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The origin of basic rocks of the Korosten AMCG complex, Ukrainian shield: Implication of Nd and Sr isotope data

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Abstract

The Korosten complex is a Paleoproterozoic gabbro–anorthosite–rapakivi granite intrusion which was emplaced over a protracted time interval — 1800–1737 Ma. The complex occupies an area of about 12 000 km^2 in the north-western region of the Ukrainian shield. About 18% of this area is occupied by various mafic rocks (gabbro, leucogabbro, anorthosite) that comprise five rock suites: early anorthositic A_1 (1800–1780 Ma), main anorthositic A_2 (1760 Ma), early gabbroic G_3 (between 1760 and 1758 Ma), late gabbroic G_4 (1758 Ma), and a suite of dykes D_5 (before 1737 Ma). In order to examine the relationships between the various intrusions and to assess possible magmatic sources, Nd and Sr isotopic composition in mafic whole-rock samples were measured. New Sr and Nd isotope measurements combined with literature data for the mafic rocks of the Korosten complex are consistent and enable construction of Rb–Sr and Sm–Nd isochronous regressions that yield the following ages: 1870 ± 310 Ma (Rb–Sr) and 1721 ± 90 Ma (Sm–Nd). These ages are in agreement with those obtained by the U–Pb method on zircons and indicate that both Rb–Sr and Sm–Nd systems have remained closed since the time of crystallisation. In detail, however, measurable differences in isotopic composition of the Korosten mafic rock depending on their suite affiliation were revealed. The oldest, A_1 rocks have lower Sr ($^{87}Sr/^{86}Sr_{(1760)}$ = 0.70233–0.70288) and higher Nd ($\varepsilon Nd_{(1760)}$ = 1.6–0.9) isotopic composition. The most widespread A_2 anorthosite and leucogabbro display higher Sr and lower Nd isotopic composition: $^{87}Sr/^{86}Sr_{(1760)}$ = 0.70362, $\varepsilon Nd_{(1760)}$ varies from 0.2 to −0.7. The G_3 gabbro–norite has slightly lower $\varepsilon Nd_{(1760)}$ varying from −0.7 to −0.9. Finally, G_4 gabbroic rocks show relatively high initial $^{87}Sr/^{86}Sr$ (0.70334–0.70336) and the lowest Nd isotopic composition ($\varepsilon Nd_{(1760)}$ varies from −0.8 to −1.4) of any of the mafic rocks of the Korosten complex studied to date. On the basis of Sr and Nd isotopic composition we conclude that Korosten initial melts may have inherited their Nd and Sr isotopic characteristics from the lower crust created during the 2.05–1.95 Ga Osnitsk orogeny and 2.0 Ga continental flood basalt event. Indeed, $\varepsilon Nd_{(1760)}$ values in Osnitsk rocks vary from 0.0 to −1.9 and from 0.2 to 3.4 in flood basalts. We suggest that these rocks being drawn into the upper mantle might melt and give rise to the Korosten initial melts. $^{87}Sr/^{86}Sr_{(1760)}$ values also support this interpretation. We suggest that the Sr and Nd isotopic data currently available on mafic rocks of the Korosten complex are consistent with an origin of its primary

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melts by partial melting of lower crustal material due to downthrusting of the lower crust into upper mantle forced by Paleoproterozoic amalgamation of Sarmatia and Fennoscandia.

Keywords: Proterozoic AMCG complex; Nd and Sr isotopic composition; Partial melting; Source region; Initial melts

1. Introduction

The origin of Proterozoic anorthosite–mangerite–charnockite–granite (AMCG) suites is amongst the important problems in modern igneous petrology. It has several aspects, one of which is the nature of the source rock for the parental melts of anorthosites. Detailed investigation of isotopic compositions of anorthosites and related rocks offers an approach to the identification of their source regions. However, several serious problems complicate interpretation of isotopic data for anorthosites. In many cases massif-type anorthosites have been subjected to medium- to high-grade metamorphism that may have disturbed isotope systems, especially Rb–Sr, rendering these ineffective for assessing the source region. Another complication concerns the lack of equilibration of isotopic systems at the pluton scale, a problem identified by Geist et al. (1990) in the Laramie anorthosite, Wyoming.

On the whole, inferences about the source region of initial AMCG melts can be divided into two end-member hypotheses. The first emphasizes the broadly basic composition of anorthosites and the fact that anorthosites and anorthosite-related rocks often yield positive εNd values suggesting that initial melts originated from a depleted mantle source. This model commonly involves underplating of continental crust by mantle melt with subsequent differentiation and contamination by lower crustal material (e.g. Ashwal, 1993; Emslie and Hegner, 1993). The second class of hypotheses (Taylor et al., 1984) is based on the inconsistency of anorthosite geochemical characteristics with a mantle origin. Moreover, Sr and Nd isotope characteristics could also be taken to support a lower crustal origin of initial melts because some AMCG complexes rock display high initial $^{87}Sr/^{86}Sr$ and negative εNd. Such models have recently gained support from experimental studies of crystallisation pathways of melts of jotunitic (ferrobasaltic) composition considered as parental to some AMCG complexes at various P and fO_2 conditions (Vander Auwera and Longhi, 1994; Longhi et al., 1999).

In this paper we present an overview of previously published Nd isotope data (Bogatikov et al., 1988; Dovbush et al., 2000) for the Korosten gabbro–anorthosite–rapakivi complex, as well as newly obtained Nd and Sr isotopic compositions. Although these data are not extensive, preliminary interpretations regarding the origin of the Korosten complex can be made.

2. Korosten complex: geological background

An excellent overview of the geology and geochronology of the Korosten complex may be found in the recent work of Bogdanova et al. (2004). The complex is situated at the north-western part of the Ukrainian shield (Fig. 1). It was emplaced during several successive episodes of magmatic activity during an age interval of 1737–1800 Ma (Skobelev, 1987; Amelin et al., 1994; Verhogliad, 1995). It forms a nearly isometric body occupying a total area of about 12 000 km^2 (Fig. 2). Approximately 82% of this area is occupied by rapakivi and rapakivi-like granites, whereas various types of mafic rocks with predominant gabbro–anorthosites represent 18% of the territory (Bogdanova et al., 2004).

The Korosten complex intruded a Paleoproterozoic (ca. 2.20–1.95 Ga) basement composed of amphibolite facies metamorphic rocks of the Teteriv series and granites of the Zhitomir and Osnitsk complexes. Metasedimentary rocks of the Pugachivska Formation, which apparently represent ancient continental supracrustals, now occur as xenoliths of variable dimensions in the pluton, and probably were derived from the roof. A series of graben-synclines form the north-western, northern and north-eastern boundaries of the complex. These are filled with greenschist facies metasedimentary and metavolcanic rocks. The latter show geochemical affinity with intrusive rocks of the Korosten complex (Bogdanova et al., 2004).

According to geophysical data, the crust in the Korosten area is complex. Down to 15–20 km the complex consists of alternating sheets of granitoids and mafic rocks. Their thickness varies from 0.5 to 3 km (e.g. Ilchenko and Bukharev, 2001). The mafic sheets, associated with steeply dipping gabbro–noritic feeder dikes, crop out as gabbro–anorthosite bodies, including the Volodarsk–Volynskyy, Chopovichskyy, and Fedorivskyy massifs. These bodies include anorthosite, gabbro–anorthosite, leucogabbro, and various gabbroic

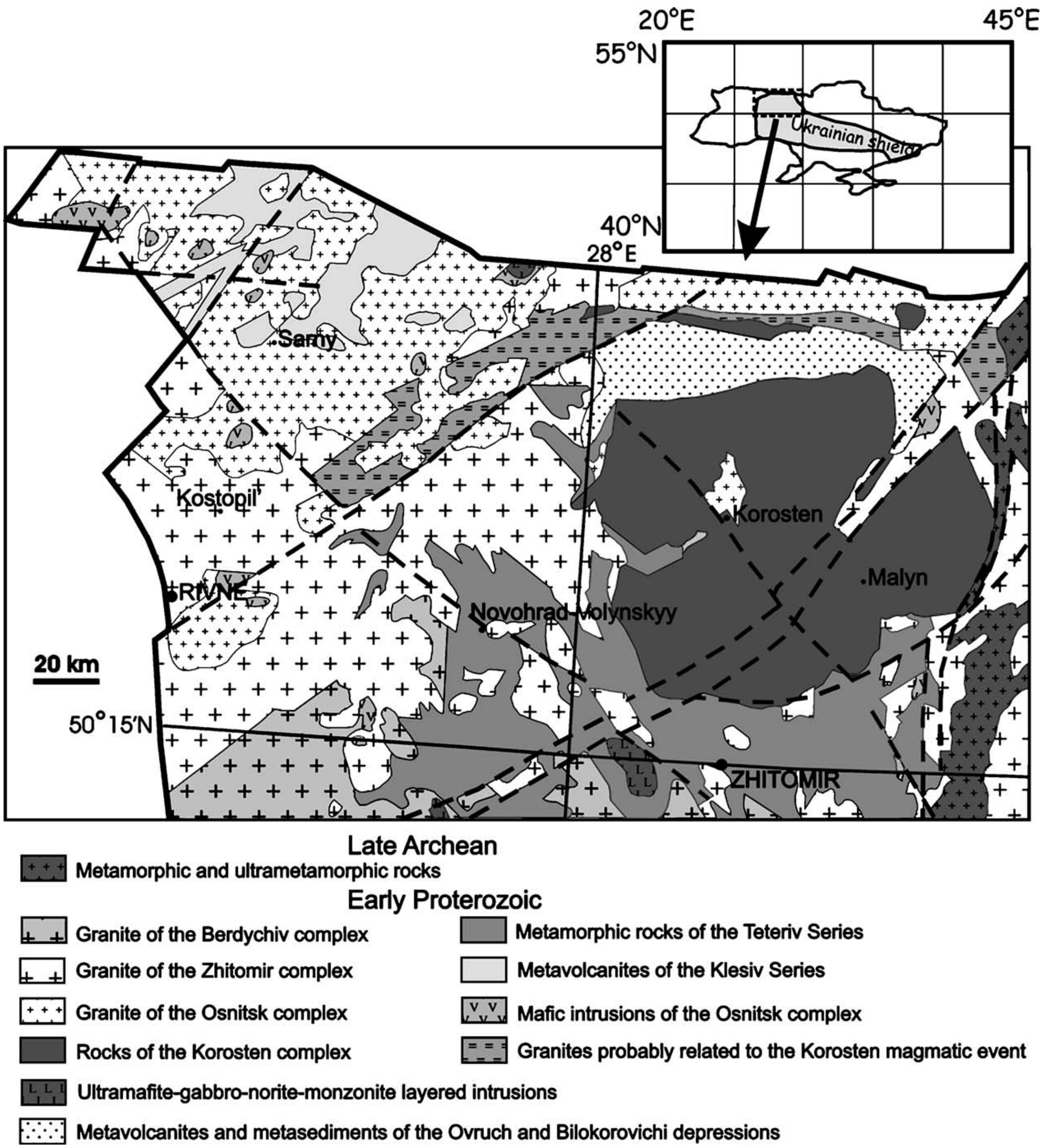

Fig. 1. Simplified map of the north-western region of the Ukrainian shield.

rocks. Recent detailed geophysical investigations (Bogdanova et al., 2004) revealed the presence of a relatively non-magnetic body with anomalously high seismic velocity and density beneath the pluton. This body was interpreted as a gabbroic stock with a vertical extent of ca. 20 km penetrating the entire lower crust. We infer a uniform distribution of anorthosite, leucogabbro and gabbro with depth, hence large-scale magmatic layering is apparently absent. The predominant rock types are gabbro and anorthosite.

The large gabbro–anorthosite massifs of the Korosten complex are multiphase intrusions. At least five rocks suites may be distinguished on the basis of field relationships and isotopic data: early anorthositic (A_1,

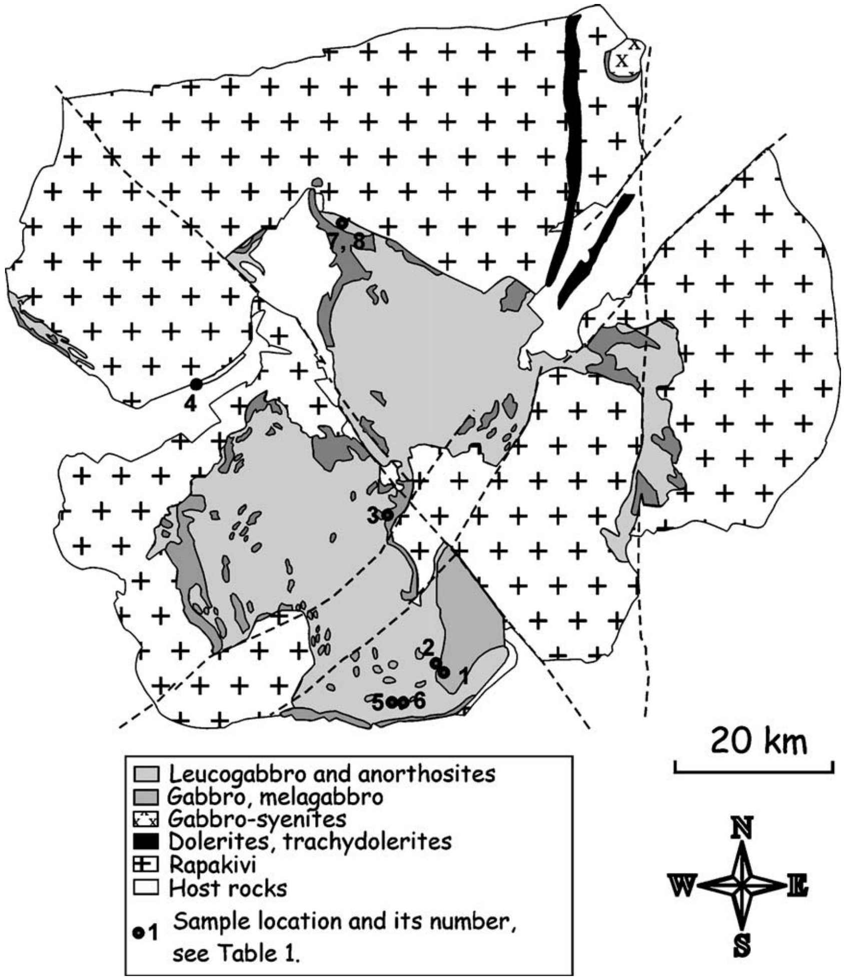

Fig. 2. Map of the Korosten plutonic complex.

1800–1780 Ma), main anorthositic (A_2, 1760–1758 Ma), early gabbroic (G_3, between 1760 and 1758 Ma), late gabbroic (G_4, 1758 Ma) and a series of dyke (D_5, which were emplaced until at least 1737 Ma) suites (Mitrokhin, 2001; Bogdanova et al., 2004; U–Pb ages mainly after Amelin et al., 1994; Verhogliad, 1995). Detailed descriptions of the mineralogical composition and geochemical peculiarities of these rock suites were provided by Mitrokhin (2001), and Bogdanova et al. (2004).

3. Previous results

Rocks from the Korosten AMCG complex were analysed for Nd isotopes by Bogatikov et al. (1988) and Dovbush et al. (2000). Unfortunately, neither of these authors report details of the measurement procedure. Bogatikov et al. (1988) investigated whole-rocks and mineral separates taken from three open pits. The first of these samples represents the main anorthosite suite (A_2), the second is from the early gabbroic suite (G_3), and the third sample is from the typical rapakivi granite widespread within the Korosten complex (rapakivi granite will not be considered in this paper). Dovbush et al. (2000) analysed four whole-rock samples for Nd isotopes. Two of these were taken from the same anorthosite localities as sampled by Bogatikov et al. (1988), while the third represents gabbro of the late gabbroic (G_4) suite and the fourth represents the early anorthosite (A_1) suite.

4. Analytical techniques

Samples were weighed into in PFA teflon screw-top beakers (Savillex®) and then dissolved using ultra-pure reagents in a HF–HNO_3–HCl digestion. Rb and Sr were separated in 2.5 N HCl using Bio-Rad AG50W X8 200–400 mesh cation exchange resin. A rare earth element (REE) concentrate was collected by elution of 3 N HNO_3. Ba was then removed from the REE concentrate using elution of 1.5 N HNO_3 through Eichrom Industries Sr Spec® resin. Nd was separated in a "cocktail" of acetic acid (CH_3COOH), methanol (CH_3OH) and nitric acid (HNO_3) using Bio-Rad AG1x8 200–400 mesh anion exchange resin. Total procedure blanks for Sr and Nd were less than 0.5 ng.

In preparation for mass spectrometry, Sr samples were loaded onto single Ta filaments with 1 N phosphoric acid, and Nd samples were loaded directly onto triple Ta–Re–Ta filaments. Sr and Nd samples were analysed on a VG Sector 54-30 multiple collector mass spectrometer. A ^{88}Sr beam intensity of 1 V (1×10^{-11} A)±10% and a ^{144}Nd beam intensity of 1 V (1×10^{-11} A) were maintained. The ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd ratios were corrected for mass fractionation using ^{86}Sr/^{88}Sr=0.1194 and an exponential law, and ^{146}Nd/^{144}Nd=0.7219 and an exponential law. The VG Sector 54-30 mass spectrometer was operated in the peak-jumping mode with data collected as 15 blocks of 10 ratios while measuring Sr isotope composition, and as 12 blocks of 10 ratios while measuring Nd isotope composition. For this instrument NBS987 gave 0.710246±10 (1 SD, n=14) and the internal laboratory standard (JM) gave ^{143}Nd/^{144}Nd=0.511502±4 (1 SD, n=9). Sm and Nd concentrations were measured using VG Elemental PQ2 plus ICP-MS (Olive et al., 2001). Sr and Rb concentrations were measured by XRF on pressed pellets utilizing an ARL 9400 Sequential XRF at Liège University, Belgium.

5. Results and discussion

We have measured ^{143}Nd/^{144}Nd and ^{87}Sr/^{86}Sr ratios, as well as Sm, Nd, Rb and Sr concentrations in five samples, two of which represent anorthosite of the A_1 suite, one — anorthosite of the A_2 suite, and the other two represent the G_4 suite. Analytical results are shown in Table 1, together with results of Dovbush et al. (2000) and Bogatikov et al. (1988). All the Sr and Nd isotopic data for

Table 1
Sm–Nd isotope data for mafic rocks of the Korosten complex

Rock suite	Point at Fig. 2, open pit location	Reference	Rock name	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr$_{(0)}$	^{87}Sr/^{86}Sr$_{(1760)}$	εSr$_{(1760)}$	^{147}Sm/^{144}Nd	^{143}Nd/^{144}Nd$_{(0)}$	εNd$_{(1760)}$	Model age, Ma Tchur	Model age, Ma Tdm
A_1	7, Mezhyrichka	This study	Anorthosite	0.0349	0.703213±14	0.70233	−3.2	0.1124	0.511741±18	1.6	1617	1950
A_1	8, Vaskovichi	This study	Anorthosite	0.0178	0.703326±14	0.70288	4.5	0.1035	0.511603±10	0.9	1689	1985
A_1	4, Pugachivka	Dovbush et al. (2000)	Anorthosite					0.1058	0.511524	−1.2	1862	2139
A_2	2, Gorbuliv	This study	Anorthosite	0.0662	0.705297±13	0.70362	15.2	0.1197	0.511754±6	0.2	1745	2077
A_2	5, Golovino	Dovbush et al. (2000)	Anorthosite					0.1248	0.511769	−0.7	1837	2178
A_2	5, Golovino	Bogatikov et al. (1988)	Leucogabbro					0.1233	0.511782	−0.1	1773	2120
A_2	5, Golovino	Bogatikov et al. (1988)	Anorthosite					0.1259	0.511781	−0.7	1846	2190
G_3	6, Slipchitsy	Dovbush et al. (2000)	Gabbro–norite					0.1309	0.511830	−0.9	1866	2216
G_3	6, Slipchitsy	Bogatikov et al. (1988)	Gabbro–norite					0.1512	0.512069	−0.8	1907	2384
G_3	6, Slipchitsy	Bogatikov et al. (1988)	Gabbro–norite					0.1380	0.511925	−0.7	1851	2251
G_4	1, Torchin	This study	Monzogabbro	0.3473	0.712134±12	0.70334	11.2	0.1241	0.511724±6	−1.4	1822	2240
G_4	2, Gorbuliv	This study	Dolerite	0.1048	0.706008±13	0.70336	11.4	0.1295	0.511820±6	−0.8	1853	2204
G_4	3, Buky	Dovbush et al. (2000)	Gabbro					0.1242	0.511755	−0.9	1851	2195

Table 2
Sm–Nd isotope data for the host for the Korosten complex rocks at 1760 Ma

Complex, series	Rock	$^{143}Nd/^{144}Nd_{(1760)}$	$\varepsilon Nd_{(1760)}$	Reference
Teteriv series	Gneisses, metaplagioporphire	0.51018÷0.51023	−3.6÷−2.5	Dovbush et al. (2000)
Zhitomir complex	Granite	0.51018	−3.6	Stepanyuk (2000, unpublished data)
Osnitsk–Mikashevichi igneous belt	Granite, granodiorite, rhyolite, gabbro	0.51023÷0.51036	0.0÷−2.5	Claesson et al. (2001), Shumlyanskyy et al. (in press)
Xenolith in Devonian diatreme	Granulite	0.51047÷0.51026	+2.1÷−2.1	Markwick et al. (2001)
2.0 Ga continental flood basalts	Troktolite, olivine dolerite, dolerite	0.51037÷0.51054	+0.2÷+3.4	Shumlyanskyy et al. (in prep.)

mafic rocks of the Korosten complex is rather consistent. It is possible to construct Rb–Sr and Sm–Nd isochronous regressions through the currently available data that yield the following ages: Rb–Sr isochron — 1870±310 Ma (Initial $^{87}Sr/^{86}Sr=0.70294\pm0.00076$, MSWD=2.1), Sm–Nd isochron — 1721±90 Ma (Initial $^{143}Nd/^{144}Nd=0.510350\pm0.000081$, MSWD=0.41). These ("average") ages are in good agreement with those obtained by the U–Pb method on zircons (see above) and suggest that both systems remain closed since their crystallisation. However, there are measurable differences in isotopic composition of the Korosten complex mafic rock depending on their suite affiliation. Two A_1 samples from our study have positive $\varepsilon Nd_{(1760)}$ values — +1.6 and +0.9 (in contrast to the sample studied by Dovbush et al. (2000), that have $\varepsilon Nd=-1.2$) and relatively low initial $^{87}Sr/^{86}Sr$ (0.70233–0.70288). The most widespread anorthosite and leucogabbro of the A_2 suite display higher initial $^{87}Sr/^{86}Sr$ ratio and a lower εNd value. Only one A_2 sample has been analysed for Sr isotopes and has $^{87}Sr/^{86}Sr_{(1760)}=0.70362$. $\varepsilon Nd_{(1760)}$ of four measured samples vary from +0.2 to −0.7. The gabbros and norites of the G_3 suite have very limited distribution but are exposed in the Slipchitsy open pit. The three available Nd isotopic analyses for the G_3 gabbro–norite reveal slightly lower εNd values that vary from −0.7 to −0.9. The gabbroic rocks of the G_4 suite have higher initial $^{87}Sr/^{86}Sr$ (0.70334–0.70336) and the lowest εNd values (varies from −0.8 to −1.4) of all the mafic rocks of the Korosten complex that have been studied. Hence, the older Korosten mafic rocks are, the lower their initial $^{87}Sr/^{86}Sr$ ratio and the higher their εNd value. This tendency, with few exceptions, is supported by all the Korosten samples so far examined.

Investigation of the origin of the Korosten complex requires detailed knowledge of the composition of the possible source region, as well as of any rock that may contaminate initial and subsequent melts en route to the ultimate magma chamber. Relatively little is known about the Nd and Sr isotopic characteristics of the rocks surrounding the Korosten complex and the lower crust in the region. As mentioned above, the host rocks of the Korosten complex include amphibolite facies metamorphic rocks of the Teteriv series and widespread plutonic rocks of the Zhitomir and Osnitsk complexes. Approximately 2.0 Ga old continental tholeiites, although not exposed widely, probably also compose a significant portion of the crust in the region. Measured and recalculated to 1760 Ma isotopic compositions of Nd and Sr in host rocks are listed in Tables 2 and 3. As can be seen from these and Fig. 3, Teteriv and Zhitomir rocks did not play an important role in the origin of initial melts of the Korosten complex. However, this does not exclude possibility of contamination of some portions of the Korosten melts by the Teteriv and Zhitomir rocks. The Sr and Nd isotopic composition of 2.0 Ga continental flood basalts generally overlap with the isotopic composition of the earliest Korosten rocks (i.e. A_1 anorthosite) that display the highest εNd values. However, the most widespread rocks of the A_2 and G_4 suites had much lower εNd values at 1760 Ma and cannot be derived by direct melting of lower crustal (or lithospheric mantle) analogues of flood basalts. Another source is required to explain the negative εNd values

Table 3
Rb–Sr isotope data for the host for the Korosten complex rocks at 1760 Ma

Complex, series	Rock	$^{87}Sr/^{86}Sr_{(1760)}$	Reference
Teteriv series	Gneisses, metaplagioporphire	0.7034÷0.7179	Scherbak et al. (1989), Verhogliad and Skobelev (1995)
Zhitomir complex	Granite	0.7089÷0.7112	Scherbak et al. (1978)
Osnitsk–Mikashevichi igneous belt	Gabbro	0,7022÷0,7033	Shumlyanskyy et al. (in press)
Xenolith in Devonian diatreme	Granulite	0.7023÷0.7032	Markwick et al. (2001)
2.0 Ga continental flood basalts	Troktolite, olivine dolerite, dolerite	0.7017÷0.7039	Shumlyanskyy et al. (in prep.)

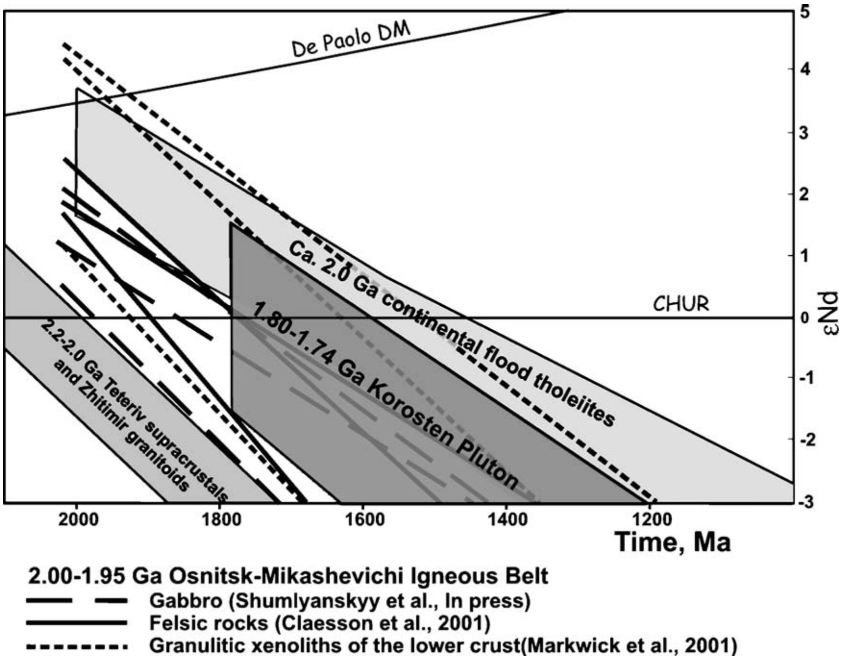

Fig. 3. Comparison of the evolution with time of Nd isotopic composition in the Korosten basic rocks with that of the Teteriv–Zhitomir rocks, and 2.0 continental tholeiites. Felsic rocks and gabbro of the Osnitsk–Mikashevichi igneous belt, and low crustal granulite xenoliths are also shown.

common in the mafic rocks of the Korosten pluton. One of the possible sources is represented by rocks of the Osnitsk–Mikashevichi igneous belt (OMIB) that reveal negative εNd values at 1760 Ma. The OMIB marks the contact zone between the two major segments of the East-European craton — Sarmatia and Fennoscandia and has geochemical signatures indicating Andean-type calc-alkaline magmatism (Claesson et al., 2001). Markwick et al. (2001) studied lower crustal granulite xenoliths in Devonian diatremes cutting the OMIB. On the basis of geochemical evidence, they suggested an affinity between the granulites and the Osnitsk intrusive rocks. However, only one of these xenoliths has a Sr and Nd isotopic composition similar to the OMIB rocks (Tables 2 and 3, Fig. 3) while the others fall into the field defined by the flood basalts. Hence, we infer that the granulites investigated by Markwick et al. (2001) may be related to both Osnitsk orogenic rocks and continental flood basalts. Both these rock suites may constitute lower crust in this region. We propose that Korosten initial melts may have inherited their Nd and Sr isotopic characteristics from the lower crust created during the 2.05–1.95 Ga Osnitsk orogeny and the 2.0 Ga plume event thought responsible for the outpouring of flood basalts. Indeed, $\varepsilon Nd_{(1760)}$ values in OMIB rocks vary from 0.0 to −1.9 and from +0.2 to +3.4 in the flood basalts (Table 2), and, hence, under appropriative (upper-mantle) conditions these rocks may constitute a substratum for the Korosten initial melts. $^{87}Sr/^{86}Sr_{(1760)}$ values also support this interpretation (Table 3).

There is an important question about the source of heat that may cause partial melting of lower crustal or mantle rocks. Taking into account dry character of the AMCG magmas, the source materials must be raised to high temperatures to induce melting. There are not many alternative mechanisms that may lead to generation of voluminous portions of mantle or lower crustal melt. One such mechanism is melting induced by emplacement of a hot mantle plume. However, any such plume might be expected to lead to continental break-up and to formation of a continental flood basalt provinces (Courtillot et al., 1999; Condie, 2001). Both the tectonic consequences and the composition of melts generated by emplacement of a mantle plume differ from those that are common for AMCG magmatism. Another possible scenario that may lead to melting of lower crustal mafic material is downthrusting of this crust into the mantle that would result in heating and could induce partial melting of crustal material. Such a model was proposed by Duchesne et al. (1999) who suggested re-melting of a crustal tongue under mantle conditions to produce initial AMCG melt. We propose that such a scenario may have operated during the collision of two continental terrains, i.e. in the Korosten case during amalgamation of Sarmatia and Fennoscandia that occurred in Paleoproterozoic. Longhi et al. (1999) in their extensive experimental work have established that a mafic source region, such as lower continental crust or foundered mafic plutons, is required for liquids parental to massif anorthosites and associated mafic intrusions. They provide strong support for the idea that melts parental to AMCG complexes cannot be residual to more primitive liquids derived by melting of peridotitic mantle.

We suggest that the data available for the Korosten AMCG complex, although still rather sparse, are consistent with a hypothesis that initial melts were originated by partial melting of lower crustal material related to the ca. 2.0 Ma old Osnitsk orogeny and flood basalt event mafic granulites. In this hypothesis, these lower crustal rocks were downthrusted into the upper mantle thereby causing partial melting leading to the formation of the Korosten initial melts.

6. Conclusions

1. Sr and Nd isotopic data for mafic rocks from the Korosten allow construction of Rb–Sr and Sm–Nd isochrons. These yield ages of 1870±310 Ma (Rb–Sr) and 1721±90 Ma (Sm–Nd). These ages are in good agreement with those obtained by the U–Pb method on zircons and indicate that both systems remain closed since time of crystallisation.
2. There are, however, measurable differences in isotopic composition of the Korosten mafic rock depending on their suite affiliation. The general rule is: the older the Korosten mafic rocks are, the lower their initial $^{87}Sr/^{86}Sr$ ratios and the higher their εNd values are.
3. Korosten initial melts may have inherited their Nd and Sr isotopic characteristics from lower crust created during the 2.05–1.95 Ga Osnitsk orogeny and 2.0 Ga continental flood basalt event. $\varepsilon Nd_{(1760)}$ values in Osnitsk rocks vary from 0.0 to −1.9 and from 0.2 to 3.4 in flood basalts, and under upper-mantle conditions may constitute a substratum for the Korosten initial melts. $^{87}Sr/^{86}Sr_{(1760)}$ values also support this interpretation.
4. The available data for the Korosten AMCG complex are consistent with the hypothesis that its initial melts originated by partial melting of lower crustal material due to downthrusting into the upper mantle. The forces responsible for downthrusting may be related to Paleoproterozoic amalgamation of Sarmatia and Fennoscandia.

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