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A "mesosiderite" rock from northern Siberia, Russia: Not a meteorite

ALLAN H. TREIMAN[1]*, DAVID J. LINDSTROM[2], CRAIG S. SCHWANDT[3], IAN A. FRANCHI[4] AND MATTHEW L. MORGAN[5]

[1]Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston, Texas 77058, USA
[2]NASA Johnson Space Center, Mail Code ST, Houston, Texas 77058, USA
[3]Lockheed Martin, Mail Code C-23, 2400 NASA Road 1, Houston, Texas 77058, USA
[4]Planetary and Space Sciences Research Institute, Open University, Walton Hall, Milton Keynes MK7 6AA, U.K.
[5]Mile-High Meteorites, P.O. Box 151293, Lakewood, Colorado 80215, USA
*Correspondence author's e-mail address: treiman@lpi.usra.edu

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Abstract–A possible mesosiderite meteorite was found in the area of the Putorana Plateau, Noril'sk district, Siberia, Russia. Although this rock resembles a mesosiderite in its hand-sample aspect and in having Ni-bearing iron metal, it is not a meteorite. This inference is based on the lack of a fusion crust, the lack of cosmogenic nuclides, oxygen with terrestrial isotope ratios, and several mineral chemical criteria. Most likely, the rock is from the iron-metal-bearing basalts of the Siberian Trap basalt sequence, which are mined for their base and platinum-group metals. Mesosiderite imposters like this may be recognized by (1) the presence of Cu metal in hand sample or as microscopic blebs in the low-Ni metal (kamacite), (2) the absence of high-Ni metal (taenite), and (3) the presence of iron carbide (cohenite) enclosing the kamacite. Even if these macroscopic tests are inconclusive, isotopic and mineral chemical tests will also distinguish rocks like this from mesosiderites.

INTRODUCTION

In November 2000, one of the authors (M. Morgan) acquired a rock from the Putorana Plateau area of central Russia as a possible meteorite. That sample, which is called here the Putorana rock, had most of the macroscopic and qualitative chemical characteristics of a mesosiderite meteorite: fragments of basaltic material in a matrix of rounded areas of silicate and iron-rich metallic minerals (Fig. 1), and a positive qualitative test for nickel using dimethylglyoxime. Based on these criteria, the first author was asked to determine whether the Putorana rock actually was a meteorite. After several false starts and analytical confusions, enough evidence was collected to conclude that the Putorana rock is not a meteorite. Rather, it is a rock fragment from the metal-bearing basalt formations mined for platinum group elements in the Putorana area (Bazhenov *et al.*, 1959; Ryabov and Anoshin, 1999). These metal-bearing basalts are little known in the meteorite research community, unlike similar metal-bearing basalts from Greenland (Goodrich and Bird, 1985; Klöck *et al.*, 1986).

The find and discreditation of a possible meteorite are not particularly newsworthy, especially in this time of high prices and extensive publicity for meteorites. However, the Putorana rock resembles a mesosiderite so much that it could not be discredited with a cursory examination. We hope that our experience may be of value to curators, dealers, and collectors faced with classification of potential new mesosiderite meteorites.

SAMPLES AND METHODS

Two part slabs of the Putorana rock were studied in detail, one of 13 g and the other of 10.7 g. The slabs were smoothed and polished with one-quarter micron diamond paste for electron microprobe (EMP) analyses. No thin section was available, so petrography was entirely by reflected light microscopy, backscattered electron imagery, and qualitative energy-dispersive x-ray analysis. A full slab and a larger fragment of the rock were examined for macroscopic features. Gamma ray counting was done with both slabs simultaneously in the detector. Fragments of both slabs were removed for oxygen isotope analysis. Additional oxygen analyses were obtained on fragments of another slab, provided by Dr. G. Kurat, Naturhistorisches Museum, Vienna.

Electron Microprobe Analyses

Chemical analyses of minerals were obtained by EMP analysis with the Cameca SX-100 at the ARES Office (Building 31), Johnson Space Center. Operating conditions were standard: 15 kV potential, focused beam, beam current of 30 nA into a Faraday cup. Count time on each peak was 30 s, as was total count time on backgrounds. Standards for silicates included kaersutite (for Si, Al, Fe, Mg, Ti, Na, and K), spessartine-rich garnet (for Mn), and Cr metal. Standards for metals included pure metals and alloys.

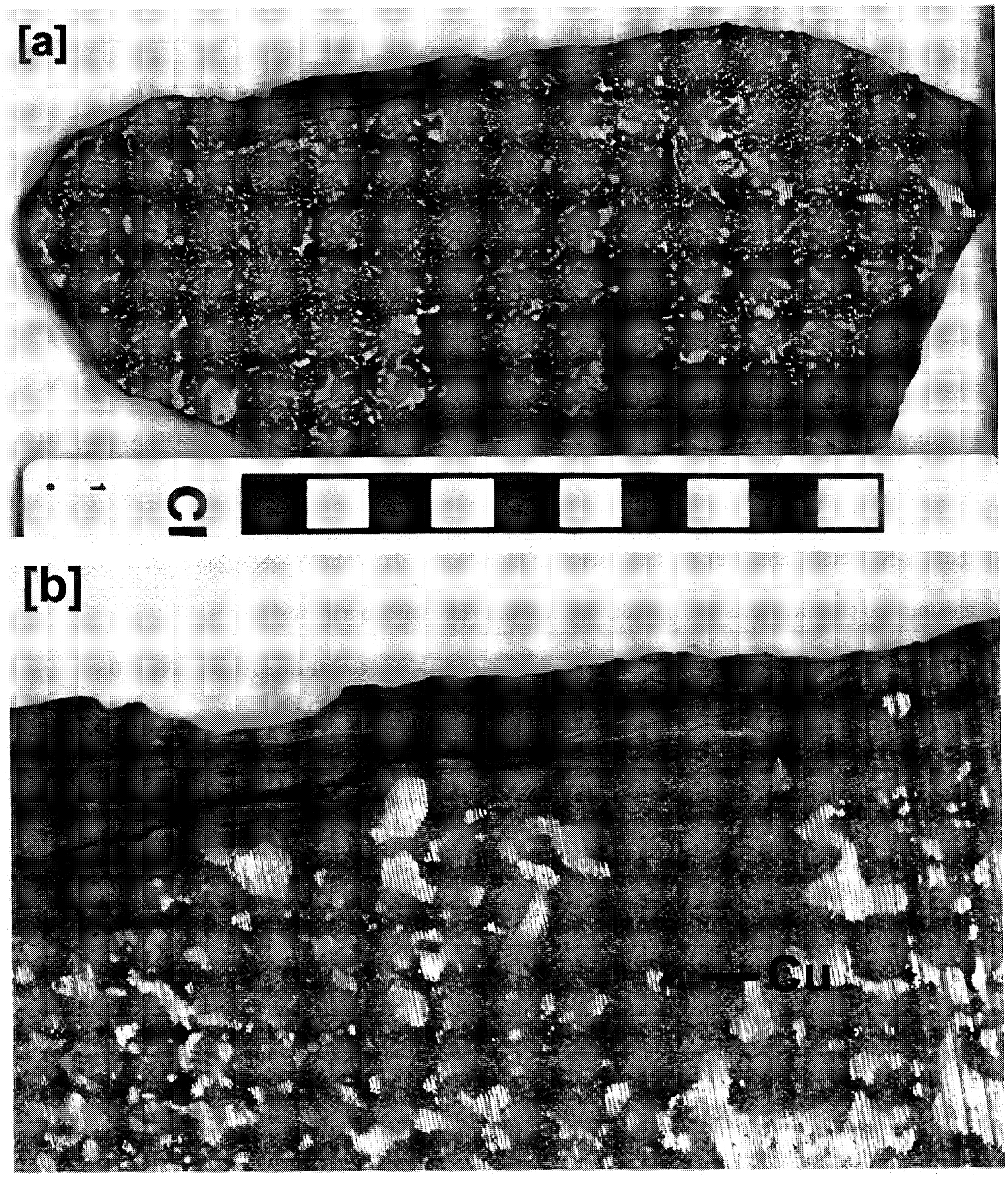

FIG. 1. Putorana Rock: macroscopic. (a) Sawn surface of a slab; scale bar in centimeters, dot at far left is 1 mm in diameter. Light areas in rock are Fe metal and cohenite; dark areas are silicate. Note emulsion-like texture of rounded metallic grains in silicate matrix, and larger basaltic clasts (dark, metal-free). Rusty alteration present only on edges of rock (see far right) and in cracks. (b) Detail of emulsion texture (upper central portion of (a)). Veinlets of fine-grained alteration material (serpentine and chlorite?) at top. Bleb of copper metal (Cu) is the only such grain larger than tenths of a millimeter visible on either side of the slab. Field of view is 2 cm.

Gamma Rays

Natural radiation in two samples of the Putorana rock, combined mass of 25 g, was measured at the low-background counting facility of Johnson Space Center, following the procedures of Lindstrom (2001). Counts were obtained in two consecutive periods of 1×10^6 s.

Oxygen Isotopes

Oxygen isotope ratios of silicates from the Putorana rock were analyzed at the Open University, Milton Keynes, U.K. using a laser fluorination method on crushed samples (Miller *et al.*, 1999; Franchi *et al.*, 1999). Standard deviations for $\delta^{18}O$ and $\Delta^{17}O$ are ~0.09 and ~0.025‰, respectively.

MINERALOGY AND PETROLOGY

Description

The Putorana sample consisted of several fragments with a total mass of ~20 kg. Samples used here were from a 3 kg irregular mass, approximately 15 × 20 × 16 cm. Its exterior is dark-brown to black, with patches of yellowish limonitic alteration and gray-colored bleached feldspar. There is no fusion crust. Smooth areas on the rock's surface could be interpreted as fusion crust, but are surface expressions of veins of alteration materials, probably fine-grained serpentine and chlorite. Elsewhere, the weathered surface of the rock is rough on a millimeter scale, with iron metal standing above silicates. Freshly sawn surfaces of the interior are mottled between metallic and silicate patches.

The metallic phases form nodules and droplets as large as ~1 cm across (Fig. 1a,b). Most of the larger metallic nodules appear circular or elliptical on sawn surfaces, and some appear amoeboid, with elongate rounded protrusions from a central mass. The smaller metallic masses are rounded but generally 2–3× as long as wide (*e.g.*, 3 × 1.5 mm), and are commonly angled in "dog-leg" shapes. The impression is of an immiscible mixture or emulsion of metallic and silicate liquids. The metallic material is bright and fresh, and shows only rare signs of alteration or rusting. Nearly all of the metallic material, which includes α-iron and cohenite, is white. Rare, rounded millimeter-sized grains of copper metal or pyrrhotite are visible on sawn surfaces with the iron and cohenite.

The silicate phases form a matrix for the metallic globules and also are present as discrete, rounded or elongate areas without metal, up to 1 cm^2 or 2 × 0.5 cm on sawn surfaces. The silicate material is dark greenish gray, with only rare traces of limonitic or hematitic alteration along cracks. Little can be seen of the silicate textures in hand sample.

Silicate Phases–Viewed in backscattered electron images, the Putorana rock is revealed to be an annealed breccia of basaltic clasts in a matrix of basaltic and metallic minerals (Fig. 2a–c). The silicate minerals are of nearly constant compositions (Table 1): olivine Fo_{42}, FeO/MnO = 110; pigeonite

TABLE 1. Silicate minerals of Putorana rock: EMP analyses.

	Average olivine	Average pigeonite	Average augite	Average plagioclase	Most calcic plagioclase
SiO_2	33.79	50.53	50.46	50.89	47.37
TiO_2	0.04	0.56	0.85	0.07	0.05
Al_2O_3	0.01	0.69	1.27	31.12	33.41
Cr_2O_3	0.01	0.02	0.02	0.01	0.00
FeO	46.25	27.41	16.73	0.58	0.18
MnO	0.42	0.40	0.27	0.01	0.00
MgO	19.04	16.62	12.73	0.08	0.03
CaO	0.09	2.92	16.68	14.07	16.44
Na_2O	0.01	0.02	0.13	3.10	2.01
K_2O	0.00	0.01	0.00	0.45	0.17
Total	99.64	99.16	99.12	100.37	99.67
*Mg#**	0.42	0.52	0.58	–	–
Fe/Mn†	111	69	63	–	–
En‡	–	49	37	–	–
Fs‡	–	45	28	–	–
Wo‡	–	6	35	–	–
An§	–	–	–	67	79

**Mg#* = molar ratio Mg/(Mg + Fe).
†Molar ratio.
‡En is molar Mg/(Mg + Fe + Ca); Fs is molar Fe/(Mg + Fe + Ca); Wo is molar Ca/(Mg + Fe + Ca).
§An = molar ratio Ca/(Ca + Na + K).

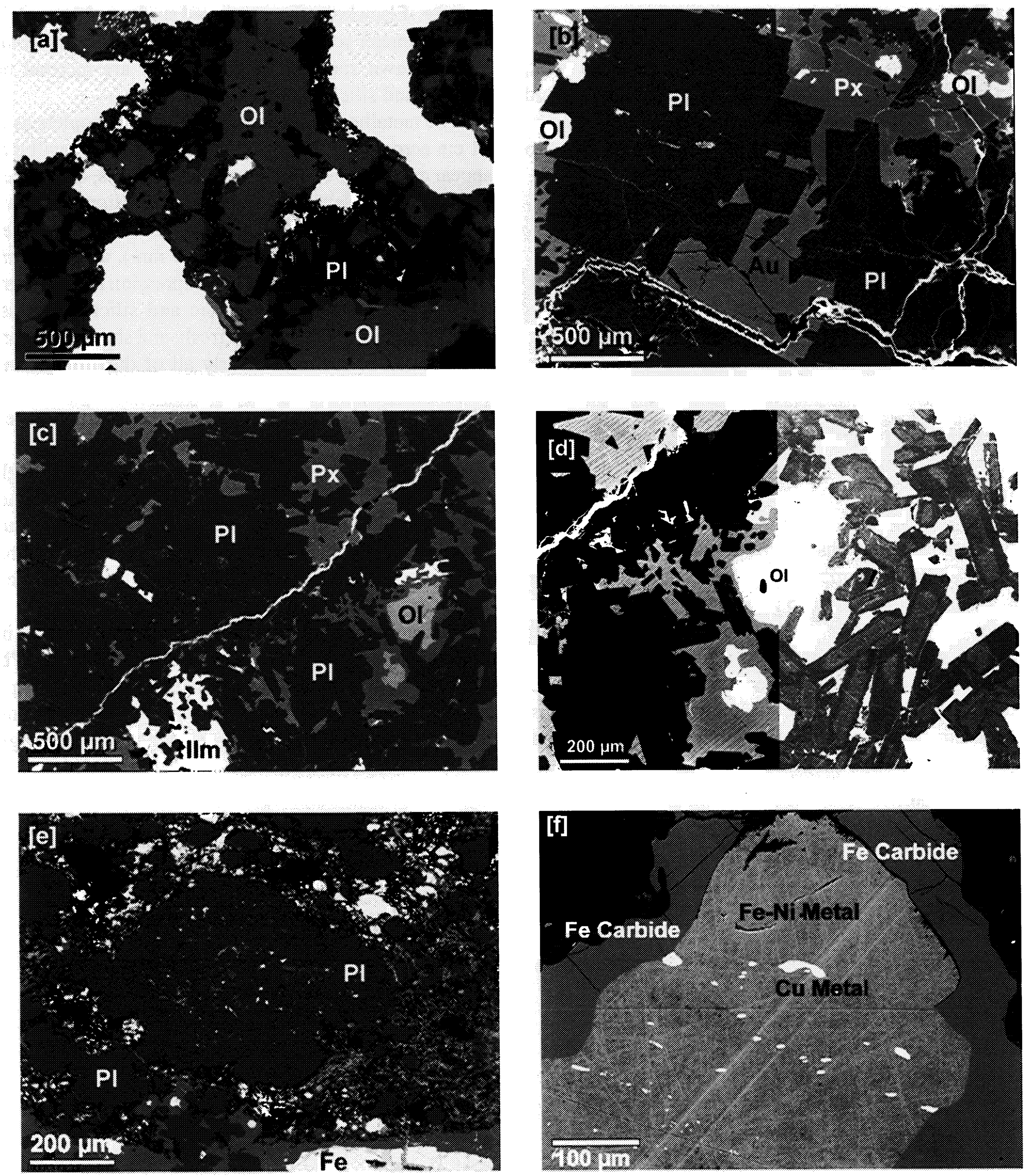

FIG. 2. Putorana Rock: backscattered electron images with scale bars (15 kV, Cameca SX100 electron microprobe). Abbreviations are Ol, olivine; Pl, plagioclase; Px, pyroxene (exsolved pigeonite); Au, augite; and Ilm, ilmenite. (a) Matrix. Rounded globules of metallic phases (white) and interstitial silicate, here rich in olivine. (b) Basaltic clast. Plagioclase euhedra to 2 × 1 mm. Rounded olivine grains enclosed by (partially replaced by) pigeonite. Abundant augite adjoins anorthite. Open cracks to bottom and left of image partially filled by iron oxides/hydroxides. (c) Basaltic clast. Masses of plagioclase laths ~200 μm long by ~50 μm wide (dark). Spiky euhedra of ilmenite (white) encloses plagioclase. Olivine (rounded, light gray) enclosed by (partially replaced by) exsolved pigeonite (medium gray). Abundant augite absent. Crack filled with iron oxides/hydroxides. (d) Close-up, right-central portion of (c). Left half enhanced to show exsolution lamellae in pigeonite; right half enhanced to show plagioclase cores and rims. (e) Anorthosite globule. Portion of a 0.75 × 0.75 mm clast, in basalt like that of (c), composed of rounded fine-grained, plagioclase-rich nodules. Cores of nodules consist of >90% plagiolcase with interstitial metal and pyroxene. Rims of nodules and smaller nodules are nearly 100% plagioclase. (f) Metallic globule in Putorana matrix. Iron metal (kamacite) is medium gray with many linear scratches, contains rounded blebs of copper metal (white). Surrounding the kamacite is a continuous rind of Fe carbide, cohenite (dark gray). Silicate minerals are black.

$En_{49}Fs_{54}Wo_{06}$, FeO/MnO = 69; augite $En_{37}Fs_{28}Wo_{35}$, FeO/MnO = 63; orthopyroxene; and plagioclase, average $An_{67}Ab_{30}Or_{03}$. Other minerals present in the basaltic clasts and matrix include ilmenite, pyrrhotite/troilite, Fe-Cu-sulfides, and a Ca-phosphate, probably apatite(?).

Plagioclase is the only mineral with detectable chemical variability (Fig. 2d). Viewed with backscattered electron imagery at high contrast, the larger plagioclase grains show cores of slightly higher brightness (*i.e.*, higher atomic number). These core zones, the anorthitic (high-Ca) chemical analyses to An_{79}, have euhedral shapes and are central to the whole grain. The outer, rim zones have compositions as sodic as $\sim An_{59}$ (Table 1). This zoning could be relic from an original normal igneous zoning. This qualitative division between core and rim is confirmed by EMP analyses, which divide into two distinct ranges: An_{55-67} and An_{73-79}; out of 36 analyses on core-to-rim traverses, none were between An_{67} and An_{73}. This gap does not correspond to any known solvus in the plagioclase feldspars (Smith, 1975).

The larger silicate areas include several petrographically distinct types of basalt and an unusual fine-grained "anorthosite". Plagioclase is the most abundant mineral in the basaltic clasts, comprising significantly >50% of most clasts (Fig. 2b–d). The plagioclase occurs as elongate to blocky euhedra (0.1 to 1 mm long) and as clumps of euhedra. The next most abundant mineral is pyroxene, which occurs between the other mineral grains. Most of the pyroxene is a fine lamellar intergrowth of augite and orthopyroxene, which represents exsolved pigeonite. Surrounding the exsolved pigeonite are discontinuous rims and patches of augite. The rim augite and that exsolved from pigeonite appear to be the same chemical composition, although the latter is too fine grained for good analysis. Olivine is present as rounded grains that lie in the larger spaces among plagioclase laths, and are completely enclosed in exsolved pigeonite. The olivine grains are not surrounded by coronas of other minerals.

Although several different basalt textures are present, all show the same crystallization sequence. Plagioclase was clearly the first mineral to crystallize, and was followed shortly by ilmenite. The hollow, spiky shapes of the ilmenite suggest fairly rapid cooling. Olivine crystallized next, possibly with the ilmenite although textures are not definitive. Pigeonite crystallized later, filling spaces among plagioclase euhedra and partially replacing olivine.

Small areas of other basaltic lithologies can be recognized, but most may be local concentrations of one or another mineral—a feldspathic dunite area could well be an olivine-rich fragment from a basalt. One lithology that cannot be explained in this way is a fine-grained anorthosite (Fig. 2e). This unique clast in a basalt fragment consists of rounded masses, 50–200 μm across, of fine-grained plagioclase grains, each on the order of 10 μm long. The clast is >90% plagioclase. The remainder is (was) mostly iron metal, with only a few percent of pyroxene among the plagioclase grains.

Metallic Phases–Approximately half of the matrix among the basalt clasts is metallic. Rare discrete grains of copper and iron sulfide are apparent on sawn faces, but none were exposed on the polished slab surface. The white metallic grains are mostly α-iron metal (kamacite) with 2.3% Ni (Table 2; Fig. 2f). This Ni content was enough to give a strong positive response to a qualitative colorimetric test with dimethylglyoxime. The kamacite contains aligned blebs of Cu metal (Fig. 2f). No Ni-rich metal (taenite, tetrataenite) was found. Continuous rinds of cohenite, Fe_3C, surround the kamacite grains (Fig. 2f). The cohenite is recognized by its hardness (scratch-resistance) relative to kamacite, its low totals in EMP analysis consistent with stoichiometric Fe_3C (Table 2), and the presence of a significant CKα x-ray peak in its energy-dispersive x-ray

TABLE 2. Nonsilicate minerals of the Putorana rock and terrestrial rocks: Average EMP analyses.

Weight percent	Putorana cohenite	Putorana copper	Putorana α-iron	Khungtukun α-iron*	Disko Island α-Iron†
Fe	91.11	6.54‡	96.64	98.7	–
Ni	0.62	1.20‡	2.31	0.79	2.54
Co	0.05	0.05‡	0.54	0.17	0.80
Cu	0.04	96.18	0.12	0.32	0.13
C§	6.58	–	–	–	–
Total	98.40	103.97‡	99.65	99.98	–
Ni/Co#	–	–	4.3	4.6	3.2

*Ryabov and Anoshin (1999).
†Goodrich and Bird (1985).
‡Fe value is too high to be consistent with known phase relations (Moffatt, 1984). Possibly, the data reduction did not properly correct for fluorescence of Fe, Ni, and Co by CuKα x-rays.
§Calculated assuming a stoichiometry of $(Fe,Ni,Co,Cu)_3C$.
#CI chondritic Ni/Co is 19.

spectra. Based on its scratch-resistance and petrographic setting, the cohenite was originally misidentified as taenite. Other metallic minerals were identified in reflected light microscopy as pyrrhotite/troilite, chalcopyrite, and possibly other Fe-Cu sulfides.

Geological History

The earliest discernable event in the history of the Putorana rock (at least from the area studied) is formation of the fine-grained anorthositic material, which is a clast embedded in basalt. Next was formation of the basalts themselves. Then, the basalts were brecciated, probably partly melted and mixed with metallic liquid to form the observed emulsion texture. This mix must have cooled relatively rapidly to subsolidus conditions to prevent gravitational separation of metallic and silicate phases.

Following crystallization of the basalt/matrix/metal mixture, the rock experienced a protracted period of subsolidus (metamorphic) chemical equilibration. This is clearly seen in the homogeneous composition of the pigeonite and its extensive exsolution, and in the restricted range of plagioclase compositions. The composition of the augite suggests an equilibration temperature near 1000 °C (Lindsley, 1983).

Metamorphic effects are apparent also in the metallic phases, but reflect equilibration at lower temperature. The α-iron contains no exsolutions or inclusions of cohenite (*i.e.*, perlite structure; Fig. 2f), implying that its equilibration with cohenite must have been below the 740 °C transition from γ- to α-iron (γ-iron in equilibrium with cohenite contains 1–2 wt% C; α-iron contains nearly no C; see Chipman, 1973; Moffatt, 1984; Goodrich and Bird, 1985). This lower equilibration temperature is consistent with the low Cu content of the α-iron (Table 2; Moffatt, 1984). The analyzed Fe content of the Putorana copper metal is probably incorrect (Table 2) because solid Fe in equilibrium with Cu metal can contain at most 5.4 wt% Cu (Moffatt, 1984).

METEORITE OR NOT?

The goal of this study was to determine if the Putorana rock is a meteorite, specifically a mesosiderite. The rock is almost certainly a fragment of the iron-bearing trap (plateau) basalts of Siberia (Lightfoot and Hawkesworth, 1997; Sharma, 1997), which are moderately common near the Putorana plateau, and which are mined there for base and platinum-group metals. Evidence suggesting a terrestrial origin includes lack of fusion crust, availability of similar terrestrial material near the find site, lack of cosmogenic nuclides, oxygen isotope ratios characteristic of the Earth, and a plethora of geochemical and mineralogical characteristics. However, a few characteristics of the Putorana rock are not consistent with common, or even uncommon, Earth rocks.

Structure

As noted above, the Putorana rock has no fusion crust. Without a fusion crust, a definitive sign of extraterrestrial origin, a terrestrial source must be considered. While iron-bearing basalts that resemble mesosiderites are rare on Earth, they do occur in Putorana find area (Bazhenov *et al.*, 1959; Ryabov and Anoshin, 1999).

There are also structural and petrologic differences between the Putorana rock and the mesosiderites. Mesosiderites commonly contain clasts with a range of Fe/Mg ratios, including highly magnesian olivines and low-Ca pyroxenes (Nehru *et al.*, 1980; Mittlefehldt *et al.*, 1998); Putorana does not. Basaltic clasts in mesosiderites are relatively rich in silica minerals and do not contain early olivine (Nehru *et al.*, 1980; Mittlefehldt, 1990; Rubin and Mittlefehldt, 1992); Putorana basalt clasts do. Olivine grains in mesosiderites are commonly surrounded by coronas rich in orthopyroxene (Nehru *et al.*, 1980; Delaney *et al.*, 1981), reflecting chemical reactions between them and their silica-rich basalt clasts and matrices. The Putorana basalts and matrix all contain olivine, and no reaction coronas are expected or observed. Although these differences would probably have prevented Putorana from having been classified as a "normal" mesosiderite, they would not have necessarily suggested that it was terrestrial.

Cosmogenic Nuclides

The Putorana rock shows no ^{26}Al radioactivity, <5 dpm/kg (2σ). It does however show ^{60}Co activity at ~400 dpm/kg, presumably because the rock is so rich in Co (Table 2) and was exposed to cosmic rays at the Earth's surface. The absence of detectable ^{26}Al activity is consistent with either short or no exposure to interplanetary cosmic radiation or a very long terrestrial age. If, for instance, the Putorana rock were a recent fall, its lack of detectable ^{26}Al activity implies an interplanetary exposure shorter than ~1/10 of the half-life of ^{26}Al, or ~74 000 years. If, on the other hand, the Putorana rock had been exposed to interplanetary cosmic rays for millions of years, it must have lain on the Earth for several half-lives of ^{26}Al (*i.e.*, longer than 2 Ma).

Of these two options, it seems most likely that the Putorana rock experienced short or no exposure to interplanetary cosmic rays. A separate rock from central Siberia, similar to the Putorana sample, was analyzed as a possible meteorite and contained no detectable cosmogenic noble gases (A. Bischoff, pers. comm.).

Oxygen Isotopes

The average value of $\Delta^{17}O = -0.01 \pm 0.03‰$ for the Putorana rock is indistinguishable from zero (Table 3); a separate sample of similar iron-bearing basalt from central

TABLE 3. Oxygen isotope composition of putorana bulk silicates.*

	$\delta^{18}O$	$\delta^{17}O$	$\Delta^{17}O$
Putorana	+4.29	+2.24	+0.01
Putorana†	+3.32	+1.67	–0.05
	+2.61	+1.39	+0.03
	+1.69	+0.85	–0.03

*Values in ‰ relative to SMOW.
†Sample c/o G. Kurat.

Siberia was analyzed earlier as a possible meteorite and also had $\Delta^{17}O$ = 0‰ within error (A. Bischoff, pers. comm.). A value of $\Delta^{17}O$ = 0‰ is characteristic of only a few solar system materials: terrestrial rocks, lunar rocks, E chondrites, aubrites, and some CI chondrites (Clayton, 1993; Franchi *et al.*, 1999; Weichert *et al.*, 2001). It is not characteristic of other known solar system materials and basalts including mesosiderites (Clayton, 1993; Clayton and Mayeda, 1996). The $\Delta^{17}O$ of the Putorana rock is indistinguishable from that expected from iron-bearing Siberian trap basalts from the general area where the Putorana rock was found.

The $\delta^{18}O$ values of Putorana samples (+1.7 to +4.3‰, Table 3) are not characteristic of these meteorite types with $\Delta^{17}O$ near 0‰: these CI chondrites have $\delta^{18}O$ near +20‰; E chondrites and aubrites have $\delta^{18}O$ between +4 and +6‰; and lunar basalts have values between +4.2 and +6.4‰ (Clayton, 1993; Clayton and Mayeda, 1996; McKeegan and Leshin, 2001; Weichert *et al.*, 2001). In fact, the $\delta^{18}O$ values of Putorana samples are significantly lower than the range of +5 to +8‰ of nearly all terrestrial basalts (Carlson, 1984; Peng *et al.*, 1994; Harmon and Hoefs, 1995; Eiler, 2001). Basalts with $\delta^{18}O$ values as low as those in the Putorana rock have generally been affected by low-temperature or hydrothermal processes. While the Putorana rock appears essentially unaltered in most views (Figs. 1 and 2), there are veinlets of ferric oxide/hydroxides; the samples analyzed for oxygen, being from the edges of slabs, may have oversampled these alteration materials. The range of $\delta^{18}O$ values from the Putorana rock is beyond that expected from pyroxene and plagioclase equilibrated at high temperature (fractionation factors of Clayton and Kieffer, 1991), and so cannot merely represent variable proportions of pyroxene and plagioclase in the analyzed samples. It is unusual that the oxygen composition is so variable while the cation compositions of the silicates and metallic phases does not vary.

Mineralogy and Mineral Chemistry

The minerals and mineral chemistry of the Putorana rock are inconsistent with known basaltic meteorites and lunar basalts (Table 4). Most of these tests are consistent with a terrestrial origin, but some are anomalous.

TABLE 4. Structural and geochemical features of the Putorana rock compared to some solar system basalts.

	Common Earth basalts	Earth basalt with iron	Lunar basalts	Martian basalts	Meso-siderites
Metal-silicate emulsion*	×	✓	×	×	✓
Basaltic breccia†	×	o	✓	×	✓
No live ^{26}Al	✓	✓	?	×	×
$\Delta^{17}O$ = 0‰‡	✓	o	✓	×	×
An of plagioclase§	✓	o	×	×	×
Or/Ab of plagioclase§	✓	o	×	×	×
Fe/Mn in pyroxene§	?	o	✓	×	?
Cr *vs.* Mg* in pyroxene§	✓	o	×	×	×
Iron metal with low Ni#	✓	✓	✓	×	×
Abundant cohenite#	×	✓	×	×	×
Copper metal#	×	✓	×	×	×

Symbol key: ✓ = Putorana characteristic is consistent with basalt type; × = Putorana characteristic is not consistent with basalt type; ? = Putorana characteristic may be consistent with basalt type; o = Data on iron-metal-bearing basalt is not available.
*See Fig. 1a,b.
†See Fig. 1a–e.
‡See Table 3.
§See Table 1, Fig. 3.
#See Fig. 2f, Table 2.

Alkali Elements and Calcium–Abundance ratios of alkali and alkaline earth elements in a basalt are monitored to some extent by the composition of its plagioclase. Ratios of those elements in plagioclase are consistent with a terrestrial origin for the Putorana rock. Plagioclase in the Putorana rock is too sodic (low An content) to be consistent with mesosiderites, eucrites, or lunar basalts, and too calcic to be from a martian basalt (Papike, 1998). Similarly the potassium content of the plagioclase is consistent with the K–Na–Ca trend of terrestrial plagioclases, and inconsistent with the trends of mesosiderite, eucrite, lunar, or martian plagioclases (Papike, 1998). The very low Cr content of the Putorana pyroxenes is consistent with pyroxenes from terrestrial basalts, but not with pyroxenes in basaltic meteorites (including mesosiderites), martian basalts, and nearly all lunar basalts (data in BVSP, 1981; unpublished compilation).

Iron and Manganese–The molar ratio Fe/Mn in minerals of the Putorana rock deserves special mention, as it was emphasized as an anomalous feature that could suggest a non-terrestrial origin (Treiman *et al.*, 2001). Pyroxenes of the Putorana rock have molar Fe/Mn ≈ 70 and olivines have molar Fe/Mn ≈ 110, which are identical to those in lunar basalts (Fig. 3). These Fe/Mn ratios are not consistent with an asteroidal or martian origin for the Putorana rock, as both are considerably higher than in nearly all known mesosiderites and eucrites and martian basalts (Fe/Mn ratios of about 30–35 and ~50 in pyroxene and olivine, respectively: Papike, 1998; Karner *et al.*, 2001; Papike *et al.*, 2001). Similarly, the Fe/Mn ratios of pyroxene and olivine from the Putorana basalt are distinctly higher than those of most common terrestrial basalts (Fe/Mn ratios of ~45 and ~70 in pyroxene and olivine, respectively: BVSP, 1981; Karner *et al.*, 2001; Papike *et al.*, 2001). It is worth noting that metal-free basalts of the Putorana plateau have bulk rock Fe/Mn ratios typical of common Earth basalts (Sharma *et al.*, 1991; Hawkesworth *et al.*, 1995) and thus their minerals could be expected to have Fe/Mn ratios typical of common Earth basalts (although mineral analyses are not available).

However, Fe/Mn ratios may not be conclusive indicators of planetary origins, as there are some notable exceptions to the general ratios given above. Basalts from some areas on Earth have Fe/Mn ratios approaching those of the Putorana rock; a notable example is the Hawaiian islands province, where the pyroxenes tend to have molar Fe/Mn ≈ 66 (BVSP, 1981) and the olivines can have molar Fe/Mn ≈ 110 (Wilkinson and Hensel, 1988). Some highly metamorphosed eucrite meteorites show a similar effect. Pyroxenes in the Northwest Africa

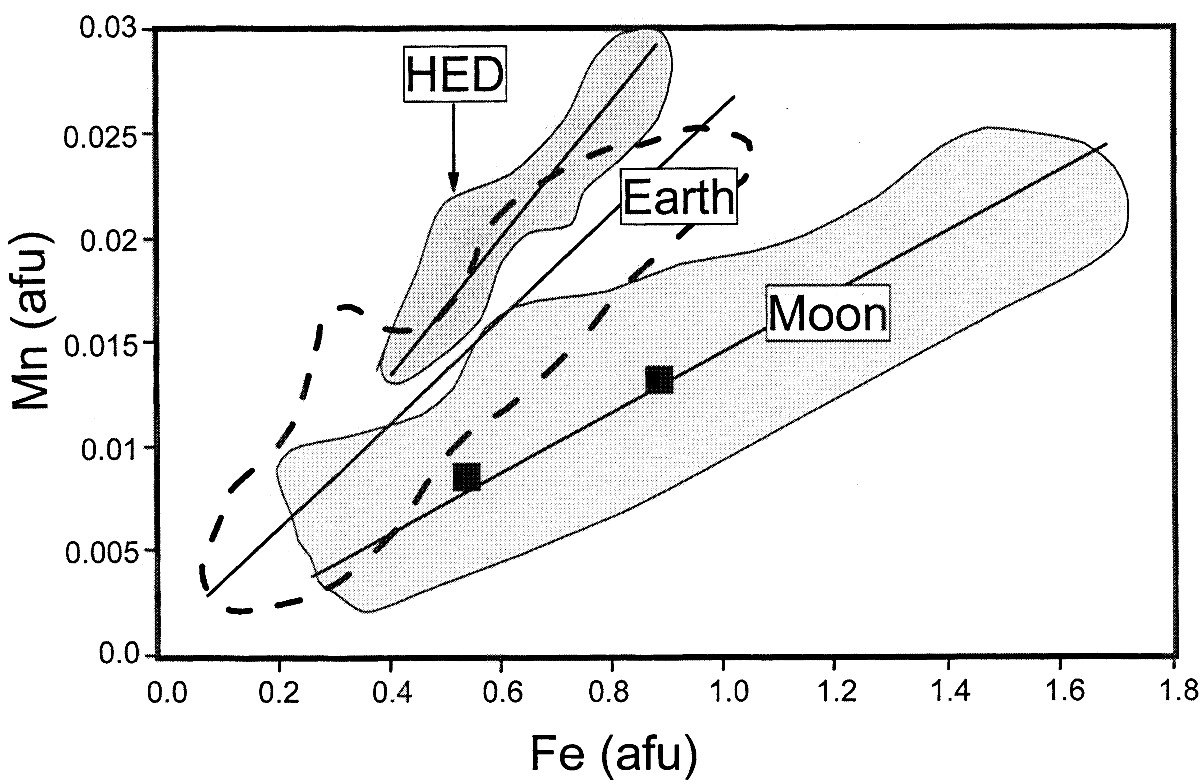

FIG. 3. Fe/Mn in pyroxenes of the Putorana rock compared to other planetary bodies. Axes are atoms of Mn and Fe per four-cation atomic formula unit of pyroxene. Diagram after Papike *et al.* (2001) from data of BVSP (1981). Light gray field is for lunar pyroxenes; dark gray for asteroidal basaltic rocks of howardite–eucrite–diogenite (HED) association and mesosiderites; uncolored field surrounded by dashed line is for terrestrial pyroxenes. Solid lines through each field are best-fit regression lines from Papike *et al.* (2001). Solid squares mark average pyroxenes of the Putorana rock (pigeonite and augite), which graph with lunar pyroxenes and are distinct from terrestrial and HED pyroxenes.

(NWA) 011 eucrite have Fe/Mn ≈ 65, with some analyses as high as 70 (Afanasiev *et al.*, 2000; Yamaguchi, 2001). Similarly, the pyroxenes in the Ibitira eucrite are reported to have high but variable Fe/Mn, ranging from the common eucrite value (~35; Wilkening and Anders, 1975), up to those of NWA 011 (Yamaguchi, 2001). Like these two eucrites, the Putorana rock is highly metamorphosed, and it is possible that a minor metamorphic Mn mineral has drained Mn from their pyroxenes. It is also possible that oxygen fugacity variations affect the distribution of Fe and Mn (Delaney and Dyar, 2002), although reduction of iron in the Putorana rock should lead to low Fe/Mn, not high as is observed. More work is needed to clarify these variations in Fe/Mn ratio.

Metallic Minerals–Even though metallic minerals are rare in Earth basalts, those in the Putorana rock match the terrestrial examples far better than those in extraterrestrial samples. Iron metal in Putorana has far less Ni than any known mesosiderite or iron meteorite (Mittlefehldt *et al.*, 1998), although it is comparable to the some iron metal grains in eucrite and lunar basalts (Papike *et al.*, 1991, 1998). Iron metal is extremely uncommon in terrestrial basalts, but (when present) has low-Ni compositions like those of the Putorana rock, see Table 2 (Bazhenov *et al.*, 1959; Goodrich and Bird, 1985; Klöck *et al.*, 1986; Ryabov and Anoshin, 1999). Cohenite is common in the Putorana rock as rinds around the Fe-metal, while cohenite is not indigenous to mesosiderites, eucrites, martian basalts, and lunar basalt (Papike *et al.*, 1991; Rubin, 1997). However, cohenite is present in terrestrial iron-bearing basaltic rocks as rinds around its iron metal (Bazhenov *et al.*, 1959; Goodrich and Bird, 1985; Ryabov and Anoshin, 1999). The Putorana rock also contains copper metal, which is not reported from achondrites or lunar rocks, and occurs only sparingly in chondrite and iron meteorites (Papike *et al.*, 1991; Rubin, 1997). However, native copper metal occurs on the Earth and is moderately common in the iron-bearing basalts of the Putorana area (Bazhenov *et al.*, 1959; Ryabov and Anoshin, 1999).

CONCLUSION

Although the Putorana rock bears a strong resemblance to the mesosiderite meteorites, it is clearly a terrestrial rock (Table 4). Meteorite researcher, curators, dealers, and collectors should be aware that material like the Putorana rock is available from Russia, and has been submitted as potential meteorites at least twice in recent years. On hand-sample examination of such a rock, the presence of copper metal should be a warning that the rock is not a mesosiderite. However, masses of copper metal are rare in the Putorana rock, and commonly are not visible. On polished surfaces, microscopic inclusions of copper metal in the iron metal (kamacite) suggest that the rock is not a mesosiderite, as does the absence of a Ni-rich metal phase (taenite). However, iron-bearing basalts from the Noril'sk district do contain Ni-rich kamacite and also taenite (Ryabov and Anoshin, 1999). Cohenite that surrounds the iron metal is hard and brittle like taenite, but will not react to dimethylglyoxime. In more detailed analyses, the tests of Table 4 and others can be applied.

On the other hand, material like the Putorana rock may yet be of value to meteorite studies. Its structural similarities to mesosiderites may suggest similar processes of formation, and so provide useful insights into the controversial origins of the mesosiderites (*e.g.*, Mittlefehldt *et al.*, 1998; Scott *et al.*, 2001).

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