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Pennsylvania Geology

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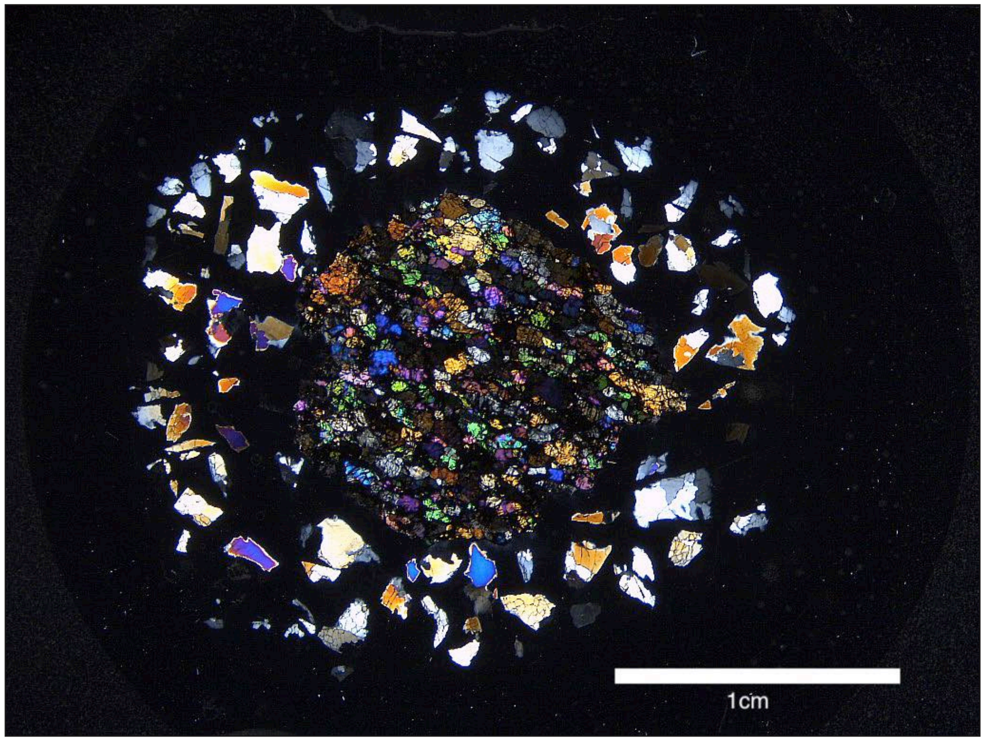


Photomicrograph with crossed Nicols of a thin section from a meteorite that was observed to smash through the window of a vehicle in Carbon County, Pa., on May 17, 2023. The large grains around the outside are mineral grains that were inserted as references to assist the preparer in grinding the thin section and are not part of the meteorite. Photomicrograph courtesy of Anthony Love, Appalachian State University. (See article on page 3.)

EDITORIAL

The Year 2024 in Review

Gale C. Blackmer, State Geologist
Pennsylvania Geological Survey

Here we are at the end of another year, with a lot of good work under our belts. Working in any large bureaucracy has its frustrations, and I want to thank the entire staff for their dedication and perseverance to "get stuff done," as Governor Shapiro likes to say. As of this writing, the bureau has released 13 publications this year—ten maps and three issues of this magazine. The maps include surficial geology, bedrock geology, compilations, and a karst-density map. We made our first foray into true 3D mapping with a digital elevation model of a "subsurface surface," the base of the Fulton coal in the Broad Top Basin. We also released our first hydrography map. It's exciting to see the staff working on new and innovative methods and products. We also made significant improvements and added much data to our two flagship digital data repositories—Pennsylvania Groundwater Information System (PaGWIS) and Exploration and Development Well Information Network (EDWIN). Our rock-sample holdings expanded also, with the incorporation of donated material and improvements to the physical plant. We gained increased recognition from all levels of government, including the Governor's office, for leadership in carbon storage, innovative geothermal energy development, and geospatial services.

There were many happenings on the "people" side in 2024. Liz Cushman joined us in a new position focused on groundwater modeling. A couple of retirements triggered internal movement. A clerical vacancy in the Petroleum and Subsurface Geology Section was reclassified to Management Technician to better reflect the technical nature of the work that person does with EDWIN. Callie Merz moved into that position; we are currently working on reclassifying the clerical vacancy she left. We created a new supervisor position from a vacancy in the Geologic and Geographic Information Services Division (GGIS). Ellen Fehrs moved up into that position. Hailey Filippelli will move from the Mapping Division into the vacancy Ellen left in GGIS, and I hope we'll soon be advertising for a new geologic mapper. Sadly for us, both of our administrative staff members, Emily Parkovic and Ashley Edwards, are moving on to other agencies before the end of the year. I thank them for leaving us in better shape than they found us. We will miss them and wish them well. On a people-related front, we have really strengthened the bureau's presence in secondary schools, colleges, and professional events. The increased visibility is good for us, for other state surveys, and for the discipline of geosciences as a whole. Outreach is coordinated by Stacey Daniels, but it is truly a bureau-wide effort. It is gratifying to see the staff so engaged in raising the profile of our profession.

This is just a taste of the work we were able to accomplish in 2024. We look forward to new challenges and advances in 2025.

Gale C. Blackmer

The “Ice Cream Drop”[1] Meteorite

Robert C. Smith, II, and John H. Barnes
Pennsylvania Geological Survey, retired

James T. Herbstritt
Pennsylvania Historical and Museum Commission

THE FALL

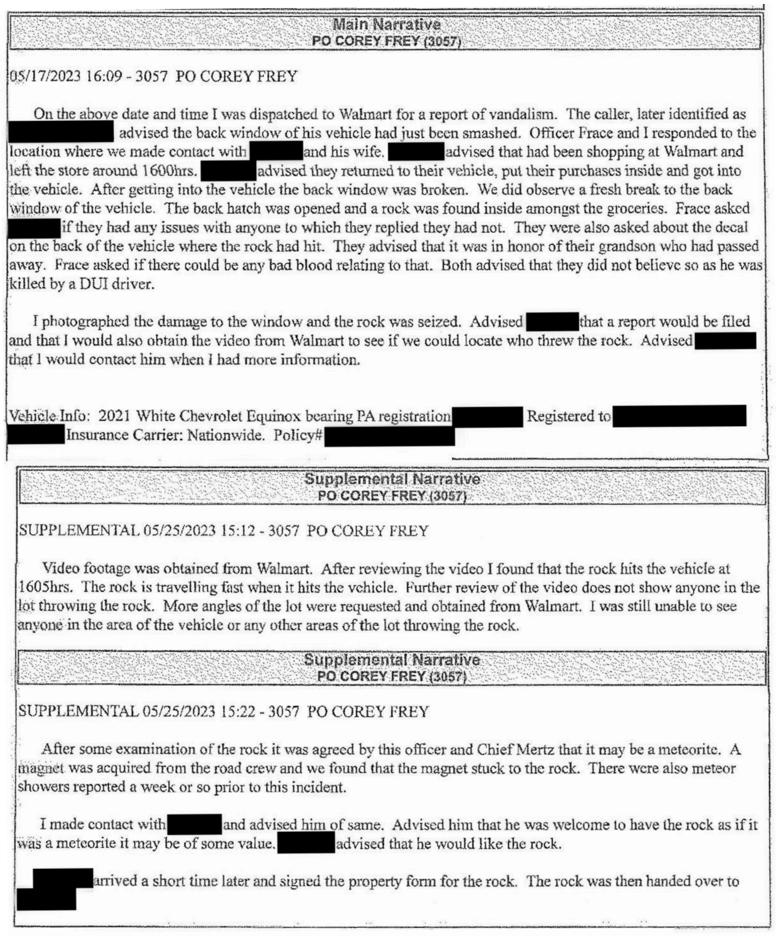
On May 17, 2023, at approximately 4:05 p.m. Eastern Daylight Time, a rock smashed through the rear window of a parked vehicle in Carbon County, Pa., landing in a 1.5-quart (1.41-liter) container of Breyers Natural Vanilla Ice Cream. As it smashed through the window, it passed through a decal that had been placed on the outside of the rear window in memory of a grandson who had been killed by a drunk driver, the safety glass of the window itself, and a tinted film on the inside of the window (Figure 1). The local police were called at 4:09 p.m. to investigate the broken window. The rock in question was retained for a period by the police as evidence of possible vandalism, although security cameras that are constantly trained on the parking lot showed no sign of a perpetrator who might have thrown the rock. The only odd thing in the security footage was a SW-to-NE smoky trail in the sky. The police filed a report (Figure 2) giving specific information that they gathered while investigating the fall. Unfortunately, a later sweep of the parking lot failed to recover any additional fragments.

After the police released the rock, the vehicle owner, anticipating that it might be a meteorite, contacted several prominent institutions. The only one that showed any interest in examining it was the Pennsylvania Historical and Museum Commission (PHMC), which operates the State Museum of Pennsylvania. At that point, the third author contacted the other two authors, friends who had previously analyzed artifacts for the PHMC and are retired staff members of the Pennsylvania Bureau of Geological Survey who now serve there as DCNR Conservation Volunteers.

The Pennsylvania Geological Survey has a long history of engaging in cooperative work with the PHMC, and it has experience describing meteorites that were found in Pennsylvania. Both of these aspects of the Survey’s history are exemplified by the publication *Meteorites Found in Pennsylvania*, a compilation

Figure 1. Photograph showing the hole that was punched through the rear window of a vehicle when the meteorite landed. After passing through the window, it landed in a just-purchased 1.5-quart container of ice cream.

[1]“Ice Cream Drop” (ICD) is an unofficial name that we are applying to this object pending further study by meteorite specialists.



Main Narrative
PO COREY FREY (3057)

05/17/2023 16:09 - 3057 PO COREY FREY

On the above date and time I was dispatched to Walmart for a report of vandalism. The caller, later identified as [redacted] advised the back window of his vehicle had just been smashed. Officer Frace and I responded to the location where we made contact with [redacted] and his wife. [redacted] advised that had been shopping at Walmart and left the store around 1600hrs. [redacted] advised they returned to their vehicle, put their purchases inside and got into the vehicle. After getting into the vehicle the back window was broken. We did observe a fresh break to the back window of the vehicle. The back hatch was opened and a rock was found inside amongst the groceries. Frace asked [redacted] if they had any issues with anyone to which they replied they had not. They were also asked about the decal on the back of the vehicle where the rock had hit. They advised that it was in honor of their grandson who had passed away. Frace asked if there could be any bad blood relating to that. Both advised that they did not believe so as he was killed by a DUI driver.

I photographed the damage to the window and the rock was seized. Advised [redacted] that a report would be filed and that I would also obtain the video from Walmart to see if we could locate who threw the rock. Advised [redacted] that I would contact him when I had more information.

Vehicle Info: 2021 White Chevrolet Equinox bearing PA registration [redacted] Registered to [redacted] Insurance Carrier: Nationwide. Policy# [redacted]

Supplemental Narrative
PO COREY FREY (3057)

SUPPLEMENTAL 05/25/2023 15:12 - 3057 PO COREY FREY

Video footage was obtained from Walmart. After reviewing the video I found that the rock hits the vehicle at 1605hrs. The rock is travelling fast when it hits the vehicle. Further review of the video does not show anyone in the lot throwing the rock. More angles of the lot were requested and obtained from Walmart. I was still unable to see anyone in the area of the vehicle or any other areas of the lot throwing the rock.

Supplemental Narrative
PO COREY FREY (3057)

SUPPLEMENTAL 05/25/2023 15:22 - 3057 PO COREY FREY

After some examination of the rock it was agreed by this officer and Chief Mertz that it may be a meteorite. A magnet was acquired from the road crew and we found that the magnet stuck to the rock. There were also meteor showers reported a week or so prior to this incident.

I made contact with [redacted] and advised him of same. Advised him that he was welcome to have the rock as if it was a meteorite it may be of some value. [redacted] advised that he would like the rock.

[redacted] arrived a short time later and signed the property form for the rock. The rock was then handed over to [redacted]

Figure 2. Portions of the police report describing the event when the meteorite smashed through the vehicle window. Personal information has been redacted.

created in the 1930s by the appropriately named coauthors Ralph W. Stone of the Pennsylvania Geological Survey and Eileen M. Starr of the Pennsylvania State Museum (Stone and Starr, 1932, revised 1967) (see photographs on pages 30 and 31). The topic was revisited in 2013 by former bureau staff geologist Mark A. Brown, who wrote a lengthy article for *Pennsylvania Geology* describing in some detail the eight meteorites that were known to have been verified in Pennsylvania as of that date and providing clues on how to distinguish a meteorite from a terrestrial rock or a human artifact such as slag (Brown, 2013). In that article, no mention was made that an excellent clue that a rock might be a meteorite is if it falls from the sky and smashes through your car window with a gunshot-like sound.

The three authors agreed to study the rock with the facilities that we have available, and with some outside help, to verify that it is, indeed, a meteorite and to describe it as thoroughly as possible. Over many years, scores of samples have been submitted to the bureau for examination and proclaimed by the staff to be “meteorwrongs.” The senior author himself collected small grains from the bottom of the sump for the filter pump on his swimming pool; therefore, he alone can be credited with a few of the micrometeorwrongs that have been examined. His samples typically turned out to be sand-sized fused anthracite coal ash or fragments of ceramic-coated Catoctin Metabasalt roofing granules. Most other meteorwrongs that have come to the bureau were slag, various alloys used in making specialty steel, and iron ores. However, after our careful examination, the present authors are claiming that the specimen that was retrieved in Carbon County is definitely a small meteorite, which we here informally refer to as the Ice Cream Drop (ICD) because it dropped into a container of ice cream.

THE INITIAL EXAMINATION

The first step was an initial examination of the specimen. Figures 3A and 3B show the as-received meteorite with the atmospheric entry leading side down and a surface that was broken in flight. The latter reveals apparent olivine crystals with a hint that some are subhedral and have a preferred orientation. Metallic glitter from the decal on the car window apparently contributed microscopic bits of metals adhering to the rock. The leading side of the rock still retains traces of adhesive from the decal and/or the window-tint film.

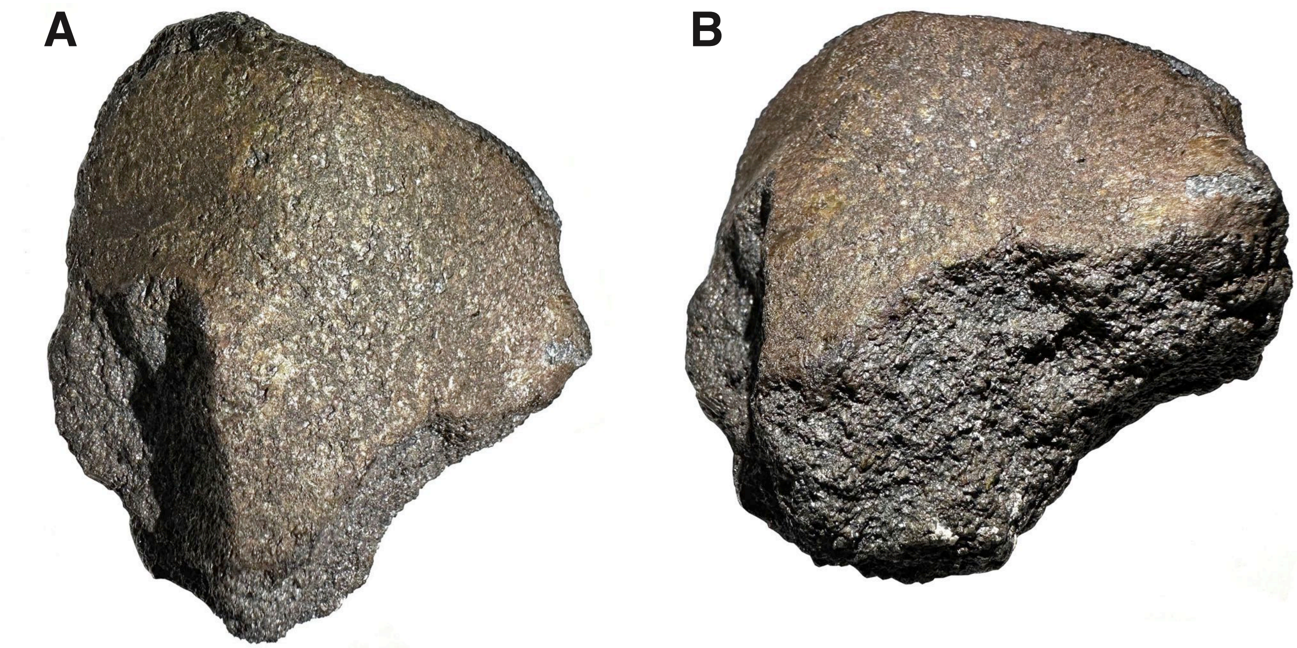


Figure 3. A. Photograph of the specimen with the leading side facing down. B. Photograph of the specimen showing an exposed surface that was broken in flight, revealing apparent olivine crystals, some of which appear to be subhedral, meaning that they show some characteristic crystal faces for olivine. The specimen is approximately 1.5 by 2.5 inches.

Because the surface of the specimen was contaminated by the materials that it encountered on its final impact, as well as from handling and storage as evidence at the police station, the first day's geochemical analysis of the exterior was largely a wasted effort, but good scanning electron microscope (SEM) images of the primary fusion crust were obtained, showing that one side of the sample lacks mineral grains and appears to be a glassy crust, which is consistent with thermal melting (fusion) as would be the case if the ICD was rapidly heated while plunging into Earth's atmosphere. Figure 4 is a magnified image of the exterior of the primary glassy crust. With the owner's permission, a small piece was removed via thin-blade diamond sawing for study of the pristine interior. The density of the small piece having primary fusion crust on one side was determined to be 3.13 grams/cubic centimeter. The sawn surface of the main mass has a color of N4 or medium dark

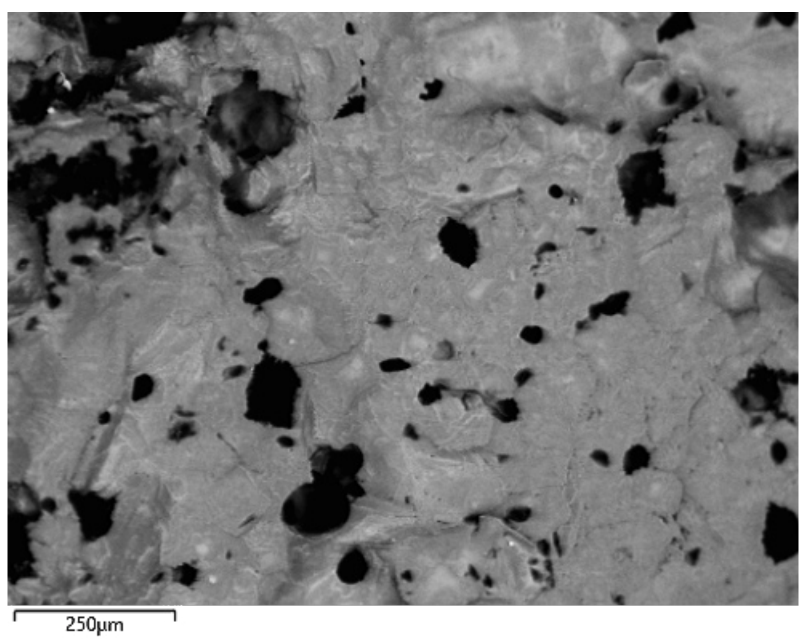


Figure 4. SEM backscatter image of the outer crust of the meteorite. The light uneven surface is an apparent silicate glass formed by melting during entry into Earth's atmosphere. The dark areas are bubbles (vesicles) that developed as volatile materials were driven off by the intense frictional heat.

gray on a Munsell Rock Color Chart, the outer surface of the primary fusion crust is 5Y/R 2/1 or brownish black, and the secondary fusion crust is 5Y 2/1 or olive black.

The small piece being studied was donated by the owner of the main mass to the PHMC in memory of his deceased grandson. At this point, the specimen was believed to be a type of meteorite known as a primitive achondrite, partly based on the lack of chondrules large enough to be visible with a 10x hand lens. (Chondrules are spherical grains that are found in many common types of meteorites.)

MINERALOGY AND CHEMISTRY

The second long day was spent examining the specimen's interior, which was revealed on the sawn surface of the small donated piece. The surface was lapped smooth using a bonded –1000 mesh diamond lap. A small amount of silt recovered from that lapping was studied using Rietveld X-ray powder diffraction, which would reveal what minerals are present. That study suggested that forsterite and a magnesian orthopyroxene were the major minerals and that graphite was a minor component. (The forsterite was later shown to have a d_{130} spacing of 2.771Å, suggesting an approximately 92.4 ± 3 mol percent forsterite end member.) Polishing down to 1 and then ¼ micron diamond was avoided to reduce what is sometimes called polishing smear from one mineral to an adjacent mineral. Unfortunately, intrinsic graphite caused some smearing anyway.

The second day's analyses of the sample's smoothed surface suggested that it has a pristine, vesicular (bubbly), glassy, primary fusion crust on one side (Figure 5), which might have caused the density reported above to be very slightly low. Table 1 presents analyses of the outer primary crust and cross section. As seen in Figure 5, the glassy material in the primary crust is hardly homogeneous and is complexly intergrown. In fact, some point analyses taken within the cross section of the crust tended to resemble those of the minerals pyroxene and olivine, suggesting that the material that melted as it plunged through Earth's atmosphere did not have enough time and/or a high enough temperature to homogenize before being ablated and quenched. Despite that, we consider the possibility that the slightly less than 0.1- x 0.2-mm area analysis of a relatively clean area in the cross section of the two-component melted crust (intergrown glassy material) might represent an approximation of the lowest melting fraction of the bulk ICD. Converted from elements to oxides, this melt contains (approximately) the following (in weight percentages): SiO_2 50.95, TiO_2 0.12, Al_2O_3 0.77, Cr_2O_3 0.60, FeO 6.08, MnO 0.45, MgO 37.91, CaO 2.94, Na_2O 0.15, and K_2O 0.02. In Table 1, we have added a column to permit comparison of the intergrown glassy material with analyses of a more representative sampling of the interior. We shall return to those data farther on.

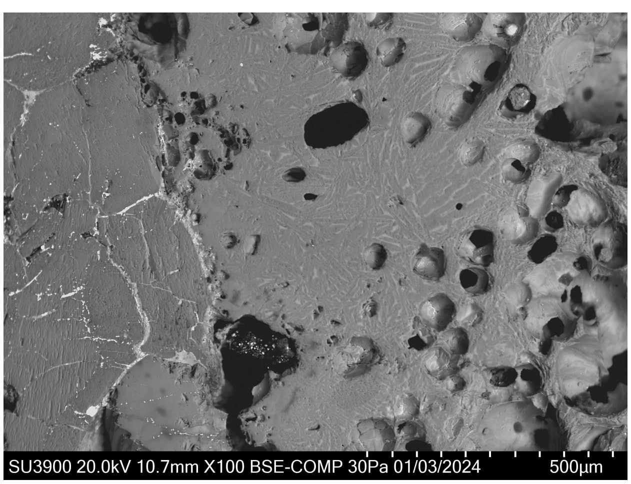


Figure 5. SEM backscatter image of the transition from vesicular (bubbly), glassy primary fusion crust to the interior of the meteorite. The brightness gives an indication of the composition, with heavy elements such as iron and nickel creating the light-gray to bright-white lines in the interior (on the left). The maze-like array of light- and dark-gray lines in the glassy material on the right is a reflection of its symplectic (related to or being an intergrowth of two different minerals) heterogeneous character.

Table 1. *SEM-EDS Analyses of the Primary Crust of the ICD*[1]
(Values in weight percent)

	Primary crust								
	Outer surface			Cross section					
				Lower Z Symplectic		Higher Z Symplectic			
Element	[2]Spectrum 29	Spectrum 30	Average of 2	Spectrum 65	Spectrum 95	Spectrum 66	Spectrum 96	Area analysis Spectrum 120	Median of 5
O	42.94	41.33	42.14	43.65	43.54	44.90	44.28	44.42	44.04
Na	.10	.06	.08	.04	.05	.14	.16	.11	.08
Mg	23.04	28.18	25.61	28.41	30.00	15.18	9.61	23.09	25.75
Al	.40	.23	.32	.19	.17	.81	.94	.41	.30
Si	24.18	23.06	23.62	22.04	21.32	25.80	25.89	24.06	23.05
P	.02	.01	.02	.01	.00	.01	.02	.02	.02
S	.00	.01	.01	.04	.03	.06	.02	.03	.04
K	.01	.01	.01	.00	.01	.01	.00	.02	.01
Ca	1.92	1.52	1.72	.94	.60	5.26	8.73	2.12	1.53
Ti	.06	.03	.05	.03	.02	.15	.22	.07	.05
Cr	.18	.22	.20	.41	.39	.56	.47	.42	.42
Mn	.40	.37	.39	.28	.25	.58	.71	.36	.32
Fe	6.65	4.78	5.72	3.92	3.51	6.47	8.87	4.77	4.35
Co	.01	.05	.03	.02	.02	.04	.06	.03	.03
Ni	.10	.14	.12	.10	.10	.04	.03	.07	.09
Total	100.01	100.00	100.01	100.08	100.01	100.01	100.01	100.00	100.04

[1] Cross section fusion crust is not homogenous.
[2] Each SEM-EDS analysis is called a "spectrum" because it records a wide spectrum of X-ray energies that yield data for multiple elements.

As noted, the two major minerals within the interior of the ICD are the olivine-group mineral forsterite and a magnesium-rich orthopyroxene. Together, they make up the matrix and, as shown in Figure 6, their typical grain size is about 1.5 x 0.8 mm, or fine to medium grained.

We made an attempt to better understand what type of meteorite this specimen might be by comparing various types of data between the ICD and other meteorites. This included obtaining multiple SEM-EDS analyses of major and minor minerals in the ICD's interior, and performing the same kinds of analyses on samples of other, previously well-characterized meteorites that we had access to.

Thirteen spot analyses of the olivine group mineral from throughout the interior of the ICD are presented in Table 2. Their median forsterite content of 93.9 mol percent Fo (compared with 92.4 mol percent determined less accurately by XRD [X-ray diffraction]) is too magnesian to be from common chondritic meteorites, also known as ordinary H, L, or LL chondritic meteorites. Instead, the olivine data are a better fit for the uncommon-to-rare primitive achondrites: ureilite, acapulcoite, lodranite, and winonaite (Weisberg and others, 2006, p. 28, table 2).

Analyses of the pyroxene group minerals are presented in Tables 3 and 4. The pyroxene analyses presented in Table 3 are interpreted to be magnesian orthopyroxene, which comprises perhaps roughly half of the sample. Pigeonite chondrules within a single, embayed, approximately 3- x 1-mm mitten-shaped augite xenocryst were found that were so oriented as to exhibit good cleavage traces within the chondrules (Figure 7). Table 4 presents analyses of pyroxenes that are believed to be two different clinopyroxene minerals, based in part on the two minerals having slightly and distinctly higher Ca and Al contents than the orthopyroxene. In the single, lapped surface of the donated piece that we worked

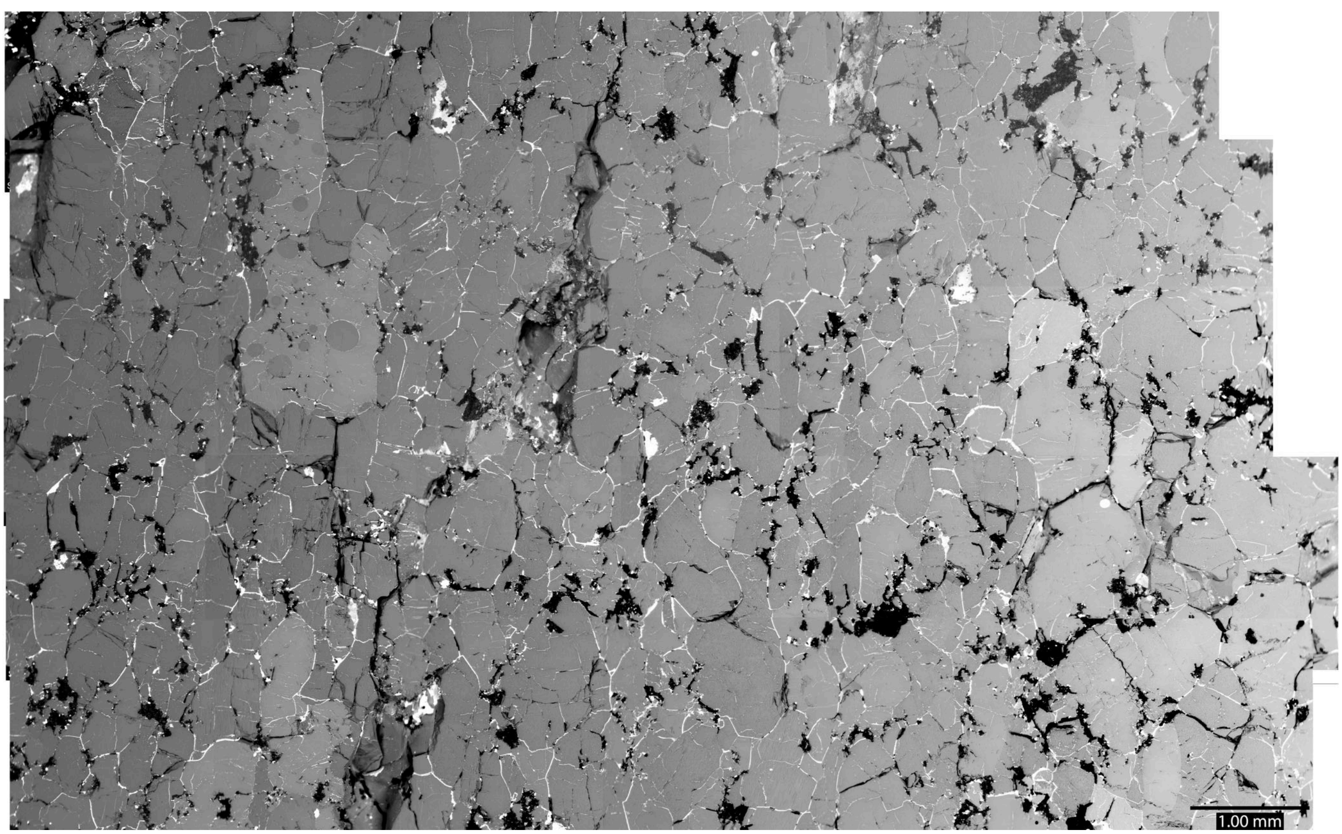


Figure 6. Mosaic of 30 SEM backscatter images covering an area approximately 10 mm wide by 7 mm high.

Table 2. *Olivine Analyses as Oxides, and End-Member Calculations*
(Values in weight percent)

Oxide	Spectrum[1]													Median[3]
	[2]97	70	207	99	208	60	205	201	203	202	206	103	108	
SiO_2	42.87	42.29	42.53	42.91	42.70	42.81	42.81	42.70	42.23	42.12	44.24	45.22	44.32	43.60
TiO_2	.05	.02	.02	.03	.03	.03	.02	.02	.02	.02	.03	.03	.02	.03
Al_2O_3	.25	.09	.11	.17	.13	.15	.09	.09	.09	.09	.13	.19	.13	.19
Cr_2O_3	.50	.50	.50	.51	.54	.50	.53	.51	.50	.53	.61	.61	.61	.56
FeO	4.75	4.80	5.13	5.25	5.36	5.57	5.65	5.67	6.06	6.36	6.37	6.59	6.82	5.78
MnO	.48	.48	.48	.50	.53	.46	.53	.52	.50	.53	.59	.58	.59	.54
MgO	50.89	53.41	53.26	52.18	52.60	53.03	53.92	53.73	53.71	53.59	53.54	53.11	54.72	52.81
NiO	.04	.04	.03	.04	.04	.00	.04	.05	.08	.05	.06	.08	.08	.06
CoO	.03	.03	.04	.04	.03	.04	.04	.03	.04	.04	.03	.04	.05	.04
ZnO	.06	.06	.05	.06	.05	.01	.07	.04	.05	.06	.06	.06	.05	.06
CaO	1.92	.39	.36	1.15	.91	.45	.36	.36	.35	.38	.49	.67	.59	1.25
Total	101.82	102.10	102.50	102.85	102.92	103.05	104.06	103.71	103.62	103.76	106.16	107.19	107.98	104.90
FeO/MnO	9.90	10.0	10.7	9.9	10.1	12.0	10.7	10.8	12.1	12.0	10.8	11.3	11.4	10.65
End-members[4]														
Percent forsterite	94.5	94.7	94.4	94.2	94.1	94.0	94.0	93.9	93.6	93.3	93.2	93.0	92.9	93.7
Percent fayalite	4.95	4.77	5.10	5.32	5.38	5.54	5.52	5.60	5.92	6.20	6.22	6.47	6.50	5.72
Percent tephroite	.50	.48	.48	.52	.54	.47	.52	.51	.50	.52	.59	.58	.57	.54

[1] Spectra columns are arranged in order of increasing FeO in weight percent. The authors are concerned that totals increase with FeO, but they have no remedy at this time.
[2] Spectrum 97 is an analysis of a unique olivine chondrule that has an apparent diameter of 115 *μ*m. The apparent host is a rare, possibly embayed, augite crystal.
[3] The median was calculated from 12 groundmass olivines plus 1 one chondrule olivine (spectrum 97).
[4] End-members were calculated from a Gabbrosoft.org (2024) spreadsheet modified to permit entry of data as elements.

Table 3. *Orthopyroxene Compositions and Mol Percent End-Members*

(Values in weight percent)

Oxide	Spectrum 78	Spectrum 69	Spectrum 104	Spectrum 109	Spectrum 63	Spectrum 111	Median N=6 Orthopyroxene
SiO_2	53.69	56.09	56.52	55.36	58.19	58.08	56.30
TiO_2	.12	.15	.13	.13	.15	.17	.14
Al_2O_3	.72	.87	.85	.85	.89	.83	.85
Cr_2O_3	.57	.67	.75	.72	.76	.82	.74
FeO	6.06	3.91	4.68	4.30	5.57	6.42	5.12
MnO	.43	.45	.49	.48	.52	.56	.48
MgO	36.30	35.75	35.98	35.52	36.50	36.30	36.14
CaO	2.18	2.45	2.56	2.55	2.67	2.94	2.55
Na_2O	.05	.11	.11	.03	.00	.00	.04
K_2O	.00	.00	.00	.01	.01	.00	.00
Total	100.12	100.45	102.07	99.94	105.25	106.11	102.36
Percent wollastonite[1]	3.8	4.4	4.5	4.6	4.6	5.0	4.6
Percent enstatite[2]	87.6	89.5	88.4	88.8	87.3	85.9	88.0
Percent ferrosilite[2]	8.6	6.1	7.1	6.6	8.1	9.1	7.6

[1] Analyses are arranged in order of increasing mol weight percent wollastonite end-member.
[2] Calculation of the pyroxene end-members (enstatite and ferrosilite) was accomplished using a spreadsheet modified from Gabbrosoft.org (2024).

Table 4. *Low and Intermediate Ca Clinopyroxene Compositions and Mol Percent End-Members*

(Values in weight percent)

Oxide	Presumed pigeonite; largest chondrule[1] Spectrum 122	Second-largest chondrule Spectrum 121	Largest chondrule Spectrum 88	Median N=3 Pigeonite	Presumed augite; host to chondrules[2] Spectrum 98	Host to chondrules Spectrum 89	Host to chondrules Spectrum 124	Median N=3 Augite
SiO_2	56.18	59.34	60.05	59.34	52.90	54.74	55.17	54.74
TiO_2	.17	.18	.18	.18	.27	.28	.32	.28
Al_2O_3	.91	.93	.91	.91	1.32	1.36	1.34	1.34
Cr_2O_3	.72	.83	.88	.83	.76	.79	.86	.79
FeO	3.31	3.85	4.31	3.85	2.62	2.29	2.60	2.60
MnO	.46	.54	.57	.54	.37	.39	.43	.39
MgO	34.26	34.76	34.72	34.72	24.92	23.60	23.21	23.60
[3]CaO	3.90	4.41	4.62	4.41	15.59	16.82	17.91	16.82
Na_2O	.11	.12	.11	.11	.34	.34	.31	.34
K_2O	.00	.00	.01	.00	.01	.00	.00	.00
Total	100.01	104.96	106.35		99.11	100.60	102.15	
Percent wollastonite	7.1	7.8	8.1	7.8	29.3	32.1	33.7	32.1
Percent enstatite[4]	87.2	85.7	84.9	85.7	65.2	62.7	60.8	62.7
Percent ferrosilite[4]	5.4	6.1	6.7	6.1	4.4	4.0	4.4	4.4
Percent aegirine	.4	.4	.3	.4	1.2	1.2	1.1	1.2

[1] Spectra 122, 121, and 88 are presumed to be pigeonite.
[2] Spectra 98, 89, and 124 are of the same embayed grain that is presumed to be augite. That grain hosted definitive silicate chondrules, including one rare forsterite.
[3] Analyses arranged in order of increasing CaO.
[4] Calculation of the pyroxene end-members (enstatite and ferrosilite) was accomplished using a spreadsheet modified from Gabbrosoft.org (2024).

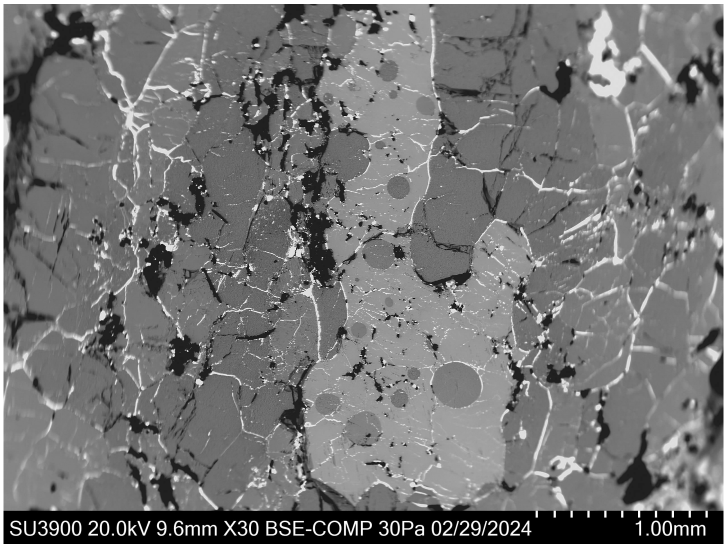


Figure 7. SEM backscatter image of pyroxene-group mineral augite hosting chondrule-like structures consisting of pigeonite and, in one instance, olivine.

on, clinopyroxenes occur as rare chondrules of pigeonite up to 284 µm (~0.3 mm) as well as the above-mentioned, more calcium-rich clinopyroxene mineral augite. The augite hosts both the pyroxene chondrules and one small, verified forsterite chondrule (Figure 7.) Additionally, a moderately high-Ca clinopyroxene such as augite was subsequently observed in thin section.

Minor minerals found by SEM-EDS analysis included an iron-nickel mineral mixture (typically containing 93 percent Fe and 5 percent Ni), which tends to form thin rims on the olivine and orthopyroxene (Table 5 and Figures 8A and 8B) The metal might be kamacite, but we did no reflected light or etching studies to confirm the mineral species. Likewise, we did not specifically look for schreibersite, $(Fe,Ni)_3P$, as a possible carrier of phosphorus in a meteorite that is too chemically reduced to contain oxygen-bearing phosphate minerals such as the apatite group. Schreibersite has been reported in the only observed winonaite fall, Pontlyfni in Wales, Great Britain (Bendix and others, 1998, table 3), and so it might be present in the ICD as well. A minor mineral we did find that day was graphite, having both an amorphous appearance and, rarely, a hexagonal outline. (At least one graphite grain appears to have a hexagonal outline and a hollow core, as if it were a vapor-deposited solid.) As noted above, more lapping smear from adjacent mineral grains was encountered than expected. It has hindered obtaining clean analyses of phosphorus minerals near the graphitic areas. Our present hypothesis is that graphite in the sample yielded micro particles of graphite that almost flowed during lapping and carried micro particles of other abraded minerals with them. A trace of dark-gray scum that was observed flowing off the laps used to smooth the sawn surface of the sample was apparently graphite.

Near the end of the second day, in addition to the one observed augite grain containing about a half dozen chondrules, a single apparent 80-µm (almost 0.1-mm) iron-nickel chondrule was observed elsewhere in the specimen and analyzed. It was found to have Cr-bearing troilite in two semicircular inclusions in one edge (Table 6 and Figure 8C). At the very end of the second day, it was intuitively estimated that there was a 99.5 percent chance that the sample was indeed a meteorite, and the owner of the main mass was so notified the next day.

POSSIBLE CLASSIFICATION

At this point, the senior author interpreted the compositions of the olivines and pyroxenes to suggest that the sample is a primitive achondrite in the acapulcoite-lodranite clan, or a winonaite. Because the

Table 5. *SEM-EDS Analyses of Fe-Ni Metal Rims in the ICD*[1]

(Values in weight percent)

	~25 μm thick inner rim paired with spectrum 114	~50 μm thick outer rim paired with spectrum 115	Triple point	Triple point	Thin, discon-tinuous rim	~125 μm blob	Bimetal lower Z part of blob	~20 μm rim on ~270 μm augite chondrule Chondrule spectrum 121	Nonhomoge-neous ~80 μm metal chondrule paired with spectrum 92	Nonhomoge-neous ~80 μm metal chondrule paired with spectrum 91
Element	Spectrum 115[1]	Spectrum 114[1]	Spectrum 101[1]	Spectrum 74	Spectrum 105[1]	Spectrum 68	Spectrum 85	Spectrum 90	Spectrum 91	Spectrum 92
P	0.44	0.60	0.67	0.64	0.64	1.13	0.56	0.63	0.44	0.52
S	.26	.07	.07	.09	.19	.13	.28	.07	.36	.32
Cr	.19	.18	.18	.17	.23	.11	.11	.21	.22	.15
Mn	.15	.09	.09	.10	.24	.08	.12	.12	.08	.07
Fe	96.63	93.16	92.99	92.96	92.88	92.79	92.48	93.10	96.05	90.74
Co	.59	.81	.80	.81	.81	.83	.79	.79	.72	.92
Ni	1.74	5.10	5.20	5.22	5.00	4.93	5.66	5.08	2.13	7.28
Total	100.00	100.01	100.00	100.00	99.99	100.00	100.00	100.00	100.00	100.00
Ni/Co	2.9	6.3	6.5	6.4	6.2	5.9	7.2	6.4	3.0	7.9

[1] Spectra 101 through 115 were performed after the specimen was wiped using isopropyl alcohol and a Q-tip (on January 3, 2024), which removed surficial carbon that was detected previously.

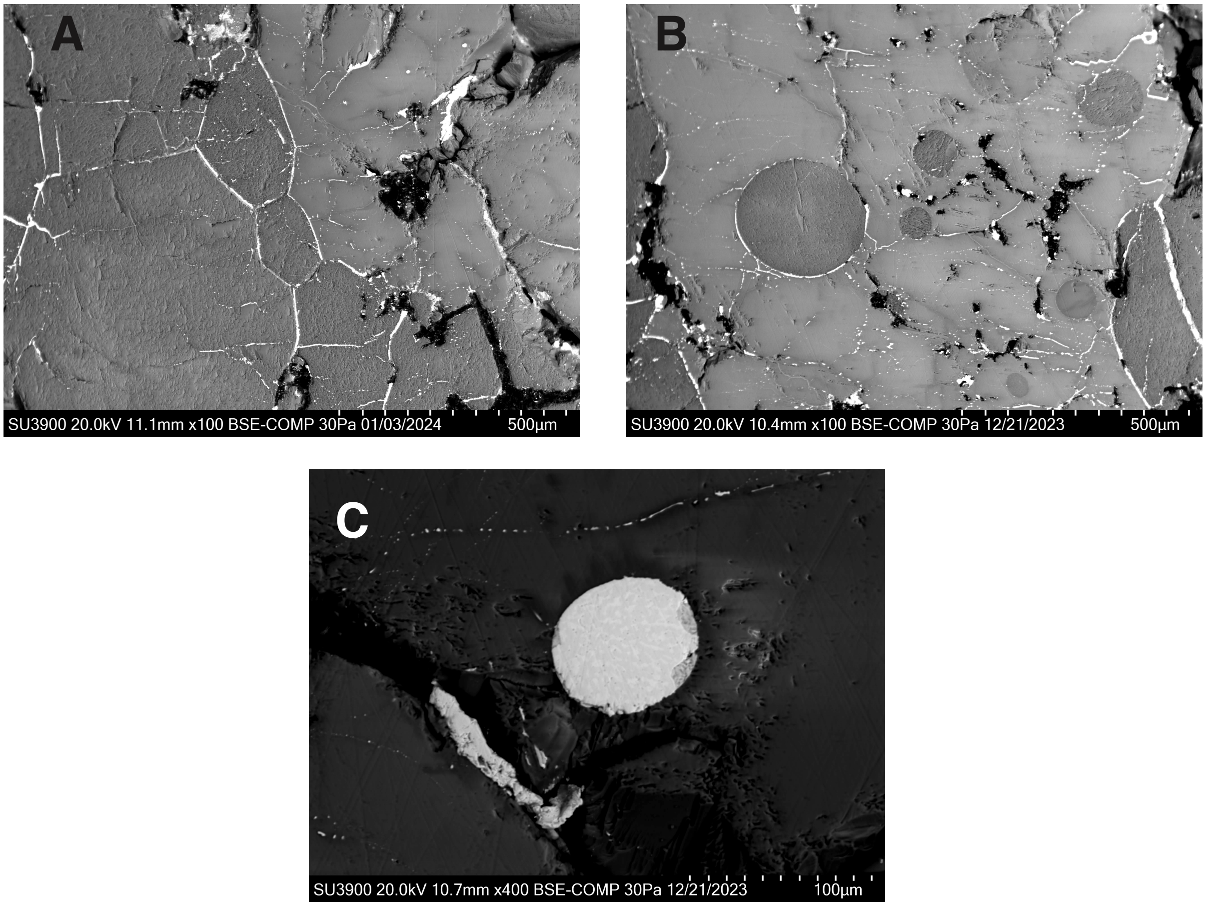


Figure 8. A. SEM backscatter image showing 120º triple junctions of Fe-Ni alloy. B. SEM backscatter image of Fe-Ni alloy rimming the largest pigeonite chondrule that we observed. C. SEM backscatter image of a possible chondrule composed of Fe-Ni and having two semicircular outer sections composed of chromian troilite.

presence of plagioclase feldspar would be consistent with either the acapulcoite-lodranite clan or a winonaite (Weisberg and others, 2006, p. 28, table 2), it was actively sought via SEM-EDS but not detected. However, the presence of a small, characteristic peak of albite was spotted in an X-ray powder diffraction pattern. Rietveld calculations based on that showed that the sample might contain approximately 2 percent albite. The low CaO content of the olivines in the specimen seemed to eliminate the ureilite and especially the angrite classes of achondrites. Having played Theodore Seuss Geisel's (aka Dr. Seuss) cat, who sang "Calculatus Eliminatus" (a song that tells how to find lost things), and considering the recent research by Stephant and others (2022), we suspected that the specimen might be placed in what was formerly the no-man's-land between the acapulcoite-lodranite clan and winonaites.

To better understand how the ICD compares to other meteorites that have been well-documented by meteorite specialists, we present Figure 9, which shows a plot used to characterize the geochemistry of olivine in different types of primitive achondrites. (The points in Figure 9 utilize our data and are color coded to the classes reported in the *Meteoritical Bulletin,* not to what we determined.) In Figure 9, this characterization is accomplished by plotting the percent fayalite (Fa) endmember of the olivine vs. the FeO/MnO contents of the same individual olivine grains in our ICD specimen, and similarly for other primitive achondrite olivines we analyzed for comparison. For most other meteorites, the median of analyses of a minimum of three different olivine grains is plotted. Some of the exceptions for which

Table 6. *SEM-EDS Analyses of Sulfide Minerals Observed in the ICD.*

	Irregular blob paired with spectrum 117		Irregular blob paired with spectrum 116		Edge of metal chondrule analyzed as spectra 91 and 92 in Table 5	
Element	Spectrum 116 weight percent	Spectrum 116 mol percent	Spectrum 117 weight percent	Spectrum 117 mol percent	Spectrum 93 weight percent	Spectrum 93 mol percent
S	39.81	1.2416	38.56	1.2026	35.59	1.1100
V	.15	.0029	.16	.0031	.07	.0014
Cr	5.70	.1097	5.64	.1085	3.98	.0765
Mn	.60	.0109	.72	.0131	.23	.0042
Fe	53.34	.9551	54.41	.9743	59.48	1.0650
Co	.25	.0042	.30	.0050	.29	.0049
Ni	.15	.0026	.21	.0036	.36	.0061
Total	100	2.3270	100	2.3102	100	2.2681

more analyses are shown include the following: (A) NWA 13839 (N=13), an acapulcoite from northwest Africa for which we analyzed olivines in three different slices because it contains both lighter areas and more metal-rich darker and lower percent Fa olivine areas as implied by Stephant and others (2022). (B) NWA 725 (N=5), a meteorite from Morocco that has been classified as an acapulcoite, then as a winonaite, and is sometimes also known as Tissemoumine, for which the samples available to us were significantly more lodranite-like than those reported by Stephant and others (2022). (C) NWA 7474 (N=7) from northwest Africa because it is listed as a lodranite, although two of the analyses from near grain centers suggest it is a winonaite. (D) NWA 14438, also from northwest Africa, because it is listed as a winonaite, but our analyses of the olivines suggest it is an acapulcoite.

We considered the possibility that our specimen, the new arrival to Pennsylvania, might belong to the newly recognized class of achondrites being called Tissemouminites by Stephant and Davidson (2023)—if that proposed class stands the test of time. Many believe that oxygen isotopes are needed to properly classify achondrites, and we certainly think that oxygen-isotope analyses are a very powerful tool. However, plotting percent Fa vs. FeO/MnO (Stephant and others, 2022, fig. 5) has some advantages, including being able to efficiently characterize many areas within a given specimen. For one example noted above, based on our reconnaissance-quality work on olivines in a small 0.37-g polished partial slice of the fairly fresh Fortuna meteorite from Argentina, which somewhat resembles the ICD, we cannot rule out that it contains local acapulcoite domains in addition to predominant winonaite.

OXYGEN-ISOTOPE ANALYSES

Weisberg and others (2006) noted that petrologic studies are the first tool of choice to identify and classify meteorites. However, analyses to determine the ratio of oxygen isotopes in stony (silicate) meteorites is generally considered to be the second tool of choice. Either method is close to being a “gold standard” to assist in identifying and classifying meteorites. As part of a brief email exchange early on, a professional meteoriticist kindly suggested that, although the high magnesium content of the olivine and the presence of moderate graphite suggested a winonaite, oxygen-isotope analyses of a

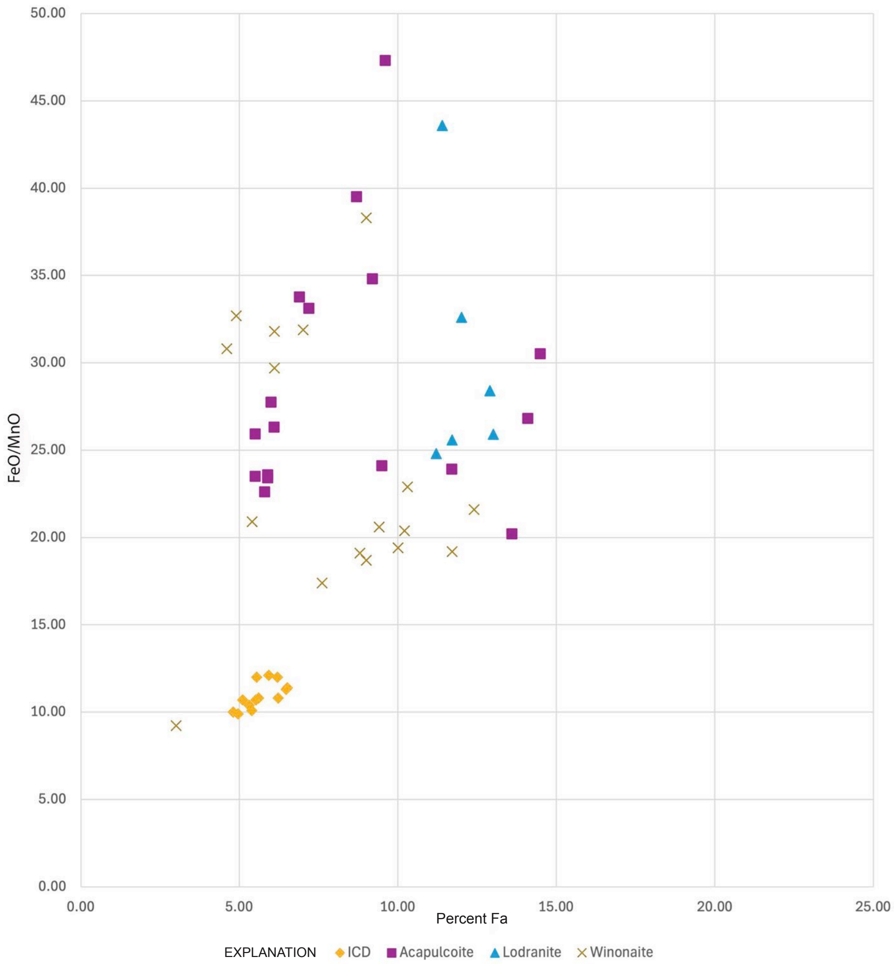


Figure 9. Plot comparing the olivine compositions of the ICD with acapulcoites, lodranites, and winonaites. Modified from fig. 5 of Stephant and others (2022), but using our own analyses of both the ICD (analyses of 13 individual olivine grains plotted), the median olivine analysis for each of 5 different meteorites listed as acapulcoites in the Meteoritical Bulletin*, 6 different meteorites listed as lodranites, and 10 listed as winonaites plus one listed as winonaite-anomalous but color coded with the winonaites. Because of within-sample moderate variability, we have shown our 13 individual points for NWA 13839, 3 for Fortuna, and 5 for NWA 725.*

sample from the interior would be needed to make the classification definitive. We have attempted to follow that suggestion.

Obviously, attempts to analyze oxygen isotopes in iron-nickel meteorites would be fruitless because they contain negligible oxygen, but most stony meteorites such as the ICD can be distinguished from terrestrial rocks by this method. The exceptions to the rule are meteorites that originated on the Moon. Lunar materials have the same oxygen-isotope ratios as rocks of earthly origin because the Moon and Earth share a common early history. The isotopic compositions of both terrestrial and extraterrestrial materials can be expressed as the difference (δ) in the abundance of each isotope in parts per thousand (‰) from a series of Standard Mean Ocean Water reference samples. The oxygen-isotope composition of a meteorite is expressed by three parameters: $\delta^{17}O$, $\delta^{18}O$, and $\Delta^{17}O$. The first two are determined in a specialized mass spectrometer. The third, $\Delta^{17}O$, is calculated from the first two as distance from the oxygen-isotope Terrestrial Fractionation Line (TFL), which is shared by oxygen originating on Earth and the Moon. The TFL is presently thought to have a slope of 0.528.

Two analyses of oxygen isotopes in the ICD were obtained by the Ibarra Isotope Laboratory at Brown University in Providence, R.I. Two tiny interior chips lacking any fusion crust were removed using metal tools. The first, a tiny 2-mg fragment, was analyzed without leaching by graduate student Jiquan Chen under the direction of Professor Daniel Ibarra and yielded 1.525‰ in $\delta^{17}O$, 6.087‰ in $\delta^{18}O$, and $\Delta^{17}O$ of –1.680‰ using laser fluorination to release the oxygen. This result verified that the ICD was neither of terrestrial nor lunar origin, nor was it a common H, L, or LL meteorite. To confirm the result, graduate student Riley Havel, also under the direction of Professor Ibarra, crushed and homogenized a larger 12.23-mg chip, leached it with twice-distilled 1M HCl, sonicated and vortex mixed it at room temperature for 5 minutes to remove any possible trace of terrestrial iron oxides, and ran it. This more representative sample yielded statistically identical results as the first analysis: 1.509‰ in $\delta^{17}O$, 6.113‰ in $\delta^{18}O$, and $\Delta^{17}O$ of –1.710‰. This confirms that the ICD exhibits no detectable terrestrial weathering, and thus, this information is a significant contribution to our knowledge about achondrite meteorites.

PETROLOGY

As we observed, one of the two largest surfaces of the as-received main mass of the ICD was planar, had a different color, and lacked melted primary fusion crust. The amount that the owner of the main mass allowed us to remove for study was obtained via a cut perpendicular to that planar surface lacking primary fusion crust. With some trepidation, the sawing was carefully done by our Cullinan man using a thin, worn diamond blade in order to waste as little material as possible. During subsampling for oxygen-isotope analyses, the ICD fragments broke parallel to that planar surface.

The cover for this issue shows a thin section in plane polarized light with crossed Nicols at very low magnification. The thin section was expertly made by Anthony Love of Appalachian State University in Boone, N.C. A closer view of the thin section is shown in Figure 10. In both images, a mineral orientation from upper left to lower right is quite noticeable, especially in the olivine (forsterite mineral species) grains. The orientation is similar to the texture described in brachinite achondrite meteorites by Gruber and others (2024). Bernard and others (2019) noted that "the alignment of olivine grains lacking internal deformation may be due to passive alignment in a melt-rich environment." Alternatively, Gruber and others (2024) found preferred orientation due to ductile deformation in the presence of 4–6 percent melt. Both studies suggested that these achondrites were partial melt residues, that is, the solid minerals left behind after a rock partly melts and the liquid migrates away. The olivines they studied were reported to be in equilibrium with one another based on 120° triple points. Based on strongly preferred orientation of forsterite grains and terrestrial mid-ocean ridge basalt-like light rare earth element (LREE) depletion (see the Major, Minor, and Trace Elements section below), the ICD seems to represent a partial melt residue. In terrestrial rocks, these are sometimes called restites. Presumably, a more siliceous alkali-rich magma has been lost and, as we shall see, it took LREE with it, possibly to form something resembling an acapulcoite or the ungrouped achondrite NWA 6704.

When we first observed the small end-cut of the ICD under the electron beam of the SEM-EDS, one of the first things we noticed was the presence of euhedral iron-nickel (Fe-Ni) triple points where many forsterite olivines met. Their undeformed nature (Figure 8A) was one feature that suggested little or no deformation since their formation. Such Fe-Ni triple points are thought to form under equilibrium (Gruber and others, 2022) metamorphic conditions.

The overall fabric of the ICD appears to be granoblastic using the criteria of Streckeisen (2020) or Williams and others (1954) for terrestrial rocks. Thus, if the ICD were a terrestrial rock, it would be considered to be metamorphosed ultramafic rock. Based on the Rietveld X-ray powder diffraction data

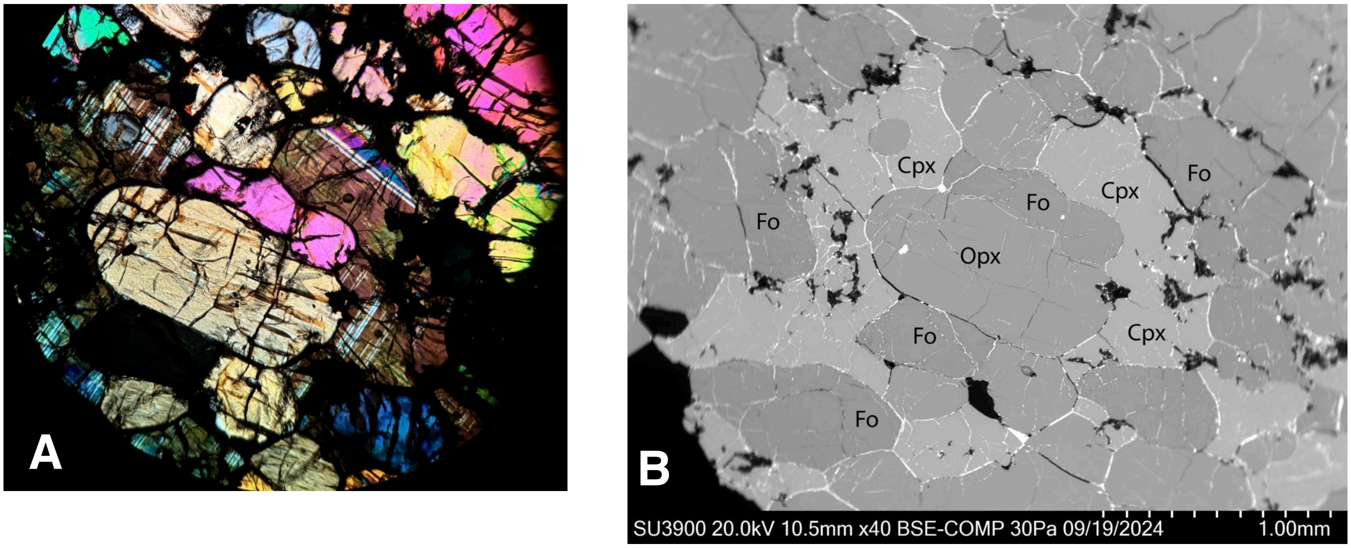


Figure 10. A. Photomicrograph of a portion of the thin section of the ICD. B. SEM backscatter image of the same portion of the thin section with labels identifying the major minerals clinopyroxene (Cpx), orthopyroxene (Opx), and forsterite olivine (Fo). The 11 ticks at the bottom right indicate a total of 1 millimeter. The median composition of five SEM-EDS analyses of the large orthopyroxene crystal is 5.2 percent Wo, 89.6 En, and 5.2 Fs. The median of three analyses of clinopyroxene crystals shown in this image is 31.6 percent Wo, 63.4 En, 4.2 Fs, and 1.1 Ac. Ten additional analyses of clinopyroxenes observed in the thin section are similar to this and are available upon request. The median of five analyses of olivines in this image is 94.2 percent Fo, 5.3 Fa, 0.52 Tp.

below, it might be considered to be a metapyroxenite, but within analytical error of being on the 40 percent olivine boundary with a metaperidotite. Such borderline terrestrial ultramafics having roughly equal amounts of olivine and pyroxene are often called websterites after the type locality in Webster, N.C. Rietveld X-ray powder diffraction analysis of a small, approximately 85-mg interior sample of the ICD yielded 38 percent forsterite, 58 percent enstatite, 19 percent graphite, and 2.7 percent albite. An earlier Rietveld analysis of an even smaller amount of silt recovered from lapping yielded 65.4 percent forsterite, 34.0 percent enstatite, and 0.6 percent graphite, suggesting that the ICD is not homogeneous but still within the field of websterite.

MAJOR, MINOR, AND TRACE ELEMENTS

The bulk chemical composition of the ICD could only be approximated using indirect methods because sacrificing a relatively large representative sample of the ICD for traditional major and minor element analyses was not an option. Instead, we determined the median of 30 SEM-EDS analyses, each from a rastered area approximately 2.47 x 1.87 mm, representing a total area of 1.39 square centimeters. This area is shown in Figure 6, which is a mosaic of the 30 areas that were analyzed. However, we consider the resulting median to be only an approximation of the bulk composition of the ICD for several reasons, an important one being that the ICD is not homogeneous. The medians for each element in these analyses, expressed as oxides, are as follow: Na_2O 0.15 percent, MgO 41.84, Al_2O_3 0.53, SiO_2 47.79, P_2O_5 0.06, SO_3 1.29, K_2O 0.00, CaO 2.32, TiO_2 0.08, Cr_2O_3 0.64, MnO 0.46, FeO 9.64 (here unintentionally overestimated because much of the iron in this highly reduced meteorite is present as Fe-Ni metal), CoO 0.01, and NiO 0.37. When we look at these interior analyses, it appears that the ICD is somewhat similar to the ultramafic rocks from the basal portion of the Baltimore Mafic Complex (believed to be an island arc) examined by Smith and Barnes (2008).

Comparison of these interior analyses to the melted fusion crust symplectic glass (Table 1, spectrum 120) suggests that oxygen was added to the crust of the ICD during its entry into Earth's atmosphere and that S was lost to it. Similar loss likely applies to C, which we did not quantify. Si, Ca, Al, and K seem to have accumulated in low-melting-temperature glasses. Based on Fe-Ni veins having positive relief on relatively fresh, ablated primitive achondrites, Fe-Ni might have resisted melting, but in the case of finds, it might be hard to distinguish that resistance to ablation from resistance to terrestrial weathering.

A pulp prepared from 0.51 g of crumbs from the ICD was analyzed by a commercial laboratory to obtain trace element data without utilizing too much sample. (The actual weight consumed was 0.20 g.) We were especially interested in data for rare earth elements (REE). To avoid contamination from metal, the crumbs were removed from the specimen using aged, end-grain wild cherry wood tools. Microscopic wood fibers were removed by air elutriation, also known as gentle blowing. A small amount of fusion crust from the ICD was included in the sample, so the reported analyses for volatile elements, such as for gallium (Ga) and germanium (Ge), might be low because the outer crust was partly melted during the meteorite's passage through Earth's atmosphere. A blind split of the U.S. Geological Survey (USGS) standard mafic rock reference sample, W–1 (a diabase from Centreville, Va.), was analyzed at the same time, as a test of the analytical laboratory's procedures. The analyses that were reported by the laboratory were very favorable. For the trace element analyses of the ICD, we hand-ground the crumbs in an agate mortar and pestle under alcohol to avoid sample loss. The resulting powder was then air-dried. The agate mortar and pestle were pre-cleaned using diatomaceous earth. After grinding, the agate mortar and pestle had a very thin film of a material that looked, felt, and wrote on paper like graphite.

The two samples were sent to Activation Laboratories Ltd. of Ancaster, Ontario, Canada, where they were analyzed for 41 elements by research-grade inductively coupled plasma/mass spectrometry (ICP/MS) of a sample dissolved in lithium metaborate-tetraborate. Even using this sensitive method, many elements in the ICD were below the detection limits. Table 7 lists the measured results of the ICP/MS analyses and the ratios obtained by normalizing those same analyses to the carbonaceous chondrite Ivuna. Ivuna was chosen because it is generally considered to be a good representative of the composition of our early solar system for nonvolatile elements. This normalization was accomplished by dividing the measured concentration of each element in the ICD by the concentration of that element in Ivuna. In Figure 11, the ratios of ICD REE data to Ivuna REE data are shown in graphic form.

As shown in Figure 11, except for the five heaviest REE (Ho, Er, Tm, Yb, and Lu), normalized REE in the ICD are all significantly less than 1. Because chondrite meteorites, both ordinary and carbonaceous, plot as a horizontal line having a value of 1 (Korotev, 2009), we can again safely assume that the ICD is not a chondritic meteorite. Comparison with the chondritic ratios provided by McDonough and Sun (1995), shown in Table 8, confirms that the ICD is not a chondrite. The only other relevant meteorite class left is that for primitive achondrites. In addition, the greater depletion of LREE relative to intermediate and heavy REE suggests that the ICD was likely depleted by the loss of an igneous melt that included the plagioclase group (Patzer and others, 2004). In this case, the melt possibly also yielded the mineral albite and minor amounts of a member of the apatite group. Such a hypothesized melt would have preferentially depleted the ICD in LREE. This is consistent with our ability to find only possible minor amounts of albite and, especially, of apatite group minerals in the ICD, even though they occur in many primitive achondrites. At this point, we knew that we were dealing with an achondrite and that it had a multi-stage history.

Table 7. *Trace-Element Data by Inductively Coupled Plasma/Mass Spectrometry for the ICD*

Element	ICD[1,2]	Ivuna[2] (Barrat and others, 2012)	ICD normalized to Ivuna
La	0.05	0.242	0.21
Ce	.12	.614	.20
Pr	.02	.092	.22
Nd	.13	.417	.31
Sm	.03	.152	.20
Eu	.012	.0597	.20
Gd	.14	.213	.66
Tb	.02	.0388	.52
Dy	.16	.26	.62
Ho	.05	.0579	.86
Er	.15	.165	.91
Tm	.025	.0271	.92
Yb	.17	.171	.99
Lu	.025	[3].0248	1.01
Co	150	554	.27
Cr	3,930	2,570	1.53
Ga	3	9.67	.31
Ge	4.9	[4]36.5	.13
Ni	1,810	12,000	.15
V	99	54	1.83
Y	1.1	1.6	.69
Zn	220	330	.67
Zr	1	3.48	.29

[1] Data for ICD that are below detection limit are omitted from table as follows: As <3, Ba <5, Bi <0.1, Cs <0.1, Cu <10, Hf <0.1, In <0.1, Mo <2, Nb <0.2, Pb <5, Sb <0.2, Sn <1, Sr <2, Ta <0.01, Th <0.05, Tl <0.05, U <0.01, and W <0.5.
[2] Data in parts per million.
[3] Lu value for Ivuna from British Museum 2008 M1 stone specimen.
[4] Ge value for Ivuna from Orgel sample ORG–1 (Palme and Zipfel, 2022, table 1).

CONCLUSIONS

In this preliminary study of a meteorite that was directly observed to fall and hit, aka "hammer," a vehicle in Pennsylvania, we have utilized meteorite classification approaches that are mainly based on both our own olivine chemistry determinations (percent fayalite vs. FeO/MnO) and Ibarra Laboratory oxygen-isotope analyses, which we compared with published analyses of fresh falls as well as judiciously leached (neither too harshly nor too mildly leached), less-fresh finds (Greenwood and others, 2017). In doing so, we attempted to follow the spirit of Weisberg and others (2006), but as they have noted, these methods might not always be consistent with one another. The description of the fall, the analytical methods that we used, and our observations are summarized in Table 9.

The δ^{17}O‰, δ^{18}O‰, and Δ^{17}O‰ isotope data obtained for the ICD by the Ibarra Laboratory certainly falls on the Carbonaceous Mighei type (CM) portion of the Carbonaceous Chondrite Anhydrous Minerals (CCAM) oxygen-isotope reference line. However, data for ungrouped achondrites NWA 11187, 11562, 12969, and 14879 seem to be more relevant. Oxygen-isotope data for all but those winonaite finds having a low weathering grade might require very judicious leaching with HCl.

Based on plots of our analyses in a percent Fa vs. FeO/MnO plot modeled after Stephant and others (2022, fig. 5), it appears, as others have noted, that some achondrite meteorite finds might presently be misclassified. Based upon our observed data, it seems as though the ICD might provide one link between the acapulcoite-lodranite clan and winonaites, where samples such as NWA 725, aka Tissemoumine, might already reside. If this is correct, we might be peering far back in time

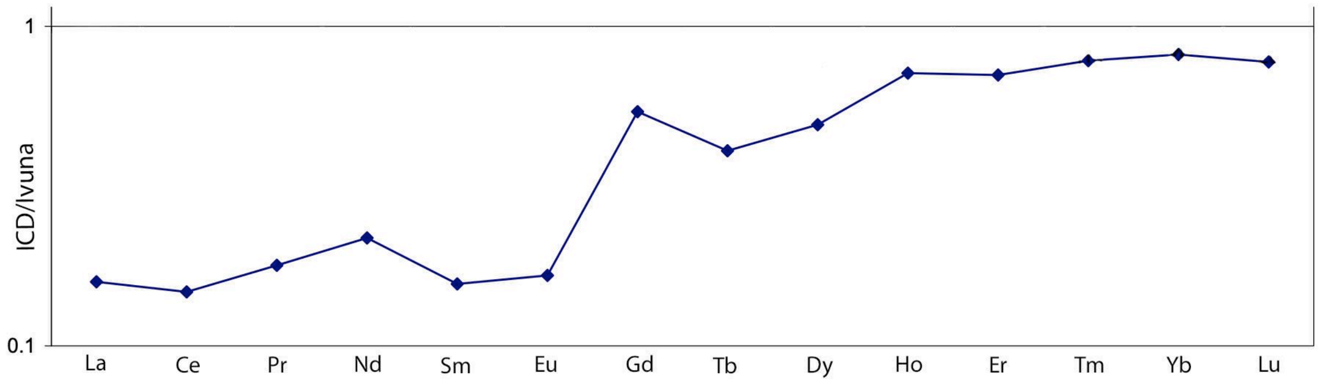


Figure 11. Logarithmic plot of ratios of rare-earth element data for the ICD to published data for the carbonaceous chondrite meteorite Ivuna (ICD/Ivuna).

with respect to the origin of our solar system and its outer reaches. Chondrite-normalized REE analyses indicate that the LREE elements are strongly depleted. Low-Ca and high-Ca pyroxenes appear to be in equilibrium and suggest a closure temperature of about 1,250.0ºC.

We are not meteorite experts, but we tried to maintain an open mind when the owner of the main mass brought it to us for examination after being rebuffed by others. We do not control custody of the main mass of this specimen, but we hope that our efforts on the material that was made available to us

Table 8. *Elemental Ratios of ICD Interior Composition Compared to Ivuna, Carbonaceous Chondrites, and Ordinary Chondrites*[1,2]

Elemental ratio	ICD interior	Ivuna carbonaceous chondrite	Carbonaceous chondrites	Ordinary chondrites
Mg/Si	1.13	0.91	0.91	0.81
Al/Mg	.011	.089	.105	.081
Ca/Al	5.93	1.076	1.07	1.08
Al/Ti	5.60	19.5	19.9	19.6
Ca/Ti	33.2	21.0	21.1	21.0
Fe/Al	26.8	21.0	16.2	24.
Fe/Mg	.297	1.88	1.68	1.9
Fe/Ni	25.8	17.2	18.1	17.5
Fe/Cr	17.0	68.3	66.	74.
Mg/Cr	57.3	36.4	39.	39.
Cr/Mn	1.22	1.4	2.2	1.51

[1]Taken together with the Ivuna chondrite normalized rare earth element data, the ICD is shown not to be a chondrite.
[2]Data for all but ICD interior adapted from McDonough and Sun (1995, table 3).

Table 9. *Summary*

BASIC INFORMATION

- "ICD" (or "Ice Cream Drop") is an unofficial name that is being used informally for this report.
- This was an observed fall from the southwest into a 1.5-quart (1.41 liter) frozen ice cream container in a parked vehicle at 40°48'38"N, 75°44'16"W. The time of the fall was approximately 20:05 UTC on May 17, 2023. Police were called and filed a formal report. A smoky trail was observed on security camera footage.
- The total mass is 117.6 g. Of that, 91.6 g was retained by the discoverer and 23.5 g was donated to the State Museum of Pennsylvania for nondestructive study and analysis, and for preservation. The 2.5-g discrepancy was probably because of loss during sawing and polishing.

ANALYTICAL HISTORY

- The specimen has not received an official classification but is believed to be an achondrite such as an acapulcoite or a winonaite.
- Methods of study included measurements of Munsell color, density, optical petrography, Rietveld X-ray powder diffraction (XRD), scanning electron microscope-energy dispersive spectrometry (SEM/EDS), inductively coupled plasma-mass spectrometry (ICP/MS), and oxygen-isotope determinations.

OBSERVATIONS

- Color of primary fusion crust is 5Y/R 2/1. Color of secondary fusion crust is 5Y 2/1. Color of sawn surface of main mass is N4.
- Density of small piece having primary fusion crust on one side: 3.13 $g/cm.^3$
- Major minerals via Rietveld XRD: forsterite (~92.4±3 mol percent Fo) and magnesian orthopyroxene. Graphite is also believed to be present.
- Median olivine composition via SEM-EDS: ~93.9 mol percent Fo.
- A single, embayed, ~3- x 1-mm augite xenocryst contains pigeonite chondrules.
- An iron-nickel mineral, typically ~92 percent Fe and ~5 percent Ni, forms thin rims on most olivine and orthopyroxene.
- Bulk chemistry of symplectic glass in crust via SEM-EDS: SiO_2 50.95 percent, TiO_2 0.12, Al_2O_3 0.77, Cr_2O_3 0.60, FeO 6.08, MnO 0.45, MgO 37.91, CaO 2.94, Na_2O 0.15, and K_2O 0.02.
- Normalized ratios of trace-element data via ICP/MS to data for Ivuna: La 0.21, Ce 0.20, Pr 0.22, Nd 0.31, Sm 0.20, Eu 0.20, Gd 0.66, Tb 0.52, Dy 0.62, Ho 0.86, Er 0.91, Tm 0.92, Yb 0.99, Lu 1.01, Co 0.27, Cr 1.53, Ga 0.31, Ge 0.13, Ni 0.15, V 1.83, Y 0.69, Zn 0.67, Zr 0.29.
- Oxygen-isotope data: Without leaching, 1.525 $\delta^{17}O$ parts per thousand, 6.087 $\delta^{18}O$‰, and $\Delta^{17}O$‰ of –1.680 using laser fluorination. With leaching using twice-distilled 1M HCl, 1.509 $\delta^{17}O$‰, 6.113 $\delta^{18}O$‰, and $\Delta^{17}O$‰ of –1.710.

will lead to additional research of this worthy specimen by others. Such research might include cosmic-ray-exposure age and ^{53}Mn-^{53}Cr isotopes, in particular.

To be sure, observed meteorite falls are rare, but meteorites can and do land in Pennsylvania!

ACKNOWLEDGMENTS

The authors gratefully acknowledge that the owner of the main mass of the ICD was extremely gracious and patient with us as our studies evolved. We also thank him and his family for bringing it to our attention and donating a portion of it to the State Museum of Pennsylvania. This work is dedicated to the memory of his grandson.

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APPENDIX A. ADDITIONAL THOUGHTS ON CLASSIFICATION

Using the Meteoritical Society's online oxygen-isotope search tool (Meteoritical Society, 2024a), both sets of oxygen-isotope results were initially reported to be near the CM portion of the CCAM oxygen-isotope reference line. However, the ICD lacks many of the definitive properties of carbonaceous chondrites, perhaps the most obvious ones being that most such chondrites contain hydrous minerals and distinct chondrules in the matrix, both of which the ICD lacks, and, most importantly, carbonaceous chondrites have solar-like compositions (Weisberg and others, 2006), which the ICD does not. Using the online oxygen-isotope search tool of the Meteoritical Society, when $\delta^{18}O$, $\delta^{17}O$, and $\Delta^{17}O$ values for the ICD are considered, the five "closest of kin" list includes ureilite-anomalous NWA 11511, but its *Meteoritical Bulletin* (Meteoritical Society, 2024b) entry lists three reasons why it differs from typical ureilites. The other four that come up as nearest neighbors from this list include ungrouped achondrites NWA 11187, 11562, 12969, and 14879, the latter three of which are reported to be Low Weathering (Low W) grade and paired. So, in addition to eliminating the possibility of the ICD being a terrestrial rock or a lunar, H, L, or LL meteorite, oxygen-isotope analyses appear to have found a potential family of mineralogically and texturally heterogeneous, ungrouped achondrites to which the ICD might become an honored member! Do these Low W grade achondrites represent a new group, or do they merely have more reliable oxygen-isotope data because they are low weathering? We should note that oxygen isotopes for the ICD do not seem to plot close to the values for the field of silicates in IAB and IIICD iron meteorites, nor with their winonaite *fall* cousin (Bendix and others, 1998; Norton, 2002).

As noted, following Weisberg and others (2006), we consider olivine-composition data to be the other potential "gold standard." Hence, our literature search returned to the rare class of primitive achondrite meteorites known as winonaites. Unfortunately, there has been only *one* observed winonaite fall, the Pontlyfni meteorite that landed in Wales in 1931, with which to compare our oxygen-isotope data. Unfortunately, the Pontlyfni meteorite potentially had many decades to react with the terrestrial atmosphere. When standard oxygen-isotope analyses of winonaites were determined (Greenwood and others, 2012, table 1), the Pontlyfni meteorite was found to have 2.71 $\delta^{17}O$‰, 6.18 $\delta^{18}O$‰, and $\Delta^{17}O$ of –0.52‰ and seems to be on the projection of the line from more weathered winonaites. Note that Bendix and others (1998, table 3) report 3.1 and 4.6 percent terrestrial weathering products in Pontlyfni at the time of their research on the 1931 Pontlyfni fall. Thus, a sample of Pontlyfni leached of terrestrial weathering products should plot farther from the Terrestrial Fractionation Line or TFL and closer to the ICD. The ICD does not plot on the TFL projection line.

In our present state of ignorance, we cannot rule out the possibility that the ethanolamine thioglycolate (EATG) leaching procedure that is in common use might not remove all oxygen that was incorporated into terrestrial minerals that could have formed on winonaite meteorite finds that were on Earth for extended periods following their unobserved landings. Indeed, the writeup accompanying the *Meteoritical Bulletin* oxygen-isotope plotting tool for primitive achondrites, including ureilites, contained these statements: "Individual winonaite and acapulcoite-lodranite clan samples are very highly susceptible to terrestrial weathering resulting in large shifts in $\delta^{18}O$ and to a lesser extent $\Delta^{17}O$. Most analysis points for the acapulcoite-lodranite clan plotted on the Meteoritical Society's oxygen-isotope diagram have been cleaned in ethanolamine thioglycolate (EATG) in order to reduce the influence of terrestrial weathering" (Meteoritical Society, 2024b). We cannot rule out that terrestrial alteration products in winonaite-like meteorites might include minerals such as smectites and the lower temperature species of the serpentine group, lizardite, that formed after a meteorite landed and interacted with Earth's atmosphere and water. Greenwood and others (2017) did a superb job with EATG leaching and oxygen-isotope analysis. Perhaps others might wish to emulate that work and run oxygen-isotope analyses of some homogenized, 1M HCl-leached small chips of winonaites to see if unleached terrestrial minerals might be a possible source of error. Faust and Nagy (1967) confirmed the earlier work of Nagy and Bates (1952) that, to avoid armoring lizardite, leaching in 1N HCl for 1 hour at 95°C was desirable for dissolving lizardite, but then, of course, forsterite gelatinizes in HCl (Gaines and others, 1997) and, ideally, one does not wish to remove that extraterrestrial mineral from oxygen-isotope analysis. It would be a long shot, but a more reliable winonaite oxygen-isotope reference line might result from moderate HCl leaching of winonaites in particular.

Independent of the leaching method, it would seem prudent to avoid including any fusion crust that formed as the meteorite was plunging through and interacting with Earth's atmosphere in samples to be run for oxygen isotopes, but some published figures suggest that this might not always have been the case. Apparent changes in the oxygen-isotope composition of EATG-leached samples relative to unleached samples suggests that latitude and climate were factors in influencing the oxygen isotope of weathering products (Greenwood and others, 2017). Fortunately, the ICD oxygen isotopes for both the untreated samples and the HCl-leached samples were the same within analytical error. In any case, Greenwood and others (2017) showed that EATG removal of iron oxides seems to move oxygen-isotope compositions in the direction of the ICD fall. Might a gently leached, interior sample of the Pontlyfni fall and the ICD data the Ibarra laboratory provided for us yield a good estimate of the oxygen-isotope composition of winonaites?

Additional data from our analyses of better-known achondrites will be made available as requested for those desiring to more thoroughly evaluate our analytical methods and data reduction. Unfortunately, many winonaites and acapulcoites appear to be nonhomogeneous and this complicates such evaluation.

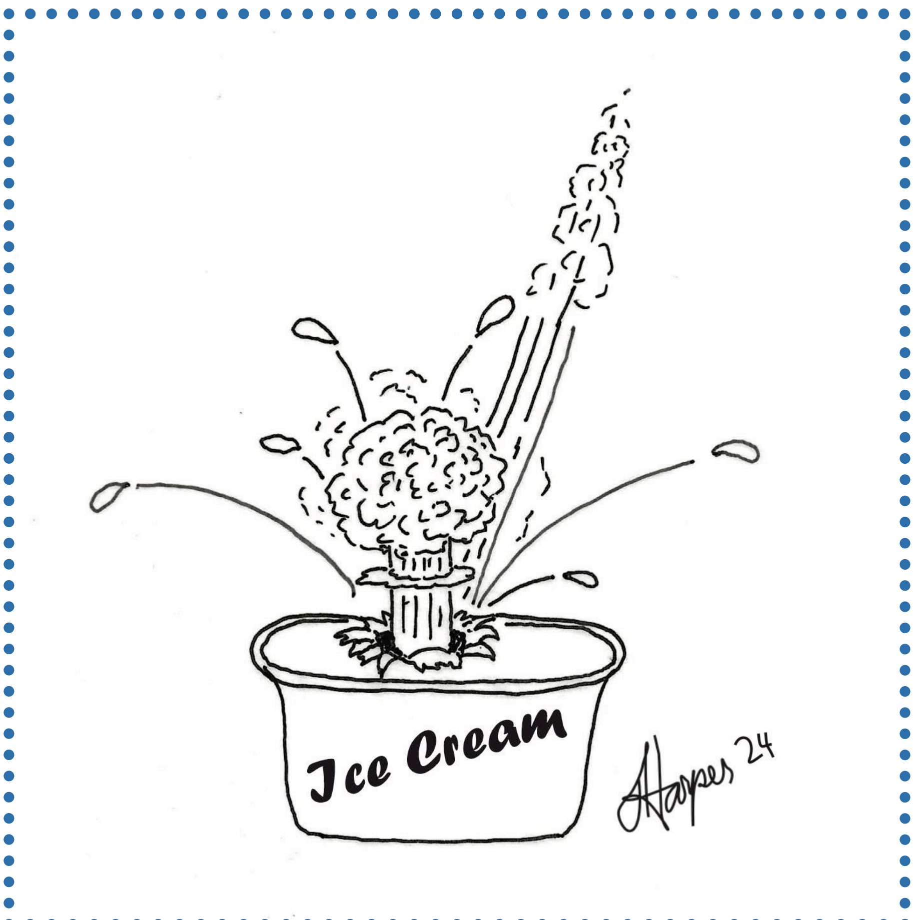
APPENDIX B. ADDITIONAL THOUGHTS ON PETROLOGY AND MAJOR, MINOR, AND TRACE ELEMENTS

Having worked with several different populations of metabasalts in the Pennsylvania area, Smith and Barnes (1994) noted that the overall LREE depletion for the ICD resembles that of ocean floor basalts (OFB), such as the Bald Friar Metabasalt of Lancaster and York Counties, Pa., and Cecil County, Md. The depletion of LREE in OFBs is generally thought to be the result of formation in a region of the upper mantle that had been previously depleted during earlier magma formation. We believe that similar previous depletion applies to the ICD's loss of a partial melt. This lost melt probably removed feldspars enriched in LREE and alkalies. Europium (Eu) depletion in the ICD relative to Ivuna appears to have been caused by the same process Smith and Barnes (1994) encountered in the products of mafic terrestrial magmas that were sufficiently reduced so as to have preferentially lost reduced Eu^{2+} by substitution for Ca^{2+} into a plagioclase and lost via the partial melt. As to the positive neodymium (Nd) anomaly and negative samarium (Sm) anomalies in the ICD shown in Figure 11, they might result from nucleosynthetic processes such as described by Burkhart and others (2016). For gadolinium (Gd) (+) and terbium (Tb) (–) anomalies, we can only note that the results for blind reference sample USGS W–1 analyzed at the same time as the ICD lack such anomalies and this partially rules out analytical problems.

Geothermometry and Oxygen Fugacity. We have made an attempt to determine the lowest temperature at which the major orthopyroxene mineral that was observed in the ICD would have been in equilibrium with the minor amount of augite that was observed. That would be the lowest temperature at which both were still forming and competing for the available calcium. Knowing this provides a clue to the nature of the body from which the ICD originated long ago. For geothermometry and availability of oxygen purposes, we entered the medians of six analyses of orthopyroxene from Table 3 and three analyses of the augite grain from Table 4 into the online calculator created by Putirka (2008 and 2018) at California State University, Fresno. Putirka's two different equations for calculating two-pyroxene thermometry yielded 1,250.0ºC and 1,250.1ºC, and the analyses passed his mathematical test screen for being in equilibrium. Putirka's geothermometery equation for clinopyroxene alone yielded 1,258.9ºC.

Interestingly, using low-Ca and high-Ca pyroxene thermometry, Stephant and Davidson (2022, fig. 7) obtained about 1,240ºC for the Pontlyfni winonaite meteorite. These temperatures are similar to terrestrial rocks and consistent with partial melting. Putirka's two equations to estimate pressure yielded 10.1 and 10.4 kbar for the ICD, which on Earth would occur at depths of roughly 30 km. If impact shock can be ruled out, this would mean that the protoplanet from which the ICD originated once had a diameter of at least 60 km or about 35 miles.

Bendix and others (2005) worked out the fugacity of oxygen (fO_2=oxygen availability) for highly reduced winonaites and related silicate inclusions in IAB iron meteorites. If one extrapolates their meteorite data to higher temperatures, the fO_2 for the ICD can be roughly estimated as log base –13.5, or about 2 orders of magnitude more reducing than the winonaites they plotted, which were close to the iron-wüstite oxygen buffer. The ICD was once very hot and very much reduced. Once again, perhaps fresh falls such as the ICD and Pontlyfni might be used to understand winonaites rather than "finds" from unobserved falls that have been on Earth for many years before they were found and are now permanently contaminated by terrestrial materials.



What might have happened when the meteorite landed in the ice cream (drawing imagined and created by John A. Harper, Pennsylvania Geological Survey, retired).

From the Stacks . . .

Jody Smale, Librarian
Pennsylvania Geological Survey

The cold winter months are upon us—what a great time to cozy up to one of these recent additions to the Geological Survey library's collection! Learn more about the geologic forces that shaped Yellowstone and Grand Teton National Parks. Read real-world examples of how GIS is being used by earth science organizations. Several resources on groundwater modeling have also been added, as well as a new book that provides an account of Delaware County's rich mining history.

Is there a publication pertaining to geology that you are looking for but can't find in the bureau's library? Suggestions for new purchases can be sent to ra-pagslibrary@pa.gov.

- ***Addressing Earth's challenges—GIS for earth sciences*** / edited by Lorraine Tighe and Matt Artz, Esri Press, 2023.
- ***Applied groundwater modeling—simulation of flow and advective transport*** (2nd ed.) / Mary P. Anderson, William W. Woessner, and Randall J. Hunt, Academic Press, 2015.
- ***Effective groundwater model calibration—with analysis of data, sensitivities, predictions, and uncertainty*** / Mary C. Hill and Claire R. Tiedeman, Wiley, 2007.
- ***The mines and minerals of Delaware County, Pennsylvania*** / Ronald A. Sloto, [Ronald A. Sloto], 2024.
- ***Modeling groundwater flow and contaminant transport*** / Jacob Bear and Alexander H.-D. Cheng, Springer, 2010.
- ***Scientific papers and presentations*** (3rd ed.) / Martha Davis, Kaaron Davis, and Marion Dunagan, Elsevier, 2012.
- ***Windows into the Earth—The geologic story of Yellowstone and Grand Teton National Parks*** / Robert B. Smith and Lee J. Siegel, Oxford University Press, 2000.

A Look Back in Time

Former bureau geologist Ralph Stone is seen here examining a meteorite that was found on Bald Eagle mountain in September 1891. This meteorite weighed over five pounds and was said to "resemble the shape of a clubfoot." The Bald Eagle meteorite is currently on display at the William Bucknell Observatory in Lewisburg, Pa.; however, the observatory is open to the public only during special events. This photograph was taken on May 19, 1931.

A recently discovered meteorite is described in this issue (see page 3). To learn more about meteorites in general and Pennsylvania meteorites in particular (including the Bald Eagle meteorite), please see the following:

- Brown, M. A., 2013, Identifying a piece of the cosmos: Pennsylvania Geology, v. 43, no. 3, p. 3–16.
- Owens, W. G., 1892, A meteorite from central Pennsylvania: American Journal of Science, v. 43, p. 423–424. [Available online at https://ajsonline.org/article/62998, accessed August 14, 2024.]
- Stone, R. W., and Starr, E. M., 1932, Meteorites found in Pennsylvania (revised, 1967): Pennsylvania Geological Survey, 4th ser., General Geology Report 2, 35 p.

- Ward, H. A., 1902, Description of four meteorites: Proceedings of the Rochester Academy of Science, v. 4, p. 79–88. [Available online at https://nyheritage.contentdm.oclc.org/digital/collection/p16694coll84/id/2759/rec/1, accessed August 14, 2024.]

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—Jody Smale, Librarian

EDITOR'S NOTE

It is ironic that the authors of a publication about meteorites would be named Stone and Starr (see previous page). In order to give consideration to the second author, we include this photograph of Eileen Starr from a newpaper clipping (the Harrisburg Evening News, July 1, 1965, p. 25).

RECENT PUBLICATIONS

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- Map 24–09.0, Hydrography Map Showing Automated Stream Permanence Identification for the Catawissa 7.5-Minute Quadrangle, Columbia County, Pennsylvania (ZIP)

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Calling All Authors

Articles pertaining to the geology of Pennsylvania are enthusiastically invited.

Pennsylvania Geology is a journal intended for a wide audience, primarily within Pennsylvania, but including many out-of-state readers interested in Pennsylvania's geology, topography, and associated earth science topics. Authors should keep this type of audience in mind when preparing articles.

Feature Articles: All feature articles should be timely, lively, interesting, and well illustrated. The length of a feature article is ideally 5 to 7 pages, including illustrations. Line drawings should be submitted as jpg files. Ensure that black and white drawings are not saved as color images.

Articles should be submitted as Microsoft Word files. Feature articles will be reviewed by at least one bureau staff member. It is the author's responsibility to obtain approval for use of any illustrations that are copyrighted, including those taken from the Internet.

Earth Science Teachers' Corner: Articles pertaining to available educational materials, classroom exercises, book reviews, and other geologic topics of interest to earth science educators should be 5 pages or less in length and should include illustrations where possible.

Announcements: Announcements of major meetings and conferences pertaining to the geology of Pennsylvania, significant awards received by Pennsylvania geologists, and other pertinent news items may be published in each issue. These announcements should be as brief as possible.

Photographs: Photographs should be submitted as separate files and not embedded in the text of the article. Please ensure that photographs as submitted are less than 10 inches wide in Photoshop or equivalent. Also ensure that black and white photographs are not saved as color images.

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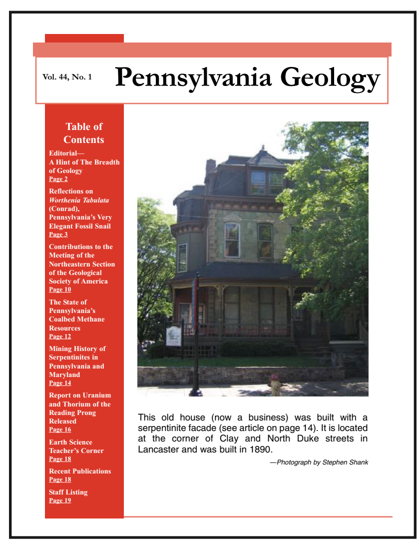
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This old house (now a business) was built with a serpentinite facade (see article on page 14). It is located at the corner of Clay and North Duke streets in Lancaster and was built in 1890.

—*Photograph by Stephen Shank*

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