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IMPACTITE[1] SLAG AT BARRINGER CRATER

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ABSTRACT. Impactite has been found at the Arizona meteorite crater; it differs from the impactite described by L. J. Spencer in connection with the meteorite craters at Henbury, Australia, and at Wabar, Arabia, which was silica glass. The Arizona material is composed of dolomite, silica, and calcium carbonate. Like the silica glass of Spencer it contains particles of metallic nickel-iron but less abundantly. The ratio of iron to nickel and cobalt has been determined by F. G. Hawley. Quantitative measurements were made in one excavation, and the yield of impactite found to be from 54 to 162 pounds per cubic yard. Its tardy discovery is explained as due to confusion of the impactite with volcanic cinders in the area.

Nickeliferous silica glass such as that described by Spencer in 1933b has never been reported from the Barringer Meteorite Crater. Non-nickeliferous quartz pumice known as lechatelierite has been found in small quantity in the depths of the crater pit and has been described in some detail by Barringer (1909), Merrill (1908), Rogers (1930), and others.

In 1950, the present writer exhibited a few slivers of a nickeliferous, transparent, slightly yellowish glass that had been collected magnetically on the outer slope of the northern rim two years before. However, subsequent searches have failed to reveal any additional material of this kind whatever. As was noted at the time, this sample did not conform exactly to the description of impactite given by Spencer (1933b), but more nearly resembled the Libyan Desert glass.

In view of the many other evidences of heat in connection with this great impact, many astronomers, geologists, and meteoriticists have expressed surprise at the absence of fusion in any but the white Coconino sandstone. It is understandable that silica glass would not be formed in a pure limestone, but in an arenaceous lime such as the Kaibab formation and in the Moenkopi sandstone one would expect some products of fusion, especially now that such abundant evidence of the vaporization of iron and nickel indicates a temperature of 3200°C. or above, and the melting point of silica is only 1710°C.

DISCOVERY[2]

In 1949, an intensive and rather widespread search was made for metallic spheroids accompanied by critical observations on each sample of soil taken. During these operations certain minute, light-colored, magnetic particles of various shapes were found which, though differing markedly from the metallic spheroids, gave a positive nickel test.

The writer was inclined to regard these as small bits of lechatelierite in which spherules of metal had been captured, but has never been able to find a sample of typical lechatelierite from the crater pit that contained any nickeliferous inclusions.

[1] The word *impactite* was suggested by H. B. Stenzel and used by Virgil Barnes in 1940 (p. 558). It is adopted for use here because it now becomes evident that forms other than silica glass are produced by impact, their character differing in accordance with the formations invaded.

[2] The survey which resulted in the discovery of the impactite here described was in part financed by Mr. Alfred Knight of Phoenix, Arizona, a business man and an amateur astronomer.

We now recognize that we were dealing here with small impactite bombs containing minute particles of nickel-iron. Recently we have examined polished sections of many such.

From 1949 to 1952 these studies were almost entirely confined to the upper four inches of soil, but late in 1952, when the Arizona State Highway Department excavated for gravel in the lower part of the northwest rim, an opportunity was presented to investigate a considerable sample of that part of the rim rubble which had been protected from surface disturbances since its deposition.

Here, protected from frost and the wear and tear of wind, rain, and other sources of attrition, were found the little bits of frothy glass in their original forms. Thousands of minute, gray, porous bombs, many of which were so frail that they could be crushed readily between finger and thumb, were mingled with larger specimens, some of which were as large as filberts. The breaking of a small corner of one revealed an extreme porosity, also a frailness which had not been encountered in any of the volcanic cinders that are such a familiar feature of the plain adjacent to the crater. A magnet induced a very weak reaction in the specimen, but this was not convincing since many of the volcanic cinders show the same reaction.

The volcanic ash of this area is considered to be more recent than the formation of the crater. According to Tilghman (1906), Fairchild (1907), Jakosky, Wilson and Daly (1932), and others, the lake deposits in the pit contain a thin layer of ash which seems to correspond to the ash deposit on the plains. On the basis of archeological and tree-ring studies it seems to have been very well established that slightly less than 900 years ago there was a showering of ash from Sunset Crater, 40 miles to the northwest, which may have encompassed this area. This may well have been the source of the ash deposit in the lake beds and on the surrounding plains. On the other hand, a sample of the rim rubble taken at a depth of 4½ feet below the present surface of the rim showed abundant meteoritic spheroids and also numerous specimens of the little glassy bombs, but no ash. This would seem to indicate that there had not been a blanketing of the area with volcanic ash previous to the crater's formation. At the same time it proved that the newly found form had either preceded or accompanied the crater's formation. The new-found objects were treated in several ways:

First, one was ground and polished, revealing an extremely vesicular and spongy-looking interior, strongly rust-stained, with numerous bright metallic particles.

Next, the mass was crushed in a mortar and tested for nickel. It gave a strong positive reaction with dimethylglyoxime.

When one of the specimens was crushed and the magnetic particles removed and examined under a microscope, they were found to be much like the little metallic spheroids which had become so familiar and speculation arose as to whether the surface spheroids (Nininger, 1951) which had been collected during the last few years had been released from similar glassy bombs that had been ground up by surface attrition.

DESCRIPTION

While evidently produced by a similar force, the impactite at Barringer Crater differs in several details from the silica glass found at Wabar and Henbury craters as described by Spencer (1933b).

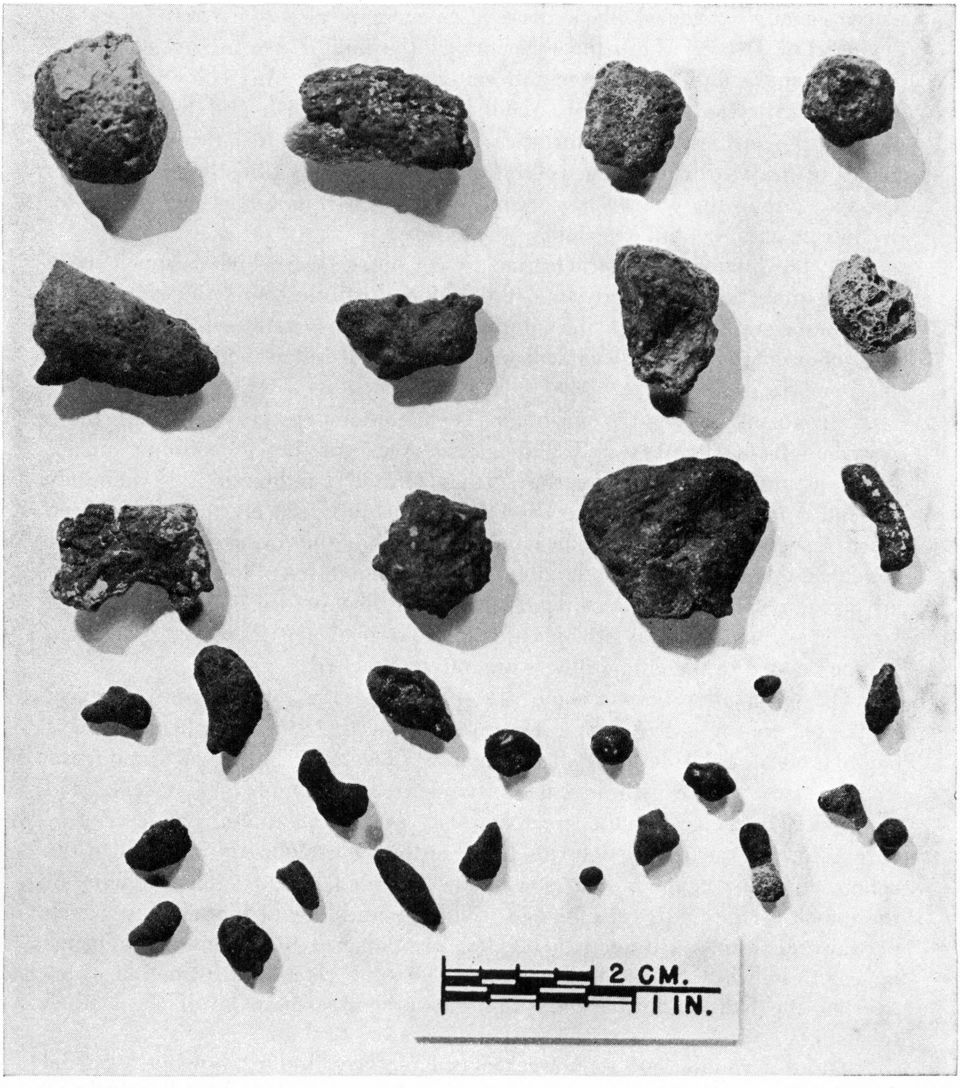

Fig. 1. Impactite bombs gathered on the rim of Barringer Crater. These bombs, when sectioned and polished, show particles of nickel-iron.

The second from the top on the right has had its original surface removed by erosion. The second from the left on the bottom shows two small attached bomblets, one almost completely imbedded. (Photograph from the Smithsonian Institution.) Magnification about 0.7X.

In the first place, although its vesicular character and often ropy appearance strongly suggest that it was produced as glass, X-ray studies in the laboratories of the Mellon Institute reveal that it is to a large extent crystallized. In the second place, its composition has been shown to be about as much dolomite as silica, and in some cases mostly dolomite. In the third place, the highly glazed black glass of Spencer is almost entirely absent at the Arizona Crater where the exteriors of the bombs are nearly all free of gloss, having a dull appearance and being usually of a gray color with many specimens varying to greenish, reddish-brown, yellowish and rarely almost white at the surface. Their interiors range from black (rare) through various shades of gray, brown, green, yellow, and amber, rarely bluish or pure white. The interiors of the vesicles are often somewhat lustrous, sometimes highly so, in contrast with the dull exteriors of the bombs.

All the bombs are characterized by an outer zone which is much more compact than the main body, and the Mellon Institute found this outer zone to be more crystalline than the interior of specimens examined. The Institute also reported that augite was a prominent mineral indentified in the interior of a bomb examined.

The forms of the Arizona bombs seem to compare very well with those described from Henbury and Wabar craters except that the pimply surface is not as prevalent as Spencer describes (1933b), although it is definitely present. Another feature, however, which seems to be closely related has been noted repeatedly in the Arizona bombs and that is the presence of subsidiary bomblets attached to large bombs (fig. 1, second from lower left). These are usually spherical and evidently had solidified before colliding with the larger mass while it was still plastic. In some instances these are more than half embedded in the latter. Others are barely attached.

Of the smaller bombs some are spherical. This form is most frequent in the microscopic size range. Quite a few of the smaller spheres show a cup-like pit on one side. Pear-shaped bombs are common, especially among the smaller sizes, as are cylinders with rounded ends, dumbbells, crescents, and claw-like specimens, but the great majority are irregular and nondescript.

A few of the rounded forms have, on being broken, shown small white spheres in their centers, and many show included rock fragments. Some of these look as if rock fragments had collided with blobs of molten glass which partially or wholly enfolded them (fig. 2). Some of the included fragments appear to be white Coconino sandstone, others the Moenkopi formation which overlies the Kaibab formation, while still others seem to be of the Kaibab formation.

Quite a number of rock fragments have been found showing a partial fusion on their surfaces. Some are fully fused on one side, others lightly fused all over, still others have a thick layer of slag plastered on one side as if a blob of molten material had fallen on them. The slag in such cases shows rounded edges as if a thick viscid mass had partially flattened itself before solidifying.

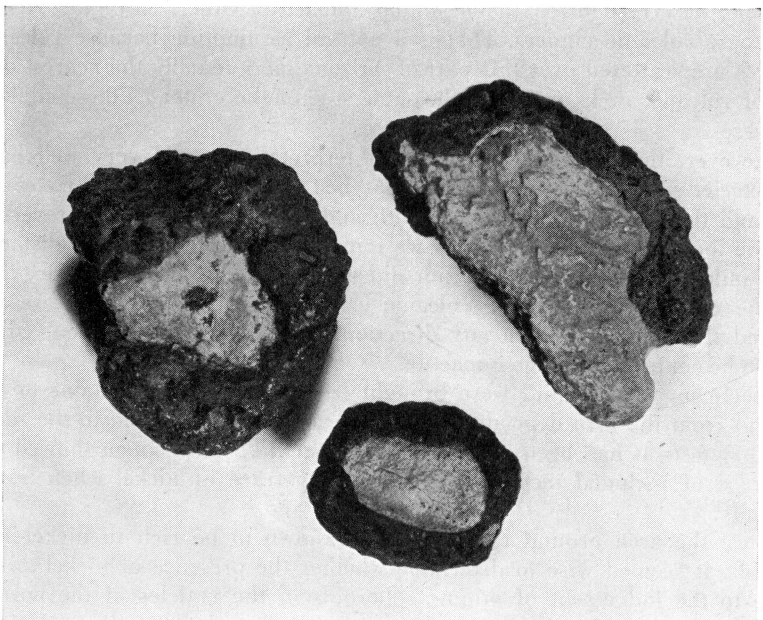

Fig. 2. Rock fragments enfolded by impactite. Magnified about 2.5X. (Photograph from the Smithsonian Institution.)

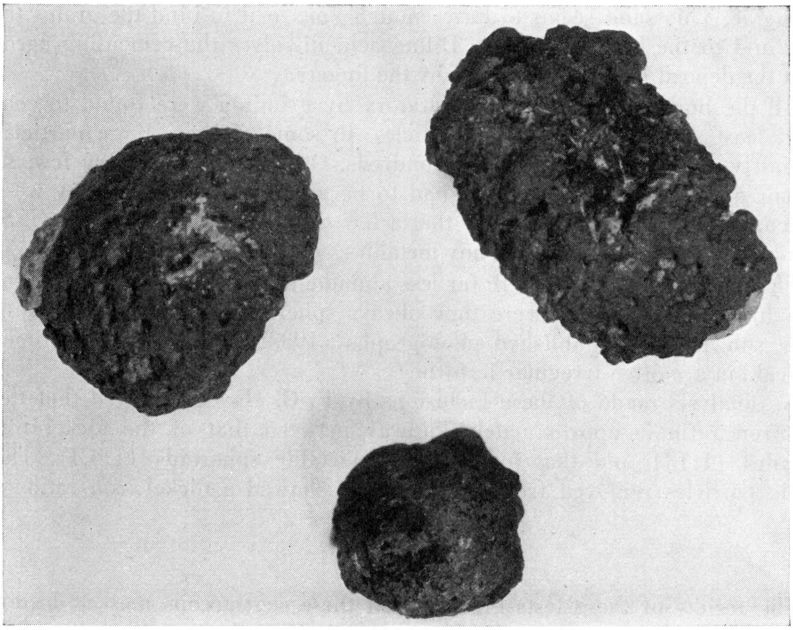

Fig. 3. Specimens of figure 2 viewed from opposite side. (Photograph from the Smithsonian Institution.) Magnification about 2.25X.

Nearly all the bombs when excavated show a layer of fine sand adhering to one side. This sand seems to have enough lime in it to bind the grains together and to the bomb's surface. Dilute acid dissolves the cementing agent so that the deposit may be rubbed off by the fingers.

All the bombs tested in our laboratory by grinding were found to contain at least some small metallic particles. In some of them these particles were fairly abundant, running into hundreds. Others contained very few, so that half or more of the specimens had to be ground away before any were revealed. E. P. Henderson reported that a few of those submitted to the U. S. National Museum failed to reveal any metallics.

The metallic inclusions were far less abundant than those found by Spencer in his silica glass nor were they always spherical as described by him and as shown in his published photographs (1933b). Ours are sometimes spherical but are often irregular in form.

An analysis made of these inclusions by F. G. Hawley showed that the nickel:iron ratio is approximately midway between that of the nickel-iron meteorites (1:13) and that found in the metallic spheroids (1:4.4). The metallic particles removed from the impactite showed a nickel:iron ratio of 1:7.4.

OCCURRENCE

The results of these tests indicate that these scoriaceous masses do not have a terrestrial origin. Hence they must be related to the impact of a meteorite. Directly across the crater from where these bombs were excavated there are considerable numbers of clinker-like masses on the surface of the crater rim slope, now recognized to be similar impactite. Others have incorrectly called these volcanic cinders. That is a natural assumption because volcanic materials are scattered over this part of Arizona, and actually the nearest outcrops of volcanic rocks occur on the same side of the crater as these clinker-like masses.

However, the incorrectness of this interpretation could very well have been detected had earlier investigators searched the area between the meteorite crater and the lava outcrops to the south and southwest. When we traversed this zone looking for impact bombs we found none after reaching a distance of 1½ miles from the crater rim nor did we find any volcanic particles that could be confused with them. Volcanic ash was more abundant as we approached the lava beds from any direction, but this ash never occurred in forms to be confused with the impactite.

Specimens of volcanics were brought from the cinder mountains to the west and from the lava deposits to the south and were subjected to the same laboratory tests as had been applied to the impactite. No specimen showed the least trace of included metal particles nor any trace of nickel when tested chemically.

Since the area around the crater was known to be rich in nickel-iron spheroids, it seemed wise to determine whether the presence of nickel might be due to the lodgement of minute spheroids in the vesicles of the porous bombs. Inspection of polished sections revealed that the metallic inclusions were not in the pores but actually embedded in the slag of the reticulum, indicating that they must have been enveloped by the liquid during the process of bomb formation.

The impactite appears to be unequally distributed on the rim. Although it has now been found on all sides of the crater, it has been found in abundance on the surface in only one sector of the rim, viz., the southeastern sector. However, it is found equally abundant in the excavation in the northwest sector. This excavation reached to the undisturbed Moenkopi formation, which is the original surface formation of the region, and the heavy deposit of bombs was found in the rubble 2 to 4 feet above this formation. The identifiable fragments which compose the rubble consist of three formations in approximately the following percentages: Moenkopi, 25 percent; Kaibab, 55 percent; and Coconino, 15 percent. Most of the latter is unconsolidated sand, some of which is bound to the bombs and rock fragments by calcareous cement. Samples of rubble taken from this horizon yielded from 54 to 162 pounds of impactite per cubic yard.

It is probable that the rich surface accumulation of bombs on the southeast rim is also in the same horizon of the rubble, although no excavation has been made to prove it. It is noted, however, that no bombs have been found in the mounds of boulders and coarser rubble but only in those areas where erosion has removed nearly all the ejectamenta. It is probable that if the mounds of coarse rubble were removed, impactite would also be revealed there. This problem of vertical and horizontal distribution needs much more extensive investigation than has been possible up to the present time.

Some shallow excavations in the outer rim slope have shown little or no impactite; others have shown many small bombs. But it is so far impossible to decide whether these differences are due to original variations in the deposit or to surface erosional drift. The latter conclusion seems inescapable in some instances where volcanic ash is mingled with the impactite because the ash deposit came long after the crater was formed. Otherwise, as already pointed out, the two should be mingled in the undisturbed rubble. This has been proved contrary to fact.

DEDUCTIONS

Apparently there was a widespread deposit of impactite mingled with the earlier deposit of ejecta. The only quantitative measurements were made on samples taken in the excavation on the northwest rim; but surface collections indicated at least as great, or possibly greater, concentrations near the base of the southeastern rim at an equal distance from the crest. Digging to depths of 18 inches one and one-half miles northeast of the rim crest showed many small bombs and fragments of slag. Very good samples were found in the vicinity of the silica diggings on the southern rim and farther south.

A few bombs were picked up on the surface on the lower southwestern rim slope, and bombs were found due east of the crater in all places examined where drift sand had not concealed them. The northern sector of the rim has been spoiled for surface investigation by the construction of the new road to the crater. Volcanic cinders were used for this road bed. They were hauled in the autumn and left exposed all winter before the oil was applied. Strong southwesterly winds scattered them far and wide so that any future investigations of the north rim will have to be by way of excavations.

Spencer (1933b) concluded that the silica glass of the Henbury and Wabar craters indicated that there had been a pool of boiling silica into which

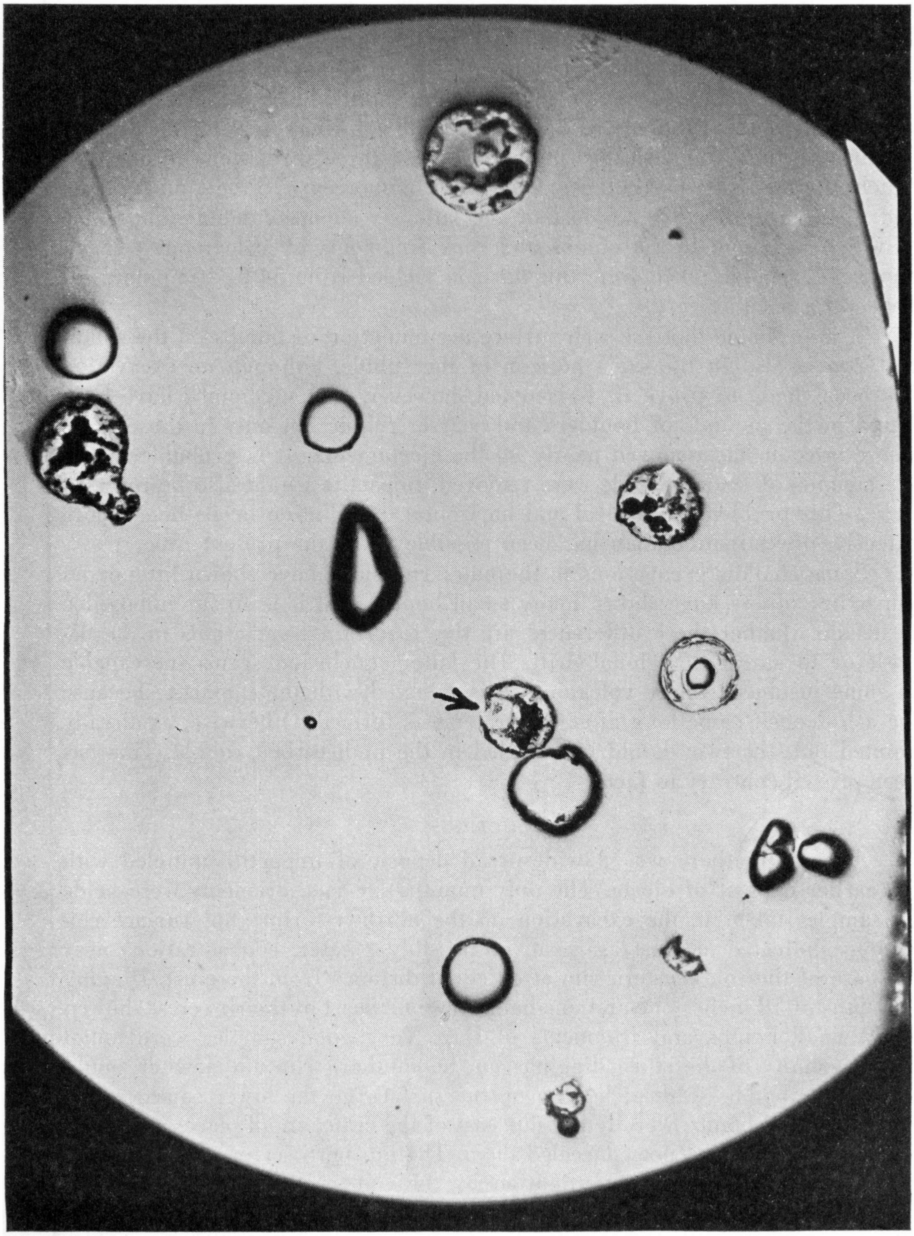

Fig. 4. Some of the smaller bomblets, X 50. Several of these show no vesicles and appear to be glass. The arrow points to a metallic inclusion in a very small bomblet. (Photograph by Dr. George Edwards, University of Chicago.)

fell a drizzle of nickel-iron droplets, condensed from metallic vapors. He also suggested that there would probably be found a wide range of conditions in different craters, and one finds difficulty in visualizing the boiling pool as a source of these bombs at the Arizona Crater. Lechatelierite has been found in the crater pit although it is not known to be very extensive. However, no nickel-iron has been found in samples of lechatelierite that have been examined, to the knowledge of the writer. Barringer (1909) mentions what seems to have been iron and nickel staining but evidently from solutions of these metals. Merrill (1908) describes lechatelierite as a pumiceous glass with no mention of any metallic particles, but he does mention that certain drill holes yielded thin metallic scales. These were never assigned to the lechatelierite formation.

If the lechatelierite in the crater pit represents a boiling pool of silica, this pool could hardly have been the source of the glassy droplets now being discovered, for these are not silica and they are loaded with metallic particles which are never found in the lechatelierite.

One wonders if the bombs were not encountered in some of the drill holes in the crater, but were crushed into unrecognizable fragments. Merrill (1908) speaks of a silico-ferruginous slag, such as it was conceived might result from a mutual fusion of sand grains and meteoric iron:

> "Nothing was found that could be thus positively identified until hole No. 20 was reached, though some of the particles showed in thin-section a very deep green or brownish, blebby glass which it was first thought might be particles of volcanic sand common to the region. A comparison of the two materials did not substantiate this view, and it would seem that such must in some way be connected with the meteoric phenomena, though it was not possible to correlate them absolutely with the nickeliferous granules."

Here the writer believes Merrill actually examined bits of the impactite, probably crushed bombs, from a depth of 640 to 680 feet below the crater floor some 300 feet east-northeast of the main central shaft. They were unable to correlate the nickeliferous granules with the "blebby glass" probably because the two had been separated by crushing drill action. However, this cannot be definitely proven at this late date.

It seems probable that the major portion of the slag that is being found was produced as a splash product of the impact as the meteorite passed through the Kaibab formation. The question then arises why should one not find an even greater amount of true silica glass since the Coconino formation is almost pure silica and is twice the thickness of the Kaibab formation, and since the meteorite is known to have penetrated both formations. Yet the only glass that one can be certain came from that formation is the lechatelierite which seems to occur in comparatively small quantity.

One possible explanation comes to mind, the validity of which rests on the following facts and assumptions: (1) The water table in the area at present is approximately 200 feet below the present floor of the crater which is about midway of the Coconino sandstone. This water table is known to have been much higher in the past and to have been unstable, since lake deposits make up a part of the crater fill below some 30 feet of alluvium and wind deposits. Jakosky (1932) describes these lake deposits as being the playa type. (2) The Kaibab formation is very compact and practically impervious to water. (3) Opik (1936) has shown that such a meteorite striking at cosmic velocity would develop pressures that exceed the elastic limit, so that both the meteorite and the target may be treated as liquids. (4) The meteorite is known to have penetrated about 1200 feet of sediments (vertical measurement). The Moenkopi and Kaibab beds account for 350 feet of this. The air cap carried by the mass was probably equivalent to another 50 feet of rock, and if the meteorite's approach before encountering the atmosphere was tangential it may have been much greater. Consequently, we may assume that from 30 to 50 percent of the projectile's energy was spent before it entered the Coconino formation. (5) The formations in its path ahead of the invading mass were subject to enormous pressures before they were actually invaded. Boon and Albritton (1938) have estimated that the pressure may have been equal to 25 million atmospheres.

Now, if it be assumed that the water table was approximately at the Kaibab-Coconino contact level, the interstitial water in the porous Coconino was changed into superheated steam well ahead of the meteorite, constituting an explosion, shattering sand grains, and producing the several stages of metamorphosed sandstone; but in the presence of steam which was restrained but not confined, very little of the sand was subjected to sufficiently high temperature to produce lechatelierite. On the other hand, the Moenkopi and Kaibab, relatively dry and being struck with maximum violence, were instantly vaporized or transformed into slag which splattered as blobs and droplets in all directions, coming to rest before the bulk of the ejectamenta landed.

The metallic particles that are embedded in the glass must likewise have been splash droplets from those parts of the meteorite which touched the rock through which it was passing. They are not, therefore, condensation droplets like the metallic spheroids. As already pointed out, the nickel-iron ratio differs from that of the spheroids.

According to this hypothesis, the relative scarcity of silica glass from the Coconino is due to the reduced energy of the meteorite and premature steam explosion together with the cooling action of water vaporization, whereas the scarcity of glass from the siliceous Moenkopi is due to the higher velocity of the impinging mass and its consequent volatilization of the surface formation on contact.

During these stages of penetration the internal temperature of the meteorite was building up to the final grand explosion of the mass itself. It was this event that gave the crater its final form and sent aloft the gigantic metallic vapor cloud from which the metallic spheroids were condensed.

An oxyacetylene flame was applied to some small pieces of the Kaibab formation. The flame was supposed to develop a temperature of 5800°F. or 3240°C. Application of the hottest part of the flame for a period of two minutes produced blebs which looked very similar to some of the impactite bombs. A carbon flame was then applied by substituting a carbon rod for the metal electrode of an arc-welder. This vaporized most of the treated material; the remainder merely puddled. Perhaps the calcareous constituent of the Kaibab in the vicinity of the meteorite contact was vaporized leaving the magnesium carbonate and silica of the formation to be fused into dolomite-silica-slag.

The Kaibab formation is known to be quite variable as to its content of silica, and judging from its appearance its content of $MgCO_3$ is likewise

Fig. 5. Small impactite bombs in section, X 50. (Photograph by Dr. George Edwards, University of Chicago.)

variable. This heterogeneous composition could account for some of the variability in appearance noted in the material examined. Chemical analyses of the different types may clear up the matter.

NEED FOR EXTENSIVE RESEARCH AT THE ARIZONA CRATER

The discovery here reported brings this crater more closely in line with the calculations of Moulton (1929), Wylie (1933), and others regarding the energy release of large cosmo-terrestrial encounters. It also brings to light an entirely new species of impactite and inevitably suggests the possibility that large impacts may have produced a wide variety of metamorphic products.

Of more immediate concern are a number of questions related directly to the amassing of a more complete assemblage of factual data regarding various aspects of the crater under investigation. The securing of such a body of facts should precede any final effort to round out the picture of such events as produced this outstanding feature of the planetary landscape.

Some of the questions that come to mind are: (1) The areal limits of the dispersal of the impactite. (2) Its horizontal and vertical distribution pattern. (3) Its range of composition. (4) An estimate of tonnage of this material. (5) An estimate of tonnage for the nickel-iron carried by this material. (6) Since the principal formation (Coconino sandstone) invaded by the meteorite is almost pure silica, why do we not find this mineral strongly dominant in the fused product? Is there some better answer than the one here suggested? (7) What is the relation between the metal-free lechatelierite found by Barringer (1909) in the crater pit and the nickeliferous, dolomite-silica bombs here described? (8) Are similar bombs also mixed with the fill in the crater pit? (9) What can be ascertained as to the quantity and distribution of lechatelierite associated with the crater? (10) Why is no nickel-iron found in lechatelierite? (11) Have the metallic spheroids been derived from impactite by attrition or were they a separate product from the moment of formation? (12) In view of the abundant evidence of extreme temperatures produced by this impact, why do the exposed formations of the inner crater wall show no glazed surfaces? (13) Or do they show such glazing in protected spots that have not been found? (14) Is the present spotty distribution of impactite due to the manner of is original dispersion or to its exposure by differential erosion? (15) May there have been atomic disintegration produced by the extreme temperatures of impact here and, if so, is it still possible to demonstrate the fact?

While this paper was in preparation an article by Dorsey Hager (1953) appeared in which its author contends that the Arizona crater is not the result of meteoritic impact but rather that it is the result of a combination of normal geological forces.

Without going into a lengthy analysis of his paper, which consists of an elaborate presentation of geological features spread over an area of some 10,000 square miles, most of which can be considered as related to the crater only on the basis of a forbidding list of assumptions, I submit the following:

Mr. Hager points to the fact that the crater lies in an area some 15 by 120 miles which is beset by sinkholes but fails to point out that the crater bears not the least resemblance to any of these. He points to the existence of many graben some 60 miles northwest of the crater and then *assumes* that four of the thirteen faults in the crater rim are connected through the floor of the crater by concealed faults, thus making it a graben.

He assumes that the crater is underlain by a bed of evaporites and cites the discovery of such underlying beds 30 to 50 miles southeast of the crater; but he fails to note that the several wells drilled on ranches adjacent to the crater encounter neither evaporites nor brackish water, and that the water taken from drill holes or shafts in the crater was never brackish.

Hager assumes also the former existence of a 1000-foot high dome where the crater now is, and to account for this, assumes a buried land mass to the east of the crater, the existence of which is supported only by an aeromagnetic survey which could be interpreted as well on the basis of a normal anticlinal fold.

He asserts that the "rock flour" is mainly just sand. However, he cites no proof. On the other hand, Jakosky et al. (1932) state positively that "the rock flour consists of extremely fine sand which the microscope shows to be angular shreds of quartz." Merrill (1908) states that this material "under the microscope is seen to be composed wholly of the sharply angular bits of quartz derived from the shattering of the individual grains of sand" and publishes a photomicrograph to prove his point. The present writer has also found the rock flour to be mainly angular quartz fragments, very different from the rounded grains of quartz in either the Coconino sandstone or the arenaceous Kaibab formation.

In attempting to depict the fall of meteorites in the area as an event unrelated to the formation of the crater, Hager (1953) reveals a notable lack of familiarity with the behavior of meteorites as they land on the earth (see diagram in fig. 12, p. 847 of Hager's paper).

More important, he failed to discover the metallic spheroids, which we have proven to exist literally in thousands of tons mixed with the soil particles around the crater, and after their discovery had been announced he made no effort to investigate them, but casually referred to them in his paper as something to be expected in connection with any meteorite fall. Actually, none have ever been found in connection with any of the more than 600 falls recorded except in association with craters.

Equally important, Hager (1953) failed to recognize the impactite described in this paper. He built this hypothesis on a long list of assumptions but apparently saw no reason for making a detailed examination of the area under consideration.

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