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New Finds of Native Metals in a Lunar Regolith from the Crises Sea

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The first native metal minerals identified in a lunar regolith delivered by the *Luna-24* automatic interplanetary station were iron, nickel, copper, and kamacite (α-FeNi) [1]. Subsequently, we identified native molybdenum along with intermetallic compounds of Fe and Sn [2], as well as Fe, Cr, and Ni, in this sample [3]. The present work is devoted to a description of native cerium, rhenium, and zinc, which have been identified for the first time in the regolith from the Crises Sea.

We studied the finest (<74 μm) regolith fraction. Based on optical microscopic investigation data, it is dominated by fragments of glass, plagioclase, pyroxene, olivine, and ore minerals. Specimens of the regolith sample for electron microscopic investigation were prepared using a specially elaborated procedure that permitted their significant enrichment in ore minerals [4].

The investigation was conducted on a JSM-5300 SEM (Japan) equipped with a Link ISIS energy-dispersive spectrometer (England) enabling to register elements from Be to U. The use of our collection of standards made it possible to perform semiquantitative and quantitative analyses, including the determination of oxygen.

Native cerium. A back-scattered electron image of this mineral shows a round particle ~2.5 μm in size (Fig. 1a). Due to its high brightness, this particle sharply stands out against the background of other lunar ground particles mainly composed of fragments of plagioclase, quartz, and calcite grains characterized by significantly lower average atomic numbers. In its energy-dispersive spectrum, the most intense peaks belong to Ce, while the remaining REE peaks are absent. The spectrum also contains significantly less intense peaks of Al, Si, Ca, and O. The lack of REE other than Ce in the particle composition is confirmed by the semiquantitative analysis. To elucidate the mineral nature of the phase registered, we obtained its images in the characteristic radiation of Ce (Fig. 1b), O (Fig. 1c), Al (Fig. 1d), Si (Fig. 1e), and Ca (Fig. 1f). Examination of these images has demonstrated that only Ce is incorporated into the composition of the studied particle and, which is of a special importance, the particle contains no oxygen. Therefore, it is comprised of native cerium. In this case, the Al, Si, Ca, and O peaks on the spectrum belong to anorthite associated with the native mineral that fell into the X-ray excitation zone. Native cerium has not been registered on the Earth, but a synthetic α-cerium phase is known here [5].

Native rhenium. In the studied suspension specimen, two bright isometric particles ~5 and ~9 μm in size are present in an area with widely spaced regolith particles (Fig. 2a). Energy-dispersive spectra obtained from both of these particles exhibit distinct peaks of Re and only insignificant peaks of Ca (Fig. 2b). Based on quantitative analysis data, the Ca content of the particles is ~1–2%. The direct quantitative determination yielded an oxygen content below the detection threshold. In addition, the specimen contains a group of submicron-sized particles characterized by high brightness against the background of lunar regolith particles with significantly lower average atomic numbers. Energy-dispersive spectra obtained from the bright particles mainly contain peaks of Re, as well as small peaks of Ca and Si. The data obtained made it possible to assume that the particles consist of native rhenium. To confirm this conclusion, we obtained characteristic radiation images of Re, Ca, Si, and O. They confirmed that the bright particles contain only Re and lack oxygen. These experimental data unambiguously demonstrate the native form of Re. A comparison between the distribution patterns of elements suggested that the particles associated with the native rhenium apparently represent silicon oxide and calcium carbonate ($CaCO_3$).

Native zinc. Studying the suspension specimen in back-scattered electrons revealed a bright isometric particle with dimensions on the order of 1 μm (Fig. 3a). Qualitative analysis revealed that it contained only Zn. Scanning images in the characteristic radiation of oxygen (Fig. 3b) and Zn (Fig. 3c) also confirmed the presence of Zn and the lack of oxygen in this particle. These experimental data demonstrate that the particle under consideration is comprised of native zinc.

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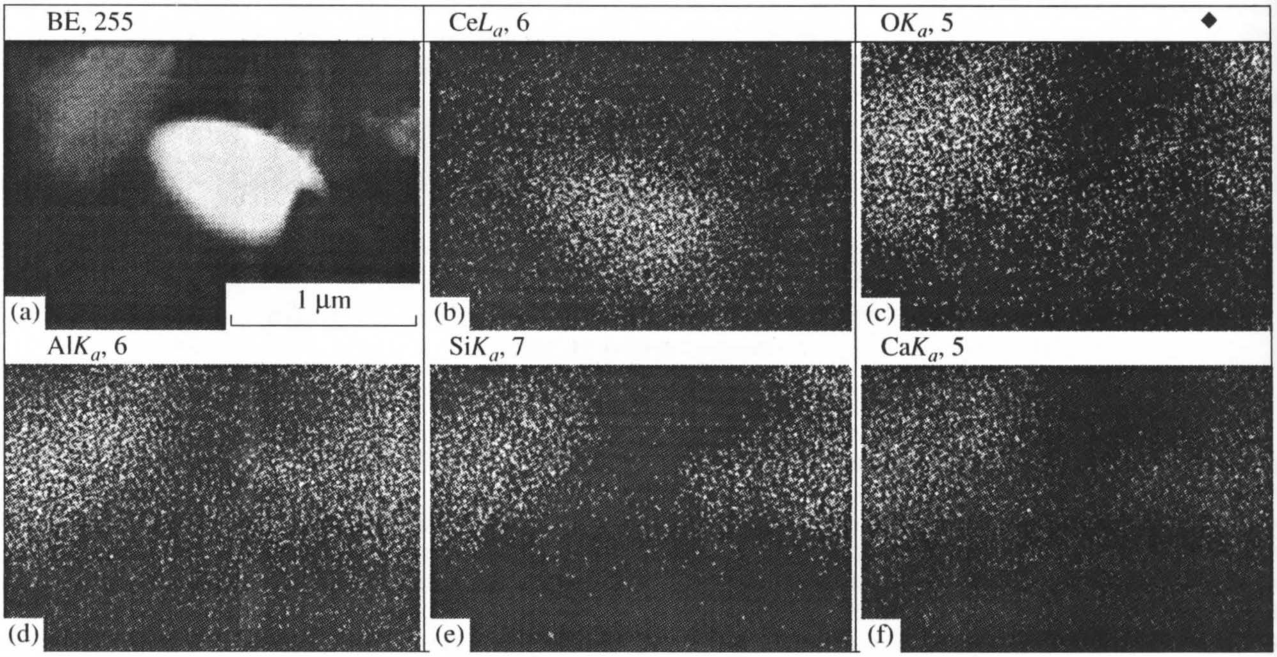

Fig. 1. Images of native cerium particles: (a) in back-scattered electrons; in characteristic radiation of (b) Ce, (c) O, (d) Al, (e) Si, and (f) Ca.

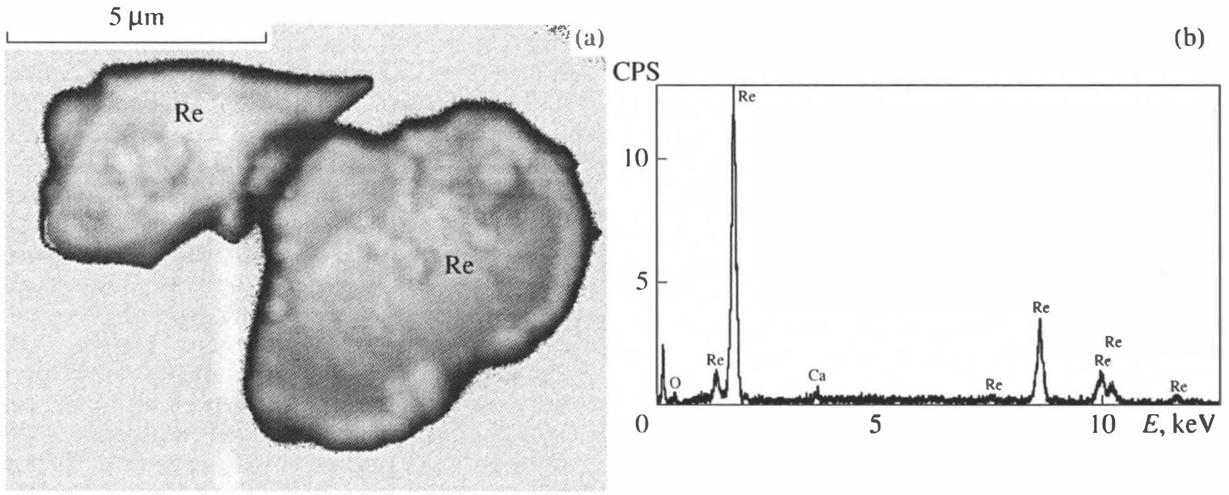

Fig. 2. (a) Back-scattered electron image of native rhenium particles and (b) energy-dispersive spectrum obtained from one of the particles.

Discussion. As far as we know, contamination with technogenic native zinc, rhenium, and cerium is practically ruled out at stages of the sampling, transportation, and storage of the lunar material. All possible precautions were also taken in the course of the analytical works. Therefore, we consider the probability of anthropogenic contamination of the sample to be insignificant and, hence, believe that the detected native minerals are not artefacts.

Native zinc is encountered comparatively rarely and in small quantities in the Earth's crust. Its first finds were made in platinum and gold placers. In the last few years, native zinc was found in hydrothermal ore veins, alkaline granites, and effusive rocks of diverse composition. In the context of the present communication, the most interesting form of native zinc is its micron-sized films found on the surface of volcanic glass fibers (Pele's hair) [6]. It forms here through the condensation of volcanic gas emanations from high-temperature and highly liquid lava. If such a mechanism of native zinc formation could be realized under conditions of the Earth's oxic atmosphere, the probability of its formation under the airless conditions of the Moon is significantly higher. The deposition and conservation of

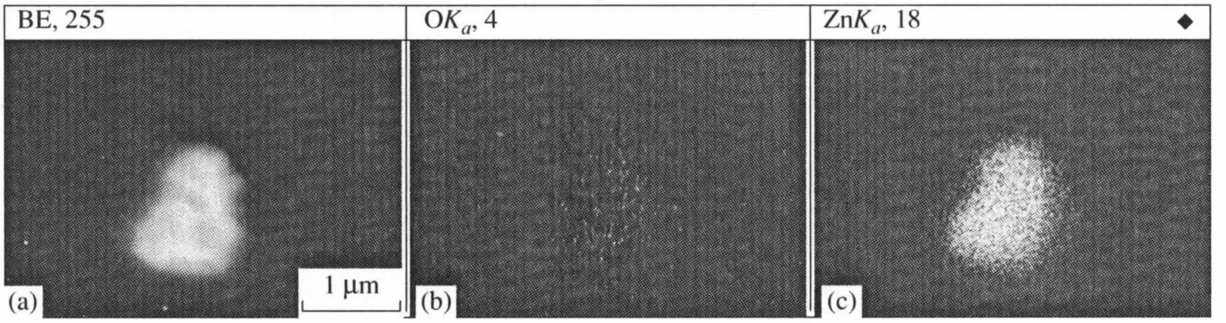

Fig. 3. Images of a native zinc particle: (a) in back-scattered electrons; in characteristic radiation of (b) O and (c) Zn.

micron-sized native zinc particles could also be facilitated by the high *PT* gradient during the transfer of exhalations from the fumarole vent to the practically open cosmic space.

Native rhenium was first discovered as micron-sized ingrowths in wolframite from the Transbaikal region [7]. The mineral from this locality was highly pure (99.9% Re). A year later, native rhenium was identified as dusty particles in Ni-bearing iron and silicates from the Allende meteorite [8]. The composition of the mineral from the meteorite was 97% Re and 3% Ru.

It seems likely that we are the first to describe native cerium. Its most remarkable feature is the lack of other REE admixtures. We have obviously encountered here the final product of strong REE fractionation. We believe that the metallic cerium could only originate in the lunar regolith owing to some poorly studied processes of the lunar substance evaporation during impact events. It is very possible that the anomalous REE fractionation on the lunar surface is also related to these events and governed by different rates of substance evaporation and condensation under practically open space conditions.

Based on the data obtained, we can suppose that native zinc owes its origin to lunar magmatism. Native rhenium represents a relict of cosmogenic meteoritic assemblages. Native cerium was already formed on the Moon surface during impact processes. Thus, the native element assemblage encountered in the studied regolith sample is substantially heterogeneous in its origin.

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