SPHERULES RECOVERED FROM THE PACIFIC OCEAN SITE OF THE CNEOS 2014-01-08 (IM1) BOLIDE.

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Introduction: On 8 January 2014 US government satellite sensors detected three atmospheric detonations in rapid succession about 84 km north of Manus Island, outside the territorial waters of Papua New Guinea (20 km). Analysis of the trajectory suggested an interstellar origin of the causative object CNEOS 2014-01-08: an arrival velocity relative to Earth more than ~45 km s^{-1}, and a vector tracked back to outside the plane of the ecliptic [1]. In 2022 the US Space Command issued a formal letter to NASA certifying a 99.999% likelihood that the object was interstellar in origin. Along with this letter, the US Government released the fireball light curve as measured by satellites, which showed three flares separated by a tenth of a second from each other. The bolide broke apart at an unusually low altitude of ~17 km. The object was substantially stronger than any of the other 272 objects in the CNEOS catalog, including the ~5%-fraction of iron meteorites from the solar system [2]. Calculations of the fireball light energy suggest that about 500 kg of material was ablated by the fireball and converted into ablation spherules with a small efficiency. The fireball path was localized to a 1 km-wide strip based on the delay in arrival time of the direct and reflected sound waves to a seismometer located on Manus Island [3].

Sampling Expedition: The expedition was mounted from Port Moresby, Papua New Guinea (PNG), to search for remnants of the bolide, labeled hereafter IM1. It utilized a 40-meter catamaran workboat, the M/V Silver Star. A 200-kg sled was used with 300 neodymium magnets mounted on both of its sides and video cameras mounted on the tow-bridle. Approximately 0.06 km^2 were sampled in the target area. The fine material collected on the neodymium magnets was extracted and brought in a wet slurry up to a laboratory set up on the bridge of the vessel for further examination. There, an initial wet-magnetic separation took place. Subsequently, both magnetic and non-magnetic separations were processed through sieves and dried. Spherules were handpicked with tweezers using a binocular zoom microscope. They ranged in size from 100 microns to 2 mm. We obtained a total of ~850 spherules by this method.

Analytical Methods: Most samples (~780) were first analyzed by microXRF with a Bruker Tornado M4 for their bulk major element composition, followed by imaging (SEM and EDS chemical mapping) and spot chemical analyses of ~80 samples with a JEOL Model JXA 8230 Electron Probe Microanalyzer (EPMA). Measurements of elemental abundances for about 60 major and trace elements were performed for 69 samples with an iCAP TQ triple quadrupole ICP-MS (ThermoFisher Scientific).

Classification of the Spherules: Cosmic spherules are sub-divided into three compositional types [4]. These are the silicate-rich spherules or S-type, the Fe-rich spherules or I-type and glassy spherules or G-types. Relatively rare spherules have been called *differentiated* as they have similarities to achondrite meteorites and have been treated as a subgroup of S-type spherules. Differentiated spherules have major-element compositions with higher Si/Mg and Al/Si ratios, and higher refractory lithophile trace element contents relative to chondritic spherules [5].

The major element compositions of 745 spherules from the IM1 site, measured by micro-XRF, are plotted in a Mg-Si-Fe ternary diagram (**Fig. 1**), since such a diagram has been shown to effectively distinguish the S-, I- and G-type groups [5]. We note that there are two distinct trends of spherule compositions in this plot. About 78 % of the spherules fall along the trend of S, G and I-type spherules. These are referred to as primitive spherules as they are thought to be related to primitive chondritic meteorites and represent materials that have not gone through planetary differentiation. The remaining 22% of the spherules have low Mg and plot close to the Si-Fe side of the diagram. The high-Si part of this group plots within the range of terrestrial igneous rocks that are shown for comparison. These spherules are thus called differentiated, meaning they are likely derived from crustal rocks of a differentiated planet. Since they are clearly different from the differentiated subgroup of S-type spherules we give them a new name *D-type* *spherules*. The primitive and differentiated spherules are divided based on their Mg/Si ratio. Primitive spherules have Mg/Si >1/3, while differentiated spherules have Mg/Si < 1/3, so this ratio is used to distinguish the two groups.

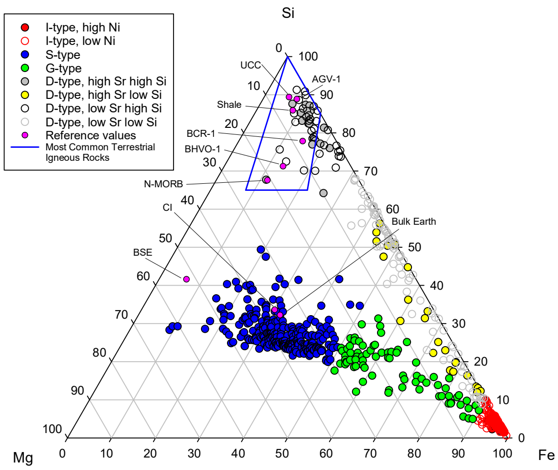

Figure 1. Atomic Mg-Si-Fe plot of micro-XRF data for 745 IM1 site spherules. The spherule groups are compared to reference values of Earth materials (Bulk Earth, bulk silicate Earth (BSE), upper continental crust (UCC), shale, normal midocean ridge basalts (N-MORB), Hawaiian basalt (BHVO-1), Columbia River basalt (BCR-1), Guano Valley andesite (AGV-1) and CI meteorites. Also shown is the range of chemical compositions of terrestrial igneous rocks.

For the primitive spherules we use 100Fe/(Fe+Si+Mg) > 90 to distinguish I-types from S- and G-types, as the I-type group is supposed to be primarily made of iron compounds. The I-group is further subdivided into high Ni (>4000 ppm) and low Ni (<4000 ppm) groups, as high Ni spherules are most likely of cosmic origin. The S- and G-type dividing line is 100Si/(Fe+Si+Mg) = 50, relatively consistent with previous literature [5-7]. The primitive spherule groups are compared to reference values of Bulk Earth, bulk silicate Earth (BSE), and CI meteorites that are as expected on the primitive trend.

The Sr content of differentiated spherules is a good indication of the enrichment of refractory lithophile elements in the spherules. The differentiated spherules are thus divided into high- (>450 ppm) and low Sr groups (<450 ppm). They are further subdivided, based on the Si-content. For high Sr spherules we use 100Si/(Fe+Si+Mg) = 60 as the dividing line and for low Sr spherules a value of 100Si/(Fe+Si+Mg) = 70.

We note that the high Si varieties of D-spherules plot close to or within the range of terrestrial igneous rocks, while the low Si groups do not. Thus, the D-type spherules have been divided into four distinct groups. This results in 8 distinct spherule groups that are all shown in **Figure 1**.

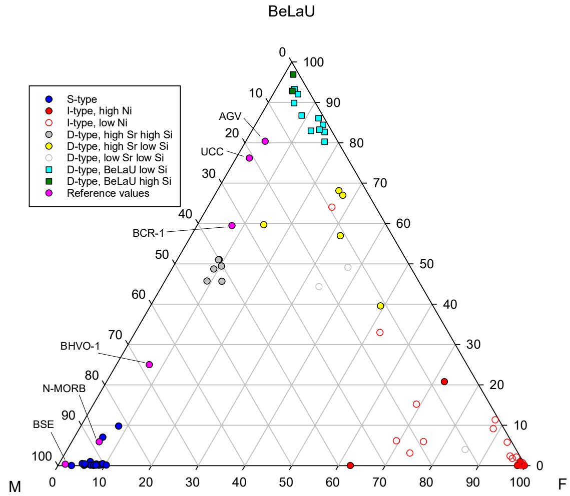

Figure 2. Ternary diagram for identifying the spherules that are most enriched in Be, La and U (BeLaU) relative to Mg (M) and Fe (F). The parameters are CI chondrite normalized.

BeLaU Spherules: We use **Fig. 2** to identify spherules with particularly high contents of refractory lithophile elements, based on the enrichments of Be, La and U relative to Mg and Fe. First the concentrations of these elements are normalized to the same elements in CI chondrites. The CI-normalized values (Be_{CI}, La_{CI}, U_{CI}, Mg_{CI} and Fe_{CI}) are used to calculate the plotting parameters for the ternary diagram in **Fig. 2.** The BeLaU parameter $(Be_{CI}+La_{CI}+U_{CI})/(Mg_{CI}+Fe_{CI}+Be_{CI}+La_{CI}+U_{CI})$ was divided by 100, while the M-parameter was multiplied by 10 to make use of the entire area inside the ternary diagram. We define a BeLaU spherule as having BeLaU > 80, with the high and low Si varieties being defined by the Al/Fe ratio. This procedure identifies 10 of D-type spherules as low Si BeLaU spherules and 2 high Si BeLaU spherules (**Fig. 2**). While these spherules clearly appear to be derived from material formed by igneous fractionation, their chemical composition differs from any known solar system material, with the KREEP component of the lunar crust being closest.

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