

## Mineralogy, Trace Element Composition, and Classification of Onello High-Ni Ataxite

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**Abstract**—The trace element composition of the Onello meteorite is analyzed in detail using SEM and LA-ICP-MS. The following Ni contents of minerals are determined (wt %): 23.0–25.4 in taenite, 5.8–8.8 in kamacite, 22–26 in schreibersite, 44–52 in nickelposphide, 20.6–21.8 in allabogdanite, and 75–81 in awaruite. In the trace element content, the Onello meteorite corresponds to the IAB group of iron meteorites. Inside this group, it mostly matches the sHH subgroup (with high Au and Ni contents). The presence of allabogdanite in the meteorite indicates the high *PT* parameters of its formation: >8 GPa and 1000–1400°C. Thus, the formation of the Onello meteorite is related to impact metamorphism of a parental body of iron meteorites of the IAB group and vinonaites, in which a P- and Ni-rich area underwent melting and further crystallization.

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It is likely that almost all iron meteorites formed as a result of fast differentiation of primitive planetesimals at an early stage of evolution of the solar system before the formation of the main mass of chondrite bodies [1]. The fractionation processes were complicated by impact events, mixing with silicate bodies, and remelting. In accordance with these features, the iron meteorites were divided into groups that correspond to a single parental body or similar ones. A large group of meteorites, however, remains unclassified due to insufficient characteristics or the absence of analogs. The identification of an individual group of iron meteorites requires at least five similar members according to the current classification [2, 3].

The high-Ni Onello ataxite is one of the unique iron meteorites previously described by Kopylova et al. [4, 5], who first described the trace element composition and mineralogy of the meteorite. Its primary minerals include taenite, kamacite, schreibersite, barringerite (FeNi)<sub>2</sub>P, nickelposphide, troilite, and Ni sulfide. The structure of phosphide (FeNi)<sub>2</sub>P was deciphered later [6]: this mineral was found to be a

high-pressure modification of barringerite and was named allabogdanite. In this work, we provide a detailed analysis of the trace element composition of the Onello meteorite and reach a conclusion on its relationship to anomalous members of the IAB group.

We studied several polished plates of the meteorite 0.5–2.0 cm in size. The microstructure and composition of minerals were studied on a Tescan MYRA 3 LMU SEM equipped with an ED X-Max-80 (Oxford Instruments) at the Institute of Geology and Mineralogy, Siberian Branch, Russian Academy of Sciences (IGM SB RAS, Novosibirsk) at 20 kV and 1.5 nA. The trace element composition was analyzed using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) on a Thermo Scientific Element XR mass spectrometer at the University of Tokyo (Japan). The standards for most siderophile elements included alloy Ni-5 and metal of a homogenous sample of the Campo del Cielo meteorite [7]. The radiation intensity of the Nd-YAG laser was 80 μJ/cm<sup>2</sup>. The beam diameter was 100 μm. The analysis time was 3 min including 60 s of background measurements, 60 s for signal acquisition from the sample, and 60 s for signal reduction to background values. Standards were analyzed prior to and after measurements of the meteorite samples. We also used data of instrumental neutron activation analysis (INAA) conducted during initial classification of the Onello meteorite at the Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences (Moscow, analyst G.M. Kolesov).

The detailed mineralogical analysis revealed the presence of major minerals similar to [4–6] except for

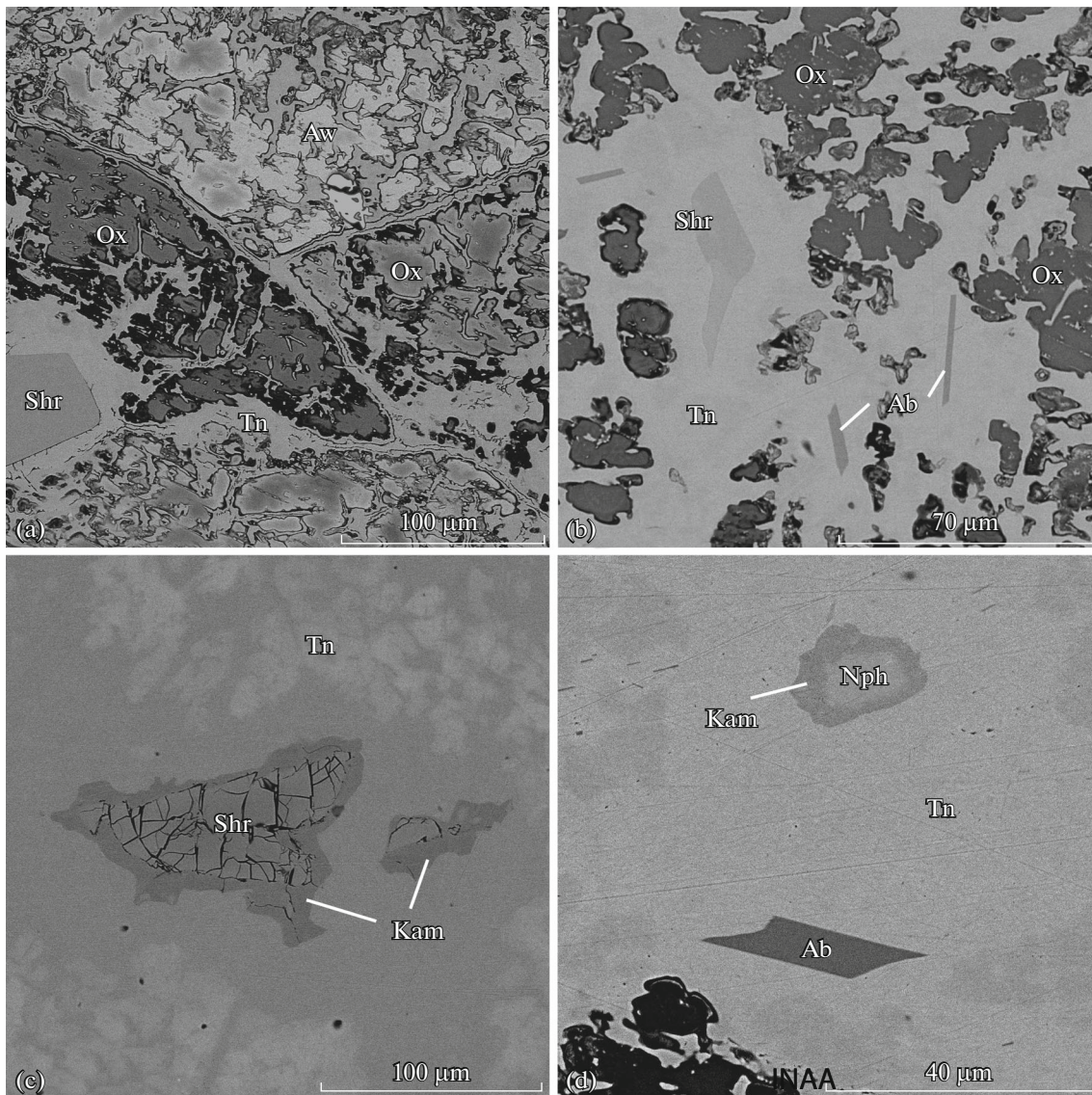
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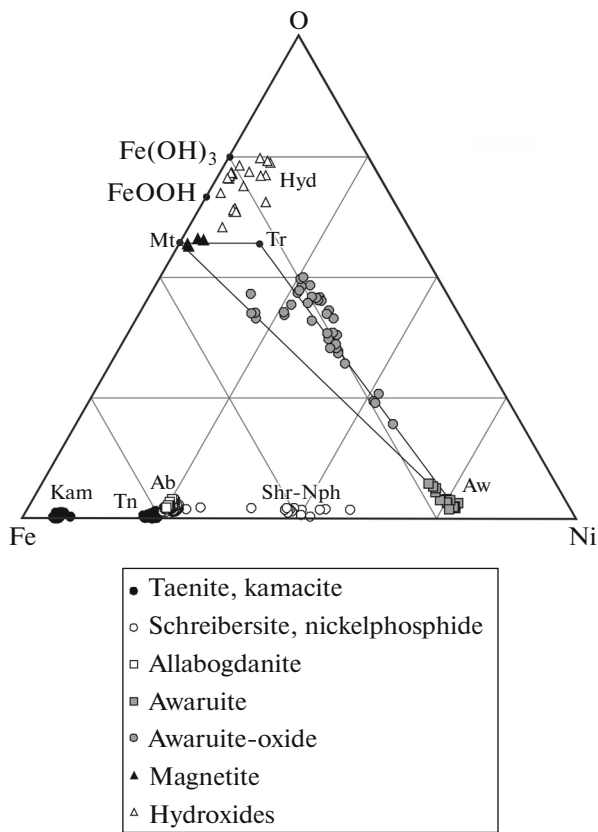


**Fig. 1.** BSE images of the Onello meteorite: (a) awaruite (Aw) and products of its oxidation (Ox); (b) allabogdanite (Ab) and schreibersite (Shr) in a taenite (Tn) matrix; (c) kamacite (Kam) rim around fractured schreibersite grain in the taenite matrix (light and dark areas of taenite are similar in composition); (d) the same around a small nickelphosphide (Nph) grain close to allabogdanite.

a P-bearing sulfide. We also characterized awaruite (Fig. 1a) and pentlandite. The fragments of the Onello meteorite contain zones of unaltered taenite with inclusions of tabular crystals of schreibersite, nickelphosphide, and rare allabogdanite (Figs. 1b, 1e), as well as areas of cloudy aggregates of awaruite and related zones of secondary alteration (Fig. 1a). The taenite matrix hosts grains of schreibersite and nickelphosphide with a kamacite rim (Figs. 1c, 1d). Large schreibersite grains up to 3 mm are associated with rare troilite and pentlandite grains.

The compositions of minerals are shown in Fig. 2. The following Ni contents are determined (wt %): 23.0–25.4 in taenite, 5.8–8.8 in kamacite, 22–26

(28–36 in single analyses) in schreibersite, 44–52 in nickelphosphide, and 20.6–21.8 in allabogdanite. The nonstoichiometric awaruite contains 75–81 wt % Ni, corresponding to formula  $\text{Ni}_{3.0-4.1}\text{Fe}$ , as well as 1.0–2.5 wt % O. Its alteration products are characterized by an unusual composition with an oxygen deficit and form variation trends toward trevorite (Fig. 2). No heterogeneous structure of individual areas of alteration zones of awaruite has been revealed under an electron microscope even at maximum magnification. These zones, most likely, contain nanosized inclusions of oxides, because no intermediate compounds have been found between metallic and oxide components in phase correlations of the Fe–Ni–O system (e.g., [8]).



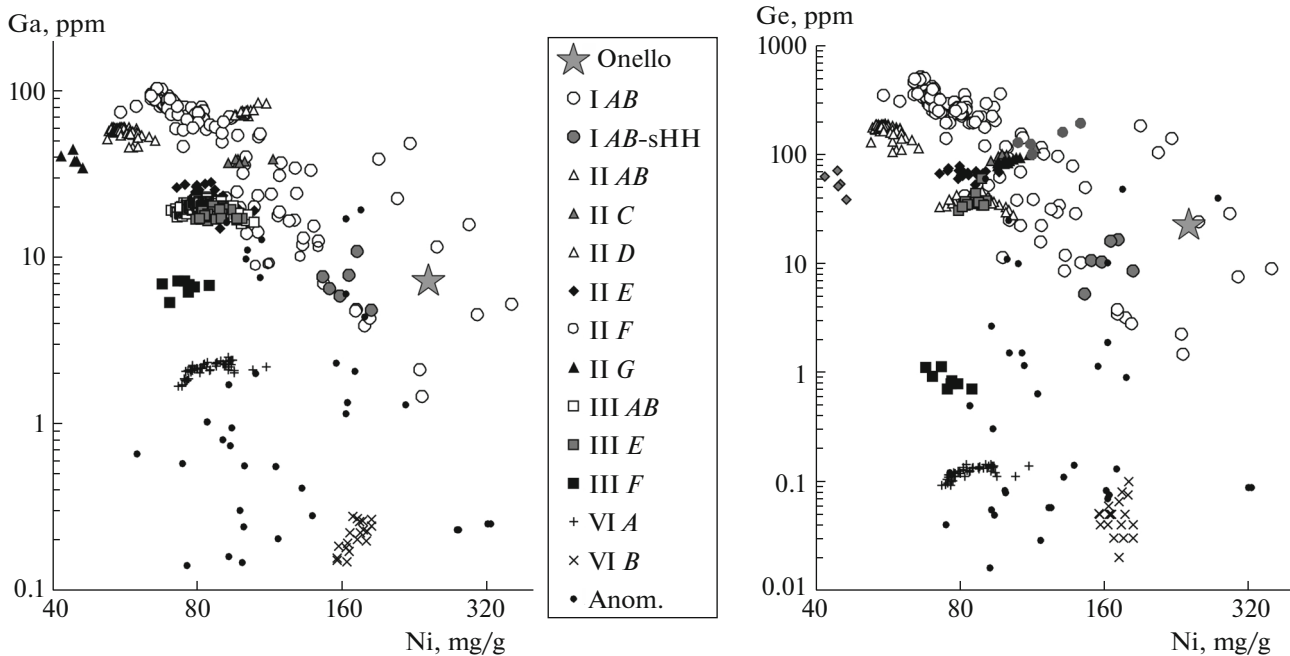
**Fig. 2.** Fe–Ni–O diagram for minerals of the Onello meteorite. The triangle shows the compositional field of awaruite (Aw)–magnetite (Mt)–trevorite (Tr) with a similar anomalous composition of awaruite–oxide.

Nonetheless, an accurate answer on the origin of the intermediate compounds between awaruite and trevorite/magnetite remains open.

The mean trace element composition of taenite is shown in Table 1. The LA-ICP-MS and INAA data are comparable for most elements excluding Ga (7.2 and 1.3 ppm), as well as As, Ru, and Au. The composition of awaruite, in general, is similar to that of taenite, whereas the contents of most trace elements of schreibersite are significantly lower (Table 1).

New data allow us to classify in detail the Onello meteorite. According to the contents of most elements, it corresponds to anomalous members of the IAB group (Fig. 3). Inside this group, the meteorite is most similar to those of subgroup sHH (with high Au and Ni contents) (Fig. 4) excluding the significantly higher Ni contents [3] of our meteorite and the absence of similar mineralogical features (e.g., the presence of  $(\text{Fe}, \text{Ni})_2\text{P}$ ) of sHH meteorites.

The presence of allabogdanite in the composition of the Onello meteorite ambiguously indicates high *PT* formation conditions. According to static experiments in a diamond cell,  $\text{Fe}_2\text{P}$  with the structure of allabogdanite crystallizes at >8 GPa and 1000–1400°C [9]. Its crystallization is also possible at a high P content (>13–15 wt %) of the system, which approximately corresponds to the composition of the peritectic  $\text{Fe}_3\text{P} = \text{Fe}_2\text{P} + \text{melt}$  at 0.1 MPa and 23 GPa [10, 11]. This process is possible, for example, under impact transformation of areas of a parental body enriched in or composed of schreibersite.

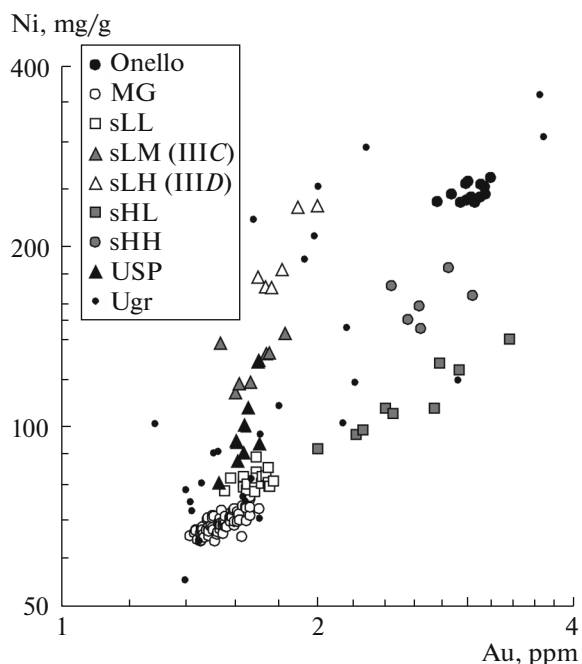


**Fig. 3.** Classification diagrams with the Ni, Ga, and Ge ratios in various groups of iron meteorites (sources from [2] and Meteorite bulletin database (<http://www.lpi.usra.edu/meteor/>)). Subgroup IAB-sHH is highlighted. Anom., anomalous meteorites.

**Table 1.** Trace element composition of minerals of the Onelle meteorite

Mineral no.	Taenite 14	$\sigma$	INAA 1	Awaruite 2	Schreibersite 2
P	1573	330		1123	153504
Cr	0.32	0.12		4.01	0.35
Mn	0.22	0.05		0.09	7.25
Co	6780	85	6550	4273	1550
Ni	24.12	0.09	21.70	76.05	23.22
Cu	1075	99		1487	1285
Ga	7.21	1.00	1.30	12.87	1.95
Ge	22.19	2.19		39.59	5.53
As	30.42	2.17	66.40	25.90	4.21
Mo	10.50	1.15		15.30	19.46
Ru	2.71	0.21	0.92	3.97	2.62
Rh	0.90	0.06		1.12	0.59
Pd	17.25	0.91		18.03	10.71
Sn	0.75	0.11		1.10	0.12
Sb	1.36	0.18	1.64	0.95	0.12
W	0.24	0.03	0.03	0.52	0.25
Re	0.05	0.01		0.12	0.03
Os	0.46	0.05	1.10	1.30	0.45
Ir	0.58	0.07	0.60	1.06	0.95
Pt	3.07	0.31	3.78	3.86	1.14
Au	3.03	0.14	4.45	2.78	0.93

Ni, wt %; other elements, ppm (mg/kg); no., number of analyses;  $\sigma$ , standard deviation (for taenite); INAA, data of instrumental neutron activation analysis (other data, LA-ICP-MS analysis).



**Fig. 4.** Au vs. Ni contents in subgroups of IAB iron meteorites. Symbols of subgroups are after [3]. USP, subgroups Udei Station and Pitts; Ugr, ungrouped IAB meteorites.

Thus, the formation of the Onello meteorite is probably related to secondary impact metamorphism of a parental body of iron meteorites of the IAB group and vinonaites (or a body of similar composition), in which a P- and Ni-rich area underwent impact melting and further crystallization. This leads to the formation of the unique assemblage of the Onello meteorite with high-grade (allabogdanite) and high-Ni (awaruite) phases.

#### FUNDING

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