The Lost City, Oklahoma, Meteorite: An Introduction to Its Laboratory Investigation and Comparisons with Příbram and Ucera

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The first stone to be recovered from the Lost City, Oklahoma, meteorite shower of January 3, 1970, was a 9.8-kg individual. It arrived in our laboratory on January 10, 1970, for preliminary examination and distribution to others for study. Later a 6.6-kg specimen was purchased, and a 272-gram and a 640-gram specimen were lent to us for examination. The 9.8-kg aerodynamically shaped individual and the 6.6-kg and 272-gram specimens can be fitted together on the basis of morphology. Mineralogical and chemical investigations were undertaken on the Lost City meteorite as well as the Příbram, Czechoslovakia, fall of April 7, 1959, and the Ucera, Venezuela, fall of January 16, 1970. All three meteorites are olivine-bronzite chondrites, type H5 of the Van Schmus and Wood classification, and are similar in composition and mineralogy. The three meteorites can be distinguished on the basis of petrologic characteristics that apparently relate to their shock histories.

The spectacular fall of the Lost City, Oklahoma, meteorite on January 3, 1970, and the incredible recovery activities of the Smithsonian Prairie Network staff have been described in a preceding paper by Richard E. McCrosky and co-workers [*McCrosky et al.*, 1971; also see *McCrosky*, 1970]. Four individual meteorites from this shower have been found, and two of these are now in the collection of the National Museum of Natural History. The other two are in the hands of the original owners, but we have been fortunate in having them lent to us for brief periods of nondestructive examination. The specimens with the names of their finders, dates of find, and dimensions are listed in Table 1.

Our initial effort with Lost City centered on the prompt distribution of material for study from the 9.8-kg mass recovered by Gunther Schwartz. Making samples available for the measurement of rapidly decaying radionuclides was our most pressing responsibility. Comprehensive interpretation of these studies, however, depends on a knowledge of the meteorite's composition, mineralogy, and orbital and atmospheric history. These factors, combined with the normal enthusiasm for participation in the study of a newly fallen meteorite, generated a demand for the immediate and comprehensive examination of Lost City by the varied techniques available to modern meteoritic science. Conservation of material for future generations was a constraint, as was the requirement to sample satisfactorily for one type of experiment without introducing contamination that would interfere with a second experiment. Compromise was required. The reader can draw his own conclusions as to the degree of our success in this area on the basis of information given below.

Two assumptions concerning scientific priorities were made before any handling of specimens in the laboratory. They are: (1) aerodynamic features preserved in the surfaces of Lost City specimens are of particular importance; and (2) studies of organic matter in this meteorite are not currently of great interest. The probability of a canine's contribution of terrestrial biological substances to the 9.8-kg specimen was a factor in reaching the latter conclusion [*McCrosky et al.*, 1971]. Each of the four Lost City specimens was photographed, and good models were prepared for preservation of surface features and aerodynamic study. Our laboratory investigation included chemical analysis and preliminary mineralogical investigation of the Schwartz specimen (NMNH 4848). Comparative chemical and mineralogical studies have also been undertaken on two meteorites that are historically associated with Lost City: the Příbram, Czechoslovakia, fall of April 7, 1959, and the Ucera, Venezuela, fall of January 16, 1970. Příbram is of interest because it is the only other meteorite with a photographically determined orbit; the Ucera, Venezuela, meteorite was studied because it fell within two weeks of Lost City and came promptly to hand for study. All three meteorites are olivine-bronzite chondrites.

DISTRIBUTION FOR STUDY

The 9.8-kg Lost City specimen (NMNH 4848) reached the Smithsonian Division of Meteorites early in the morning of Saturday, January 10, 1970. Arrangements were made to have a mold of the specimen prepared that same day, and the specimen was photographed Sunday morning. Later in the day the first cuts were made and material was distributed for analysis. Material from specimen NMNH 4848 was made available to scientists in 16 laboratories in five countries by the end of September 1970 (Figure 1). As of this writing, all material distributed for research has been from this one specimen.

The mold of the Schwartz fragment (NMNH 4848) was made under pressure to complete the job quickly. It was prepared by coating the meteorite with silicone rubber containing a relatively large amount of tin octoate hardening agent. A Plastilene (oil-based clay) parting-line construction was used that required the use of shellac in close proximity to the meteorite. Residues from the parting line were cleaned from the meteorite by using commercial grades of both ethyl alcohol and acetone. This procedure was not completely successful in areas of vesicular fusion crust. An asbestos parting-line construction was used on the Halpain fragment, and carved wood parting-line construction was used on the other two fragments. The wood parting-line technique was most satisfactory from the standpoint of protection of the meteorite, but it is more difficult and time consuming to use. All the models were made of pigmented (to provide base color) fiber-glass–reinforced polyester resin. A few of the Halpain fragment models were weighted with lead-filled epoxy resin. Final color reproduction was applied by an artist.

The meteorite was hand held for cutting; diamond saw blades were used, with distilled water as a lubricant. A 10-in.-diameter, 0.050-in.-thick bronze blade was used for the four major cuts, a process that consumed 3% of the meteorite. The slices were in turn cut with a 5-in.-diameter, 0.015-in.-thick bronze blade. The cuts are indicated in Figure 1. The bottom surface of the specimen, a dashed line indicating its right edge in the sketch, is the surface illustrated in Figure 3*a*. The sketch was prepared looking down on the surface that is shown at a slightly different angle in Figure 3*b*. The area marked 'nose' in the sketch is the highlighted area in the photograph, Figure 3*b*. The slices have been numbered in the order of their removal (1, January 11, 1970; 2, January 15, 1970; 3, April 28, 1970). Slices 1 and 2 had essentially parallel cut surfaces, whereas slice 3 was slightly wedged (Figure 1).

The purpose of Figure 1 is to show the spatial relationships of the various pieces examined by different workers. The numbers on the slices are keyed to a list of individuals to whom that particular sample material was sent. Unnumbered areas indicate material that is still on hand. Specimens were distributed on a loan basis for nondestructive analyses, and conservative amounts were also distributed for studies that required destruction of material.

TABLE 1. Lost City, Oklahoma, Meteorite Specimens

Finder	Date of Find	Weight, grams	Dimensions, cm	Catalog Number
Gunther Schwartz	Jan. 9, 1970	9830	22 × 17 × 14	NMNH 4848
Philip Halpain	Jan. 17, 1970	272	6 × 6 × 2	...
G. Schwartz, Ivan Burr, J. Sohl, and J. T. Williams	Feb. 2, 1970	6580	18 × 14 × 10	NMNH 5307
James Sohl	May 4, 1970	640	8 × 6 × 4	...

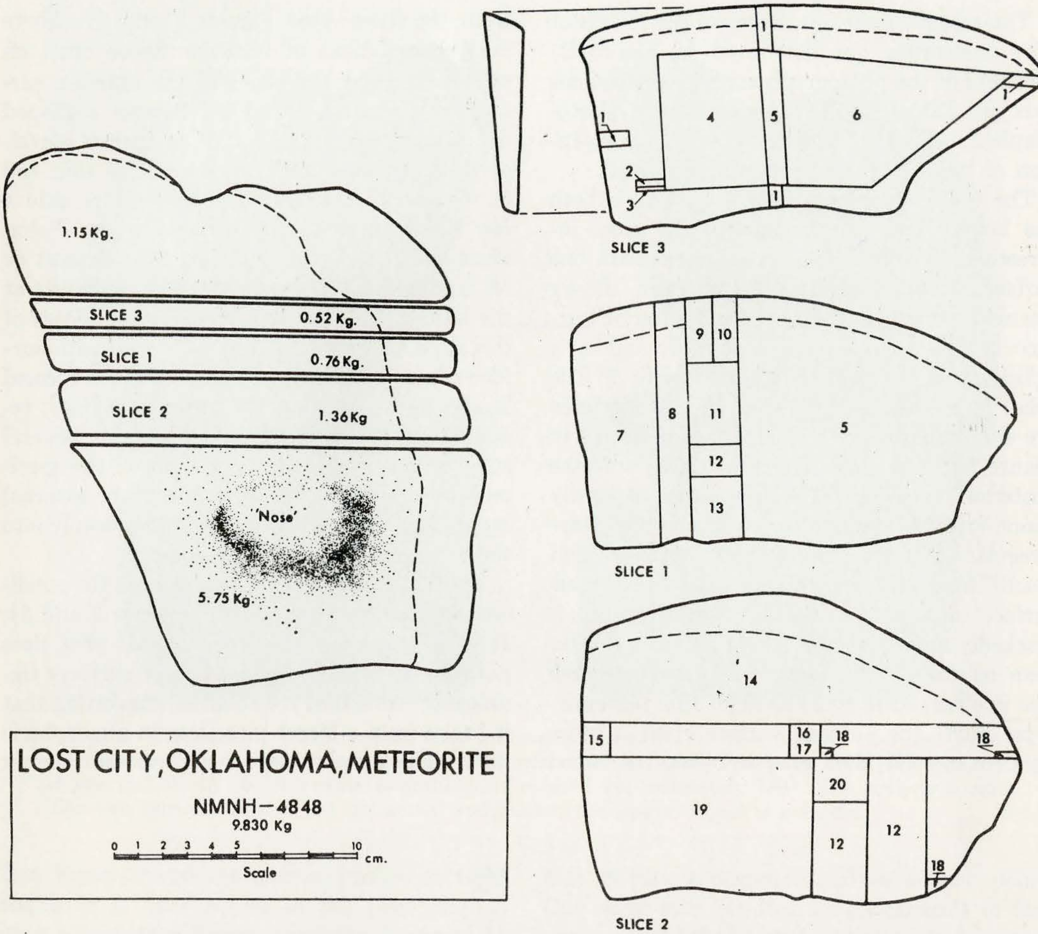

Fig. 1. Distribution of the Lost City, Oklahoma, meteorite specimen NMNH 4848 for research purposes. The diagram on the left indicates where slices were removed from the 9.830-kg mass. Sketches on the right show how the slices were subdivided. Numbers on the slices indicate recipients as follows: (1) James R. Arnold, University of California, San Diego, and Paul Pellas, Muséum d'Histoire Naturelle, Paris; (2) W. S. Lyon, Oak Ridge National Laboratory, Tenn.; (3) Archibald Reid, NASA Manned Spacecraft Center, Houston, Tex.; (4) Murry Tamers, Instituto Venezolano de Investigaciones Cientificas, Caracas; (5) Philip Cressy, Goddard Space Flight Center, NASA, Greenbelt, Md.; (6) Joseph Zähringer, Max Planck Institut für Kernphysik, Heidelberg; (7) James H. Kaye, Batelle Memorial Institute, Richland, Wash.; (8) Edward Fireman, Smithsonian Astrophysical Observatory, Cambridge, Mass.; (9) Ursula Marvin, Smithsonian Astrophysical Observatory, Cambridge, Mass.; (10) Roy S. Clarke, Jr., Smithsonian Institution, Washington, D. C.; (11) Eugene Jarosewich, Smithsonian Institution, Washington, D. C.; (12) H. Wänke, Max Planck Institut für Chemie (Otto Hahn Institut), Mainz, Germany; (13) Louis S. Walter and David Nava, Goddard Space Flight Center, NASA, Greenbelt, Md.; (14) James Keith, NASA Manned Spacecraft Center, Houston, Tex.; (15) M. H. Carr, U.S. Geological Survey, Menlo Park, Calif.; (16) Michael A. Reynolds, NASA Manned Spacecraft Center, Houston, Tex.; (17) William D. Ehmann, University of Kentucky, Lexington; (18) S. A. Durrani, University of Birmingham, England; (19) Donald Gault, Ames Research Center, NASA, Moffett Field, Calif.; (20) Raymond Davis, Brookhaven National Laboratory, Upton, New York.

MORPHOLOGY

The relative sizes and shapes of the four Lost City meteorites are illustrated in Figure 2; numbers in the photograph correspond to numbers in Table 1. The actual objects photographed in Figure 2 are models, with the exception of number 4, the 640-gram specimen.

The 9.8-kg specimen (NMNH 4848) is both the largest and morphologically the most interesting. It is apparently a fragment with one surface strongly affected by ablation during oriented atmospheric flight. This anterior surface is shown in Figures 2 and 3*b*, and it is indicated as the top surface in Figure 1. The other four major surface areas of this specimen are either shown or their edges are indicated in Figure 3*a*. The three lateral surfaces and the posterior surface give the appearance of lightly fusion-crusted freshly broken rock. They are irregular surfaces, lacking the smoothness that results from stronger ablation, and their intersurface angles are sharp. Fusion crust is markedly more vesicular and apparently thicker than on the anterior surface. A slight reddish hue is observed in some areas of this posterior-type crust; the anterior surface crust is more uniform in color, dark gray to black. Its domed surface has flow lines in the crust that radiate from the 'nose' (see Figures 1 and 3). There are accumulations of vesicular fusion crust on side surfaces at the edges of the anterior surface (see Figures 2 and 3). Several scalloped depressions suggestive of thumbprints developed by ablation may be seen at the thin end of the specimen (Figure 2). There were only a few small areas on the surfaces where fusion crust had spalled either during final descent or on landing. The largest such area is shown at the base of the specimen in Figure 3*b*. Scars of this type are preferentially associated with surface edges. A network of fine cracks was formed in the fusion crust of the anterior surface, resulting in a polygonal craze pattern. Several small cracks visible on the exterior of the specimen were observed on sectioning to be external expressions of cracks that penetrated deeply into the otherwise compact rock mass.

The 272-gram Halpain fragment is the smallest that has been found (see Figures 2 and 3). It is a completely crusted fragment that does not appear to have had its largest surfaces significantly smoothed by ablation, suggesting that it broke from a larger piece late in atmospheric flight. The narrow surface next to the number

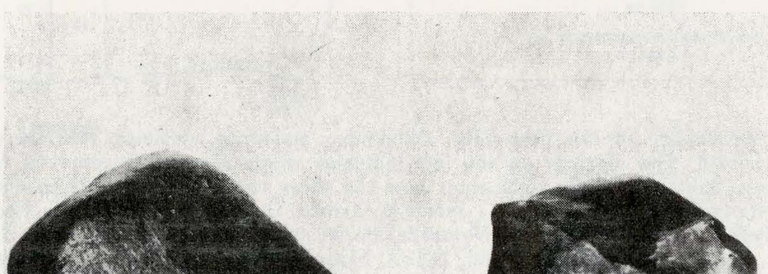

Fig. 2. Comparison of shapes and sizes of four Lost City meteorite fragments. No. 1 is a model of the 9830-gram specimen (NMNH 4848); no. 2 is a model of the 272-gram specimen; no. 3 is a model of the 6580-gram specimen (NMNH 5307), and no. 4 is the actual 640-gram specimen. The scale bar is 5 cm.

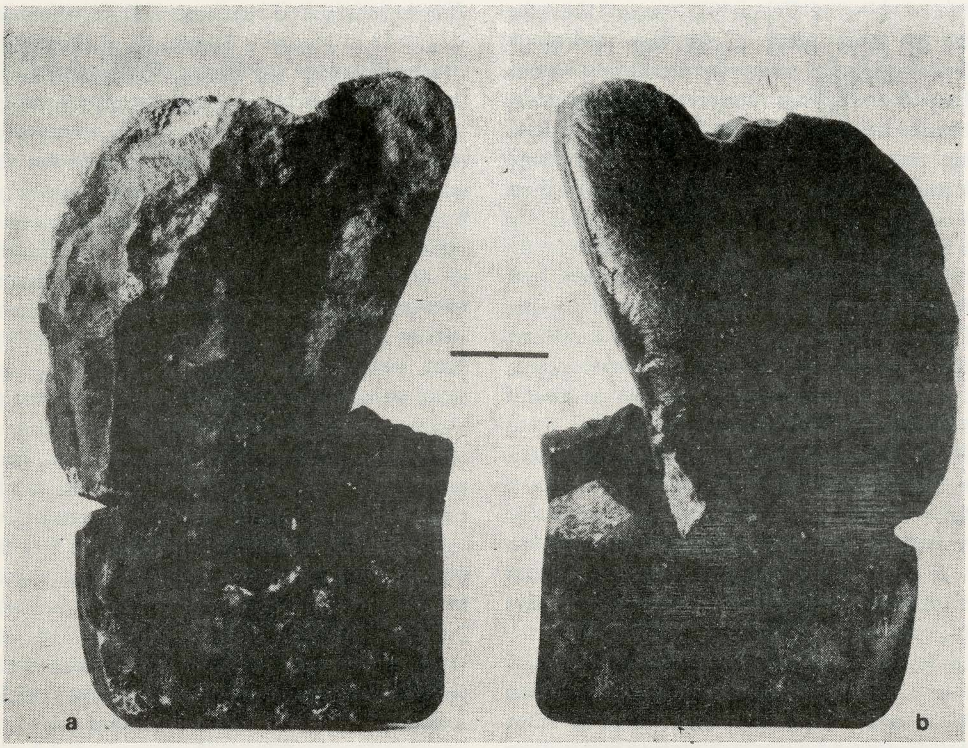

Fig. 3. Reassembly of three Lost City meteorite fragments to their relative positions prior to disruption (see Figure 2). The posterior surface of the 9.8-kg fragment (NMNH 4848) is shown in (*a*); in (*b*) the same assemblage is rotated approximately 180°. The scale is 5 cm. The two bottom objects are the actual specimens; the upper object is a model.

2 in Figure 2 and the narrow surface at right angles to it (not shown in the photograph), have a smoother fusion crust that appears to have formed prior to separation from a larger piece.

The 6580-gram specimen (NMNH 5307) is a comparatively uniformly crusted individual (Figures 2 and 3), but minor differences in crust development were noted. Most of its crust is well developed, overlying smoothed surfaces, and edges are generally rounded. The specimen has apparently undergone tumbling during flight. The bottom surface as positioned in the illustrations appears to have been particularly rounded by ablation. Flow markings and accumulations of fusion crust indicate that this may have been a leading surface at the end of high-velocity flight. Its opposite surface (top surface in Figure 2, no. 3) is thumbprinted and appears least affected by ablation. Accumulations of fusion crust at the edges of this surface and the side surfaces support the conclusion that it was a posterior surface at one point. One small area (approximately 20 cm^2) of this surface is lightly crusted and appears to represent a particularly late break. The surface of this specimen shown in Figure 3*a* more closely resembles the top surface (posterior) than the other main surfaces of this specimen. It appears to have been somewhat less modified by ablation.

A particularly interesting observation on the three Lost City fragments discussed so far is that they can be fitted together on the basis of morphology. Figure 3 illustrates two orientations of this reconstruction, *b* rotated approximately 180° from *a*. The actual meteorites were photographed in the case of the smaller specimens, and a model was used for the 9.8-kg mass. The surfaces where specimens join conform well, the fit being poorest where ablation has been the strongest. The general character of the fusion crust seems to correspond on contacting or adjacent surfaces. The rounded surfaces at the right-hand edge of Figure 3*b* suggest that the parent of these three pieces has undergone significant ablation prior to disruption. After breakup the Halpain fragment (272 grams) apparently tumbled through ablative flight long enough to uniformly crust fresh fracture surfaces and then was quickly retarded. The 6.6-kg fragment (NMNH 5307) tumbled independently for a greater distance and became completely crusted. Corners and edges were rounded, and the fresh fracture surfaces were smoothed. Toward the end of its high-velocity flight, however, it appears on the basis of fusion-crust accumulations and flight markings to have briefly experienced oriented flight. The 9.8-kg mass (NMNH 4848) appears to have entered oriented flight with little tumbling, resulting in a strongly aerodynamically shaped specimen. Other fragments were certainly produced at the time of the disruption that produced these three pieces. It is possible that large fragments remain to be recovered.

The fourth specimen (640 grams) does not obviously fit with the three specimens discussed above. It is an individual that separated from another fragment late in its ablative flight. Two of its largest surfaces have been strongly shaped by ablation, as has one small one (Figure 2, no. 4). The surface on which the specimen is resting in the illustration, however, is a lightly crusted fracture surface. Fusion-crust accumulations at the edges of this fracture surface indicate that it was probably a posterior surface during late-stage oriented flight.

Considerations of specimen morphology lead us to conclude that additional fragments of the Lost City meteorite must have reached the ground. The intriguing question of the meteoroid's mass, however, remains unanswered. It obviously was considerably more than the 17.3 kg represented by the recovered material. The observation that three of the four recovered pieces fit together probably indicates that the recovered material represents a significant fraction of the material that landed. Whether 'a significant fraction' is nearer to 20% or 80% is impossible to decide on the basis of these observations.

Mineralogical Investigations

The Lost City material reported on in this section was taken from near the middle of the anterior surface of specimen NHNH 4848, areas 10 and 11 in Figure 1. Specimens of the Příbram, Czechoslovakia, and Ucera, Venezuela, meteorites were also investigated for comparative purposes as was noted above. The Příbram material was taken from a small piece of the Velká fragment (NMNH 4840) that had recently come into our collection through the courtesy of Dr. Zdeněk Ceplecha of the Astronomical Institute of the Czechoslovakia Academy of Sciences. Mineralogical and chemical description of Příbram have been given by *Tuček* [1961] and *Rost* [1965]. The Ucera, Venezuela, meteorite came to us from Dr. J. Eduardo Vaz, Instituto Venezolano de Investigaciones Cientificas, Caracas, as a result of the activities of the Smithsonian Institution Center for Short-Lived Phenomena at Cambridge, Massachusetts. We received a small specimen (NMNH 5292) from the 4.95-kg crusted individual that was recovered by a farmer in Caserio Ucera after its fall, about 7:00 P.M. local time on January 16, 1970. Ucera (11.05°N, 69.85°W) is southwest of Coro, the administrative center of the State of Falcon. A description of the meteorite and circumstances surrounding its fall has been prepared by *Vaz* [1970].

All three of the meteorites are dense, are gray on broken surfaces, and show large amounts of fairly coarse-grained metal and sulfide on cut surfaces. The Příbram and Ucera fragments had small areas of fusion crust that appeared similar to crust on the Lost City meteorite. Polished thin sections and polished sections were prepared for microscopic and electron microprobe studies.

Microscopic examination in transmitted light of thin sections of all three meteorites shows a considerable similarity in the textural relations of the silicate minerals. Chondrules are somewhat more prominent in Lost City and Příbram than in Ucera. In Lost City the pyroxene is predominantly bronzite, but a little polysynthetically twinned clinobronzite was seen. Feldspar was not certainly detected optically in Lost City but was identified in an X-ray diffractogram of acid-insoluble material. The presence of the feldspar and the dominance of orthopyroxene indicates that Lost City is an H5 chondrite in the classification of *Van Schmus and Wood* [1967]; Ucera and Příbram are so similar that they may also be classified as H5 chondrites.

All three meteorites contain major kamacite (14 to 16% by weight, estimated) with minor taenite (1 to 2% by weight), troilite (approximately 6% by weight), and chromite (approximately 0.5% by weight) as their most conspicuous opaque mineral phases. The textural associations and structures exhibited by these phases are distinctive enough that the three meteorites can be distinguished with reasonable certainty on the basis of reflected-light microscopy. Distinguishing characteristics are emphasized in the following descriptive information.

1. *Kamacite.* Lost City has grains of single-crystal kamacite containing distorted Neumann lines, the distortion of the metal phase being particularly pronounced at the edges of some grains. In Příbram and Ucera the large metal grains are polycrystalline kamacite, free of Neumann lines. The individual crystals are equiaxial and large compared to the size of the metal grain. Příbram and Ucera occasionally have troilite in the centers of large kamacite areas.

2. *Taenite.* Lost City taenite is present in small grains as compared to kamacite; it tends to be isolated in the matrix or associated with troilite, and only occasionally associated with kamacite. It is highly colored by etching (0.5% nital), revealing a zoned-martensitic structure with infrequent pearlite areas. Taenite in Ucera is less abundant than in Lost City and is observed isolated in matrix, associated with troilite, or in contact with kamacite. Etching of Ucera taenite reveals a pronounced pearlitic structure in many grains. Příbram taenite is much less conspicuous than taenite in the other two meteorites. It does not color on etching and is present mainly at grain boundaries in large kamacite areas or in small metal grains that are made up of coarsely crystalline taenite and kamacite.

3. *Troilite.* Lost City troilite occurs in isolated grains in the siliate matrix and in association with metal and chromite. It is polycrystalline, individual crystals ranging around 10 μ across. Troilite areas several hundred microns across are common. Sulfide and metal frequently have ragged borders, and areas of an intimate fine-grained mixture of troilite and metal are common (approximately 23 vol % of metal areas in section examined). Ucera troilite occurrence is similar to that in Lost City, but there is more intermixing of metal and sulfide and these associations are somewhat coarser grained (approximately 36 vol % of metal area in section examined). Příbram troilite is polycrystalline on a much coarser scale than the other two meteorites; troilite areas measure up to several hundred microns in length, with individual crystals ranging from 10 μ to 100 μ or more in length. Troilite areas are normally divided into a relatively few crystals, and boundaries between troilite and metal are sharp.

4. *Chromite.* In all three meteorites chromite is present in comparatively large crystals in association with kamacite and troilite and as isolated grains in the silicate matrix. Areas in the silicate matrix of Ucera occasionally contain fields of smaller chromite grains.

5. *Schreibersite.* Small and sparsely distributed inclusions of schreibersite were observed in kamacite in Lost City and Příbram but were not noted in Ucera.

6. *Copper.* Small grains of copper were observed in Příbram in association with metal and troilite.

7. *Spherules.* All three meteorites contain fields of small spherules of apparently shock-melted metal or troilite within turbid (observed in transmitted light) silicate material near the edges of metal or troilite grains. These are abundant in Ucera, slightly less abundant in Příbram, and about one-quarter as abundant in Lost City.

8. *Fusion crust.* All three meteorite sec-

TABLE 2. Chemical Compositions (in per cent)

	Lost City NMNH 4848	Příbram NMNH 4840	Ucera NMNH 5292
Olivine (40)			
FeO	17.6	17.9	17.8
Range	(17.1–18.5)	(17.2–18.8)	(16.8–18.5)
Pyroxene (30)			
FeO	11.6	11.7	11.4
Range	(11.1–12.4)	(10.9–12.7)	(10.9–12.5)
CaO	0.70	0.68	0.80
Range	(0.43–1.16)	(0.50–0.96)	(0.57–1.71)

Analyst: J. Nelen.

tions contained small areas of fusion crust exhibiting typical structural and heat-altered mineralogical relationships as described by *Ramdohr* [1967]. The Lost City fusion crust was from area 10 in Figure 1, the anterior surface of specimen NMNH 4848. The presence of α_2 structure in kamacite at the edge of this section indicates that temperatures in the 500°C range penetrated as far as 1 mm below the surface but did not penetrate as far as 1.5 mm. The deepest observed penetration of α_2 structure in Příbram and Ucera was approximately 0.5 mm, indicating a steeper temperature gradient. We have no information on the orientation of these specimens, however.

Chemical and Electron Microprobe Studies

An electron microprobe investigation of these three meteorites was undertaken to characterize their olivine and pyroxene compositions and to confirm the identification of other minerals. The instrument used was an ARL probe, model EMX. Because of the availability of standards of similar composition, no corrections other than background were used in the calculation of reported values. Olivine values were based on Springwater olivine (FeO 17.1%), and Johnstown hypersthene (FeO 15.6%; CaO 1.38%) was used as a pyroxene standard. Table 2 gives our results on FeO content of olivines and FeO and CaO contents of pyroxenes. Approximately 40 olivines and 30 pyroxene grains were measured in each case, the range in values being indicated in parentheses below the average value. These values fall within the range of compositions observed in bronzite chondrites [*Mason*, 1963; *Keil and Fredriksson*, 1964]. Diopside, chromite, kamacite, taenite, and troilite were also identified with the electron microprobe and found to be within expected composition ranges.

Bulk chemical analyses of these three meteorites are presented in Table 3. The essentially classical analytical procedures employed are outlined in an earlier paper [*Jarosewich*, 1966]. The three analyses are typical of bronzite chondrites, the main difference being that Lost City contains more metal and more total iron than Příbram and Ucera.

TABLE 3. Chemical Composition (in per cent)

	Lost City NMNH 4848	Příbram NMNH 4840	Ucera NMNH 5292
Fe	16.75	14.78	14.70
Ni	1.65	1.68	1.67
Co	0.09	0.08	0.08
FeS	5.62	6.47	5.98
SiO_2	36.49	37.22	37.28
TiO_2	0.12	0.11	0.11
Al_2O_3	2.08	2.10	2.10
Cr_2O_3	0.53	0.50	0.52
FeO	9.42	9.34	10.20
MnO	0.29	0.30	0.31
MgO	23.67	23.72	23.78
CaO	1.72	1.79	1.74
Na_2O	0.89	0.87	0.88
K_2O	0.10	0.09	0.09
P_2O_5	0.33	0.29	0.26
$H_2O(+)$	<0.1	0.27	<0.1
$H_2O(-)$	0.00	0.03	0.00
C	0.01	0.07	<0.01
Total	99.76	99.71	99.70
Total Fe	27.64	26.15	26.43
Density, g/cm^3	3.73	3.69	3.74

Analyst: E. Jarosewich.

Our data on Lost City agrees well with the analysis by *Nava* [1970] employing both atomic absorption techniques and classical methods. *Ehmann et al.* [1970] have recently reported on 22 elements in Lost City. They used neutron-activation techniques as well as wet chemical procedures, and their data are generally in good agreement with ours. Their oxygen value determined by neutron activation is 32.0 ± 1.2%, in good agreement with our oxygen by difference value of 33.1%.

The Příbram analysis agrees moderately well with previous analyses by *Rost* [1965] and *Kharintova* [1965]. Rost's analysis employed the chlorination procedure [see *Moss et al.*, 1961] for separation of metal and sulfide phases from the silicate minerals, and his sample may have contained more iron than ours. Both Rost's and Kharintova's analyses have high values for Al_2O_3, and Rost reports 1.70% Fe_2O_3.

Conclusion

Four individual stones have been examined from the Lost City meteorite shower. The observation that three of these can be fitted together suggests that the meteoroid may have been a relatively small body when it entered the atmosphere. There is undoubtedly more material on the ground, but possibly there is not much more than has already been recovered. Lost City is a typical olivine-bronzite chondrite, an H5 meteorite of the Van Schmus and Wood classification. It is similar in composition and mineralogy to the Přibram, Czechoslovakia, and Ucera, Venezuela, H5 chondrites. Differences in the petrology of the opaque minerals in these 3 meteorites suggest differing shock histories.

Acknowledgments. We are indebted to Philip Halpain and Marvin Payton of Hulbert, Oklahoma, for lending us their specimens of the Lost City meteorite for study. Smithsonian co-workers who were particularly helpful in facilitating the preparation of Lost City material for study and expediting its distribution to others are John Widener (Plastics Laboratory), Victor Krantz (Photographic Laboratory), and Karl Hershey, Grover Moreland, and Sarah Scott (all of Mineral Sciences). Brian Mason and E. P. Henderson gave helpful advice, particularly relating to mineralogy and classification. David F. Nava, NASA, Goddard Space Flight Center, reviewed the manuscript.

Grants from the National Aeronautics and Space Administration partially supported the work.

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(Received January 27, 1971.)