

April 2015

Mineralogy and Petrology of Unique Native-Iron Basalts from Northern Siberia

Sara Mills

University of Tennessee, Knoxville, jross26@vols.utk.edu

Follow this and additional works at: <https://trace.tennessee.edu/pursuit>

Recommended Citation

Mills, Sara (2015) "Mineralogy and Petrology of Unique Native-Iron Basalts from Northern Siberia," *Pursuit - The Journal of Undergraduate Research at The University of Tennessee*: Vol. 6 : Iss. 1 , Article 17.

<https://doi.org/10.7290/pur6ivoa>

Available at: <https://trace.tennessee.edu/pursuit/vol6/iss1/17>

This article is brought to you freely and openly by Volunteer, Open-access, Library-hosted Journals (VOL Journals), published in partnership with The University of Tennessee (UT) University Libraries. This article has been accepted for inclusion in Pursuit - The Journal of Undergraduate Research at The University of Tennessee by an authorized editor. For more information, please visit <https://trace.tennessee.edu/pursuit>.

Mineralogy and Petrology of Unique Native-Iron Basalts from Northern Siberia

SARA MILLS

Advisor: Dr. Lawrence Taylor

Native iron, as a mineral, occurs in only three (3) geologic locations on Earth: 1) Disko Island (Greenland), 2) Bühl basalt (Kassel, Germany), and 3) Siberian flood basalts (SFB) (Taylor et al., 2014). Hypabyssal (shallow) mafic intrusions associated with the SFB in Northern Siberia contain metallic native iron, indicating formation under highly reducing environments (Olivine compositions clustered around Fo50, indicating crystallization from a parental magma with $Mg\# = 23$ ($MgO/FeO+MgO$).

This differs greatly from typical basalts from this region, which have been reported to have an $Mg\#$ between 50-60 (Wooden et al. 1993; Naldrett et al. 1992).

Pyroxenes are present as augite and pigeonite, with compositions in equilibrium with those of olivine. Fine-grained matrix crystals of plagioclase are similar in composition to the cores of zoned grains, values ranging from An46-84 and An43-82, respectively. Likewise, plagioclase phenocrysts are similar in composition to the rims of zoned grains, with compositions ranging from An54-80 and An54-77, respectively. These results show that the reduction process resulted in substantial enrichment of FeO in the melt, which is especially reflected in the compositions of pyroxene and olivine. This process also significantly reduced the oxygen fugacity to a point at which native iron became stable, a state which is almost exclusively found on extra-terrestrial bodies. Native iron in this sample occurs as the mineral kamacite (FeNi), with 1-3 wt% Ni. Other Fe-rich and terrestrially rare and unusual minerals found in this sample include: cohenite – Fe₃C; native Cu; ilmenite – FeTiO₃; troilite – FeS; chalcopyrite – CuFeS₂; and wüstite – FeO.

|||||

Introduction 1.0

Native iron – iron in its metallic state – is a common mineral in some extraterrestrial bodies, e.g. the Moon and asteroids (meteorites). However, occurrences of native iron are limited to three locales on Earth: Disko Island, Greenland; Kassel, Germany; and the northern Siberian craton. In each of these occurrences, native iron can be found as both an accessory and major mineral in intrusive and extrusive basaltic rocks (Taylor et al., 2014). The presence of native iron is indicative of an extraordinarily low oxygen fugacity for the basalts that host it, below the iron-wüstite buffer curve in fO_2 -T space (Fig. 1).

These native-Fe basalts share a common feature relating to their formation: the presence of a carbonaceous material (e.g., coal, bituminous shale) that was intersected during their intrusion from depth to the surface. The interplay between this reducing component and the tholeiitic/basaltic magma results in the production of this rare native-Fe mineral, and an associated unusual mineral assemblage (Ryabov and Lapkovsky, 2010). When a normal basaltic magma encounters a carbonaceous layer (i.e., carbon), the resulting reaction between the carbon and the volatile elements in the magma produces volatile gases (e.g., CO, CO₂, SO₂, CS₂, H₂O, CH₄), causing reduction of the magma and leaving the remaining native-Fe metal to settle and accumulate within the melt as it ascends. The accumulation process is largely due to the high density of the native iron, relative to the magma. The addition of large amounts of carbon causes the shift in thermodynamic stability of these metals, as well, and reduces the fO_2 below the iron-wüstite buffer curve.

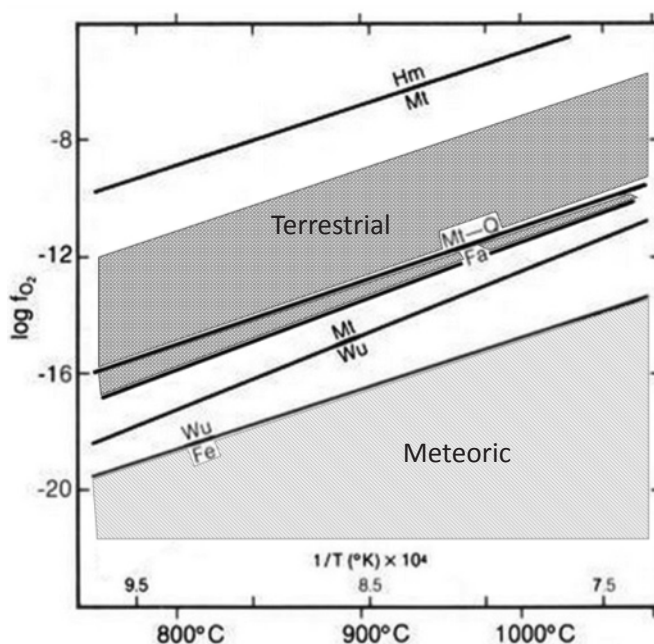


Figure 1. Fields of stability for various iron-oxide minerals as a function of oxygen fugacity vs. temperature, which also designates the conditions at which various oxidation states of iron are typically thermodynamically stable in both terrestrial (upper- shaded portion) and meteoric (lower shaded portion) settings. Abbrev.: Hm: Hematite, Mt: Magnetite, Fa: Fayalite, Q: quartz, Wü: wüstite, Fe: iron. Adapted from Heiken et al. (1991).

In the native-Fe basalts of Siberia, other minerals atypical for terrestrial rocks but common for meteorites are also present, including kamacite (FeNi); cohenite (Fe₃C); and troilite (FeS). Trieman et al. emphasizes the presence of native Cu and the absence of taenite (a metallic mineral high in Ni) in these rocks as diagnostic of a terrestrial setting, as they can easily be mistaken for meteorites (2002). In addition to this unusual mineralogy, these rocks possess high concentrations of valuable platinum-group elements (PGEs; e.g., Pt, Rh, Ir, Os, Ru, Pd), as well as Cu-, Ni-, Co-, and Ge-rich minerals (Ryabov and Lapkovsky, 2010). The native iron from northern Siberia is found in hypabyssal (shallow) intrusions that form part of the extensive plumbing system of the largest igneous province in the world – the Siberian Flood Basalts – the eruption of which probably caused the Permian-Triassic extinctions (Howarth et al., 2015). The effect of an extreme reduction process on the mineral chemistry of these Siberian basalts is the subject of this study, an outgrowth of a B.S. Senior-Project working under Dr. Larry Taylor throughout his Geochemical Analysis course at the University of Tennessee at Knoxville.

Petrographic Description 2.0

Petrographic analysis provides an avenue to investigate the unique mineralogy found in these samples and gives insight into the circumstances that formed these rocks. The huge trap basalts in Northern Siberia, including the native-Fe bearing rocks that appear to resemble stony-iron meteorites, are potential ores of PGEs – most notably in the Noril'sk Cu-Ni sulfide ore deposits. Sample OZ-244 was chosen from a suite of basaltic samples from this area, as representative of the geologic locale. A polished thin section of this specific rock was produced

and examined with a petrographic microscope. The minerals present within these rocks can be divided into two categories: opaque minerals (35 %), which include native iron (properly: kamacite), native copper, cohenite, troilite, copper sulfides (chalcocite and chalcopyrite), and ilmenite; and silicate minerals (65 %), which include olivine, pyroxene, and plagioclase. Silicate minerals (Fig. 3E, F) were studied with transmitted-light microscopy, while opaque minerals were studied with reflected-light microscopy. Three textural regions (shown in Fig. 2) were identified within the section: a Metal Region, with the highest abundance of metallic phases, a Silicate Region, with the highest abundance of silicate phases and fewest metal phases, and a Transition Region, which lies between these two and contains properties of the two adjoining regions. Grains within this sample generally, range from very-fine (<0.01 mm) to coarse-grained (up to 2.5 mm) and, thus, the sample is termed inequigranular. Based on the texture of the minerals, this rock is hypidiomorphic-granular, a texture in which some of the minerals are subhedral or euhedral (terms to express crystal morphologies), and others are anhedral (i.e., without crystal shape). This classification is given due to the high abundance of subhedral plagioclase grains, as the other minerals are sub- to anhedral. Various additional textures are observed, including poikilitic, ophitic, granoblastic, and porphyritic (Fig. 3A, C, D).

The native-Fe kamacite is bright white and ranges in size from 1-1.25 mm, while cohenite, which is commonly found on the edges of or enclosing the kamacite grains, is pale-grey and generally between <0.1- 0.4 mm. Ilmenite is light-grey in color, is sub- to euhedral, and ranges in size from <0.1-0.6 mm. Troilite and sulfide minerals are fine-grained (<0.2 mm), brown-tan grains. Plagioclase appears as both fine matrix crystals and large phenocrysts (Fig. 3B); they are generally tabular, subhedral crystals, displaying albite and carlsbad twinning, and range from <0.1-1.75 mm in length and up to 0.75 mm in width. Pyroxenes are generally anhedral, interstitial grains up to 1 mm. Fractured olivine crystals are subhedral and range in size from 0.25-2.5 mm

The overall section is heterogeneous in distribution of minerals. As a result, modal abundances (the percentage of the surface area of a mineral in the thin-section) are more accurately described per region: Metal Region – kamacite 40 %, plagioclase 25 %, olivine 10 %, cohenite 10 %, ilmenite 5 %, pyroxene 5 %, 5 % troilite and copper sulfides; Transition Region – plagioclase 40 %, pyroxene 15 %, kamacite 10 %, ilmenite 10 %, olivine 10 %, cohenite 5 %, 5 % troilite and copper sulfides; and Silicate Region – plagioclase 60 %, pyroxene 20 %, olivine 15 %, , ilmenite <5 %, <5 % troilite and copper sulfides, kamacite 1 %.

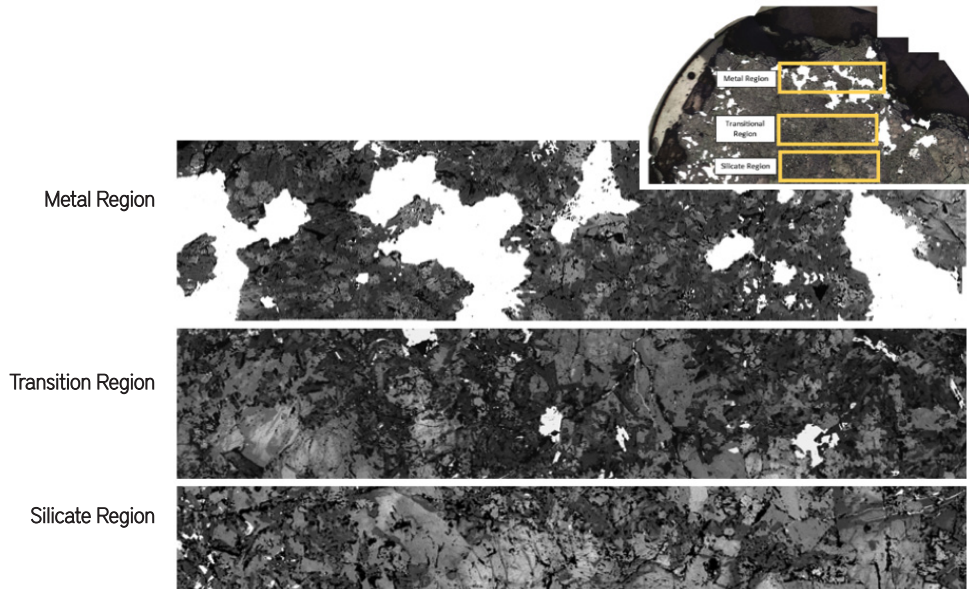


Figure 2. Reflected-light maps of thin-section sample depicting three regions, each with contrasting abundances of minerals.

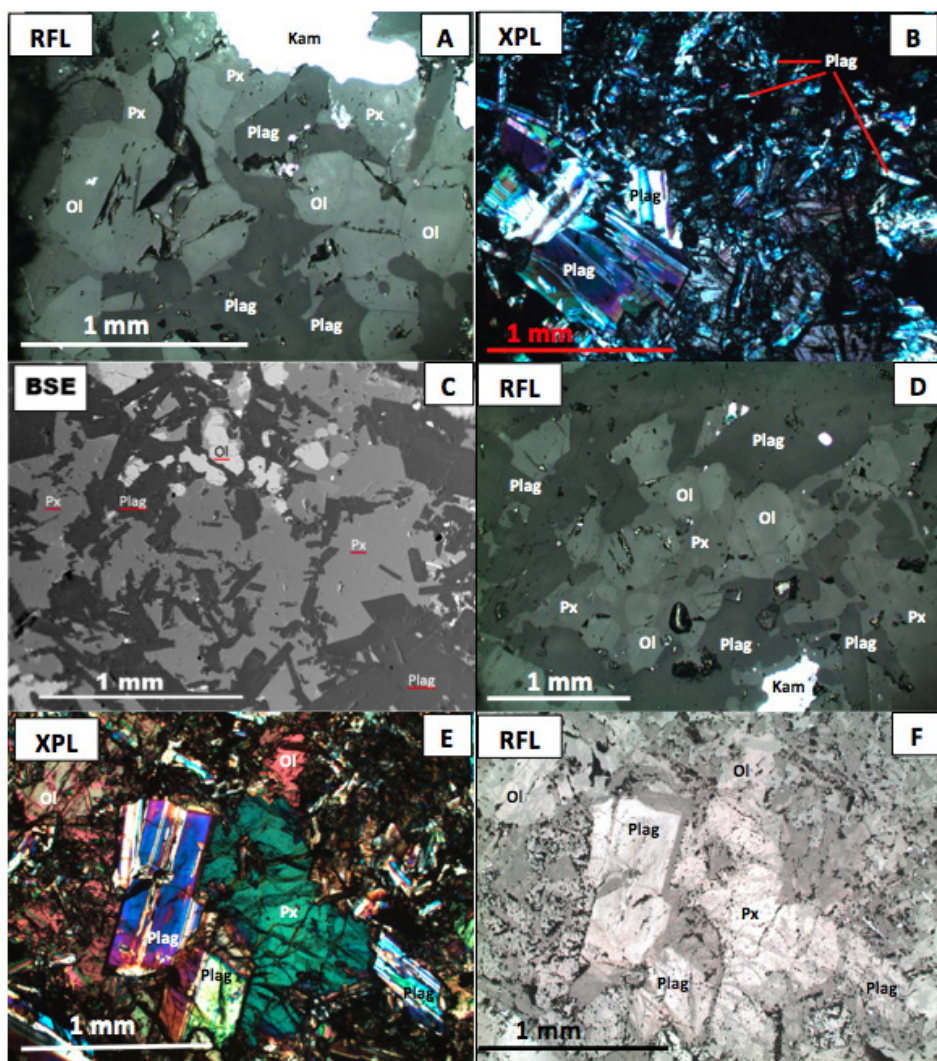


Figure 3. A: Reflected-light image showing poikilitic and granoblastic textures. B: Transmitted crossed-polarized light image depicting plagioclase matrix and phenocrysts. C: Backscattered-electron image showing poikilitic and ophitic textures. D: Reflected-light image showing poikilitic and ophitic textures. E: Transmitted crossed-polarized light image depicting grain boundaries between plagioclase, pyroxene, and olivine. F: Reflected-light image of figure 3E.

Methods 3.0

Microprobe analysis 3.1

Mineral analyses were performed in the Department of Earth and Planetary Sciences at The University of Tennessee with a fully automated Cameca SX-100 Electron Microprobe, with four wavelength-dispersive X-ray spectrometers (WDS), and with one energy-dispersive spectrometer (EDS). Approximately 600 analyses were conducted on the sample. These

analyses were performed using an accelerating potential of 15 keV, 10-30 nA beam current (depending on the phase being analyzed), 1 μm -diameter beam, 20-second count times and standard PAP (i.e., ZAF) corrections. The instrument was calibrated daily using both natural and synthetic standards. Detection limits were 0.03 wt. % for MgO, CaO, MnO, Na₂O, K₂O, P₂O₅, SiO₂, TiO₂, Al₂O₃, Cr₂O₃, and 0.06 wt. % for FeO, NiO, Co, Ni, and Cu.

Elemental X-ray Mapping 3.2

The use of X-ray maps were utilized in order to identify phases and to determine modal abundances of the various minerals, textures, and chemical zonations within phases. These data were collected using a 15 keV, 20 nA beam, with a step size of 2 μm , at 50 ms per step counting-time. This map is comprised of three elemental components. Each component was assigned a specific color, and the results were compiled to display the individual chemistry of each component. The elemental components were chosen to identify the specific minerals in question: Al, displayed in blue, was chosen to represent plagioclase; Fe, displayed in red, to represent olivine and iron-nickel phases; and Ca, displayed in green, to represent pyroxene. These combined elements are represented in the Red-Green-Blue (RGB) X-ray map shown in Figure 4.

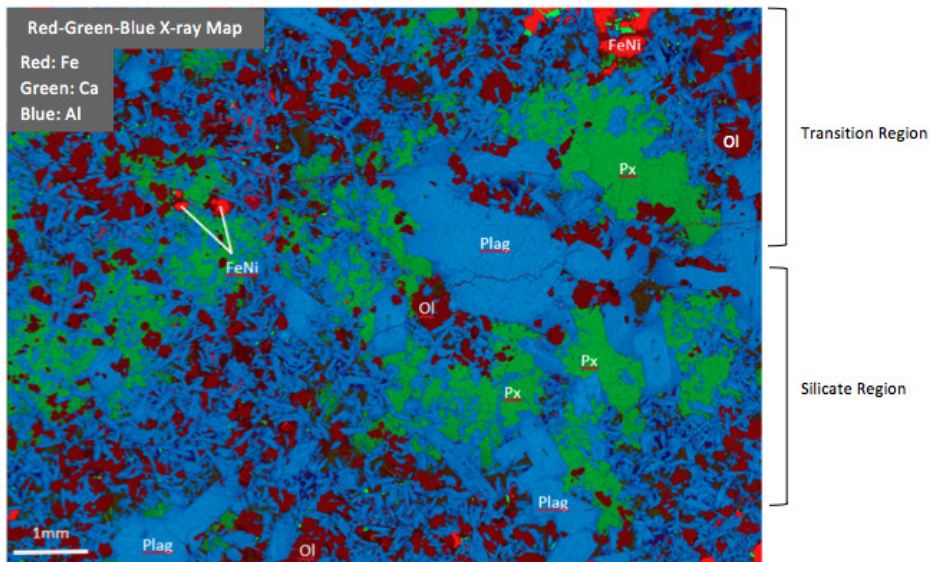


Figure 4. Red-Green-Blue (RGB) colored X-ray map displaying three elements that represent corresponding mineral phases. Px: Pyroxene, high in Ca. Plag: Plagioclase, high in Al. Ol: Olivine, high in Fe, but containing small amount of Ca. FeNi: Iron-Nickel metal.

Results 4.0

Olivine 4.1

Olivine compositions showed little inter- or intra-granular variability (see Fig. 5); overall, the concentrations averaged Fo₅₀. However, the highest and lowest values were Fo₃₆ and Fo₆₇, respectively. Compositions range from Fo₄₃₋₄₉ within the metal region and from Fo₄₅₋₅₅ within the transition region. The silicate region had the widest range of values and from Fo₃₆₋₆₇. However the bulk of these results lie between Fo₄₆₋₅₆.

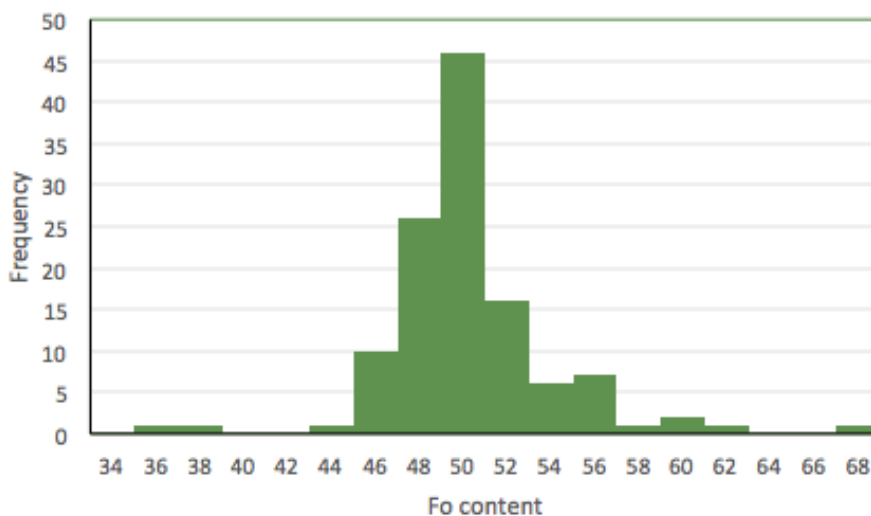


Figure 5. Binary histogram of Forsterite-Fayalite (Fo-Fa) system for olivine, representing the ratio of Fe/Mg present.

Pyroxene 4.2

Pyroxene is present as two distinct inter-grown phases (Fig. 6): augite and pigeonite. These exist as distinct, individual crystals, both touching and discrete, as intergrowths within one another, and as exsolution. Minor chemical zonations occur within grains. Comparing these compositions with that of olivine suggests that these minerals are in equilibrium and, therefore, crystallized from the same melt. Compositions were consistent among the three textural regions.

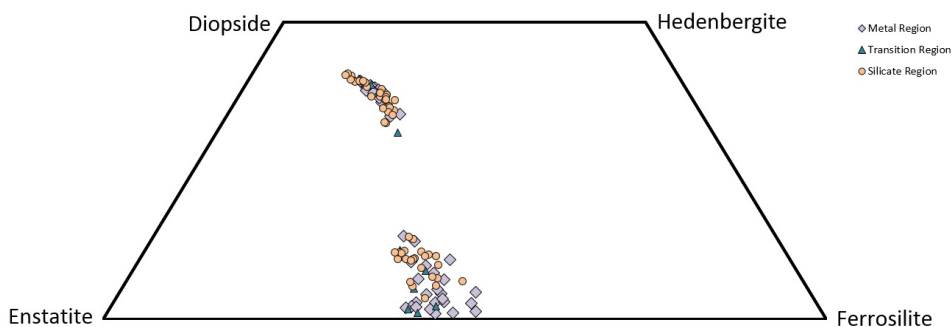


Figure 6. Ternary diagram of Ca-Mg-Fe system for pyroxenes. Clearly displays two distinct clusters of points, the top cluster representing augite compositions, and the bottom cluster representing pigeonite compositions within this sample, as well as homogeneity among textural regions.

Plagioclase 4.3

Plagioclase displays clear zoning. Core compositions range from An_{43-82} , while rim compositions vary slightly less – from An_{54-77} (Fig 7). Phenocryst compositions are in equilibrium with these rims An_{54-80} , while the fine-grained matrix crystals are in equilibrium with the cores, displaying ranges from An_{46-84} (Fig 8). Compositions range from An_{46-75} within the metal region, An_{51-77} within the transition region, and An_{52-84} within the silicate region.

Compositions of all three primary silicate minerals – pyroxene, plagioclase, and olivine, exhibit little variability among the different textural regions. Average compositions for each of these are listed in Table 1.

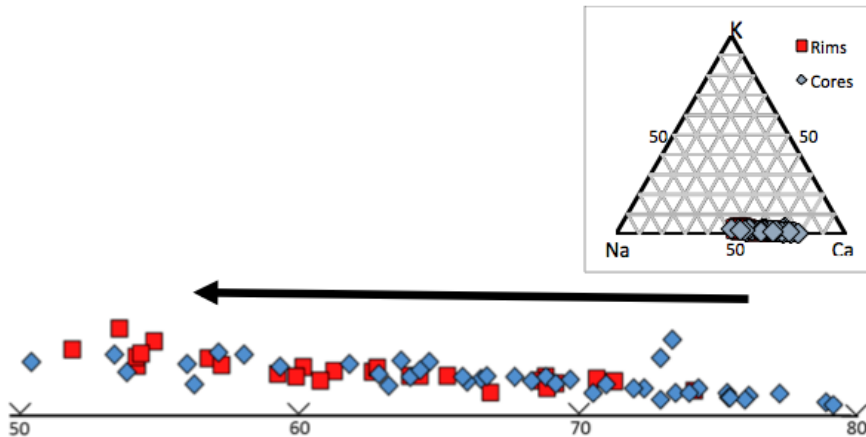


Figure 7. Plot depicting compositions of plagioclase rims (red squares) and cores (blue diamonds). Cores tend to be higher in Ca (end-member Anorthosite: $CaAl_2Si_2O_8$), while rims tend to be higher in Na (end-member Albite: $NaAlSi_3O_8$) over time.

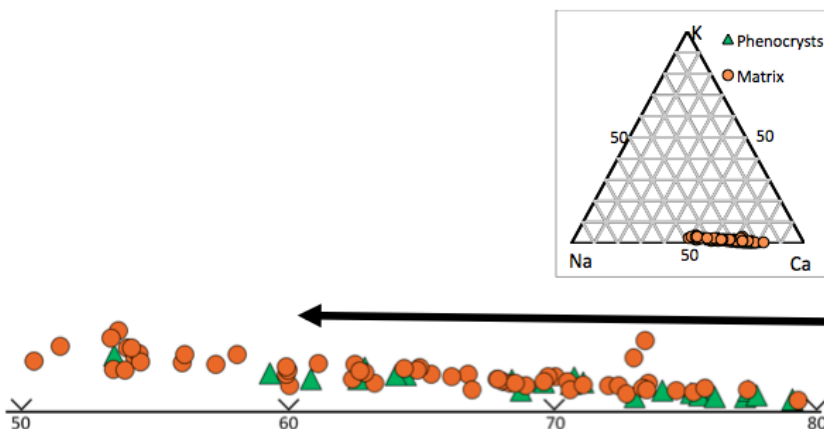


Figure 8. Plot depicting compositions of plagioclase phenocrysts and matrix crystals. Overall phenocryst compositions are more constrained at a higher Ca content, while matrix crystal compositions have a wider range of Na-Ca content.

Table 1. Analytical data of native iron basalt from Northern Siberia

Oxide wt%	Olivine	Pyroxene	Plagioclase	Ilmenite	Wüstite
# of analyses	106	124	146	24	22
P ₂ O ₅	<0.03 ¹	n.d. ²	n.d.	n.d.	n.d.
SiO ₂	34.5(1) ³	51.0(2)	51.6(2)	<0.03	0.46(1)
TiO ₂	0.04(1)	0.80(1)	n.d.	53.5(1)	<0.03
Al ₂ O ₃	<0.03	1.43(3)	30.2(1)	0.02(1)	0.07(1)
Cr ₂ O ₃	<0.03	0.03(1)	n.d.	0.04(1)	<0.03
MgO	23.0(2)	16.5(3)	0.08(2)	0.99(1)	<0.03
CaO	0.09(1)	9.41(7)	13.3(2)	0.06(1)	0.04(1)
MnO	0.47(1)	0.36(1)	n.d.	0.25(1)	<0.03
FeO ⁴	42.2(2)	19.9(9)	0.52(1)	45.4(1)	46.0(1)
Fe ₂ O ₃	n.d.	n.d.	n.d.	n.d.	51.6(1)
NiO	<0.06	n.d.	n.d.	n.d.	n.d.
Na ₂ O	n.d.	0.18(1)	3.72(1)	n.d.	n.d.
K ₂ O	n.d.	n.d.	0.30(1)	n.d.	n.d.
Total	100.4	99.6	99.8	100.3	93.0
Cations based on	4 Oxygen	6 Oxygen	8 Oxygen	6 Oxygen	6 Oxygen
P	0.000	n.d.	n.d.	n.d.	n.d.
Si	0.993	1.934	2.368	0.001	0.035
Ti	0.001	0.024	n.d.	2.007	0.001
Al	0.000	0.048	1.587	0.001	0.006
Cr	0.000	0.001	n.d.	0.001	0.001
Mg	0.989	0.937	0.029	0.074	0.001
Ca	0.003	0.444	0.642	0.003	0.003
Mn	0.011	0.012	n.d.	0.011	0.001
Fe ³⁺	1.008	0.613	0.054	1.893	5.915
Ni	0.000	n.d.	n.d.	n.d.	n.d.
Na	n.d.	0.009	0.331	n.d.	n.d.
K	n.d.	n.d.	0.022	n.d.	n.d.
Total	3.006	4.022	5.014	3.991	5.961

Mineral	Kamacite	Chalcopyrite	Troilite	Chalcocite	Cohenite
# of analyses	62	10	27	8	33
Weight %					
P	<0.03	<0.03	<0.03	<0.03	<0.03
Si	<0.03	0.07(1)	0.07(1)	0.12(1)	<0.03
S	<0.03	30.9(6)	35.9(1)	24.4(5)	<0.03
Ti	<0.03	<0.03	<0.03	<0.03	<0.03
Fe ²⁺	98.5(1)	32.9(4)	63.2(1)	1.89(1)	93.6(2)
Co	0.51(1)	0.23(1)	<0.06	<0.06	0.09(1)
Ni	1.39(1)	0.33(1)	<0.06	<0.06	0.39(1)
Cu	0.09(1)	34.8(7)	0.32(1)	72.9(6)	<0.06
Al	<0.03	<0.03	0.05(1)	0.09(1)	<0.03
Mg	<0.03	<0.03	<0.03	<0.03	<0.03
C	n.d. ³	n.d.	n.d.	n.d.	5.96(1)
Total	100.6	99.2	99.6	99.3	100.0
Atomic %					
P	<0.03	<0.03	<0.03	<0.03	<0.03
Si	<0.03	<0.03	0.11(1)	0.20(1)	<0.03
S	<0.03	45.5(7)	49.5(1)	38.9(7)	<0.03
Ti	<0.03	<0.03	<0.03	<0.03	<0.03
Fe ²⁺	98.1(1)	27.0(3)	49.8(1)	1.63(1)	77.1(8)
Co	0.48(1)	0.18(1)	<0.06	<0.06	0.07(1)
Ni	1.32(1)	0.29(1)	<0.06	<0.06	0.30(1)
Cu	0.08(1)	27.3(5)	0.52(2)	59.1(7)	<0.06
Al	<0.03	<0.03	<0.03	0.16(1)	<0.03
Mg	<0.03	<0.03	<0.03	0.04(1)	<0.03
C	n.d.	n.d.	n.d.	n.d.	22.5(8)
Total	100.0	100.0	100.0	100.0	100.0

¹Values <0.03 below detection limit for EMP analysis²n.d. = not determined for this phase³Units in () represent one standard deviation of replicate analyses in terms of least units cited⁴All Fe calculated as Fe²⁺

Opaque phases 4.4

Analysis of opaque phases identified the following minerals: kamacite – FeNi; native Cu; cohenite – Fe₃C; ilmenite – FeTiO₃; troilite – FeS; chalcocite – Cu₂S; chalcopyrite – CuFeS₂; and wüstite – FeO (Fig. 9-10). Average compositions of these minerals can be found in Table 1. Kamacite displays slight zonation with outer rims ~1.5% higher in Fe. Cohenite and wüstite are generally found on the rims of kamacite grains, although wüstite also occurs as distinct grains. Copper sulfides commonly occur together. Native copper is distributed mainly as inclusions or as exsolution lamellae within kamacite but also rarely occurs as fine, distinct grains, which are associated with sulfide minerals.

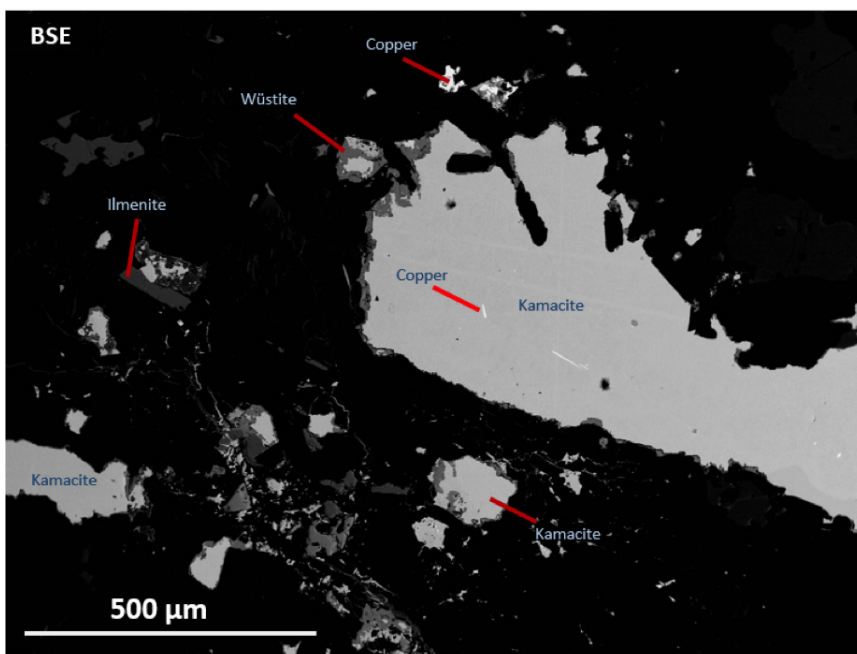


Figure 9. Backscattered-electron image displaying opaque phases and textures.

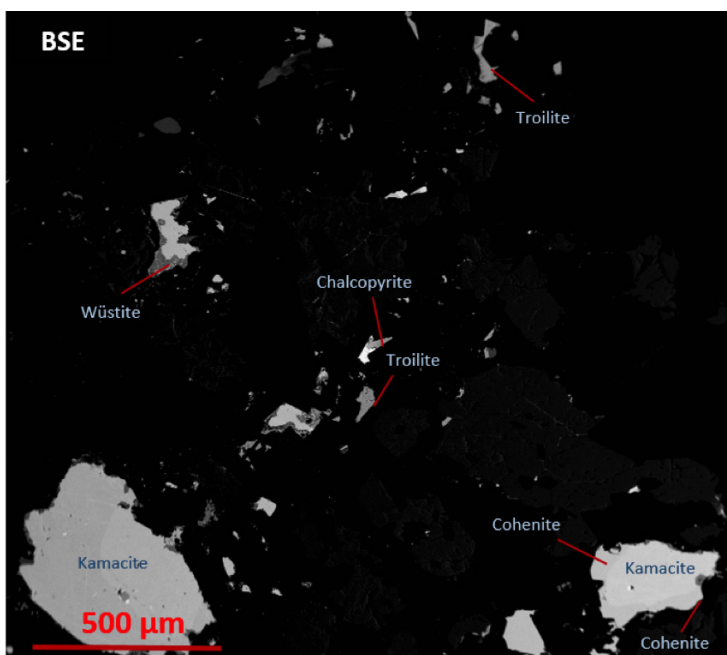


Figure 10. Backscattered-electron image displaying opaque phases and textures.

Discussion 5.0

Mineral Chemistry 5.1

The olivine Fo values were used to calculate the Mg number ($\text{MgO}/\text{FeO}+\text{MgO}$) of the melt (as seen in Fig. 11). These reduced basalts have an average Mg number of 23. Wooden et al. (1993) estimates typical, unreduced basalts in this region to have an Mg number ranging from 50-55, whereas Naldrett et al. (1992) describes an Mg number of ~60. This higher Mg number would generate an olivine composition closer to Fo80-85. The olivine composition in this sample is the first line of evidence showing how greatly enriched in FeO the parent magma must have been, in comparison to a typical basaltic magma. This represents not only a major reduction of Fe^{2+} to form FeO but also an accumulation of the native iron by settling, resulting in significant increase of overall iron content in the local magmas.

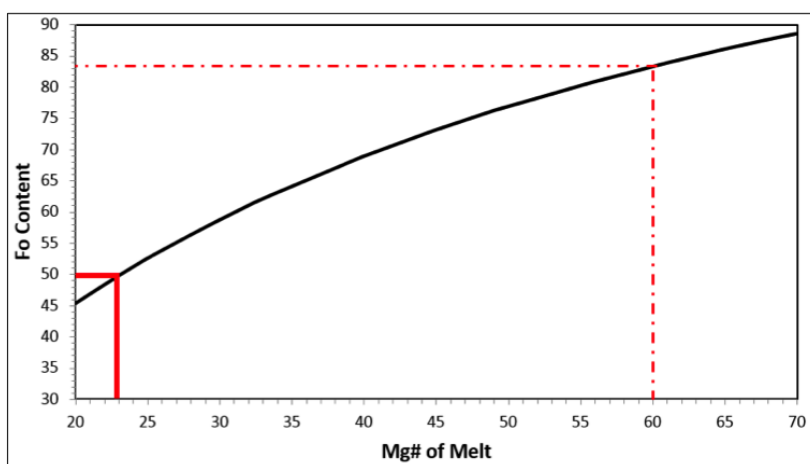


Figure 11. Graph showing the relationship between olivine composition and Mg# of the melt. Solid line signifies representative composition and Mg# of sample studied. Dashed line indicates Mg# of typical, unreduced Siberian basalts and what olivine composition this would imply (Naldrett et al. 1992).

Plagioclase compositions display trends between both rim-core and phenocryst-matrix values. Cores tend to have higher An values, while the range of rim compositions have lower An content. This indicates that throughout crystallization the melt became more-enriched in Na and less so in Ca. Likewise, overall phenocryst compositions are higher in Ca, while matrix crystals have a much wider compositional range – a result of the phenocrysts having formed earlier in the crystallization sequence.

Crystallization Sequence 5.2

Based on textures and silicate composition, one possible crystallization sequence is as follows: metal sulfides/oxides-kamacite-cohenite-plagioclase-olivine-pyroxene. This timing is supported by the poikilitic texture found within this sample – many small olivine crystals are enveloped within larger pyroxenes; metallic phases are also found as inclusions within all three silicate phases, while no silicate inclusions are found within metallic phases. Analyses of the minerals within the identified textural regions were performed in order to detect possible inter- and intra-granular chemical variations. No characteristic trends were discerned in the mineralogy between these regions other than the abundances of the phases. This compositional uniformity of the minerals indicates that the extraordinarily low $f\text{O}_2$ was pervasive and persistent both

throughout the sample and for the duration of crystallization, and cooling time was sufficient to allow kinetics to take over and for each phase to equilibrate. However, if the Fe-metal phases were to crystallize early, the remaining melt would be higher in Mg. Yet, the silicate phases are *not* enriched in Mg, which indicates that the overall complications induced by the combination of carbon reduction of the iron-component of the basaltic melt and the crystal settling of the native Fe (density >7 gm/cc) caused inhomogeneity of the resulting melts. It is possible that the silicate phases began to form first, and the metallic inclusions aggregated and formed later near the end of silicate crystallization. This unique occurrence of native iron on Earth brings about an entirely new set of crystallization/crystal settling/assimilation processes to consider.

Magmatic Model to Explain the PGE-enrichments 5.3

Li et al. (2009) describes a model for sulfides forming in unreduced Siberian flood basalts ending with the assimilation of an anhydrite (CaSO_4) layer, which produced a magma enriched in sulfides, Ni, Cu, and PGE elements. In this model, primary sulfide segregation occurred early within a staging chamber deep within the mantle. This process was driven by contamination of the magma by granitic crust forcing the formation of a sulfide-liquid immiscibility (SLI) that later scavenged the PGEs from the silicate melt. The bulk of the magma in this chamber began to ascend, leaving the denser SLI behind in the chamber. A new pulse of magma enriched in PGE-elements, as well as Ni and Cu, then entered the chamber. As these are chalcophile (“sulfur-loving”) elements, they integrated with the sulfide liquid. This new PGE-enriched SLI again remained in the chamber while the new, altered magma erupted. Finally, a magma depleted in sulfur entered and slowly filled the chamber, dissolving the residual sulfide liquid and forming a PGE-Ni-Cu enriched magma. As this magma ascended, it assimilated evaporate-rich country rock containing large amounts of the mineral anhydrite (CaSO_4). The assimilation of these rocks caused the magma to, once again, become sulfur-saturated. This reaction produced a new SLI nearer the surface that was enriched in PGEs, Ni, and Cu. This liquid eventually became ore-bearing intrusion in some locales (the Noril’sk Cu-Ni-ore deposit). However, in the specific area addressed in this study, a different geologic situation occurred. In this area, upon further intrusion of this PGE-enriched silicate melt into the crust, it intersected the carbon-bearing zone of coal and oil-rich shales, resulting in the extreme reduction of the magma, and the evolution of massive amounts of volatiles.

The presence of PGEs and native iron in the rocks involved in this study can be explained using a model largely based on the one proposed by Li et al. (2009). This adapted model (Fig. 12), instead of focusing on the importance of anhydrite assimilation (which increases oxygen fugacity), emphasizes the role of the assimilation of a carbonaceous stratum (which decreases oxygen fugacity). The upper crust of Northern Siberia contains such strata: coal beds, carbonaceous shales, and hydrocarbons. The following sequence of events occurred: first, a basaltic magma was contaminated by granitic country rock in the lower crust, resulting in the formation of an SLI, which remained in that chamber as the bulk of the magma ascended. Then, a new pulse of magma entered – carrying Ni and Cu, which remained within the sulfide melt. Another pulse of magma enriched in PGEs then filled the chamber, and this magma began to ascend, leaving behind its PGEs and chalcophile elements (including Ni and Cu), further enriching the SLI. A magma highly depleted in sulfur encountered the SLI magma chamber and incorporated this SLI. As the SLI-bearing, Ni-Cu-PGE-enriched liquid encountered the carbonaceous material, the reaction was similar to that which occurs in a blast furnace. For example, when iron oxides meet with carbon, the following reactions ensue: $2\text{Fe}_2\text{O}_3 + 3\text{C} \rightarrow 3\text{CO}_2 + 4\text{Fe}$. The carbon-rich material removes the oxygen and sulfur from metallic compounds, and volatile compounds such as CO, CO_2 , SO_2 form and escape. This reaction severely reduces all iron-bearing minerals, as well as the overall oxygen fugacity. As this magma ascended, the heavy native iron and nickel settled and accumulated within the melt before erupting, forming these unique ore deposits.

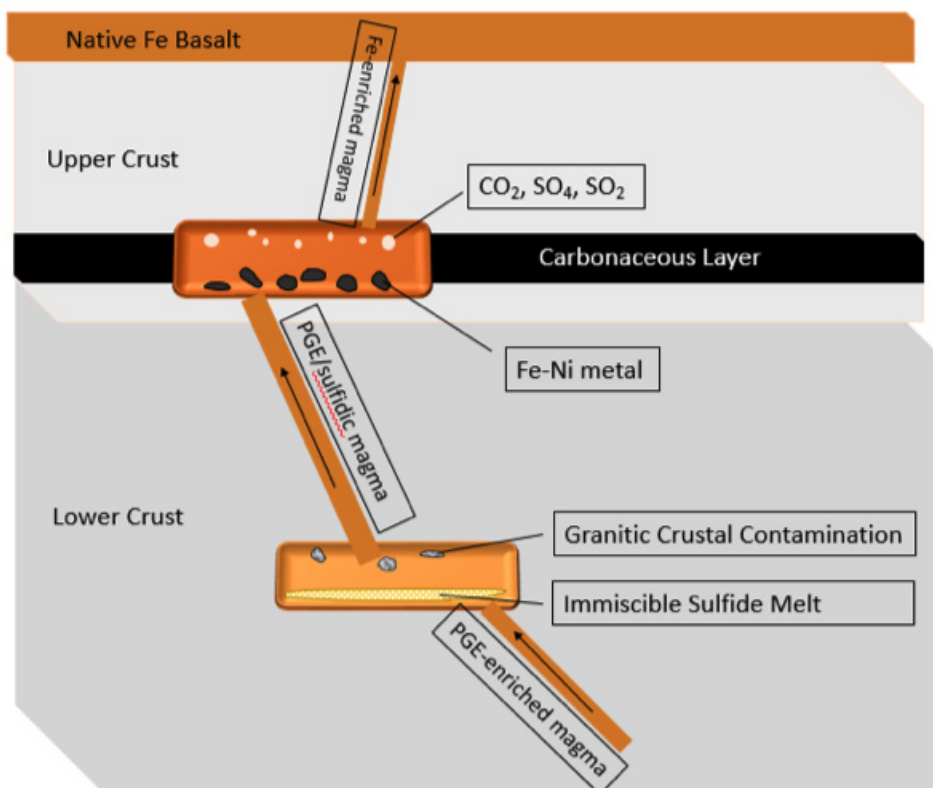


Figure 12. Model for the formation of FeNi metal in Siberian flood basalts via assimilation, contamination, and reduction.

Summary

Both the presence of native iron and the high-iron content of pyroxene and olivine throughout the sample indicate that low fO_2 was pervasive within the magma during crystallization. In order for this low fO_2 to originate, a severe reduction process near the time of crystallization was required. The most likely catalyst for this process within the Northern Siberian Traps is the interception of a carbonaceous body during the ascension of the magma body. The reaction between this body and a magma that had already undergone crustal contamination and PGE-sulfide enrichment resulted in the concentration of elements such as iron and nickel, as the volatiles in the metal sulfides were consumed by the large amounts of added carbon. Iron-nickel metal (as kamacite) was possibly the first phase to crystallize, followed by remaining metal sulfides and oxides. Then the carbon that remained in the melt crystallized with iron to form cohenite. Finally, silicates began to crystallize – first plagioclase, then olivine, and then pyroxene. This paragenetic sequence demonstrates the severity of the impact made on this altered magma body as it intercepted the carbonaceous layer and as the reduction process ensued.

References

- Arndt, N. T., Czamanske, G. K., Walker, R. J., Chauvel, C., and Fedorenko, V. A. 2003, Geochemistry and origin of the intrusive hosts of the Noril'sk-Talnakh Cu-Ni-PGE sulfide deposits. *Economic Geology*, 98, 495-515.
- Howarth, G.H., Pernet-Fisher, J., Day, J.M.D., Goodrich, C., Rivkin, V. and Taylor, L.A., 2015, Petrology and Geochemistry of native-Fe basalts of northern Siberia. *Earth and Planetary Science Letters*, in review.
- Hawkesworth, C. J., Lightfoot, P. C., Fedorenko, V. A., Blake, S., Naldrett, A. J., Doherty, W., and Gorbachev, N. S. 1995, Magma differentiation and mineralization in the Siberian continental flood basalts. *Lithos*, 34, 61-88.
- Heiken, G., Vaniman, D., and French, B. M. 1991, Lunar Sourcebook: A User's Guide to the Moon: Cambridge University Press Archive, 736 p.
- Lightfoot, P. C., Hawkesworth, C. J., Hergt, J., Naldrett, A. J., Gorbachev, N. S., Fedorenko, V. A., and Doherty, W. 1993, Remobilization of the continental lithosphere by a mantle plume: major-, trace-element, and Sr-, Nd-, and Pb-isotope evidence from picritic and tholeiitic lavas of the Noril'sk District, Siberian Trap, Russia. *Contributions to Mineralogy and Petrology*, 114, 171-188.
- Lightfoot, P. C., and Keays, R. R. 2005, Siderophile and chalcophile metal variations in flood basalts from the Siberian trap, Noril'sk region: Implications for the origin of the Ni- Cu-PGE sulfide ores. *Economic Geology*, 100, 439-462.
- Lightfoot, P. C., Naldrett, A. J., Gorbachev, N. S., Doherty, W., and Fedorenko, V. A. 1990, Geochemistry of the Siberian Trap of the Noril'sk area, USSR, with implications for the relative contributions of crust and mantle to flood basalt magmatism. *Contributions to Mineralogy and Petrology*, 104, 631-644.
- Li, C., Ripley, E. M., and Naldrett, A. J. 2009, A new genetic model for the giant Ni-Cu-PGE sulfide deposits associated with the Siberian flood basalts. *Economic Geology*, 104, 291-301.
- Naldrett, A. J., Fedorenko, V. A., Asif, M., Lin, S., Kunilov, V. E., Stekhin, A. I., and Gorbachev, N.S. 1996, Controls on the composition of Ni-Cu sulfide deposits as illustrated by those at Noril'sk, Siberia. *Economic Geology*, 91, 751-773.
- Naldrett, A. J., Lightfoot, P. C., Fedorenko, V. A., Doherty, W., and Gorbachev, N.S. 1992, *Geology and Geochemistry of Intrusions and Flood Basalts of the Noril'sk Region, USSR, with Implications for the Origin of the Ni-Cu Ores*. *Economic Geology*, 87, 975-1004.
- Ryabov, V. V., Lapkovsky A. A. 2010, Native iron (–platinum) ores from the Siberian Platform trap intrusions. *Australian Journal of Earth Sciences: An International Geoscience Journal of the Geological Society of Australia*, 57:6, 707-736.
- Taylor, L.A., Day, J.M.D., Goodrich, C.A., Howarth, G.H., Pernet-Fisher, J.F., Barry, P. Ryabov, V., and Pokhilenko, N.P., 2014. Metallic-Fe deposits in basalts: Siberia, Greenland, and Germany. *International Mineralogical Association, Johannesburg, So. Afr.*
- Trieman, A. H., Lindstrom, D. J., Schwandt, C. S., Franchi, I. A., and Morgan, M. L., 2002. A “mesosiderite” rock from northern Siberia, Russia: Not a meteorite. *Meteoritics & Planetary Science*, 37, B13-B22.
- Wooden, J. L., Czamanske, G.K., Fedorenko, V. A., Arndt, N. T., Chauvel, C., Bouse, R. M., King, B. W., Knight, R. J., and Siems, D. F., 1993, Isotopic and trace-element constraints on mantle and crustal contributions to Siberian continental flood basalts, Noril'sk area, Siberia. *Geochimica et Cosmochimica Acta*, 57, 3677-3704.