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GEOCHEMISTRY

Ankaramite: A New Type of High-Magnesium and High-Calcium Primitive Melt in the Magnitogorsk Island-Arc Zone (Southern Urals)

E. V. Pushkarev[a, *], A. V. Ryazancev[b], I. A. Gottman[a],
Corresponding Member of the RAS K. E. Degtyarev[b], and V. S. Kamenetsky[c]

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Abstract—This work describes the geological position, mineral and chemical composition of high-Mg effusive ankaramites occurring as dykes and lava flows. They were found in the mélange zone of the western margin of the Magnitogorsk island arc zone in the Southern Urals. Data on the liquidus association of phenocrysts and on the composition of the matrix of effusives are given. According to the data obtained, the conclusion was drawn that the ankaramites studied can be attributed to the primary island arc melts, which were not subject to essential differentiation. This type of effusives has not been distinguished previously among island arc volcanogenic formations of the Urals. It is shown that ankaramites can be considered to be primary melts parental for dunite–clinopyroxenites–gabbro complexes of Ural–Alaskan type. The occurrence of ankaramites in the Paleozoic island arc formations of the Urals indicates the wehrlite composition of the mantle as the reason for the extremely wide development of wehrlites and clinopyroxenites in different mafic–ultramafic complexes of the Urals.

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Ankaramites were first described by Lacroix [12] in Madagascar in 1916 in the course of studying melanocratic mafic effusives with abundant phenocrysts of augite and olivine surrounded by a fine-grained matrix, which is composed of clinopyroxene, plagioclase, titanomagnetite, and phlogopite.

These rocks are characterized by $CaO/Al_2O_3 > 1$, which is essentially higher in comparison with the majority of ultramafic and mafic rocks, the formation of which is related to melting of the primitive or depleted mantle ($CaO/Al_2O_3 = 0.8–0.9$). According to this criterion, ankaramites are attributed to high calcium rocks [7, 15]. Over the last 25 years, it has been established that high-Ca ultramafic and mafic effusives are common rock varieties in island arcs of the Pacific and Atlantic oceans [7]. The idea proposed in [7] that ankaramites are regarded as a specific type of primitive island arc magmas has been confirmed by studying high-Ca melt inclusions in phenocrysts of Mg-rich olivine and chromite from basalts of different provinces [8, 15]. At the same time, during model experiments, ankaramite melts were obtained from the wehrlite at a pressure of 1–2 GPa [14]. When studying the process of crystallization of ankaramites from Bridget Cove in Alaska, Irvine suggested that they could be a parental magma for dunite–clinopyroxenite–gabbro intrusions of Ural–Alaskan type [9]. The geological history of development of the Urals in the Paleozoic includes a long-lasting epoch of island arc volcanism, which resulted in the formation of the Tagil and Magnitogorsk volcanogenic zones and, to a large extent, determined the metallogeny of the Ural Fold Belt. However, in the scientific literature, there are no data that there are Ca-rich magnesium rocks among diverse effusives ([4, 6], etc.). Due to this, the find of primitive ankaramites within the Magnitogorsk Zone in the Southern Urals brings important consequences for understanding the composition of the Ural paleomantle, evolution of the island arc volcanism, and the formation of mafic–ultramafic complexes of Ural–Alaskan type.

Ankaramites were found at a 600 × 200 m site in the valley between the Irendyk and Aratau ridges, about 500 m to the northwest of the village of Abzakovo (Uchaly district). Ankaramite bodies occur as tectonic blocks in the serpentinite mélange on the western side of the Magnitogorsk volcanogenic zone (Southern Urals), adjacent on the east to the Main Uralian Fault

[a] *Institute of Geology and Geochemistry, Ural Branch, Russian Academy of Sciences, Yekaterinburg, 620075 Russia*
[b] *Geological Institute, Russian Academy of Sciences, Moscow, 119017 Russia*
[c] *University of Tasmania (UTAS), Hobart, Tasmania, 7001 Australia*
**e-mail: pushkarev.1958@mail.ru*

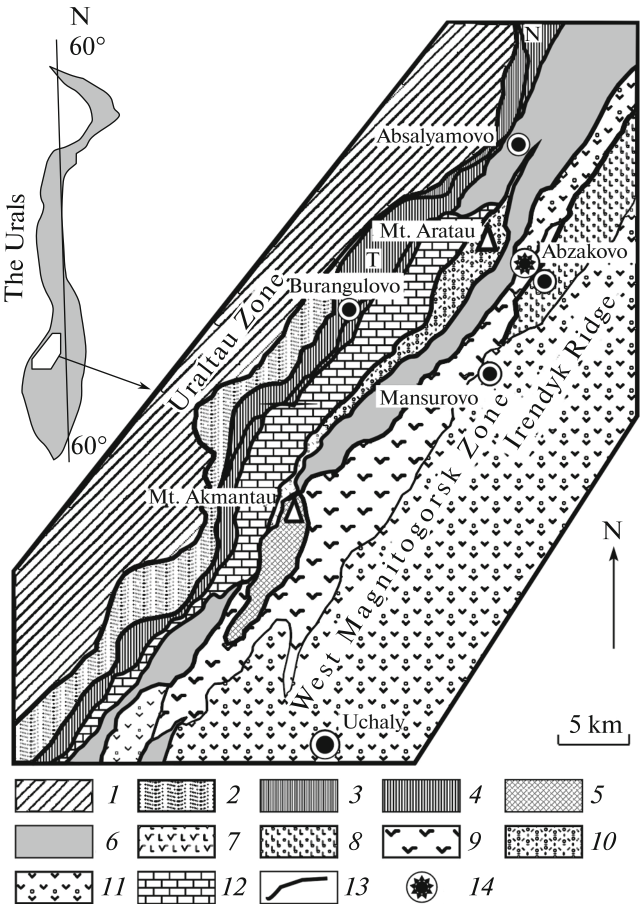

Fig. 1. Location scheme of geological structures and complexes in the northwestern segment of the Magnitogorsk Zone (Southern Urals) [1]. (*1*, *2*) Uraltau Zone: (*1*) Riphean quartzites and schists, (*2*) cherts, sandstones, siltstones (D_1); (*3*) basalts, cherts, breccias (D_{1-2}); (*4*) massifs of the "lherzolite" type and related mélanges; (*5*) massifs of the "harzburgite" type; (*6*) serpentinite mélanges associated with harzburgite-type mélanges; (*7*) basalts, cherts, tuffites (O_{2-3}); (*8*) Polyakovka Formation (O_{1-3}), basalts, cherts; (*9*) blocks of the Polyakovka Formation (O_{1-3}) and the lower part of the Baimak–Buribay Formation (D_1ems) tectonically mixed in the mélange zone, basalts, cherts, and related dykes; (*10*) lavas and tuffs of the differentiated basalt–andesite–dacite–rhyolite series (D_1ems); (*11*) Irendyk Formation (D_2ef), basalts, andesite–basalts, their tuffs, and overlying Middle to Upper Devonian volcanogenic–sedimentary formations; (*12*) cherts, sandstones, siltstones, tuffites (D_3); (*13*) tectonic boundaries; (*14*) localities of ankaramites studied. Mafic–ultramafic massifs: N, Nurali; T, Tatlembet.

zone (Fig. 1). Apart from the volcanics of the Magnitogorsk Zone, the mélange comprises bocks of Devonian limestones and cherts, Ordovician and Silurian basalts, and fragments of ophiolite complexes. In the scientific literature, this zone is called Sakmara–Voznesenka and its formation is thought to be caused by tectonic mixing at the collision between the Magnitogorsk island arc and the margin of the East European paleocontinent [1]. Within the area of study,

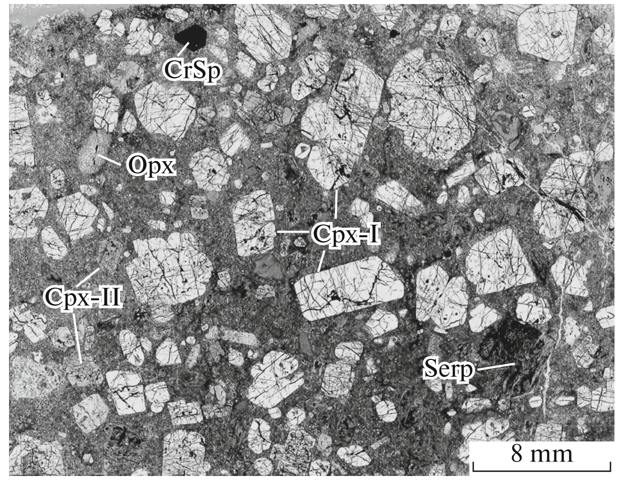

Fig. 2. Microimage of ankaramite of porphyritic texture (Pe1494). Cpx-I, phenocrysts of Type 1 chrome-diopside; Cpx-II, phenocrysts of Type 2 diopside; Opx, chlorite pseudomorphs after olivine (or orthopyroxene) phenocrysts; CrSp, chromite phenocrysts; Serp, serpentinite xenolith. Transmitted light.

ankaramites occur as dykes in serpentinites and sheet bodies, closely associated with trachyandesitic lavas. Sheet bodies vary in thickness from a few tens of centimeters to several meters, being 60–70 m long. Among trachyandesite lava flows, overlapping ankaramites, are pahoehoe structures, which mark the surface of a lava flow. We assume that ankaramite sheet bodies are fragments of lava flows. In the marginal parts of ankaramite and trachyandesite bodies are distinct quenching zones.

Ankaramites have a porphyritic texture (Fig. 2). The total number of phenocrysts is 30–35%. Phenocrysts are represented by clinopyroxene (15–30%), chromite (<1%), and olivine (or orthopyroxene) up to 5–8%. The latter phenocrysts are replaced completely by chlorite and can be recognized only on the basis of the outlines of the crystal habit. The ground mass of ankaramites have a cryptocrystalline texture with an average size of microlites of 10–50 μm. Clinopyroxene is the main mineral of groundmass (from 30 to 50%); the interstitial space between clinopyroxene crystals is filled with amphibole and clinozoisite.

Clinopyroxene phenocrysts can be subdivided into two types in the size and the pattern of zoning. The Type 1 clinopyroxene phenocrysts occur as large crystals (from 2 mm to 4 cm) of apple-green chrome-diopside (Fig. 2, Table 1). It has a high Mg-number (Mg/(Mg + Fe) = 0.93–0.87 and low Al_2O_3 content (<0.6%). The Cr_2O_3 content varies within the range of 0.5–0.7 wt %. The Type 1 phenocrysts are overgrown with narrow rims of more iron-rich pyroxene (Table 1). The Type 2 phenocrysts occur as small grains of 0.5–2 mm in size (Fig. 2). Cores are of dark green color and are composed of diopside with Mg/(Mg + Fe) =

Table 1. Representative analyses of clinopyroxene and chromite phenocrysts, wt %

Sample	Pe1490-2-1		Pe1466-1-6			Pe1490-1-2		Pe1466	
Components	core	rim	core	rim	edge	core	edge	core	edge
Ser. no	1	2	3	4	5	6	7	8	9
SiO_2	54.93	53.25	54.84	53.92	53.38	51.57	54.45	n.d.	n.d.
TiO_2	0.06	0.12	0.03	0.02	0.11	0.15	0.06	0.15	0.16
Al_2O_3	0.42	1.32	0.45	0.86	1.47	2.65	0.63	4.25	4.92
Cr_2O_3	0.51	0.03	0.55	0.2	0.02	0.06	0.53	63.82	62.31
FeO*	2.94	8.49	2.74	4.97	8.03	8.53	5.06	19.40	20.11
MnO	0.01	0.17	0.13	0.33	0.24	0.22	0.23	0.15	0.08
MgO	19.3	17.84	18.8	15.78	16.58	15.01	19.55	11.15	11.10
CaO	22.21	19.13	22.04	23.6	20.07	21.26	19.33	n.d.	n.d.
Na_2O	0.1	0.1	0.09	0.2	0.12	0.15	0.09	n.d.	n.d.
Total	100.48	100.43	99.67	99.88	100.02	99.59	99.93	98.92	98.68
Mg/(Fe+Mg)	0.92	0.79	0.93	0.85	0.79	0.76	0.88	0.56	0.56

(*1–5*) Type 1 clinopyroxene phenocrysts (see description in the text), (*6–7*) Type 2 clinopyroxene phenocrysts. (*8–9*) Chromite phenocrysts. Core, core of a phenocryst; rim, transition rim around the core; edge, edge of a phenocryst. FeO*, total iron as FeO; n.d., not detected. Analyses were performed using a Cameca SX-100 X-Ray microprobe at the "Geoanalitik" Center, Institute of Geology and Geochemistry, Ural Branch, Russian Academy of Sciences, Yekaterinburg (analyst D.A. Zamyatin).

0.75–0.80. In terms of the chemical composition, these cores are close to rims of the Type 1 phenocrysts. Cores are overgrown by Mg-rich chrome-diopside of Type I (Table 1); the latter, in turn, are surrounded by more iron-rich diopside. It is likely that the violation of the pattern of zoning in the Type 2 clinopyroxenes is caused by convective mixing of the melt, when later phenocrysts enter the more primitive and Mg-rich melt. In addition, it is possible that inflow of a new portion of the Mg-rich ankaramite melt into the magma chamber induced new crystallization of the Type 1 clinopyroxene. The compositions of clinopyroxenes from the groundmass fall into the whole range of those from ankaramites. The general evolution trend of clinopyroxene is a decreasing of Mg-number and Cr content at a simultaneous increasing in the contents of Al, Ti, and Na. This process, common both for island arc ankaramites [7, 8] and ultramafic rocks from the complexes of Ural–Alaskan type [2, 5, 9], is controlled by the olivine-clinopyroxene cotectic fractionation. Chromite occurs as phenocrysts of up to 3 mm in size (Fig. 2). It is characterized by a high Mg-number $Mg/(Mg + Fe^{2+}) = 0.60–0.56$ and Cr-number $Cr/(Cr + Al) = 0.89–0.91$ (Table 1). Chromite phenocrysts contain forsterite inclusions, as well as crystallized melt inclusions, the bulk composition of which is close to ankaramite [10], which confirms the primary nature of the effusive rocks.

In terms of the chemical composition, ankaramites of the Magnitogorsk Zone (Table 2) on classification diagrams [13] correspond to picrites, being characterized by SiO_2 in the range of 43–48% and MgO in the range of 15–19% (Fig. 3). The total of alkalis and the TiO_2 concentration in ankaramites are not higher as 0.2–0.3%. However, in contrast to picrites with $CaO/Al_2O_3 < 1$, this ratio in ankaramites is >1 [8], which is due to the high proportion of clinopyroxene in the rocks. The amount of clinopyroxene in ankaramites of the Magnitogorsk Zone approaches 50–60%, which in the absence of plagioclase determines the high $CaO/Al_2O_3 = 2.4–3.2$ (Table 2), close to that in clinopyroxenites. The correspondence of ankaramites to the primary melt is confirmed by the absence of essential differences between the bulk rock and ground mass compositions, which is an important criterion for estimating the degree of differentiation. The composition of ankaramite groundmass was determined by studying sites between phenocrysts using a JSM-6390-LV scanning electron microscope in the "Geoanalitik" Center, Institute of Geology and Geochemistry, Ural Branch, Russian Academy of Sciences. According to the MgO content, the compositions of ankaramites and the groundmass are similar (Fig. 2). The groundmass is characterized by higher contents of SiO_2 and Al_2O_3 and a lower Mg content and CaO/Al_2O_3 ratio compared to rocks (Table 2), but these differences are insignificant. Thus, in the $CaO–Al_2O_3–MgO^*$ diagram (Fig. 4), the composition points of the groundmass of ankaramites of the Magnitogorsk Zone lie in the field of ankaramites from island arcs of the Pacific and coincide with the compositions of high-Ca melt inclusions in Mg-rich olivine and chromite phenocrysts [7, 8, 15]. This allows one to assume that ankaramites of the Magnitogorsk zone correspond to primary high-Mg, high-Ca melts, which were not subject to essential differentiation. Rocks and melts of such composition are

Table 2. Chemical compositions of ankaramites from the Magnitogorsk Zone (Southern Urals), wt %

Ser. no	1	2	3	4	5	6	7	8
Sample	Pe1465	Pe1466	Pe1467	Pe1492	Pe1566	190	191	192
SiO_2	46.08	45.43	46.14	43.89	46.32	47.90	47.83	48.80
TiO_2	0.16	0.17	0.18	0.15	0.13	0.00	0.00	0.00
Al_2O_3	6.02	6.60	7.01	6.24	6.36	10.69	10.05	9.78
Fe_2O_3	5.41	4.74	3.98	5.95	3.89			
FeO	3.50	4.20	5.00	2.80	4.20	9.38*	9.85*	9.46*
MnO	0.19	0.20	0.24	0.29	0.20	0.00	0.00	0.00
MgO	18.44	17.70	16.60	17.68	15.05	16.26	17.44	16.64
CaO	16.50	16.79	17.08	20.01	21.12	15.77	14.82	15.32
Na_2O	0.10	0.10	0.11	0.07	0.18	0.00	0.00	0.00
K_2O	0.04	0.01	0.01	0.00	0.02	0.00	0.00	0.00
P_2O_5	0.12	0.11	0.13	0.12	0.06	0.00	0.00	0.00
LOI	3.40	3.70	3.50	3.10	2.50			
Total	99.94	99.75	99.97	100.30	100.04	100.00	100.00	100.00
Mg/(Fe + Mg)	0.80	0.79	0.78	0.80	0.78	0.76	0.76	0.76
CaO/Al_2O_3	2.74	2.54	2.44	3.21	3.32	1.48	1.48	1.57

(*1–5*) Bulk composition of ankaramites determined by X-ray fluorescence CPM-35 and XRF 1800 spectrometers, (*6–8*) compositions of the groundmass of ankaramite Pe1466; 190–192, number of the measured spectrum. The composition of groundmass was recalculated to 100%. 9.38* and others, total iron as FeO. Analyses were performed at the "Geoanalitik" Center, Institute of Geology and Geochemistry, Ural Branch, Russian Academy of Sciences, Yekaterinburg.

distinguished for the first time among the island arc volcanogenic formations of the Urals.

The ability of ankaramites to produce large volumes of clinopyroxene in the cotectic proportions with olivine and chromite allows to consider these rocks as the most appropriate variant of parental melt for dunite–clinopyroxenite–gabbro complexes of Ural–Alaskan type [2, 5, 9, 11]. As is seen in Fig. 4, the

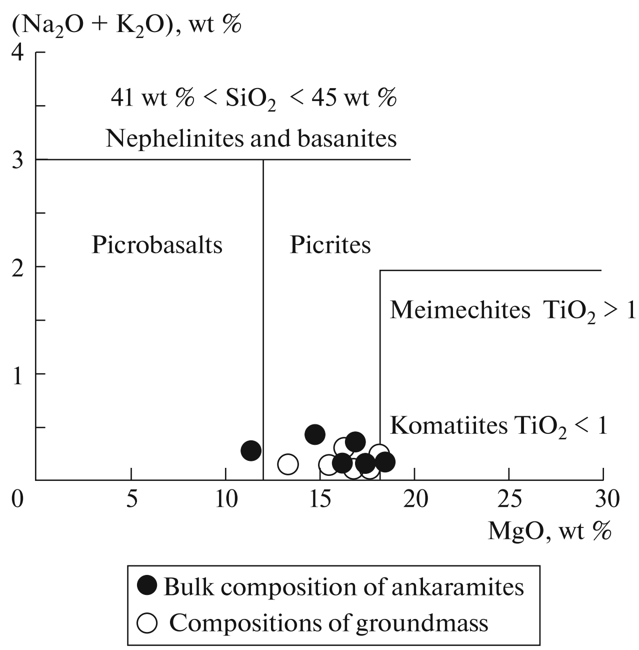

Fig. 3. Classification diagram $Na_2O + K_2O$ – MgO for high-Mg volcanic rocks [13].

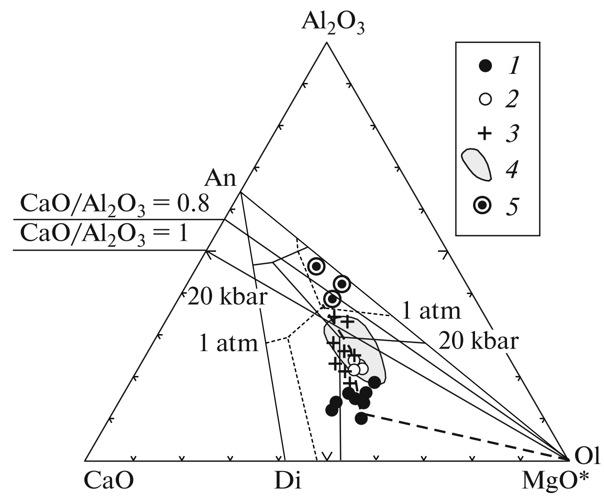

Fig. 4. The $CaO–Al_2O_3–MgO^*$ diagram (where $MgO^* = MgO + 0.5Fe_2O_3 + 0.55FeO$) [2, 5]. (*1, 2*) Ankaramites of the Magnitogorsk Zone, (*1*) bulk compositions of rocks, (*2*) compositions of groundmass, (*3*) compositions of melt inclusions from phenocrysts of high-Mg olivine and chromespinelide [7, 8, 15], (*4*) field of ankaramites from the southwestern Pacific [7, 8, 15], (*5*) average compositions of basalts [5]. The thick dashed line shows the trend of dunite–clinopyroxenite–gabbro complexes of Ural–Alaskan type [2, 5]. The diopside-anorthite-olivine system with cotectic lines corresponding to 1 atm (thin dashed line) and 20 kbar (thin solid line) is inbuilt in diagram, after [5].

composition points of ankaramites, the groundmass, and high-Ca melt inclusions lie along the olivine–clinopyroxene cotectic line at a pressure of about 20 kbar, parallel to the trend of the dunite–clinopyroxenite–gabbro complexes. The composition of ankaramites coincide practically with the calculated composition of the melt, parental for dunite–clinopyroxenite–gabbro complexes [2], which is an additional argument for this conclusion.

The find of ankaramites in the Magnitogorsk island arc zone is an evidence that wehrlite was one of the constituents of the Paleozoic mantle of the Urals. This is in consistency with the data from experiments on the genesis of ankaramites [14]. The wehrlite mantle composition may explain the abundance of Cpx-rich ultramafites in ophiolite complexes of the Urals and especially in dunite-clinopyroxenite-gabbro complexes of Ural-Alaskan type in the Platinum Belt [2, 5].

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REFERENCES

1. A. A. Belova, A. V. Ryazantsev, A. A. Razumovsky, and K. E. Degtyarev, Geotectonics **44** (4), 321–343 (2010).
2. E. V. Pushkarev, *Petrology of the Uktus Dunite-Clinopyroxenite-Gabbro Massif (the Middle Urals)* (Ural Branch Russ. Acad. Sci., Yekaterinburg, 2000) [in Russian].
3. A. E. Ringwood, *Composition and Petrology of the Earth's Mantle* (Nedra, Moscow, 1981) [in Russian].
4. I. B. Seravkin, A. M. Kosarev, D. N. Salikhov, et al., *Volcanism of the Southern Urals* (Nauka, Moscow, 1992) [in Russian].
5. G. B. Fershtater and E. V. Pushkarev, Izv. Akad. Nauk SSSR, Ser. Geol., No. 3, 13–23 (1987).
6. T. I. Frolova and I. A. Burikova, *Geosynclinal Volcanism* (Moscow State Univ., Moscow, 1977) [in Russian].
7. M. Barsdell and R. F. Berry, J. Petrol. **31**, 747–777 (1990).
8. F. N. Della-Pasqua and R. Varne, Can. Mineral. **35**, 291–312 (1997).
9. T. N. Irvine, Carnegie Inst. Washington, Year Book **72**, 478–491 (1973).
10. V. S. Kamenetsky, J-W. Park, J. E. Mungall, E. V. Pushkarev, A. I. Ivanov, M. B. Kamenetsky, and G. M. Yaxley, Geology **43** (10), 903–906 (2015).
11. J. Krause, G. E. Brugmann, and E. V. Pushkarev, Lithos **95**, 19–42 (2007).
12. A. Lacroix, C. R. Hebd. Seances Acad. Sci. **163**, 177–183 (1916).
13. M. J. Le Bas, J. Petrol. **41** (10), 1467–1470 (2000).
14. E. Medard, M. W. Schmidt, P. Schiano, and L. Ottolini, J. Petrol. **47** (3), 481–504 (2007).
15. P. Schiano, J. M. Eiler, I. D. Hutcheon, and E. M. Stolper, Geochem., Geophys., Geosyst., No. 1, 1999GC00000032 (2000).

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