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Geochemistry of the Osnitsk–Mikashevichy Volcanoplutonic Complex of the Ukrainian Shield

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Abstract—This paper addresses the geochemistry of intrusive (Osinitsk complex) and volcanic (Klesov Group) rocks of the Osnitsk–Mikashevichy volcanoplutonic belt (OMVPB) of the Ukrainian shield, which is an active continental margin existing approximately 1980–2000 Ma ago. The Osnitsk complex comprises a wide range of rocks, from ultrabasics to granitoids, and the Klesov Group is dominated by extrusive rocks of basaltic and rhyolitic compositions metamorphosed under epidote-amphibolite facies conditions. The Sr–Nd–Hf isotopic systematics (εSr_{1990} from –4 to +10, εNd_{1990} from –0.6 to +2.3, and εHf1990 from 0.1 to 1.4) indicates a juvenile source for the OMVPB rocks. Geochemical data suggest independent origin of the rocks of gabbroid ($SiO_2 < 60$ wt %) and granitoid ($SiO_2 > 60$ wt %) series. The gabbroids are subdivided into pre- and post-granite groups on the basis of the higher contents of incompatible trace elements and lower contents of compatible elements in the post-granite rocks. The geochemical characteristics of the two groups of basic rocks indicate their formation in a convergent tectonic setting. The origin of the granitoid melts is attributed to the low-degree (eutectoid) melting of basic rocks at relatively low temperatures.

Keywords: Ukrainian Shield, Paleoproterozoic, Osnitsk–Mikashevichy belt, continental margin, juvenile rocks

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INTRODUCTION

Ancient Precambrian cratons are characterized by complex structures and prolonged multistage evolution. The East European craton is not an exception in this respect and has been supposed to consist of three segments, Sarmatia, Fennoscandia, and Volgo–Uralia [1]. Each of them developed independently in the past, before their amalgamation into a single plate in the Paleoproterozoic. Fennoscandia and Sarmatia joined approximately 1800 Ma ago [2–4]. Sarmatia includes two major geostructural units, the Ukrainian Shield and the Voronezh crystalline massif, surrounded by zones with an Early Precambrian basement and a platform cover.

The boundary between the Sarmatian and Fennoscandian segments of the East European craton coincides with the northern boundary of the Osnitsk–Mikashevichy volcanoplutonic belt in such a way that the belt bounds the northern margin of Sarmatia (Fig. 1). The rocks of the belt are exposed in the northwestern Ukrainian Shield, where they have been scrutinized by many generations of Polish, Ukrainian, and Belarussian geologists. However, up to now, there are almost no reliable analytical data that could shed light on the origin of these rocks. The belt was differently interpreted by researchers as (1) a geosyncline mobile belt [5], (2) an intracontinental volcanoplutonic belt related to the tectonomagmatic activation of stabilized regions [6], (3) a collision belt formed by the Sarmatia–Fennoscandia collision [7], and (4) an active continental margin [8]. In this paper, recent geochemical and isotopic data are used to confirm and develop the suggestion on the continental margin origin of the Osinitsk–Mikashevichy volcanoplutonic belt.

GEOLOGIC SETTING OF THE OSNITSK–MIKASHEVICHY VOLCANOPLUTONIC BELT

The Osnitsk–Mikashevichy volcanoplutonic belt (OMVPB [6]) is also known in the literature as the Osnitsk–Mikashevichy magmatic belt [8] and Polessian orogenic belt [9]. It extends along the northern boundary of the Sarmatian (and in part Volga–Uralian; Fig. 1 in [8]) segment of the East European craton over a considerable distance. For instance, Aksamentova [6] traced it for 650 km from western Ukraine to the eastern boundary of Belarus. It is obvious that it extends over a much greater distance.

Most of the OMVPB is made up of granitoid massifs assigned to the Osnitsk complex in Ukraine and Mikashevichy complex in Belarus. The granitoids contain numerous xenoliths and remnants of basic and silicic extrusive rocks of the Klesov Group. In addition, there are small (up to a few square kilometers) massifs of metamorphosed and granitized gabbroids, which are

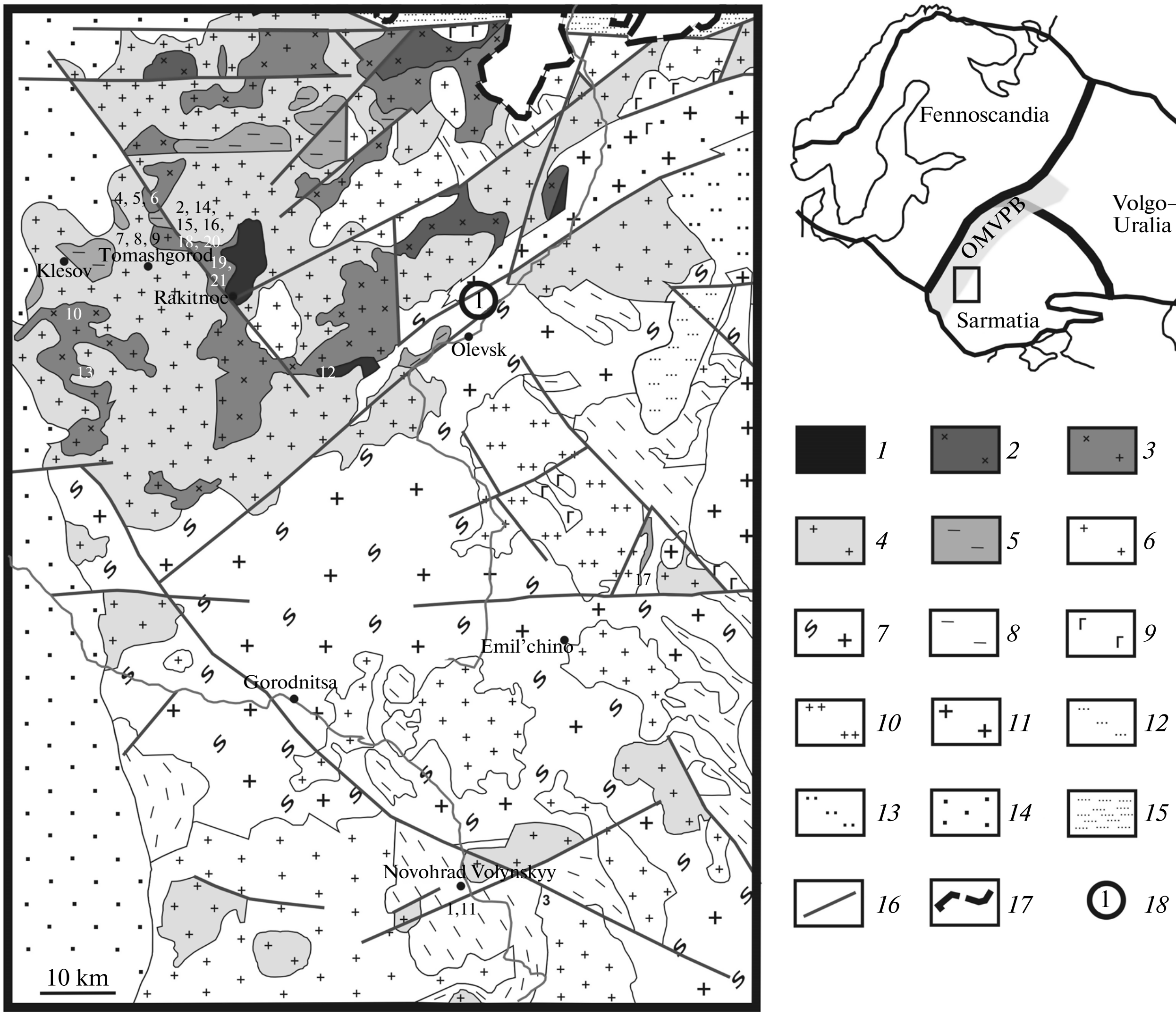

Fig. 1. Geological sketch map of the western part of the northwestern Ukrainian Shield. The inset shows the position of the Osnitsk–Mikashevichy volcanoplutonic belt in the structure of the East European craton (after [8]). (*1–4*) Rocks of the Osnitsk complex: (*1*) gabbro and pyroxenite, (*2*) diorite, (*3*) granodiorite, and (*4*) granite; (*5*) metamorphosed extrusive rocks of the Klesov Group; (*6*) granitoid of the Zhitomir complex; (*7*) fields dominated by migmatites of the Zhitomir complex; (*8*) metamorphic rocks of the Teterev Group; (*9*) gabbroids of various complexes; (*10*) granite of the Kishin massif; (*11*) granite of the Korosten complex; (*12*) extrusive and sedimentary rocks of the Belokorovichi depression; (*13*) extrusive and sedimentary rocks of the Ovruch depression; (*14*) Neoproterozoic sedimentary cover (Riphean terrigenous and Late Vendian mostly volcanogenic sequences); (*15*) Paleozoic sedimentary cover; (*16*) major fault; (*17*) state boundary of Ukraine and Belarus; and (*18*) Sushchany–Perga fault. Numbers in the map show the sites where the samples shown in Table 1 were collected.

considered as belonging to the Osnitsk complex in Ukraine and distinguished as a separate complex (Volkhvinsky) in Belarus [6]. The Osnitsk complex comprises a variety of rocks: gabbro, diorite, granodiorite, quartz monzonite, and granite. Most common are calc-alkaline (plagioclase–K-feldspar) granites [9].

The Klesov Group includes moderately metamorphosed extrusive rocks, from metabasalts to metarhyolites. The latter are often strongly recrystallized, and their primary volcanic textures may be obliterated; such rocks are refereed to as haelleflinta, leptite, etc. [5].

The area of OMVPB is strongly dominated by the rocks of the Osnitsk complex and Klesov Group (Fig. 1). Basement rocks were documented in several "windows"; they are represented by older (2090–2040 Ma) granites of the Zhitomir complex. In addition, the plutonic (granitoids) and subvolcanic (metamorphosed dolerite dikes) rocks of the Osnitsk complex and the metamorphosed extrusive rocks of the Klesov Group were observed south of the OMVPB proper, within the northwestern region of the Ukrainian Shield. Thus, the area of the occurrence of the rocks of the Osnitsk complex and Klesov Group is not sharply bounded in the south by the Sushchany–Perga fault

(Fig. 1), which is considered as the southern boundary of the OMVPB in the Ukrainian Shield.

The basic rocks of the Osnitsk complex (Volkhvinsky complex is considered in this paper together with the Osnitsk complex) occur in the following forms [10]: sheetlike (sill-like) bodies in thick sequences of metabasaltoids of the Klesov Group; small stocklike bodies penetrating the gneiss–migmatite basement; and root or (more often) rootless bodies (relics) of varying size in younger granodiorite–granite intrusions of the Osnitsk complex. A characteristic feature of the basic rocks of the Osnitsk complex is an almost ubiquitous association and reaction relationships with granitoids. Zones of varying thickness of hybrid rocks (monzogabbro, monzonite, syeno-diorite, and other rocks of elevated alkalinity) were observed at the contact with the granitoids.

In our interpretation, the Osnitsk complex includes also numerous dikes of weakly metamorphosed dolerites occurring within the OMVPB and south of it among the gneisses of the Teterev Group and Zhitomir granitoids.

According to Aksamentova [6], xenoliths and relics of metabasites are diverse in size and shape, from small angular or rounded fragments to large blocks and sheet bodies up to 10–25 m thick or even more stretching from hundreds of meters to a few kilometers. The contacts of metabasic relics with granitoids are usually sharp and uneven, although gradual transitions to quartz diorites and further to granites were occasionally observed. Relics of both extrusive bodies and rootless intrusions of basic rocks are cut by numerous granite veins (often leptite-like or aplitic) of varying thickness. The contacts of these veins with metabasic rocks are usually sharp and linear, although thin (a few centimeters thick) veins are often strongly deformed.

According to recent geochronological investigations [11–15], the OMVPB rocks (both intrusive and extrusive) crystallized at 2000–1980 Ma.

METHODS

Most of the whole-rock analyses discussed in this paper were obtained by the ICP–MS technique at the commercial laboratory of the Acme Analytical Laboratories Ltd., Vancouver, Canada. Some analyses were performed at the University of Liege, Belgium using an ARL 9400XP X-ray fluorescence spectrometer. The major components, V, Cr, and Ba were analyzed in glass discs, and other trace elements (Sr, Rb, Nb, Zr, Y, Ni, Zn, Co, and Cu), in pressed powder pellets.

Strontium and neodymium isotope ratios were determined at the laboratory of isotope geology of the Swedish Museum of Natural History, Stockholm. The contents of Sm and Nd were measured by the isotope dilution method using a mixed ^{150}Nd–^{147}Sm spike. Samples of Sm, Nd, and Sr were loaded on double Re filaments, and metal ions were measured using a Triton thermal ionization mass spectrometer. The isotopic compositions of Sr and Nd were measured in a multidynamic mode, and that of Sm, in a static mode. The Nd isotopic composition was corrected for spike, interference with Sm, and fractionation by normalizing to ^{146}Nd/^{144}Nd = 0.7219. Interference with Sm was estimated by the measurement of the 149 mass. The initial ^{87}Rb/^{86}Sr ratio was calculated from the measured ^{87}Rb/^{86}Sr value and Rb and Sr contents determined by ICP–MS. The precision of the measurement of Rb and Sr contents was estimated by Acme as ±5% (2σ). The Sr isotopic ratios were corrected for interference with Rb and normalized to the ratio ^{86}Sr/^{88}Sr = 0.1194.

Hafnium isotope analysis was carried out at the laboratory of the Bristol University (UK) by the laser ablation ICP–MS technique using a Neptune multicollector mass spectrometer. The analytical procedure was described in detail by Kemp et al. [16].

PETROGRAPHY OF OMVPB ROCKS

The most conspicuous feature of the rocks of the Osnitsk complex and Klesov Group is their significant metamorphism of late epidote–early amphibolite grade.

The basic extrusive rocks of the Klesov Group are mostly metabasalts and metabasaltic andesites. Sporadic occurrences of coarser grained rocks (metamorphosed dolerites) may represent fragments of thick flows.

The basic rocks of the OMVPB, including metamorphosed extrusive rocks, often contain up to 10% quartz. The content of plagioclase is commonly 45–55%, and that of opaque minerals is 3–5%, occasionally up to 10%. The mafic mineral assemblage includes amphibole and biotite, the contents of which are strongly variable: 5–35% amphibole (hornblende, evidently after pyroxenes) and 5–20% biotite. The central parts of plagioclase crystals are often replaced by epidote-group minerals, which may account for up to 10% of the rock.

Porphyritic metabasalt varieties containing up to 15% plagioclase phenocrysts are rather common.

The main varieties of metamorphosed gabbroids are amphibolites and amphibolized gabbro. The rocks have medium- to coarse-grained, equigranular, nematoblastic, and poikiloblastic (amphibolized gabbro) textures and massive structures. Their mineral composition is widely variable. The major minerals are plagioclase (25–60 vol %) and hornblende (40–65 vol %). Less abundant are relics of clinopyroxene (up to 5–10 vol %), opaque minerals (up to 5–7 vol %), biotite (2–5 vol %), epidote, quartz, carbonate, and apatite.

Dolerites from dikes are compositionally rather uniform. The main rock variety is amphibolized dolerite. The rocks have commonly medium- to fine-grained, equigranular, ophitic, and occasionally porphyritic textures and massive structures. The mineral composition of the rocks is the following (vol %): 50–65 plagioclase, 25–45 (occasionally, up to 60) hornblende and other products of pyroxene replacement, up to 35 pyroxene relics (in some thin sections), up to 5–10 opaque minerals, 2–3 (occasionally, up to 10) biotite, and up to 3 quartz.

The intermediate plutonic rocks (diorites) often change gradually to xenoliths and relics of metamorphosed dolerites [6]. The diorites often grade into granodiorites, although distinct contacts were also observed between these rocks. Nechaev et al. [9] reported the presence of diorite xenoliths in the granitoids. The diorites are composed mainly of plagioclase and hornblende.

According to Aksamentova [6], granites occur as compositionally uniform subisometric or elongated massifs, as well as veins and dikes. The rocks are composed of approximately equal amounts of plagioclase, K-feldspar, and quartz with a minor amount of biotite. In addition, hornblende and, occasionally, clinopyroxene were documented. Magnetite, titanite, apatite, zircon, and pyrite occur in accessory amounts. The secondary minerals are epidote, sericite, chlorite, and leucoxene.

Silicic and intermediate extrusive rocks were described in detail in [5, 17]. Dacite porphyries are fine-grained to aphanitic porphyritic rocks. Their phenocrysts are nonuniformly distributed and represented by rounded grains of quartz, albite and albite–oligoclase, and microcline. The groundmass shows felsitic, microlitic, and microgranoblastic textures and is composed mainly of quartz, albite, and microcline with minor amounts (up to 4%) of muscovite, biotite, and epidote.

Compared with the dacite porphyries, rhyolites and leptites of liparite composition have much lower contents of feldspar phenocrysts and are almost free of mafic minerals.

Leucocratic leptites (known as klesovites) are common; these are quartz–microcline rocks with a strongly heterogranular microscopic texture. The fine-grained groundmass of the rock contains well-defined phenocrysts of quartz and feldspar up to 1 mm in size. Most common are rounded and pyramidal crystals of dark quartz with resorption features. The feldspar phenocrysts appear as corroded prisms. Biotite accounts for no more than 1–2% and occurs as inclusions in K-feldspar, plagioclase, and quartz and, sometimes, in aggregates with epidote, leucoxene, and muscovite.

CHEMICAL COMPOSITION OF OMVPB ROCKS

The author compiled a database of the chemical compositions of OMVPB rocks including 189 analyses of basic rocks and 79 analyses of silicic rocks for major components. The sources of data are [6, 9, 17–20]; unpublished reports of the Zhitomir geological prospecting expedition and the Semenenko Institute of Geochemistry, Mineralogy, and Ore Formation; and the author's analytical results for the OMVPB rocks (Table 1). Most of the analyses correspond to rocks the chemical compositions of which approaches the composition of their parental melts. Among them are primarily dike, vein, and extrusive rocks irrespective of their composition and most granitoids. Typical cumulus rocks are represented by relatively rare high-magnesium amphibolized melanocratic gabbros and amphibolites.

The OMVPB rocks form continuous trends in some variation diagrams of major elements versus SiO_2 (Fig. 2). This allows us to suggest that the whole spectrum of OMVPB rocks was produced by the differentiation of a single initial melt of basic–ultrabasic composition. However, many diagrams (e.g., SiO_2–Na_2O and SiO_2–Al_2O_3) display a sharp inflection of trends or even discordant trends for the silicic and basic portions (SiO_2–TiO_2). Similar patterns can be observed in the Mg#—major oxide diagrams. Therefore, two series can be distinguished among the rocks of the Osnitsk complex and Klesov Group: (1) gabbroids and (2) granitoids (Fig. 3). The former series includes all rock varieties from amphibolized melanogabbro to diorite and metamorphosed extrusive rocks containing no more than 60 wt % SiO_2; and the latter series includes granitoids and metamorphosed extrusive rocks containing no less than 60 wt % SiO_2. The two rock series overlap considerably in Mg# (atomic ratio $Mg\# = Mg/(Mg + Fe)$), which ranges from 83 to 30 in the gabbroids and from 62 to 8 in the granitoids.

The existence of two series casts doubt on the suggestion that the gabbroids and granitoids are derivatives of a single primary melt. This problem will be addressed in more detail below.

The evolution of the basic melt is accompanied by rapid accumulation of TiO_2 and alkalis in late differentiation products (Fig. 3); the content of iron increases also; and that of CaO, in contrast, decreases. It is evident that such an evolution path was controlled by the fractionation of the assemblage of mafic minerals, pyroxenes and titanomagnetite (and, probably, chromite).

A decrease in the Mg# value of granitoids is not accompanied by significant changes in their chemical composition. There are only some increase in SiO_2 and K_2O and a decrease in TiO_2, Al_2O_3, and CaO contents. The chemical evolution of the silicic rocks of the OMVPB was controlled mainly by plagioclase fractionation.

Table 1. Chemical compositions of the OMVPB rocks

Component	Post-granite basites									
	1	2	3	4	5	6	7	8	9	10
SiO_2	50.81	52.32	51.57	46.96	47.27	47.69	50.05	51.63	55.22	46.31
TiO_2	1.65	1.92	1.82	1.31	1.22	1.10	0.75	1.00	1.74	0.75
Al_2O_3	14.07	14.61	15.39	16.22	16.32	16.81	15.64	17.23	13.76	12.77
Fe_2O_3	14.03	13.68	12.17	14.03	16.68	15.20	10.12	10.11	13.48	11.80
MnO	0.21	0.19	0.16	0.22	0.20	0.25	0.17	0.15	0.20	0.18
MgO	4.92	4.14	4.46	7.10	6.03	6.21	7.29	4.90	3.67	12.40
CaO	7.73	6.53	5.30	9.11	7.72	7.59	9.84	7.63	5.84	9.71
Na_2O	2.94	3.27	3.35	2.85	2.82	3.90	3.31	4.08	2.67	2.63
K_2O	1.87	2.01	1.92	0.85	0.72	1.18	1.14	1.60	1.35	1.03
P_2O_5	0.28	0.83	0.85	0.42	0.39	0.38	0.25	0.46	0.40	0.26
Cr_2O_3	0.011	0.006	0.015	0.010	0.008	0.004	0.053	0.008	0.004	0.121
Mg#	45.0	41.3	46.0	54.1	45.7	48.8	62.7	53.0	38.8	71.0
C	0.09	–	0.27	0.12	–	–	0.05	0.03	0.09	0.09
S	0.19	–	0.16	0.13	–	–	0.06	0.26	0.04	0.16
LOI	1.33	0.75	2.41	1.86	2.69	3.10	1.30	0.90	1.30	1.90
Total	99.86	99.52	99.50	99.64	99.37	100.31	99.92	99.71	99.64	99.89
Ni	21	18	51	75	84	60	26	13	18	160
Sc	36	–	25	34	–	–	30	23	27	30
Ba	977	1291	1008	462	620	513	776	790	933	433
Co	42	37	37	48	41	41	36	27	31	53
Cs	6	–	3	1	–	–	2	2	1	1
Ga	19	–	23	–	–	–	17	18	22	14
Hf	4	–	5	3	–	–	2	3	5	2
Nb	5	15	20	8	7	16	5	7	9	8
Rb	89.6	48.6	56.5	18.1	15.0	20.3	51.9	59.3	24.5	23.4
Sr	395.2	763.7	757.2	622.6	676.5	697.4	882.6	885.5	508.0	1043.7
Ta	0.3	–	1.0	0.3	–	–	0.3	0.3	0.4	0.3
Th	2.7	7.0	2.8	1.4	6.1	4.0	4.1	2.6	0.7	1.2
Tl	0.5	–	0.2	0.1	–	–	0.2	0.3	0.1	0.2
U	0.8	3.8	1.5	0.3	–	–	1.7	0.7	0.3	0.5
V	389	212	207	309	243	229	226	208	263	227
Zr	145	247	190	99	107	93	90	110	186	48
Y	27.1	31.4	27.1	24.5	22.9	22.6	14.7	14.6	32.7	11.5
La	19.7	–	48.9	21.5	–	–	18.3	26.9	33.8	18.7
Ce	44.6	132.2	103.0	34.5	69.0	81.1	39.6	59.1	72.4	44.5
Pr	5.8	–	13.1	6.5	–	–	5.2	7.4	9.3	5.9
Nd	24.9	–	53.8	29.7	–	–	22.2	30.0	42.5	23.2
Sm	5.1	–	9.6	6.2	–	–	4.4	5.3	7.6	4.0
Eu	1.66	–	2.72	2.10	–	–	1.39	1.52	2.52	1.21
Gd	5.11	–	7.67	5.73	–	–	3.69	4.17	6.86	3.19
Tb	0.89	–	0.95	0.82	–	–	0.56	0.62	1.15	0.48
Dy	5.31	–	5.04	4.69	–	–	2.86	2.99	6.38	2.48
Ho	0.95	–	0.90	0.88	–	–	0.47	0.49	1.23	0.40
Er	2.86	–	2.54	2.42	–	–	1.41	1.45	3.29	1.12
Tm	0.38	–	0.34	0.36	–	–	0.18	0.20	0.54	0.16
Yb	2.44	–	2.39	2.21	–	–	1.17	1.18	3.17	0.95
Lu	0.39	–	0.34	0.37	–	–	0.17	0.20	0.48	0.13
Mo	0.4	–	1.1	0.4	–	–	0.2	0.3	1.0	0.4
Cu	52	48	52	63	56	72	15	35	22	47
Pb	2.3	13.0	4.5	8.8	8.8	4.8	1.5	1.7	10.9	3.8
Zn	58	150	95	107	113	103	33	58	94	33

Table 1. (Contd.)

Component	Pre-granite rocks					Silicic rocks					Diorite
	11	12	13	14	15	16	17	18	19	20	21
SiO_2	49.32	45.05	47.26	49.01	50.09	73.34	72.25	71.56	72.22	86.25	52.72
TiO_2	0.74	0.71	0.49	0.82	1.99	0.21	0.21	0.40	0.32	0.27	1.51
Al_2O_3	10.06	16.27	15.18	16.85	14.74	14.23	13.72	13.89	12.60	5.99	17.24
Fe_2O_3	10.26	14.15	10.52	11.49	13.49	1.72	2.87	2.98	2.38	2.66	8.79
MnO	0.18	0.15	0.13	0.25	0.17	0.06	0.05	0.02	0.05	0.03	0.17
MgO	11.92	8.47	10.64	7.31	4.59	0.25	0.17	0.65	0.50	0.24	3.69
CaO	9.14	12.74	11.39	7.88	7.22	0.57	0.84	1.29	1.04	0.26	6.67
Na_2O	3.30	1.31	1.48	2.67	3.27	4.33	3.75	3.22	4.60	0.34	4.69
K_2O	1.16	0.50	0.80	2.13	2.40	4.74	5.36	5.52	5.90	3.47	2.49
P_2O_5	0.18	0.10	0.10	0.23	0.96	0.06	0.05	0.09	0.06	0.04	0.27
Cr_2O3	0.125	–	–	0.024	0.034	0.002	<0.002	0.001	0.001	0.002	0.002
#Mg	73.0	58.2	70.2	59.7	44.2	25.3	17.3	33.8	32.7	17.3	49.3
C	0.54	–	–	0.02	0.04	0.03	–	–	–	–	–
S	0.13	–	–	0.01	0.16	0.01	<0.02	0.02	0.01	0.02	0.15
LOI	3.50	0.95	1.90	1.20	0.70	0.40	0.6	–	0.62	0.09	1.59
Total	99.92	100.40	99.89	99.87	99.66	99.92	99.88	99.32	99.45	99.30	97.41
Ni	137	22	21	20	19	1	3	16	6	2	25
Sc	30			28	27	5	8	6	3	4	24
Ba	319	240	275	295	1227	654	296	1695	890	1150	954
Co	53	56	58	27	34	1	1	4	1	1	24
Cs	13	1	2	18	2	2	5	2	2	1	2
Ga	13	19	16	20	21	17	18	13	13	7	17
Hf	2	1	1	2	6	6	10	8	5	3	3
Nb	15	2	2	3	16	13	21	21	18	9	10
Rb	51.3	15.0	24.6	197.7	71.8	165.1	215.0	89.8	177.4	109.3	66.4
Sr	489.0	808.5	735.7	732.5	771.7	89.5	47.4	349.5	143.8	64.6	688.1
Ta	0.9	0.1	0.1	0.2	0.6	1.1	1.3	1.2	0.8	0.5	0.3
Th	1.4	0.8	1.9	1.9	2.1	10.9	18.6	16.1	17.1	6.8	4.6
Tl	0.3	0.1	0.1	1.0	0.3	0.1	–	0.4	0.8	0.5	0.3
U	0.5	0.3	0.7	0.9	0.6	3.6	4.7	6.6	5.5	1.8	2.8
V	195	435	177	244	241	7	<8	38	10	3	193
Zr	77	37	37	48	246	199	333	288	139	100	134
Y	13.7	9.4	8.3	15.6	34.2	21.0	38.9	28.9	12.1	15.7	15.1
La	11.1	8.1	10.4	10.5	59.3	42.4	68.1	71.3	52.7	26.3	27.5
Ce	25.4	13.8	21.0	26.1	138.9	88.4	136.3	144.3	104.0	52.3	60.1
Pr	3.5	2.3	2.6	3.4	16.7	9.5	16.5	15.4	10.3	6.2	6.9
Nd	14.6	10.1	11.4	16.4	68.5	33.7	62.4	56.2	27.1	19.6	27.9
Sm	3.1	2.3	2.5	3.6	11.6	6.2	10.91	9.4	4.0	3.6	5.0
Eu	0.85	0.78	0.89	1.03	3.33	0.86	0.7	1.47	0.44	0.52	1.41
Gd	2.72	1.98	2.21	3.22	8.83	3.92	8.79	6.99	2.63	2.87	3.98
Tb	0.47	0.29	0.30	0.44	1.26	0.63	1.27	1.02	0.40	0.43	0.56
Dy	2.57	1.52	1.57	2.68	6.62	3.57	6.86	5.35	1.97	2.49	2.95
Ho	0.49	0.30	0.31	0.49	1.27	0.69	1.33	1.03	0.39	0.51	0.56
Er	1.46	0.80	0.83	1.50	3.46	2.19	3.58	2.98	1.07	1.54	1.61

Table 1. (Contd.)

Component	Pre-granite rocks					Silicic rocks					Diorite
	11	12	13	14	15	16	17	18	19	20	21
Tm	0.19	0.13	0.12	0.23	0.46	0.37	0.54	0.42	0.16	0.23	0.21
Yb	1.27	0.81	0.75	1.47	2.77	2.24	3.44	2.95	1.10	1.59	1.44
Lu	0.21	0.11	0.12	0.22	0.38	0.35	0.53	0.40	0.16	0.25	0.21
Mo	0.5	–	–	0.3	0.6	0.3	1.2	0.9	0.7	0.4	0.6
Cu	126	93	97	2	17	3	5	112	330	4	191
Pb	1.9	1.7	1.9	1.4	2.4	6.2	15.2	26.4	30.4	5.7	19.4
Zn	28	55	23	113	99	27	50	37	44	14	96

1, Young dike in a quarry at Susly village (mean of three analyses); 2, sample 03-T18, Tomashgorod, Pshcheli quarry, thin metadolerite dike; 3, metadolerite dikes east of Novohrad Volynskyy, boreholes 814 and 835 (mean of three analyses); 4, metadolerite dike, Yarovskii quarry (mean of two analyses); 5, metadolerite dike from the same area, sample 03Ya3, central part of the same dike as analysis 4; 6, metadolerite dike, same site, sample 03-Ya5, another dike; 7, metadolerite dike, sample U98-27, quarry of the Tomashgorod rock crushing plant; 8, metadolerite dike, sample U96-157, same locality, another dike; 9, metadolerite dike, sample 06-E19-K, same locality, another dike, contact zone; 10, thin dike in a quarry at Viry village, sample U157-97; 11, older dike in a quarry at Susly village (mean of four analyses); 12, amphibolite (metagabbro), quarry at Kisorichi village (mean of two analyses); 13, amphibolized gabbro, quarry at Yasnogorka village, sample 03-BAM1; 14, metabasalt, Pshcheli quarry, Tomashgorod, sample 05-T5; 15, metabasalt, same locality, sample 05-T4; 16, granite, same locality, sample 05-T10; 17, metarhyolite, outcrop in Chmel village, sample Chmel; 18, thin granite vein intersecting a metadolerite dike (sample 03-T18, analysis no. 2), Pshcheli quarry, Tomashgorod, sample 05-T12-3; 19, granite, quarry at the settlement of Rokitnoe, sample 09-P2; 20, leptite, Pshcheli quarry, Tomashgorod, sample 05-T9; and 21, diorite, quarry at Rokitnoe, sample 09-P1. Contents of oxides, C, S, LOI, and total are in wt %, elements are in ppm, and Fe_2O_3 is total Fe in the Fe_2O_3 form.

According to the classification diagram of Irving and Baragar [21], the OMVPB rocks are assigned to the calc-alkaline series. In discrimination diagrams of Pearce et al. [22], the compositions of the granitoids and silicic volcanics fall within the field of volcanic arcs.

Geochemistry of Basic Rocks

Based on geologic relationships, the basic rocks of the Osnitsk complex were subdivided into two groups, pre- and post-granite. In terms of composition, both groups belong mainly to the basalt family. The most basic varieties fall into the field of picrites, and the most silicic and alkali-rich rocks are classified as trachybasalts and basaltic trachyandesites.

With some exceptions, the chemical compositions of the pre- and post-granite basic rocks are distinctly different. For instance, the pre-granite rocks show higher Mg# values (Table 1) and, correspondingly, higher MgO contents and elevated contents of CaO, CO_2, Cr_2O_3, Ni, Co, Cs, and Cu. The post-granite basic rocks are enriched in TiO_2, P_2O_5, S, Ba, Ga, Hf, Nb, Rb, Th, U, Zr, Y, REE, Pb, and Zn.

The distribution of REE in the two groups of basic rocks is similar: the chondrite-normalized REE patterns are smooth with negligible or very small positive Eu anomalies (Fig. 4). In general, the pre-granite basic rocks show lower REE contents, and the degree of fractionation, $(La/Yb)_N$, increases with increasing REE contents.

The primitive mantle-normalized [23] trace element patterns of the pre- and post-granite basic rocks are similar. Both groups are characterized by gradually decreasing contents from the most incompatible (Ba, Rb, and Th) to moderately incompatible elements (Fig. 5). Other common features are distinct negative anomalies of Th, Nb, and Ta and less pronounced anomalies of Zr and Hf. The basic rocks show positive anomalies of Ba, K, and Pb, and the pre-granite basic rocks display a distinct positive Sr anomaly.

Geochemistry of Silicic Rocks and Diorites

Despite their higher abundance, the silicic rocks of the OMVPB have been investigated much less extensively than the basic rocks. In terms of geochemical characteristics, they are similar to the basic rocks of the Osnitsk complex, especially their post-granite varieties. The contents of most trace elements approach those of the most enriched post-granite basic rocks. Exceptions are some incompatible lithophile elements, Rb, Th, U, and K, the contents of which in the granitoids are much higher. Similar to the basic rocks, the granitoid display negative Nb and Ta anomalies. On the other hand, the granitoids show distinct negative Sr, P, and Ti anomalies (Fig. 5), which are absent in the basic rocks. The granitoids are distinguished by moderate REE contents and the presence of a negative Eu anomaly (Fig. 4).

According to the classification diagrams of Frost et al. [24], the Osnitsk granitoids are mainly magnesian peraluminous rocks of the alkali-calcic and calc-alka-

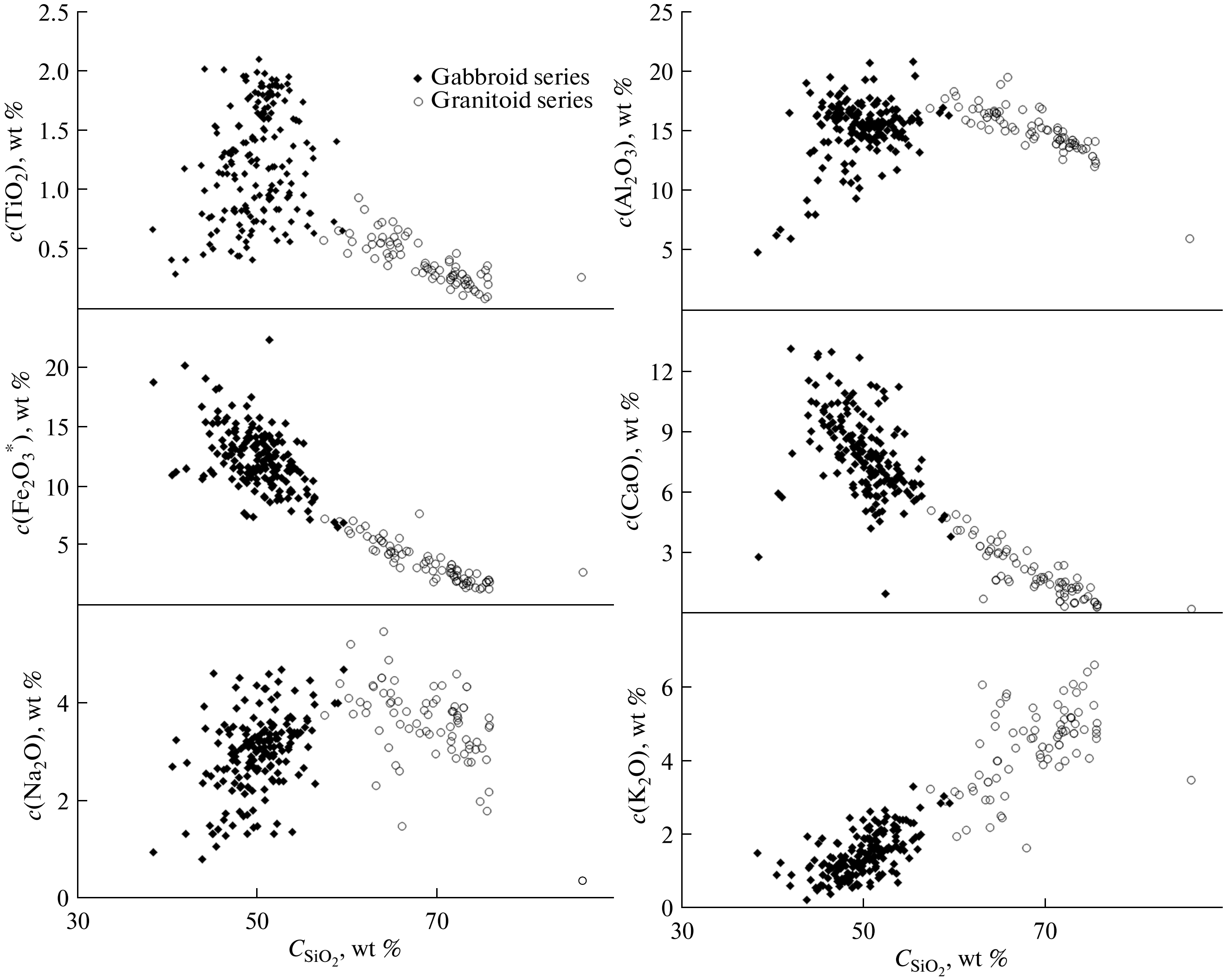

Fig. 2. Major component variations in the rocks of the Osnitsk complex and the Klesov Group in the coordinates SiO_2 versus major oxide. The diagrams show the data of [6, 9, 17–20] and the results of this study (Table 1).

line series. Their modern equivalents are granites from Cordillera-type continental margins.

STRONTIUM, NEODYMIUM, AND HAFNIUM ISOTOPE SYSTEMATICS

The author determined the Sr and Nd isotope compositions of nine samples of OMVPB rocks, including five basic rocks, two granites, and two silicic extrusive rocks of the Klesov Group (Table 2). In addition to the author's data, Table 2 gives isotopic data for the granitoids of the Osnitsk complex and silicic extrusive rocks of the Klesov Group after [8] and xenoliths of lower crustal granulites from the Devonian diatremes penetrating the OMVPB complexes. According to Markwick et al. [25], these rocks are lower crustal analogues of the rocks of the Osnitsk complex.

The basic rocks of the Osnitsk complex and lower crustal xenoliths show εSr values of around 0 (from –4 to + 11, and one anomalously high value of +117 in a dike exposed in a quarry at the settlement of Susly). The εSr value ranges from 5 to 10 in the granites and from –1 to +5 in the silicic volcanics. The Rb–Sr isochron obtained for all the analyses obtained by the author yields an age of 1994.3 +34/–7.6 Ma, which is very close to the U–Pb zircon age. Such a consistency of ages indicates evidently that the Rb–Sr system remained undisturbed since the time of rock formation.

The Nd isotope composition of the OMVPB rocks is more uniform, the εNd value recalculated to the time of crystallization (1990 Ma) ranges from –0.6 to +2.3 (taking into account the data of Claesson et al. [8] for granitoids), and only one sample showed a negative value (Table 2).

The Hf isotope composition of zircon was determined in three samples: 05-T10 (granite, Pshcheli quarry near Tomashgorod), 06-E18 (granite, quarry of

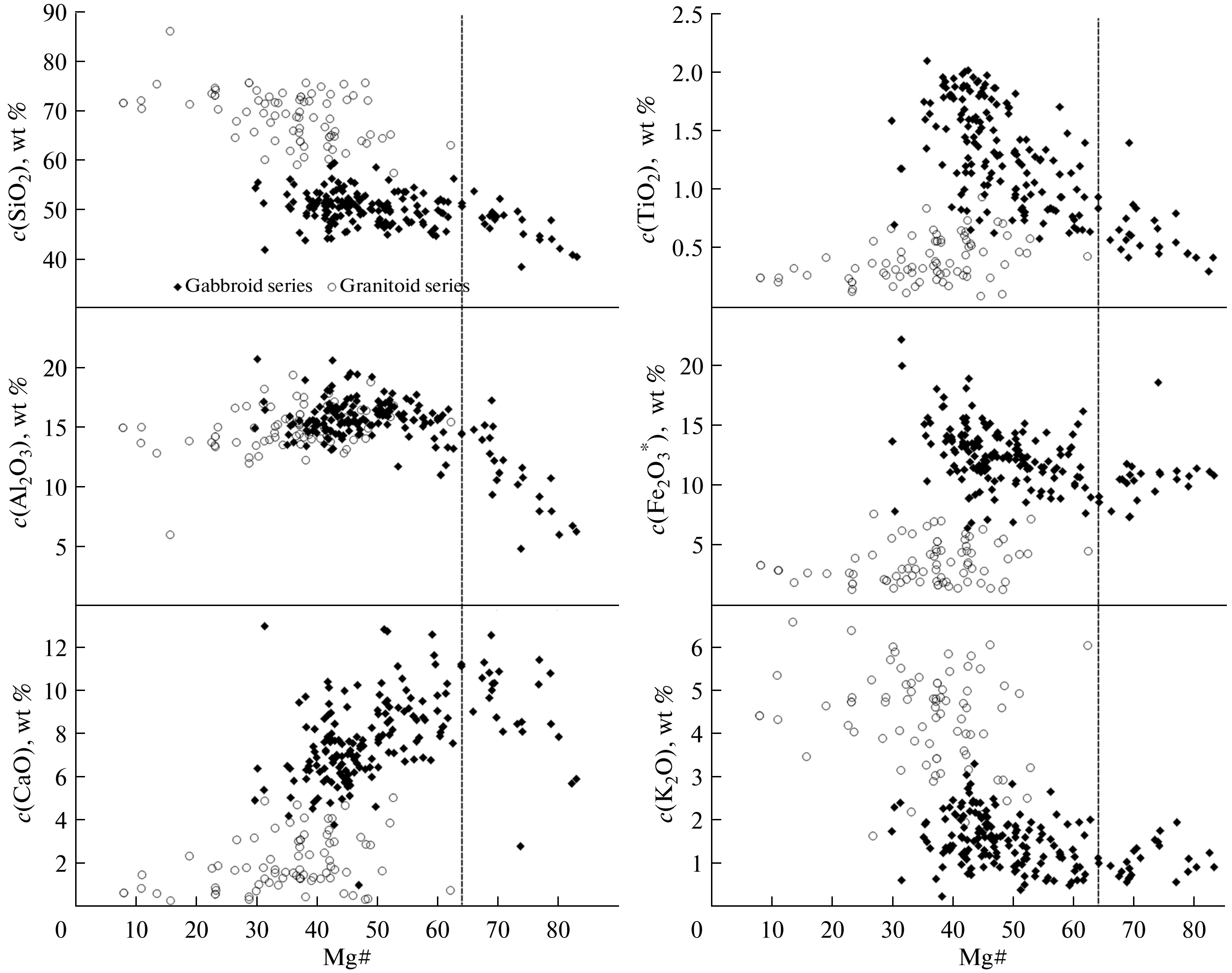

Fig. 3. Variations of major components in the rocks of the Osnitsk complex and Klesov Group in the coordinates Mg#—major oxide. The initial data and symbols are the same as in Fig. 2. The rocks plotting to the right from the vertical dashed line (Mg# > 64) are mafic cumulates.

the Tomashgorod rock crushing plant), and Chmel (felsite of the Klesov Group, Chmel village). The results are given in Table 3. The weighted mean εHf_{1990} values are 1.4 ± 1.3 for the granites and 0.1 ± 0.7 for the felsites.

DISCUSSION

The association of OMVPB rocks includes (1) granitoids strongly prevailing over all other rock types of the belt; (2) metamorphosed bodies of gabbroids and their ultrabasic differentiates; (3) metamorphosed and granitized volcanics of basalt and rhyolite compositions; and (4) dikes of metadolerites and, possibly, silicic rocks. Metasedimentary rocks are almost lacking. The association of OMVPB rocks is similar to that characteristic of modern active continental margins. It should be noted that basement windows made up of older (2100–2040 Ma) granites of the Zhitomir complex and migmatized gneisses of the Teterev Group occur among the Osnitsk granitoids. Thus, the OMVPB was formed on a continental basement that was still very young. It is evident that the OMVPB is an active continental margin formed on the Zhitomir–Teterev basement owing to the subduction of an oceanic plate from the north (in present-day coordinates).

All the rocks of the Osnitsk complex and the Klesov Group have juvenile isotopic signatures: positive εNd values and low initial $^{87}Sr/^{86}Sr$. Zircons from these rocks show positive εHf values. Such isotopic characteristics unambiguously indicate a mantle source for the initial melts. However, as can be seen in Fig. 6, the Sr and Nd isotopic characteristics of the OMVPB rocks were significantly different from the isotopic composition of the depleted mantle at the time of rock formation. On the other hand, an active continental margin setting does not imply the derivation of initial melts

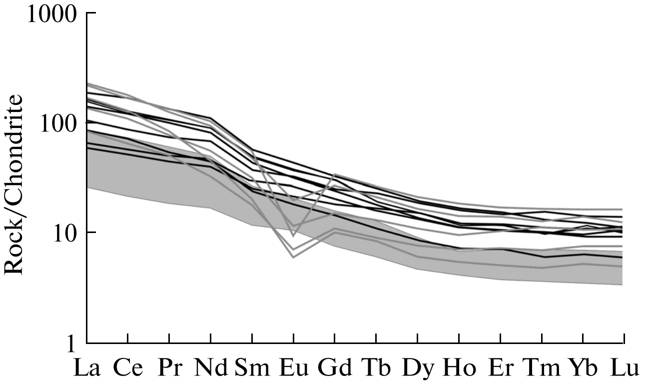

Fig. 4. Chondrite-normalized REE patterns of the rocks of the Osnitsk complex and Klesov Group. The shaded field shows the compositions of pre-granite basic rocks, black lines are post-granite basic rocks, and gray lines are silicic rocks.

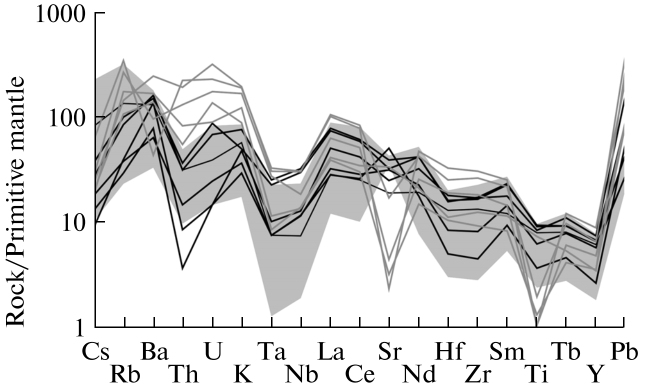

Fig. 5. Primitive mantle-normalized trace element patterns of the rocks of the Osnitsk complex and Klesov Group. Symbols are the same as in Fig. 4.

directly from the depleted mantle. Their source is a subducted oceanic slab, as well as the overlying mantle wedge and continental crust. The Nd and Hf model ages (Tables 2 and 3) obtained for the OMVPB rocks suggest that their protolith was separated from the depleted mantle 200–300 Myr before belt formation. The oceanic slab was obviously of such an age.

It is important that the Sr, Nd, and Hf isotopic characteristics of the rocks and zircons from the OMVPB are very similar to those of the basement rocks of the Teterev Group and Zhitomir complex (Fig. 6, [26]), which were formed in a similar geodynamic setting [27]. Therefore, the isotopic geochemical data do not contradict the possibility of formation of the initial magmas of the OMVPB rocks through the melting of the young Teterev–Zhitomir continental crust. However, melting of the continental crust could hardly produce basic melts. In any case, the identical isotopic characteristics of basement rocks and melts that intrude this basement prevent estimation of the degree of possible contamination.

The geochemical characteristics of the OMVPB rocks indicate that their initial melts were formed in a subduction zone setting or, in the case considered, at an active continental margin. The geochemical indicators of such environments are melt enrichment in Th, U, Ba, Rb, and Sr and depletion in Nb, Ta, Zr, and Hf [28]. The trace element distribution patterns of the basic rocks of the OMVPB (especially their pre-granite varieties) show distinct geochemical signatures of rocks related to subduction zones. The degree of REE fractionation in the pre- and post-granite basic rocks varies considerably, $(La/Yb)_N = 5–15$, but suggests a generally minor role of garnet in the melt source.

The examination of geochemical variation diagrams (Figs. 2 and 3) suggests that the basic and silicic melts of the OMVPB existed simultaneously and independently and were not differentiation products of a common primary magma. In particular, the observed discordant ($Mg\#–TiO_2$ and $SiO_2–P_2O_5$) and parallel ($Mg\#–SiO_2$) trends of the chemical evolution of rocks exclude the possibility of their crystallization from a single melt. It could have been supposed that the silicic melts were interstitial liquids separated from complementary mafic and ultramafic cumulates, and the observed independent trends correspond in fact to cumulates and residual melts. However, the compositions of the basic rocks plotted in the diagrams correspond mainly to weakly differentiated rocks rather than cumulates. Correspondingly, their evolution trends are interpreted as liquid lines of descent. Mafic cumulates proper are represented by a few highly magnesian ultramafics (Fig. 3). It is evident that their formation was the main factor of basic melt evolution. The silicic melts were formed

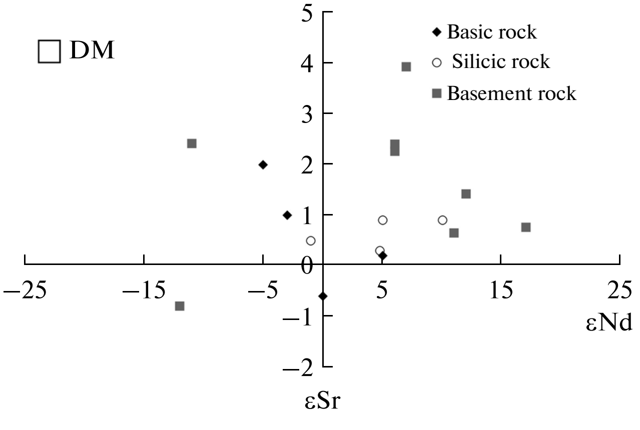

Fig. 6. Strontium and neodymium isotope compositions of the OMVPB rocks and basement rocks (granites of the Zhitomir complex and metamorphic rocks of the Teterev Group). All isotopic ratios were recalculated to an age of 2000 Ma. DM is the strontium and neodymium isotope composition of the depleted mantle at 2000 Ma ago.

Table 2. Results of the determination of Sr and Nd isotopic characteristics of the rocks of the Osnitsk complex and Klesov Group; initial isotope ratios were calculated for an age of 1990 Ma

Sample	Content, ppm		Isotope ratios			εSr	Content, ppm		Isotope ratios				Model ages, Ma		Autor
	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr_{(0)}$	$^{87}Sr/^{86}Sr_{(i)}$		Sm	Nd	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd_{(0)}$	$^{143}Nd/^{144}Nd_{(i)}$	εNd	T_{CHUR}	T_{DM}	
814/38-41	55.0	812.0	0.1960	0.708227 ± 14	0.70261	5	8.85	50.64	0.1057	0.511456 ± 6	0.51007	0.2	1972	2230	This study
03-Ya2	19.9	611.0	0.0942	0.704651 ± 8	0.70195	–5	5.73	27.06	0.1280	0.511841 ± 7	0.51016	2.0	1764	2130	
03-K2	15.4	778.9	0.0572	0.703699 ± 10	0.70206	–3	2.21	9.60	0.1391	0.511936 ± 7	0.51011	1.0	1854	2260	
05-C4	83.4	390.3	0.6195	0.728222 ± 5	0.71047	117	5.41	23.76	0.1377	0.511892 ± 6	0.51009	0.5	1920	2300	
05-C3	25.0	531.8	0.1360	0.70618 ± 4	0.70228	0	1.01	4.68	0.1305	0.511740 ± 6	0.51003	–0.6	2060	2390	
05-T10	172.0	89.5	5.6457	0.864767 ± 13	0.70296	10	5.55	32.11	0.1045	0.511475 ± 5	0.51011	0.9	1917	2180	
09-P2	175.0	155.0	3.2951	0.797047 ± 8	0.70261	5	4.80	32.4	0.0897	0.511282 ± 4	0.51011	0.9	1926	2155	
Chmel	205.0	47.4	12.9615	1.074101 ± 14	0.70261	5	3.64	20.49	0.1072	0.511481 ± 3	0.51008	0.3	1965	2235	
05-T9	100.0	67.6	4.3296	0.826313 ± 15	0.70222	–1	4.07	22.4	0.1097	0.511525 ± 4	0.51009	0.5	1943	2225	
1979	–	–	–	–	–	–	3.43	23.23	0.0892	0.511297 ± 7	0.51013	1.3	1897	2130	[8]
MK-204	–	–	–	–	–	–	2.58	13.68	0.1140	0.511673 ± 7	0.51018	2.3	1774	2090	[8]
LH-229	–	–	–	–	–	–	18.18	79.32	0.1386	0.511962 ± 7	0.51015	1.7	1768	2190	[8]
By5x	14.3	831.1	0.0498	0.70444 ± 1	0.70301	11	4.65	28.00	0.1004	0.511418 ± 5	0.51010	0.8	1925	2180	[25]
By9x	–	–	–	–	–	–	0.96	4.60	0.1262	0.511929 ± 5	0.51028	4.2	1530	1930	[25]
Bel8	25.9	838.1	0.0894	0.70458 ± 1	0.70202	–4	5.78	31.10	0.1124	0.511732 ± 4	0.51026	3.9	1634	1985	[25]

The compositions of rocks are given in the note to Table 1.

Table 3. Results of the Hf isotope analysis of zircon from the granites of the Osnitsk complex and felsites of the Klesov Group

Analysis no.	Measured ratios			Recalculated to 1990 Ma			Model ages, Ma	
	$^{176}Lu/^{177}Hf$	$^{176}Yb/^{177}Hf$	$^{176}Hf/^{177}Hf \pm 1\sigma$	$^{176}Hf/^{177}Hf_{1990}$	εHf_{1990}	$\pm 2\sigma$	$T_{(DM)}$	$T_{(DM)felsic}$
05-T10								
1	0.00459	0.22535	0.281633 ± 29	0.281459	–2.0	2.2	2502	2622
2	0.00601	0.27561	0.281608 ± 52	0.281381	–4.8	3.9	2648	2769
3	0.00251	0.09874	0.281697 ± 27	0.281602	3.1	1.9	2269	2355
06-E18								
1	0.00122	0.05094	0.281590 ± 16	0.281544	1.0	1.1	2340	2465
2	0.00233	0.09207	0.281687 ± 18	0.281599	3.0	1.3	2271	2361
3	0.00192	0.07854	0.281625 ± 17	0.281553	1.3	1.2	2334	2448
4	0.00113	0.04145	0.281612 ± 17	0.281569	1.9	1.2	2304	2417
5	0.00196	0.07203	0.281624 ± 20	0.281550	1.2	1.4	2338	2453
Chmel								
1	0.00063	0.02012	0.281549 ± 14	0.281525	0.3	1.0	2359	2499
2	0.00156	0.05376	0.281603 ± 48	0.281544	1.0	3.5	2343	2464
3	0.00071	0.02267	0.281524 ± 17	0.281497	–0.7	1.2	2399	2553
4	0.00068	0.02187	0.281563 ± 22	0.281538	0.8	1.5	2343	2476

independently and were not related to the crystallization of basic melts.

In general, the silicic rocks inherit the trace element characteristics of the basalts; however, they exhibit also new features absent or weakly manifested in the basic rocks, including distinct negative anomalies of Sr, P, Ti, and Eu. It is evident that the granites were formed from low-temperature (eutectoid) melts derived by the low degrees of melting of basic rocks (eclogites?). The elevated degree of REE fractionation, $(La/Yb)_N = 11–6$ and occasionally up to 32, indicates the presence of garnet in the residue. The basic melts could be formed from the same source (which is suggested by the identical isotopic geochemical characteristics of the basic and silicic rocks) at much higher degrees of melting. It is interesting that even the silica-rich granitoids show Mg# values of 45–48, which are high for such rock compositions (Fig. 3). Perhaps, their initial melts were in equilibrium with a highly magnesian basic residue.

CONCLUSIONS

(1) The association and geochemical characteristics of rocks from the Osnitsk–Mikashevichy volcanoplutonic belt are fully consistent with those typical of modern active continental margins.

(2) The Sr and Nd isotopic characteristics of whole-rock samples from the OMVPB and the Hf isotope compositions of zircons from these rocks indicate a juvenile origin of these rocks. The main source of melts was evidently a subducted oceanic slab with an age of approximately 200 Ma.

(3) The geochemical data suggest that the granitic and basic rocks of the belt were formed from two independent melts. The degree of melting was much lower for the granitoid melts compared with basic ones.

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REFERENCES

1. S. Bogdanova, "Segments of the east European craton," in *EUROPROBE in Jablonna 1991, Institute of Geophysics, Warszawa, Poland*, Ed. by D. G. Gee and M. Beckholmen (Institute of Geophysics, Polish Academy of Sciences–European Science Foundation, Warszawa, 1991), pp. 33–38.
2. S.-Å. Elming, N. P. Mikhailova, and S. N. Kravchenko, "The consolidation of the East European Craton: A paleomagnetic analysis of Proterozoic rocks from the Ukrainian Shield and tectonic reconstructions versus Fennoscandia," Geophys. J. **20** (4), 71–74 (1998).

3. S.-Å. Elming, L. Shumlyanskyy, S. Kravchenko, P. Layer, and U. Söderlund, "Proterozoic basic dykes in the Ukrainian Shield: A palaeomagnetic, geochronologic and geochemical study—the accretion of the Ukrainian Shield to Fennoscandia," Precambrian Res. **178**, 119–135 (2010).
4. S. V. Bogdanova, O. B. Gintov, D. Kurlovich, N. V. Lubnina, M. Nilsson, M. I. Orlyuk, I. K. Pashkevich, L. V. Shumlyanskyy, and V. I. Starostenko, "Late Palaeoproterozoic mafic dyking in the Ukrainian Shield (Volgo–Sarmatia) caused by rotations during the assembly of supercontinent Columbia (Nuna)," Lithos **174**, 196–216 (2012). DOI: 10.1016/j.lithos.2012.11.002.
5. A. Ya. Khatuntseva, *Leptite Formation of the Northwestern Ukrainian Shield* (Nauk. Dumka, Kiev, 1977).
6. N. V. Aksamentova, *Magmatism and Paleogeodynamics of the Paleoproterozoic Osnitsk–Mikashevichy Volcanoplutonic Belt* (Inst. Geol. Nauk NAN Belarusi, Minsk, 2002) [in Russian].
7. M. M. Kostenko, Extended Abstract of Candidate's Dissertation in Geology and Mineralogy (Kiev, 2012).
8. S. Claesson, S. V. Bogdanova, E. V. Bibikova, and R. Gorbatschev, "Isotopic evidence for Palaeorpoterozoic accretion in the basement of the East European Craton," Tectonophysics **339**, 1–18 (2001).
9. S. V. Nechaev, S. G. Krivdik, V. A. Semka, K. M. Buchinskaya, and S. M. Ryabokon', *Tin, Tungsten, and Molybdenum Mineralization in the Ukrainian Shield* (Nauk. Dumka, Kiev, 1986) [in Russian].
10. G. Pavlov, V. Molyavko, O. Zinchenko, L. Shumlyanskyy, and L. Derevitskaya, *Basite magmatic formations of the stabilization stage of the Ukrainian Shield, in Collection of Scientific Articles* (1996), No. 2, pp. 47–58 [in Ukrainian].
11. N. P. Shcherbak, A. M. Pap, E. N. Bartnitskii, and A. P. Zayats, "Uranium–lead isotope age of the Belorussia granitoids," Dokl. Akad. Nauk BSSR **34** (8), 740–743 (1990).
12. N. P. Shcherbak, G. V. Artemenko, I. M. Lesnaya, A. N. Ponomarenko, and L. V. Shumlyanskyy, *Geochronology of the Early Precambrian of the Ukrainian Shield. Proterozoic* (Nauk. Dumka, Kiev, 2008).
13. L. V. Shumlyanskyy, M. D. Mazur, O. V. Zinchenko, and S. G. Krivdik, "Isotope (U–Pb zircon) age and geological position of the Kishinsky Massif and rocks of its framing, northwestern Ukrainian Shield," Mineral. Zh. **31** (2), 84–91 (2009).
14. O. B. Vysotsky, Geochemistry and age of the basic rocks of the Osnitsk Block (Volhynia Megablock of the Ukrainian Shield), in *Proceedings of International Research–Practical Conference on Stratigraphy, Geochronology, and Correlation of the East European Platform* (UkrGGRI, Kiev, 2010), pp. 50–52 [in Russian].
15. O. B. Vysotsky, T. I. Dovbush, and I. M. Kotvitskaya, "Crystal genesis and age of zircon from the gabbro of the Osnitsk Complex (Volhynia megablock of the Ukrainian Shield)," in *Geokhim Rudotvoren.*, **28**, 81–83 (2010).
16. A. I. S. Kemp, G. L. Foster, A. Schersten, M. J. Whitehouse, J. Darling, and C. Storey, "Concurrent Pb–Hf isotope analysis of zircon by laser ablation multi-collector ICP-MS, with implications for the crustal evolution of Greenland and the Himalayas," Chem. Geol. **261**, 244–260 (2009).
17. V. P. Bukharev, *Evolution of the Precambrian Magmatism of the Western Ukrainian Shield* (Nauk. Dumka, Kiev, 1992).
18. V. M. Skobelev, *Petrochemistry and Geochronology of the Precambrian Rocks of the Northwestern Baltic Shield* (Nauk. Dumka, Kiev, 1987).
19. K. E. Esipchuk, E. M. Sheremet, O. V. Zinchenko, A. B. Bobrov, V. N. Borko, S. V. Bukharev, V. V. Vasil'chenko, V. M. Verkhoglyad, E. N. Golub, V. V. Demyanenko, E. I. Zhebrovskaya, V. I. Orsa, B. S. Panov, V. F. Razdorovzhnyi, K. I. Sveshnikov, V. M. Skobelev, and D. N. Shcherbak, *Petrochemistry, Geochemistry, and Ore Potential of the Ukrainian Shield* (Nauk. Dumka, Kiev, 1990).
20. K. E. Esipchuk, V. I. Orsa, I. B. Shcherbakov, E. M. Sheremet, V. M. Skobelev, V. V. Ryabokon', L. S. Galetskii, B. S. Panov, A. A. Yushin, L. V. Bochai, E. N. Golub, V. V. Demyanenko, K. M. Buchinskaya, K. I. Sveshnikov, Yu. T. Sukhorukov, D. N. Shcherbak, V. K. Osadchii, Yu. K. Piiyar, A. I. Samchuk, A. S. Kushnir, A. V. Andreev, and A. K. Cheburkin, *Granitoids of the Ukrainian Shield: Petrochemistry, Geochemistry, and Ore Potential* (Nauk. Dumka, Kiev, 1993).
21. T. N. Irving and W. R. A. Baragar, "A guide to the chemical classification of the common volcanic rocks," Can. J. Earth Sci. **8**, 523–548 (1971).
22. J. A. Pearce, N. B. W. Harris, and A. G. Tindle, "Trace element discrimination diagrams for the tectonic interpretation of granitic rocks," J. Petrol. **25**, 956–983 (1984).
23. S.-S. Sun and W. F. McDonough, "Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes," Geol. Soc. London. Sp. Publ. **4**, 313–345 (1989).
24. B. R. Frost, C. G. Barnes, W. J. Collins, R. J. Arculus, D. J. Ellis, and C. D. Frost, "A geochemical classification for granitic rocks," J. Petrol. **42**, 2033–2048 (2001).
25. A. J. W. Markwick, H. Downes, and N. Veretennikov, "The lower crust of SE Belarus: petrological, geophysical and geochemical constraints from xenoliths," Tectonophysics **339**, 215–235 (2001).
26. L. V. Shumlyanskyy, "Hafnium isotope composition in some granitoids of the Ukrainian Shield. Isotope systems and timing of geological processes," in *Processing of 4th Russian Conference on Isotope Geochronology* (IP Katalkina, St. Petersburg, 2009), Vol. 2, pp. 285–290 [in Russian].
27. L. V. Shumlyanskyy, Extended Abstracts of Doctoral Dissertation in Geology and Mineralogy (Kiev, 2012).
28. V. Chavagnac, "A geochemical and Nd isotopic study of Barberton komatiites (South Africa): implication for the Archean mantle," Lithos **75**, 253–281 (2004).

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