.056	0.428	0.036	0.209	0.768	0.929	0.412
Al	1.022	0.691	0.847	1.046	0.143	0.317	0.248	0.172
Fe^{3+}	2.885	2.700	2.515	2.958	3.695	2.879	3.083	3.463
Fe^{2+}			0.303			0.102		
Mn		0.024	0.011		0.047	0.047	0.044	0.052
Mg	0.080	0.287	0.126		0.040	0.161	0.193	
Ca	6.122	5.839	5.891	6.017	5.956	5.999	5.817	5.962
Na					0.026	0.062		
TOTAL	16.08	15.92	16.01	16.01	16.00	16.00	15.87	15.91

The structural formulae are normalized to 16 cations and 24 atoms of oxygen. Proportions of oxides are expressed in wt.% oxides. b.d.: below detection. n.a.: not analyzed.

Nepheline and cancrinite

According to Ramsay (1921), the type-locality turjaite should contain about 17% modal nepheline. Sample TUR II contains approximately 10% nepheline [0.79 < Na/(Na+K) < 0.83], with a small amount of cancrinite [Ca/(Ca + Na) = 0.15], whereas TUR I contains 15% subhedral to euhedral cancrinite [Ca/(Ca + Na) = 0.005] associated with minor pectolite, apatite and rare sulfides. The subhedral nature of most of the cancrinite in TUR I, coupled with the absence of any hydrothermal alteration in most of the other minerals, suggests that this cancrinite may represent the product of differentiation of a late-stage turjaitic magma. On the basis of its textural relationships, it appears to have formed at the same time as melilite. The reaction of a CO_2-rich magmatic fluid with nepheline can produce cancrinite and, ultimately, calcite (Watkinson & Wyllie 1971). Cancrinite could also be formed by the reaction of nepheline with a later hydrothermal Ca-rich fluid, but the extremely Na-rich and Ca-poor composition of the cancrinite in TUR I, coexisting with primary calcite, suggests that the cancrinite is primary. However, further work is needed to resolve this problem.

Calcite, strontianite and apatite

Interstitial primary calcite, found in TUR I, contains between 1 and 2% SrO and is unzoned. From observations in cathodoluminescence, the calcite seems to be in textural and chemical equilibrium with its surrounding phases. Cryptocrystalline late-stage strontianite is found within the cancrinite, and rarely as a rim around apatite grains. Apatite, virtually absent from TUR II, occurs as small hexagonal needles or as elongate stubby prisms in TUR I. That the apatite needles commonly cut most phases and occur as inclusions within mica suggests that apatite was on the liquidus throughout the crystallization sequence. Cathodoluminescence shows that the Sr-enrichment in the rim of apatite grains is no longer present where they are in contact with calcite.

Minor phases found in this study include cuspidine [$Ca_4Si_2O_7{\cdot}(F,OH)_2$], hillebrandite [$Ca_2SiO_4{\cdot}H_2O$] and pectolite [$NaCa_2Si_3O_8(OH)$]. Small anhedral to euhedral crystals of cuspidine are associated with garnet and diopside in TUR II, whereas pectolite occurs as small radiating growths within the cancrinite in TUR I. A rare crystal of monticellite (Mg# = 0.75) was found associated with cuspidine and diopside in TUR II. Trace amounts of a KFe-sulfide, believed to be djerfisherite, were found in TUR II associated with phlogopite, melilite and hillebrandite.

Oxides

Magnetite, with an exceptionally low Ti content, occurs as subhedral crystals in TUR II, commonly surrounded by a rim of perovskite. Such a rim is found around most magnetite grains in TUR II and is ubiquitous around all magnetite grains in TUR I. Rare, small grains of magnetite in TUR II, without a perovskite rim, show a corresponding increase in ulvöspinel content. Rare zoning is patchy in nature and does not seem related to crystal shape or orientation.

Perovskite is also present in both samples as deep brown, anhedral crystals that have a relatively high *REE* and Nb content. The pale rim of perovskite around the magnetite grains has a lower concentration of *REE* and Nb than the isolated grains.

TURJITE

Turjite occurs as dykes and sills along the southern coast of the Turiy massif, all of which were emplaced during the second stage of dyke activity. The dykes vary in thickness between 5 and 80 cm, with sharp contacts, quench zones and little wallrock alteration. Two samples (TU119, TU120A: Table 1) from Devichii Krest on the southern coast of the Turiy Peninsula have unusual assemblages of minerals and are texturally variable.

Sample TU119 contains concentrically zoned euhedral titanian andradite, which subophitically encloses rare needles of apatite and abundant stubby laths of a relict mineral now replaced by cancrinite, analcime and sericite. Owing to the similarities between this sample and late-stage urtite from the main massif, we believe that this relict mineral was probably nepheline, although orthoclase cannot be ruled out. Subhedral, coarse-grained $^{[IV]}Fe^{3+}$-bearing phlogopite is cut by apatite needles and contains rare aegirine inclusions. Perovskite and magnetite also are present. Coarse anhedral analcite (strongly birefringent) and interstitial calcite are late-stage phases.

Sample TU120A is inequigranular and is finer-grained than TU119. Garnet forms subhedral to anhedral grains and maintains a subophitic texture with respect to relict nepheline, and contains inclusions of phlogopite. The same subophitic texture between garnet and relict nepheline is again seen, but here the phlogopite is more Al-rich (pale green). The analcime groundmass has a fine-grained texture, and euhedral celsian is present, along with interstitial calcite. Oxides are represented by manganoan ilmenite, and titanite is present instead of perovskite. A third sample taken from the quench zone of one dyke includes heavily altered laths of melilite not in textural equilibrium with the surrounding material, and titanite veins enclosed within perovskite (Dunworth, unpubl. data). Phlogopite and garnet are the main phases in TU119 and TU120A. Where garnet and calcite are in contact, the garnet contains relatively few inclusions, is relatively fresh, and normally the grains are euhedral. This significance of this characteristic is discussed in a later section.

Mica

Mica, a primary constituent of turjite, shows an extended range in composition, from abundant phlogopite and $^{[IV]}Fe^{3+}$-rich phlogopite, to rare biotite and annite (Table 3). Sample TU119, relatively coarse-grained, contains $^{[IV]}Fe^{3+}$-rich phlogopite crystals up to 3 mm in length. In plane-polarized light, the pleochroic scheme shows ω = bright orange rim and pale orange core, and ε = bright green rim and deep brown core. The Mg# varies from 0.59 to 0.81. (Tetrahedrally coordinated ferric iron contents are <0.2 *apfu*). In addition, rare $^{[IV]}Fe^{3+}$-rich annite (Mg# ≈ 0.04, $^{[IV]}Fe^{3+}$ = 0.3 *apfu*) also was found in sample TU119. Sample TU120A is finer grained, and contains smaller clusters of phlogopite having less of the $^{[IV]}Fe^{3+}$ component. This is corroborated by its normal pleochroic scheme, which varies between pale green and brown. The Mg# lies between 0.67 and 0.74. Ba and Ti contents are low in mica from both samples, and the Al contents are also similar (10.2–13.1 wt% Al_2O_3 in TU119, and 10.8–14.5 wt% in TU120A; Fig. 4).

Garnet

In sample TU119, zoned crystals of schorlomite – andradite are common, and make up to 50% of the modal composition. An early generation is anhedral to subhedral, with a deep brown titanian andradite – schorlomite core and a pale rim. Most of the crystals subophitically enclose stubby laths of relict nepheline (or orthoclase) and rare apatite. A later generation of euhedral, concentrically zoned andradite is more abundant, commonly around the first-generation garnet, and rarely shows the subophitic texture enclosing the relict laths. The concentric zoning abruptly varies between dominant pale yellow-green, weakly birefringent Al-rich andradite, to a less common, deep brown, isotropic titanian andradite that contains trace amounts of Na. The final rim around the majority of the crystals is further enriched in the andradite component. The garnet in sample TU120A is much smaller in size than that seen in TU119 and is dominated by the first generation of anhedral and resorbed titanian andradite – schorlomite containing possible relict nepheline.

Additional phases

In TU119, Sr-rich calcite and analcime form most of the interstitial material, along with rare apatite and aegirine-augite. Oxide minerals are represented by Ti-poor magnetite (79–95 mol.% Mag) and perovskite with ~3 wt% *REE* oxides and 1 wt% Nb_2O_5. The groundmass assemblage of TU120A shows a somewhat different mineralogy, with abundant Sr-rich calcite, analcite, and significant amounts of almost pure, euhedral celsian (85–95 mol.% $BaAl_2Si_2O_8$; Table 5). Celsian occurs rarely in alkaline rocks, and is normally associated with Mn minerals. It is probably no coincidence, therefore, that the oxide phase in this sample is represented by manganoan ilmenite (≤6.5 mol.% $MnTiO_3$) instead of the titaniferous magnetite seen in TU119 (Table 5). Titanite also is found in TU120A instead of the perovskite seen in TU119.

DISCUSSION AND CONCLUSIONS

One estimate of the chemical composition of the parental liquid for most of the Turiy rocks lies close to that of an olivine melanephelinite (Bulakh & Ivanikov 1984). Listed in Table 6 is an average chemical composition for all of the alkaline silicate rocks from the Kola Peninsula from Kukharenko *et al.* (1965), as well as an average for the olivine melteigite from the central Turiy massif and the olivine melanephelinites from the Turiy dykes (Bulakh & Ivanikov 1984, Ivanikov *et al.* 1975). The earliest dykes of the third series and the early dykes of the nearby Kandalaksha Series are chemically similar to the olivine melteigite of the main complex, and to the overall average composition of the fifteen carbonatite–alkaline complexes from the Kola peninsula (Ivanikov *et al.* 1975, Kochurova & Ivanikov 1976). This similarity in composition, along with the volumetric proportions, provide supporting evidence in favor of a parental melt

TABLE 5. COMPOSITION OF CELSIAN, ANALCIME AND ILMENITE FROM TURJITE

Celsian		Analcime		Ilmenite	
SiO_2 (wt.%)	35.39	SiO_2	53.63	TiO_2	51.92
Al_2O_3	25.74	Al_2O_3	22.64	FeO	38.25
BaO	36.46	FeO	0.19	MnO	4.17
K_2O	2.11	CaO	0.15		
		Na_2O	12.69		
TOTAL	99.90	TOTAL	89.30	TOTAL	94.34
Si	2.152	Si	10.732	Ti	1.003
Al	1.834	Al	5.340	Fe^{2+}	0.979
Ba	0.864	Fe^{2+}	0.032	Mn	0.014
K	0.162	Ca	0.032		
		Na	4.924		
TOTAL	5.012	TOTAL	21.060	TOTAL	1.996

Celsian: number of cations normalized to 8 atoms of oxygen. Analcime: number of cations normalized to 32 atoms of oxygen. Ilmenite: number of cations normalized to 3 atoms of oxygen.

TABLE 6. BULK COMPOSITION OF SELECTED MELILITE–BEARING ROCKS

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]
SiO_2	34.72	38.04	30.58	40.61	36.76	30.56	33.63	36.84	36.58	36.38
Al_2O_3	12.19	6.34	9.52	9.99	7.10	11.86	13.30	12.84	7.50	7.94
TiO_2	3.31	1.95	1.64	2.13	3.42	1.16	1.73	3.04	3.33	3.22
Fe_2O_3	6.44	8.45	9.17	7.15	7.71	6.07	5.69	12.81	9.13	8.37
FeO	4.82	5.90	4.50	6.23	5.65	4.24	4.43		4.43	6.88
MnO	0.28		0.83	0.18	0.21	0.28	0.43		0.22	0.12
MgO	5.84	7.81	6.40	10.88	9.50	6.10	3.78	6.01	8.79	14.95
CaO	19.80	27.19	26.86	15.77	17.34	19.11	13.79	16.10	18.42	14.46
Na_2O	5.11	2.16	4.29	4.11	3.08	2.59	6.93	4.50	3.01	3.17
K_2O	3.05	0.12	0.71	1.62	1.54	4.20	2.04	4.00	1.95	1.52
P_2O_5	1.88	2.00	1.85	0.33	0.26		0.86		0.15	0.37
H_2O+	2.13	0.48	0.78	1.00	0.26	3.97	4.90		0.35	0.66
H_2O-	0.17	0.22	0.02			0.76				
CO_2	0.81			2.13	8.76	6.71			6.62*	1.96*
S	0.17					0.90				
TOTAL	100.72	92.83	100.66	99.28	99.77	99.12	96.14	100.00	100.30	100.00
Mg#	0.29	0.36	0.30	0.14	0.32	0.22	0.28	0.49	0.43	0.41

* (Sum of CO_2, Cl, F, SO_3). Mg# = molar Mg/(Mg+Fe^{2+}), where Fe^{2+} = total Fe. Compositions are quoted in weight %. Samples: [1] Average turjaite, Turiy Massif (Kranck 1928); [2] Uncompahgrite, Iron Hill, Colorado (Kranck 1928); [3] Okaite, Oka, Quebec (Gold *et al.* 1986); [4] Olivine melteigite, Turiy Massif (Kochurova & Ivanikov 1976); [5] Olivine melilite nephelinite, Turiy Massif (Kranck 1928); [6] Average turjite, Turiy Massif (Kranck 1928); [7] Bergalite, Kaiserstuhl, Germany (Keller *et al.* 1990), [8] Melilite nephelinite, Lake Kivu, Rwanda (Marcelot *et al.* 1989); [9] Olivine melanephelinite, Turiy Massif (Bulakh & Ivanikov 1984); [10] Bulk composition of all massifs of the Kola Peninsula (Kukharenko *et al.* 1965).

similar to an olivine melanephelinite. A melanephelinitic parental melt also was favored by Nielsen (1994) for the Gardiner Complex. Also shown in Table 6 are the compositions of some other melilite-bearing rocks from Canada, Germany, Rwanda and the United States that are similar to those from Turiy.

Bulakh & Ivanikov (1984) were able to model the diversity of rocks observed at Turiy by crystal fractionation. The similarity of many geochemical trends suggest that both phonolite and nephelinite can be generated from a parental melanephelinitic liquid. Bulakh & Ivanikov (1984) divided all of the alkaline rocks from Turiy into those derived from fractionated melts (*e.g.*, melteigite, turjaite, ijolite) and those representing cumulate rocks (*e.g.*, ultramafic rocks and some of the melilitolites). Arguments based on textural evidence favored both a magmatic and metasomatic origin for the carbonatites. The presence of carbonate ocelli in some of the silicate dykes, coupled with the volumetric proportion of the carbonatites, about 5% in both the dykes and the plutonic complexes, are features consistent with the production of at least some of the carbonates by liquid immiscibility.

It is difficult to integrate the formation of turjaite and turjite into a broader picture that encompasses the evolution of the magmatic sequences seen elsewhere on the Turiy Peninsula. On the basis of field relationships, Bulakh & Ivanikov (1984) have placed the formation of melilitolitic magmas after the formation of the early meltigite–ijolite series. There are many complicating factors controlling the differentiation and crystallization histories of the Turiy magmas, including the Ca and volatile contents of the melts, their oxidation states, and their degree of fractionation.

A comparison between the modal mineralogy and whole-rock chemical compositions of turjaite and turjite from the data listed in Tables 1 and 6 bring out the following features. The most distinctive mineralogical differences between both rock types are the higher abundances of melilite and cancrinite in turjaite and of garnet and calcite, along with the presence of analcime, in turjite. Turjaite also has a somewhat higher SiO_2 content, considerably higher Ti and Na contents, and lower K than turjite. The remaining oxide abundances are about the same.

Nielsen (1994) proposed a vapor-saturated parental olivine melanephelinitic liquid for Gardiner, that was driven toward more evolved melilitic liquids, similar to those that crystallized as turjaite, by fractionation of about 25 wt% phlogopite-bearing dunite with 10 wt% phlogopite, 17 wt% kaersutite- and phlogopite-bearing peridotite, and 41 wt% of phlogopite- and kaersutite-bearing meleigite and ijolite, all of which are exposed within the complex. Although Nielsen's model may hold for Gardiner, the scarcity of amphibole-bearing rocks and dunite at Turiy requires a different explanation. Of the two turjaite samples, TUR II may represent an early differentiate of an initial turjaitic melt, given its relatively high melilite content, coupled with preserved nepheline. An unrealistically high bulk-rock Ca content of about 35 wt% CaO, estimated using mineral compositions and modal mineralogy for this sample, suggests that it may have a cumulate origin. Kranck (1928) envisaged magmatic crystallization of a parental melt, followed by late-stage pneumatolytic activity, which produced titanian andradite and some biotite, with later hydrothermal activity altering both melilite and nepheline. Our new data show that the residual melt became enriched in volatiles, which probably explains the abundant phlogopite, *REE*-enriched apatite, calcite and Na-saturated melilite (TUR I). Down-temperature differentiation, along with elevated partial pressures of CO_2 in the fluid phase, may have produced primary cancrinite instead of nepheline. Watkinson & Wyllie (1971) have shown that the assemblage cancrinite, calcite, melilite, liquid plus vapor can occur as a result of down-temperature differentiation in the system nepheline + calcite + 25% H_2O. This finding provides a clear petrogenetic link between the nepheline-bearing TUR II and the cancrinite–carbonate-bearing TUR I. The rims of perovskite around magnetite indicate reaction between the Ca-rich melt and the ulvöspinel component. It should be noted that the enclosure of magnetite by perovskite, observed in both samples, inhibits the magnetite from buffering the oxygen fugacity of the remaining melt. On the basis of the data presented thus far, it is difficult to evaluate the role of metasomatic and hydrothermal fluids during differentiation, but these undoubtedly played important roles during the overall evolution of the complex.

The petrogenesis of the turjite samples is harder to constrain at this time, given the evidence for non-equilibrium conditions, such as the presence of both titanite and ilmenite in one sample, and perovskite and magnetite in the other. Despite the presence of relict melilite in the quench zones of these bodies, the modal mineralogy along with the compositions of the garnet and phlogopite phases, and the presence of barium feldspar, might suggest a possible link to the late ijolite–urtite series of the central massif, which contain nepheline, schorlomite, aegirine-augite, wollastonite, Ba-minerals, and $^{[IV]}Fe^{3+}$-bearing phlogopite (Dunworth, unpubl. data). Verwoerd (1978) studied the binary phase relations between a "silicate end-member" (5 aegirine + 3 nepheline + 2 Na-disilicate) and a "carbonate end-member" (6 calcite + 4 sodium carbonate), which approximates carbonatitic and ijolitic melts. The earliest crystallizing phase from the silicate end-member was nepheline, which formed before calcite; later, the dominant crystallizing phases were andradite, nepheline, aegirine and magnetite or hematite. Such phase relationships are consistent with the early precipitation of nepheline, aegirine-augite, and schorlomite – titanian andradite from a magma possibly related to the late ijolite series of the central massif, and subsequent reaction of the remaining magma with a carbonatitic melt to form the second generation of euhedral, zoned andradite. The presence of the other phases in the system can be shown by the presence of abundant interstitial analcime ("Na-disilicate"), rare aegirine, and oxides. This system helps to explain the modal mineralogy of the turjite samples that relates much of their petrogenesis to mixing or reaction of carbonatite with ijolite. In addition, the breakdown of a carbonate-oversaturated melilitolitic (turjaitic?) magma to form separate ijolite and carbonatite phases could be borne out by the relict melilite in the turjite quench zones and the unusual garnet–calcite textural features mentioned earlier.

This study shows but a small aspect of the complicated evolution of the Turiy complex, including the formation of two very unusual rock-types. Work is presently under way, using major- and trace-element data, along with Nd, Pb and Sr isotopic data, to further constrain and understand the relationships among the diverse rock-types documented in this complex.

Acknowledgements

One of us (K.B.) thanks Professor A. Bulakh of the Department of Mineralogy, the University of St. Petersburg, for organizing the field trip to the Kola Peninsula and to Turiy during the summer of 1991. Visits to Russia by K.B. and later by E.A.D. were arranged by Carleton International as part of an exchange programme between the University of St. Petersburg and Carleton University. We thank T. Nielsen, D.D. Hogarth and an anonymous reviewer for their constructive reviews of an earlier version of this paper, and R.F. Martin for some skillful editing. Scott Ercit and Bob Gault (Canadian Museum of Nature) and Peter Jones (Carleton University) are thanked for assistance with the electron microprobe and SEM mineral analyses, respectively; M. Wilson supplied the data on polzenite. This research was partly funded by NSERC Grant A7813 awarded to K.B.

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Received December 9, 1994, revised manuscript accepted December 27, 1995.