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THE GOOSE LAKE FRAGMENTS

by

C. P. Butler

Physicist, U.S. Naval Radiological Defense Laboratory
Research Associate, Department of Astronomy,
California Academy of Sciences

INTRODUCTION

The Goose Lake meteorite was discovered in Modoc County, California, by three hunters in the fall of 1938, removed from the site in May, 1939, and brought to San Francisco, where it was exhibited at the Golden Gate International Exposition. After the close of the fair it was shipped to the Smithsonian Institution where it is now on display in the United States National Museum.

The original site of the fall was re-examined in 1960, when a large meteoritic fragment field was discovered in and around the impact point. These fragments have raised several new questions to add to those already associated with this remarkable meteorite. This paper is the first report on the distribution, morphology, and metallurgy of these particles, and some speculations on their relationships to the cavities and low terminal velocity of the main mass.

BACKGROUND STUDIES

The Goose Lake meteorite is unique among most of the existing meteorites, principally because of its peculiar cavities, the origin and significance of which have been controversial for a number of years. Several of these are clearly shown in figure 1.

A typical cavity in this iron is 11 centimeters deep, 5 centimeters in diameter at the aperture, with a slightly larger diameter at the bottom of the hole. Width to depth ratios range from 0.25 to 1.10. In one case, a hole forms a tunnel completely through the mass. Around the edges of the cavities, there is an overhanging lip of deformed metal with serrated radial grooves extending back a short distance. These overturned edges are not apparently related to the origin of the cavities but may be due to some thermal action during flight through the atmosphere.

Three possibilities have been considered by Henderson and Perry (1958a) to account for such cavity formation during flight:

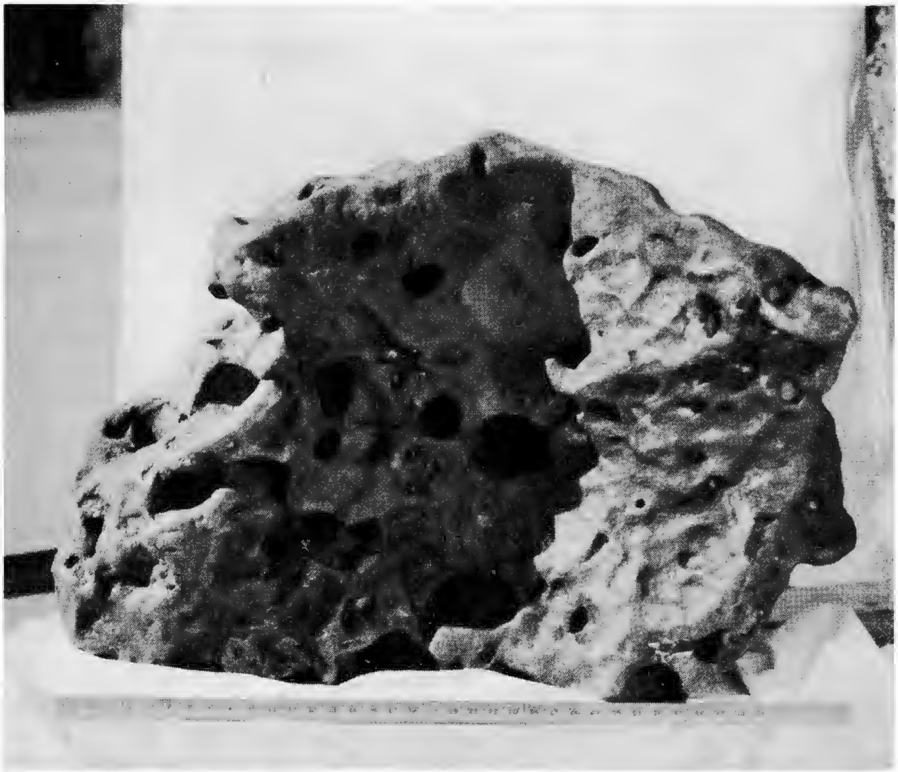


FIGURE 1. The Goose Lake meteorite, showing its cavities and two typical overturned-rim formations. This photograph was made soon after arrival at Mills College, Oakland, California, and before exhibition at Treasure Island.

1. Burned out minerals. Troilite and carbon inclusions occur in rounded masses in iron meteorites, often an inch or more in diameter, but none have been found approaching the dimensions of the cavities. The melting temperatures of troilite and schreibersite are close to 1000°C. but the microstructure of slices cut through a cavity does not indicate that temperatures this high were ever reached.

2. The energy trap. If a small crevice or hole pre-existed, particles striking this depression would erode the sides, thus deepening the hole since they would not be deflected from the surface. If such a condition existed on the leading edge or forward face of the meteorite when the stagnation temperatures and adiabatic pressures were the highest, the rim of the holes would certainly heat just as rapidly and erode away leaving a shallow depression, instead of a deep hole.

3. Wave action within a cavity. It might be assumed that during the ablation period, spallation of the surfaces would free small particles which would be caught in a pre-existing hole and enlarge them by repeated impacts around the interior. This is analogous to the holes formed in solid rock on river bottoms, where stones are rolled around by the water currents forming deep circular holes. It is hard to visualize how such a mechanism could remove the volume of metal required in the short time available during its fall.

There is ample evidence that the cavities are not due to weathering, principally because the cavities are uniformly distributed over the surface which would not be the case had the iron rested on the ground long enough for oxidation on the under side to erode away large masses. Furthermore, the Modoc Plateau is semi-arid, with an annual rainfall of about 12 inches, approximately half of which falls as snow.

Henderson and Perry (1958a) concluded that the cavities existed before the iron entered the atmosphere and further that "this meteorite is not much smaller now than when it formed in some primordial body; that no large piece broke off during flight and that this is probably not a portion of the metallic core of the planetlike body where it was formed."

All the evidence available indicates that the iron landed gently. When found, about half the mass protruded above the surface of the ground, just as though it had been dumped from a truck. Measurements of the crater depth made in 1961 showed that the distance from the surface to bedrock was about 9 inches. There are no discernible impact scars on the iron, even though it fell on hard basaltic rock. The sand and detritus are so thin in this area that one can easily scrape away the surface material by hand, exposing the bedrock underneath.

Linsley (1939), who was present at the time it was recovered, reported: "There was no evidence of shattered rocks indicating a recent fall and there were no skid marks to show that the meteorite had swept along the surface and come to rest where it was found. There was only a slight depression in which it rested, which appeared to be due in part to wind erosion as the air currents had eddied about it. A marmot seeking a bombproof shelter had made a home under it."

Something acted like a cushion at the end of its flight, and here it is tempting to suggest that it fell in winter into a deep snow bank. The total depth of accumulated snow for Modoc County is estimated to be 50 inches, but it should be noted that the deep snows do not occur in flat denuded windblown areas. Snow banks deep enough to cushion such a mass can accumulate only in the lee of canyons or in heavily wooded regions.

The cavities may be related to its slow descent as suggested by Cornish in Henderson and Perry (1958a), "The large cavity which made an opening through this iron probably would give the body considerable spin during its fall. This spin would generate enough lift to reduce the velocity of the fall." If an effect of this kind is possible, there is still the question of explaining the absence of intense ablation heating, for there are no evidences of either a fusion crust on the surface, or granulation of the Neumann lines which extend almost unbroken to the very edge.

METEORITIC FRAGMENTS

At the time the Goose Lake meteorite was discovered, the concept that molten droplets of iron from a glowing meteor would settle to the earth and could be recovered from the soil was not widely recognized, although Spencer (1933) had reported evidence of metallic rain of meteoric origin in the Henbury Craters in Australia. At that time ablation heating and the re-entry problems associated with missiles and satellites was not yet a serious scientific problem.

Professor Leonard (1940), who was present at the time the Goose Lake meteorite was removed, reported, "Although further and more conclusive evidence of the impact as well as other meteorites, were diligently searched for in the neighborhood, none was found." Ninninger (1956), another member of the recovery party apparently did not use the magnetic cane which he says had "been an essential part of our field equipment since 1933."

Since 1939, a great deal of work has been done on recovering meteoritic particles from the soil, both in Arizona around the Canyon Diablo Crater and at the site of the great Sikhote-Alin fall in 1947 in eastern Siberia. Krinov (1960) and his colleagues recovered large numbers of meteoritic particles of this fall which were scattered over an area of several square miles. Small globular droplets of nickel-iron ranging in size from 8 microns to 0.10 millimeters in diameter were found scattered over a very wide area.

These are true ablation products, blown off the melting surface of large masses during flight, and which subsequently condensed in little spheres. Their original microstructure and composition are not identical with the main masses because their temperatures were at least 1500°C. in an oxidizing atmosphere. Krinov calls these ablation products "meteoric dust." Besides the little droplets, they also found a great many fragmentation particles, ranging in size from tiny flakes to pieces weighing several pounds. Polished sections of these pieces showed that they retain both the microstructure and composition of the main body. These fragments are not ablation products, but are produced by mechanical forces set up by shock waves in the main mass during its flight. He calls these fragments "meteoritic dust," and from his descriptions they are apparently identical to the particles which Ninninger found around the Canyon Diablo Crater in Arizona and which he calls "sluglets." The Canyon Diablo is estimated to have fallen some 50,000 years ago, a sufficiently long time so that one would intuitively assume that tiny fragments of the nickel-iron would either be completely rusted away, or would be so dispersed by weathering that recovery would be very unlikely. Yet, in Ninninger's words, ". . . the idea that all small particles resulting from disintegration of large meteorites would undergo immediate oxidation was seriously in error."

An important difference between the Goose Lake and other fragment producing falls is that there is no evidence that its impact velocity was high. The Sikhote-Alin was seen to break up during flight and its fragments were found scattered over several square miles. The impact velocity of the Canyon Diablo was sufficient to produce complete fragmentation accompanied by an explosion which excavated a hole in the ground 570 feet deep and 4000 feet across. While the main mass of the Goose Lake weighs a little more than a ton, there is no evidence of any fragmentation of the main body or crater formation at the place where it was found. It has been suggested that it landed some distance away and bounced, coming to rest where it was found. In this paper, the place where it was found will be called the "impact site" as the simplest description of its terminal location.

FIRST GOOSE LAKE EXPEDITION, 1960

In the light of the work done on recovering meteoritic particles during the last two decades, it seemed odd that no particles had been reported from the site of the Goose Lake fall. Inquiry showed, however, that no magnetic survey had been made, and as far as known, no one visited the site between 1939 and 1960, except stockmen and hunters who would not have been interested by a pole marker in the midst of a barren rock strewn area.

In 1960, the California Academy of Sciences approved a preliminary survey of the site, and in June of that year, the author and his son carried out the first magnetic survey of the Goose Lake impact site.

Aside from the coordinates of the site given by Leonard (1956), the only clue to its location on current Forest Service maps is an excavated reservoir designated by a sign reading "Meteorite Stock Tank," which is

FIGURE 2. Photograph of the Goose Lake meteorite *in situ* at the time of discovery, October 13, 1938.

almost half a mile south of the actual site. When the meteorite was removed from the small crater in which it rested, the recovery party marked the spot with a pole picturesquely described by Leonard, ". . . as a rude monument or marker, hewn from the trunk of a nearby sapling."

With the able assistance of the U. S. Forest Service in Alturas, we found this same pole intact and still erect, together with other small poles lying about on the ground which were apparently used in hoisting the heavy mass onto the wagon. From pictures made at the time of discovery and before the iron had been moved, we were able to identify the same trees on the horizon, even though they were somewhat taller than 21 years ago. One very tall tree showing on the original print is now missing, but we found it lying on the ground, its stump corresponding to its original location.

Figure 2 shows a print of the Goose Lake meteorite before it was moved at the time of discovery, October 13, 1938, and figure 3 is a picture taken from about the same position in June, 1960, showing the pole marking the impact site, and the same trees in the background.

Within a matter of minutes from the time we started searching the area with a hand-held magnet, it was clear that meteoritic particles lay

FIGURE 3. Photograph of the impact site of the Goose Lake meteorite, made in June, 1960.

about in great profusion. These were bottled, labeled, and returned to the Academy for further study.

Second Goose Lake Expedition, 1961

The success of the first survey in recovering meteoritic fragments prompted plans for a second survey of the field with more people. The second Academy-sponsored expedition in September, 1961, included representatives of the U. S. Geological Survey, the California State Division of Mines, and the California Academy of Sciences. A much more thorough search of the area was conducted, including partial excavation at the impact point to determine the extent of bed-rock deformation. Many more specimens were recovered, including large oxide fragments lying quite exposed at some distance from the site.

Magnetic Recovery Methods

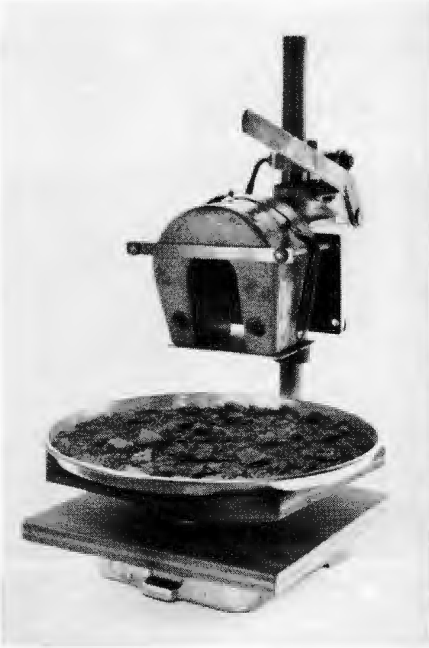
During the course of the first survey, no excavations were made, partly because we wanted the evidence perfectly clear that particles of nickel-iron and oxide were lying within a few millimeters of the surface of the ground. A handful of soil was scraped from the ground and poured over the end of a large conical magnet and during this operation magnetic particles in the soil were drawn to and held by the magnet. Some of the material is magnetite, but this was readily separated from the nickel-iron by shaking the magnet, the weaker magnetite falling off while the nickel-iron fragments adhered as tightly as an iron nail. (The small magnetite particles must be quite impure, because of their weak magnetism.) This method has the disadvantage that meteoritic oxide particles may not be recovered, because they are less magnetic and may be lost.

Similar methods were used during the second expedition, but this time the small magnet was replaced by a much larger double-pole magnet which was provided with a long handle so it could be carried and lowered over a given place. On this occasion, also, magnetic samplings of the soil were bagged, marked, and returned to the Academy for analysis.

When the distribution of the large black massive-oxide fragments was found to extend well beyond the limits of a few feet from the impact point, areas of about 10 feet square were paced off at likely distances and azimuths. Then a visual search was made by going over this area on hands and knees, looking for the distinctive sheen of the oxide fragments. After this visual search, a second scanning was made with a hand-held magnet. The material from each plot was then bagged and labeled.

A more thorough search was conducted later on these samplings by mounting the same magnet with the pole pieces facing down on a drill press stand, spreading a small amount of the field material on a shallow aluminum pan, and moving the pan around underneath the magnet. It was possible to readily adjust the height of the magnet pole so that the magnetite particles would not be drawn up as were the meteoritic particles. A thin aluminum plate held to the magnet by a spring, was placed so as to extend over both pole pieces, and each time a nickel-iron particle was separated, a distinct ping could be heard as it struck the plate. When all the particles had been removed, the magnet was inverted bringing the aluminum plate on the top with all the particles clustered around the two poles. Then, detaching the spring, the plate could then be lifted vertically and the particles scooped into bottles. This method keeps the pole pieces clean, and allows all the particles from one sample to be collected with no contamination from previous sampling.

A photograph of the separator is shown in figure 4. This is a somewhat simplified version of the automatic magnetic sampler used by Rhinehart (1958) in his magnetic survey for meteoritic particles from the Canyon Diablo area.



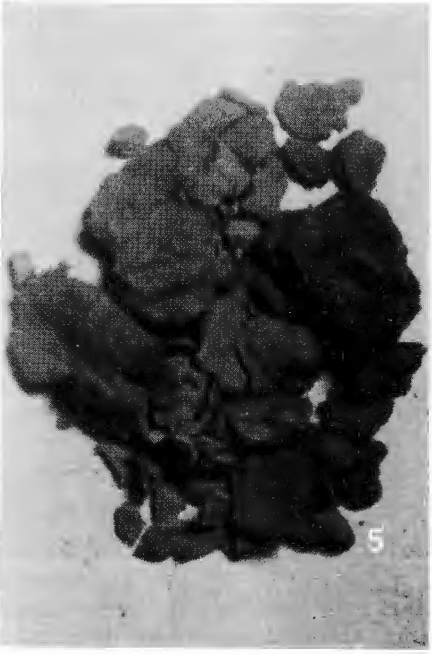


Figure 4. Photograph of the magnetic separator used to sort out the nickel-iron fragments from the soil.

Figure 5. Typical massive oxide fragments found lying on the surface of the ground, and concentrated in a small area approximately 250 feet south of the impact site. The largest piece measures about 3 centimeters in length.

After separating the particles, they were cleaned with a fine brass wire brush, the heavy crusts and adhering soils removed with a dental scaler. This latter operation must be done under a low power microscope.

After cleaning in this manner, some of the particles were mounted in 1-inch diameter lucite blocks, ground down with course emery paper until an appropriate area for study had appeared and finished with 600-grit paper. They were then carefully washed with water to remove any remaining grits, and polished on a wheel with a felt lap saturated with AB alumina polishing compound. The polishing was carried on until a good specular finish was obtained with few scratch marks or comet tails. Since the lucite is so much softer than the iron, it polishes away faster making the surfaces slightly convex, especially at the edges where the nap of the polishing cloth cuts away the interface between the iron and lucite. For this reason, the Neumann lines which extend to the edges are not quite in the same vertical plane as those in the center. All etching was done with Nital. Alternate polishing and etching was followed until the lines were clear.

MORPHOLOGY OF THE GOOSE LAKE FRAGMENTS

1. THE NICKEL-IRON PARTICLES. The shape and appearance of eight fragments of the nickel-iron found during the first expedition in 1960 are shown in figures 6 and 7. Their dimensions are indicated by scales and their in-

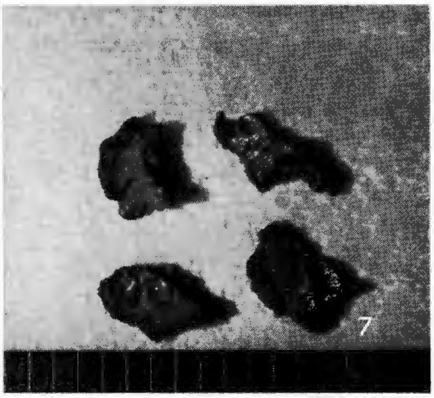


FIGURE 6. Typical nickel-iron fragments before cleaning. These were found within a radius of 10 feet from the impact site. The scale shown along the lower margin indicates millimeters. The weights of the fragments given in grams are 0.148, 0.162, 0.183, and 0.122 respectively.

FIGURE 7. Typical nickel-iron fragments which have been cleaned with a soft wire brush. The scale shown along the lower margin indicates millimeters. The weights of the fragments given in grams are 0.383, 0.250, 0.525, and 0.217 respectively.

dividual weights are given in each caption. Those in figure 6 are just as they were removed from the magnetic separator, those in figure 7 have been cleaned with a soft wire brush.

The color of the nickel-iron particles before cleaning is a light brown or mahogany shade, identical with the soil. It is very difficult to distinguish these by visual inspection from similarly shaped particles of rock. They do not exhibit the characteristic brick red of freshly oxidized iron. When cleaned, however, they look very much like many of the large iron meteorites which exhibit the typical dull dark-grey sheen.

One feature common to almost all the nickel-iron particles is that they are flattened. A rough estimate gives the average thickness to length ratio of about 1/10. These dimensions were measured by placing each particle between the jaws of a micrometer, so that the thickness figure includes any protuberance or nodule. Some of the fragments excavated at the crater during the second expedition measured 0.1 centimeter thick and 1.0 centimeter long. The nickel-iron fragments from below the surface show a greater size range than those found on the surface. There is a marked similarity between the shape of these flattened particles and the Algoma, which Farrington (1915) calls a peltoid or shield shape, even though the dimensions differ by a factor of at least 50.

These pictures of the Goose Lake fragments should be compared to Ninninger's sluglets from Canyon Diablo. The hook shape is common to both and the tiny hole in the lower right hand specimen in figure 7 is very much like the holes in some of the sluglets. The protuberances have the same general appearance. The dimensions of the sluglets are about the same as those just described from Goose Lake.

One of the smallest individual nickel-iron specimens of the Sikhote-Alin shown by Krinov has the same weight as that of the lower right specimen in figure 6, and shows much the same surface topography. The Goose Lake fragments, even after cleaning, do not appear to be as shiny and smooth as those of the Sikhote-Alin.

2. The massive oxide fragments. The shape and appearance of the Goose Lake meteoritic oxide fragments is entirely different from the nickel-iron fragments. A few of these oxide fragments are shown in figure 5, photographed soon after they were found. These are most easily recovered by simply scanning the ground visually for their distinctly black sheen. There are no other rocks in the vicinity which have quite the same color. They are all magnetic, intermediate between magnetite and the nickel-iron, and hence can be immediately checked in the field for meteoritic origin. The fine powdery soil which was so adherent to the nickel-iron had apparently been blown or washed from these fragments, leaving the surfaces

quite clean. No large pieces of the oxide were recovered from the pit excavated at the impact site. However, there were many tiny oxide fragments mixed with the nickel-iron fragments, not only on the surface but below as well. Those found mixed with the soil did not have the characteristic black sheen of the surface specimens, since they were covered with the light-brown soil. However, they can often be recognized from their shape.

All the oxide fragments recovered show sharp fracture planes, including the very smallest. The larger specimens taper toward the edges, giving an elliptical cross-section. The sloping edges are not smooth, however, but reveal steps formed by the lamellae planes.

The shapes of the ends of these oxide fragments suggest a block puzzle. Of all these pieces of the oxide, only two were found which fitted together just as though they had recently been broken. As shown in figure 8, it is obvious that they were originally one piece. These large pieces are quite homogeneous, are very hard and cannot be broken by hand. By contrast, the thin oxide flakes can be pinched in two with the fingers.

FIGURE 8. Two pieces of massive oxide which fit together perfectly. It is not known how close together these lay. The larger weighs 8.19 grams, the smaller 3.70 grams. The scale indicates a length of 1 centimeter.

FIGURE 9. Circular raised rim of hydrous iron oxide on one of the massive oxide fragments. Weight 2.08 grams. The number (9) shown directly above the scale is the figure number and is not related to the scale. The scale indicates a length of 1 centimeter.

In the interstices of the lamellae, tiny deposits of salts and soil can be seen under the microscope. The salts appear white when dry, green when wet, can be removed easily with a pointed scaler.

One specimen of the oxide shows a small circular raised rim of brown hydrous iron oxide, shown in figure 9. It has been suggested that this might also be the remains of an impact crater when the original metal was in a near molten state. This example should be compared with a similar structure found on one of the Canyon Diablo oxide fragments as given by Buddhue (1957).

The oxide fragments collected from the surface of the ground only, appear to increase in size from the crater or impact point out to about 250

TABLE 1

Weights of the massive oxide fragments found on the surface of the ground by the second expedition to the Goose Lake site.

Specimen No.	Azimuth from Crater (degrees)	Distance from Crater (feet)	Weight (grams)
1	170	125	5.44
2	"	"	2.75
3	"	"	3.61
4	"	"	1.00
5	"	"	1.00
1	180	150	2.61
2	"	"	1.17
3	"	"	1.11
4	"	"	0.75
5	"	"	0.62
6	"	"	0.48
7	"	"	0.36
8	"	"	0.25
9	"	"	0.24
10	"	"	0.19
1	170	200	10.85
2	"	"	2.18
3	"	"	2.08
4	"	"	1.28
5	"	"	0.91
6	"	"	0.26
7	"	"	0.21
8	"	"	0.18
9	"	"	0.15
10	"	"	0.11
1	174	250	13.31
2	"	"	12.34
3	"	"	11.45
4	"	"	8.20
5	"	"	6.91
6	"	"	4.32
7	"	"	4.16
8	"	"	3.70
9	"	"	2.69
10	"	"	3.24

feet to the south and then terminate. There are also many small ones mixed with these large pieces. The east and west distribution is roughly 20 feet on either side. It should be emphasized that the terrain slopes gently to the south, so that the natural drainage is in the same direction as the principal distribution of the surface oxide fragments. The prevailing wind however, is at right angles to this, *i.e.,* from the west.

The individual weights of the large oxide fragments collected from the four principal concentration areas to the south of the crater are given in table 1. These were found only on the surface, during the second expedition and may or may not represent the true aerial distribution. This list includes only the ten largest specimens from each area, but does not include any of the nickel-iron particles.

An effort was made to estimate the total number of nickel-iron individuals and their weight distribution, but this was not satisfactory. It is a simple matter to weigh and count the larger specimens, but as they get smaller and smaller, their individual weights are more and more affected by the thin oxide layer covering all the nickel-iron fragments. Besides this, the amount of adhering soil and salts on each particle contributes more and more to their weights.

A few of the larger nickel-iron fragments weighed about 0.200 grams, but most weighed much less than this. When the weights approached 20 milligrams, the uncertainties mentioned above introduced very large errors. We have not estimated how many of the smallest sizes were recovered, but the number is certainly in the thousands.

During the course of both expeditions, it was anticipated that ablation products in the form of spherical particles would be found. There are some tiny, nearly spherical particles, but under the microscope they are seen to have a crystalline form suggesting magnetite. The fact that we found no true ablation products adds further evidence to confirm Henderson's theory that this iron fell through the atmosphere at a low velocity.

METALLURGY OF THE FRAGMENTS

A number of the nickel-iron particles were examined under the microscope to determine their internal structure and composition. These are shown in figures 10 through 15, with some description of each. In all cases examined, Neumann lines appeared. Since these lines appear only in kamacite, it can be stated that all the nickel-iron particles recovered and examined are kamacite. A few thin threads of taenite were found traversing the fragment. The Goose Lake iron is a coarse octahedrite, and if all the nickel-iron fragments are kamacite, then there is no question that they are

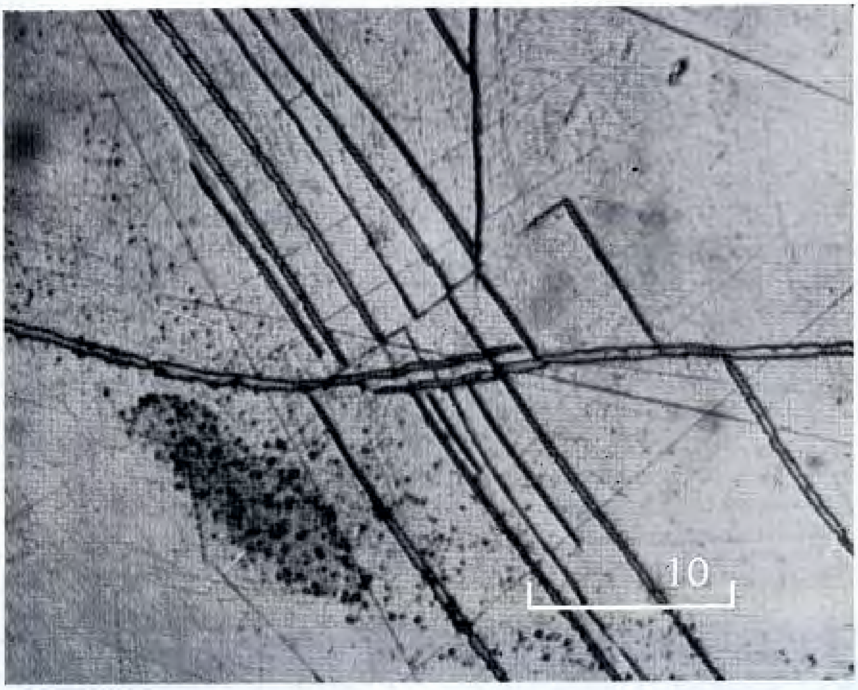


Figure 10. Undistorted Neumann lines near the center of a nickel-iron fragment. The number (10) shown directly above the scale is the figure number and is not related to the scale. The scale indicates a length of 10 microns.

not fragments of the parent body, *i.e.,* the particles were not removed either during flight, or mechanically by shock when it landed. However, no nickel-iron particles have been found and examined which are greater than the widest kamacite bands in the main mass, so if some mechanism could selectively remove fragments like those we discovered, this would support the possibility that the main mass is the parent body.

It is generally agreed that Neumann lines disappear at temperatures above approximately 400°C, and since every nickel-iron fragment shows these lines clearly, it seems evident that they were never heated above this temperature and hence cannot very well be ablation products. If they were not formed this way, then they must have been broken from a larger body mechanically. Since there is no evidence that the main mass suffered a severe shock on impact, we must conclude that the particles existed before entry and were carried down through the atmosphere in the cavities or in the wake of main mass.

In all specimens the nickel-iron particles show evidence of mechanical strain or mechanical shock in the displacement and bending of the Neumann lines. Many show the lines extending undistorted to the edge of one side, while at the other side of the specimen the lines are bent and twisted and in some cases completely granulated. The appearance of cross sections of these particles suggests that they were projectiles at one time and that they struck something hard. Their impact velocity was not sufficient to raise their temperatures above 400°C, but was high enough to cause deformation at the leading edge.

One case in particular shown in figure 16 is that of an elongated fragment which apparently suffered a head-on collision, bending completely back on itself, in exactly the same way as a nail driven through a thin board backed with an iron plate. One Neumann line could be followed all the way around the end until it was nearly parallel to itself going in the opposite direction. As in some of the other examples, the small end of this specimen was apparently the leading edge, since all lines were obliterated at the tip. At the other end, the lines appear in their normal undisturbed form. This little spike was apparently traveling like an arrow when it collided with a solid surface just hard enough to double it back.

The hypothesis that an extraterrestial shock effect can be observed in meteoritic iron is not new. From analyses of the deformation structure in

FIGURE 11. The same specimen as shown in figure 10, taken near one edge, showing deformation of the lines. The scale shown in the upper part of the figure indicates a length of 1 millimeter.

kamacite, Maringer and Manning (1962) tentatively conclude that a relatively slow impact velocity between a large and a small body in space could produce this kind of deformation. The gross forms as well as the internal evidence of the Goose Lake fragments apparently confirm this suggestion.

One slice of the Goose Lake meteorite was available for making comparisons between its internal structure and that of the fragments. There are some likenesses, but the long clean curving Neumann lines at the edge of this slice have not been found among the nickel-iron fragments. In this slice, there are many well formed rhabdite inclusions mixed with the kamacite, but none have been found in the Goose Lake particles. Likewise, no troilite inclusions have been found, although they are found in the main mass. This may not be unusual, however, because the troilite inclusions are roughly the same size as the fragments, and since this mineral is non-magnetic, it may not have been recovered from the soil by our techniques.

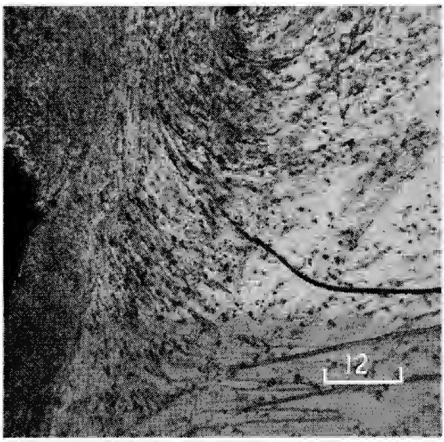
A few of the larger massive oxide fragments were ground and polished, one of which is shown in figure 17. Etching was unnecessary to reveal either the laminar structure, or the rhabdite inclusions. This characteristic laminar form is almost identical to that of the massive oxide from Canyon Diablo as can be seen in a similar specimen shown by Buddhue. Likewise, the rhabdite crystals in the oxides appear identical to those found in the Canyon Diablo as shown in figure 18.

The Origin of the Goose Lake Fragments

The principal conclusion of these preliminary studies of the Goose Lake fragments centers around the question of whether the particles we discovered were once a part of the main body.

Since well developed Neumann lines have been found in all nickel-iron particles so far examined, it is clear that they are not ablation products. If they had been torn away mechanically from the surface of the main body, either by violent vibrations during flight or by the shock of impact with the ground, evidence of surface spallation should show on the surface of the iron. None has been found.

Since taenite melts at a lower temperature than kamacite, Henderson (1956a) has suggested that at the leading edge of the main mass where the layers show some thermal deformation, ablation heating could loosen or at least weaken the bonds between the taenite and kamacite plates. Then the shearing action of the atmosphere during deceleration might tear off some of the kamacite plates. If this occurred, it seems reasonable that some of these particles of kamacite would be caught in the turbulent wake, or in the cavities and be carried to the ground. There remains the question of how this process could produce so many particles, and whether the heating time required to weaken the bonds would also obliterate the Neumann lines



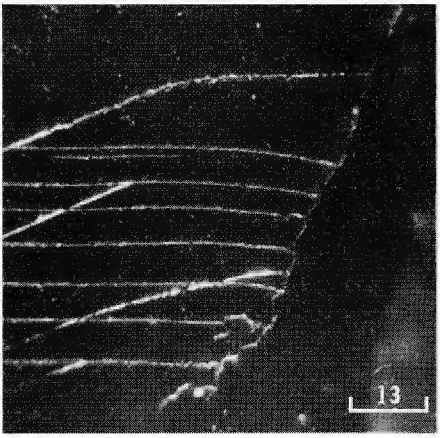


Figure 12. Leading edge of a nickel-iron fragment showing three undistorted Neumann lines completely granulated toward the edge. The number (12) shown directly above the scale is the figure number and is not related to the scale. The scale indicates a length of 100 microns.

Figure 13. The same specimen as shown in figure 12, taken from the opposite side of the fragment. Note that the lines extend completely undisturbed to the edge. These same lines connect with the three of figure 12. The number (13) shown directly above the scale is the figure number and is not related to the scale. The scale indicates a length of 100 microns.

in the kamacite plates. The outer surface of the main mass does not show that such a phenomenon took place, but it is conceivable that subsequent heating and pressure smoothed the leading edge where the fractures took place. While this concept has some attractive features, it does not appear to explain the occurrence of the fragments as simply as the following account.

Another alternative which seems more attractive, is that the fragments pre-existed and accompanied the main mass when it was captured by the gravitational field of the earth. If this third concept is tenable, then some hypothesis is required to account for the high concentration of particles so close to the point where the meteorite was found.

While we have no direct information on this point, it is tempting to suggest that they were transported through the atmosphere in the cavities. After reaching the ground, weathering on the top and gravity on the bottom removed the nickel-iron particles from the holes, scattering them in the immediate vicinity of the impact point. The highest concentration was actually in the bottom of the pit, directly under the place where it fell. So far as we know, no one at the time of discovery thought to make a thorough examination of those cavities facing upward to see if any of the fragments were lying in the bottom.

It is quite certain that we have not recovered all the material at the site, but the total volume of all we have found, including the large oxide fragments could easily fit into the cavities, with room to spare. Cavity transportation of the fragments would account for their concentration around the impact point.

If we assume that the main mass of the Goose Lake meteorite had passed through swarms of tiny particles such as we have discovered, it seems reasonable to suppose that during the thousands of years it was orbiting through the solar system, there would have been hundreds of collisions, say one a year. Further, if the orbits of the particles and of the main mass are nearly identical so that the collisions made soft impacts, then there would be no spallation of the surface of the main mass nor fusion of the particles owing to heating by their sudden loss of kinetic energy. We will assume that the impact velocity is just sufficient to partly deform the particles which we have described. This would explain the deformation of the Neumann lines on the leading edge of the particle, leaving those on the trailing edge intact.

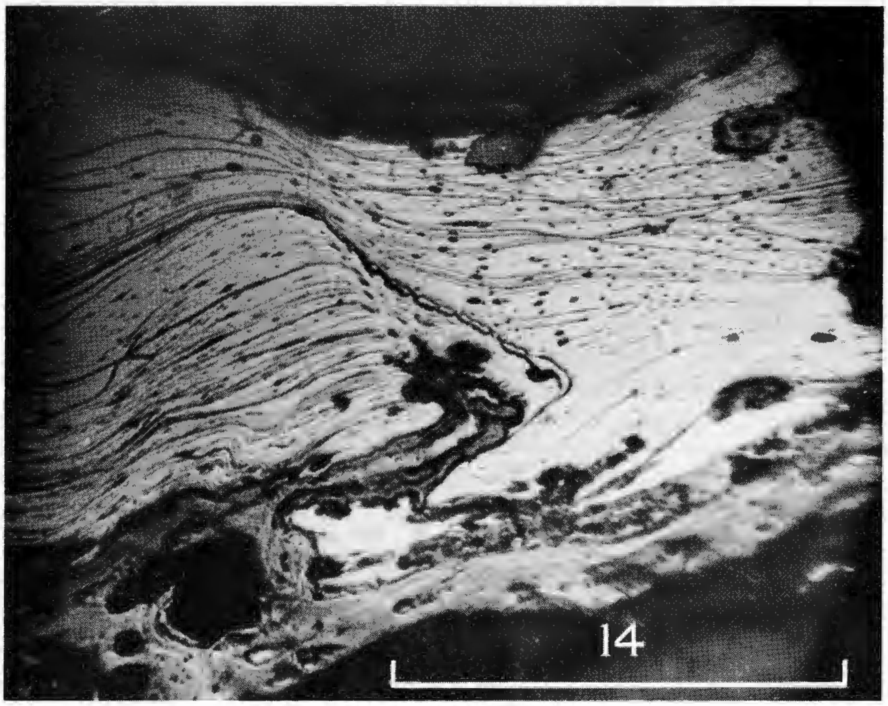


Figure 14. Lateral displacement in Neumann lines. The number (14) shown directly above the scale is the figure number and is not related to the scale. The scale indicates a length of 1 millimeter.

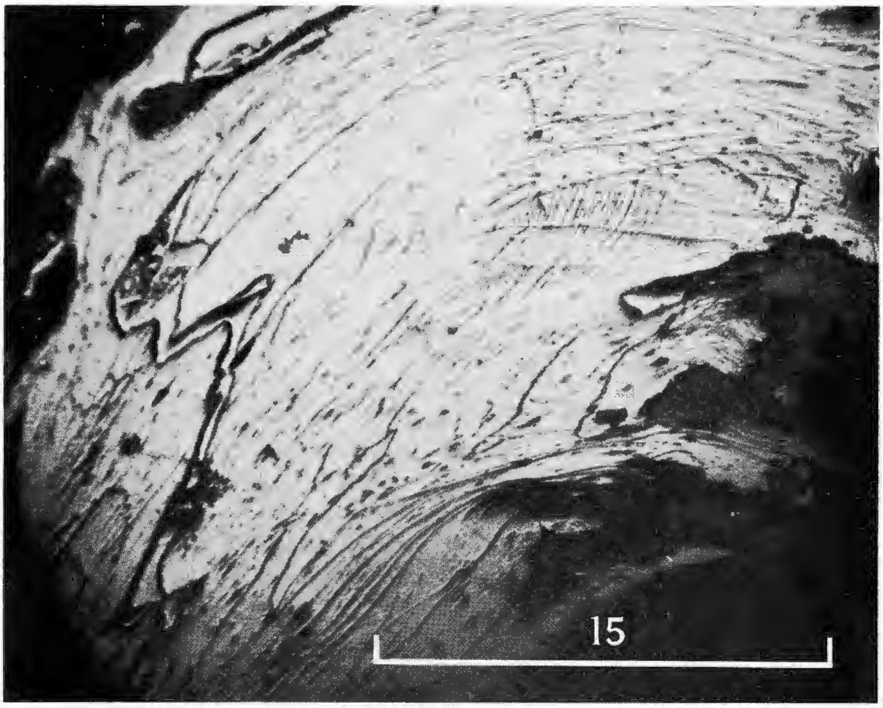


FIGURE 15. Large bend in a nickel-iron fragment, showing an inclusion of taenite bent in a jagged Z-shape. The number (15) shown directly above the scale is the figure number and is not related to the scale. The scale indicates a length of 1 millimeter.

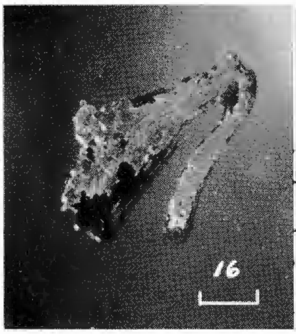
Now, if the magnetic and gravitational forces between the main mass and these particles is sufficient, those which have collided in this manner will adhere to the main mass and be carried along with it, until it begins to encounter atmospheric drag as it approaches the earth. At this time, those particles which are on the outside will be swept away by the violent turbulence of the air stream and will fall to the earth over very widely scattered areas. Those others, however, which enter the apertures and collide with the bottoms of the cavities will be protected from the streaming atmosphere and will remain in their protected holes until arriving at the surface of the earth.

The oxide fragments present another puzzling problem. Had these not been found, we would have concluded that the large numbers of small nickel-iron particles on the surface show further evidence that the Goose Lake fall is of recent origin. Furthermore, if our preliminary conclusions are correct, that these nickel-iron fragments are not a part of the main mass, we have suggested a method by which they could have been transported from the orbit of the main mass to the ground.

The thick oxide fragments, however, indicate that they have been subjected to oxidation processes for a very long time. Their thicknesses are not greatly different from the massive oxidation fragments from the Canyon Diablo. It is not clear how pieces of this meteoritic oxide ranging in size from a few milligrams to 13 grams could still be clustered on the surface of the ground so close to the impact point for even a fraction of the time required to form this thick stable oxide. This area is wind whipped by violent storms characteristic of the high Sierras, especially in winter. These winds would certainly scatter particles like these over wide areas in a fraction of the time presumably required to form these thick laminar oxide layers.

It is possible, of course, that we are dealing with more than one fall. In this case, there should be evidence of a fall nearby and many more of these fragments throughout Modoc County.

However, if no more oxide fragments are discovered, and if the Goose Lake meteorite did fall within the last fifty years or so, then we must conclude that the oxide fragments were transported in a manner similar to that of the nickel-iron fragments, *i.e.*, in the wake of the main body or in its cavities. The origin of pre-entry massive oxide meteoritic fragments requires further study.



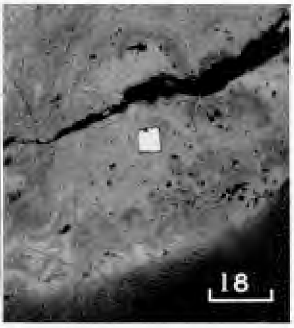


Figure 16. Hook-shaped nickel-iron fragment. Individual lines can be followed all the way around the bend. The number (16) shown directly above the scale is the figure number and is not related to the scale. The scale indicates a length of 1 millimeter.

Figure 17. Flat side and edge of massive oxide fragment revealing laminar structure. The number (17) shown directly above the scale is the figure number and is not related to the scale. The scale indicates a length of 1 centimeter.

Figure 18. Rhabdite crystal in one of the massive oxide fragments. No etching. The number (18) shown directly above the scale is the figure number and is not related to the scale. The scale indicates a length of 100 microns.

SUMMARY OF THE EVIDENCE

Two types of meteoritic particles have been discovered at the site where the Goose Lake meteorite was found; nickel-iron fragments of kamacite whose weights are in tenths of grams and massive laminar oxide fragments weighing up to 13 grams. The former are concentrated close to the assumed impact point, the latter distributed out to distances of approximately 300 feet.

The appearance of Neumann lines in the nickel-iron fragments indicates that they were never heated above about 400°C. The bending and twisting of the lines shows that they were deformed while cold.

The massive laminar oxide fragments, showing rhabdite inclusions, are identical to those found at Canyon Diablo.

CONCLUSION

Evidence that the Neumann lines in the nickel-iron fragments are dissimilar to those in the Goose Lake meteorite indicates that their origin is independent of this mass of iron, that they were swept up by the meteorite during its long life in orbit around the solar system. Only those fragments which found their way into the cavities were recovered, any others were blown off by the air stream during its final flight. Cavity transportation explains their abundance at the impact site, as well as protection against aerodynamic heating. Deformation of the nickel-iron fragments occurred when they collided with the main mass in space.

The massive laminar oxide fragments suggest a second meteorite fall in the same vicinity as old as Canyon Diablo.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to the California Academy of Sciences for its support in this work, especially in view of the fact that all published data on the Goose Lake meteorite up to the time of the first expedition were silent on the subject of fragments. A number of people were most helpful in the early stages of this work before the problem had been fairly defined. Dr. Max Hey of the British Museum and Dr. E. M. Shoemaker of the Geological Survey made valuable suggestions as well as providing me with specimens of other meteorites for comparison studies. Special mention should be made of the voluminous correspondence and personal discussions with E. P. Henderson of the Smithsonian Institution. He very kindly made available a slice of the main mass, together with permission to polish and etch it in the same way as the fragments.

For some 12 years, the author has been fortunate in having the advice and counsel of Dr. G Dallas Hanna in problems relating to optical materials,

eclipse instrumentation, and in meteoritics. His enthusiastic and youthful outlook has been an inspiration, and it was largely through his encouragement that the first formal proposal was submitted to go in search of the Goose Lake fragments.

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