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Meteor Ablation Spheres From Deep-Sea Sediments

M.B. Blanchard, D.E. Brownlee, T.E. Bunch,
P.W. Hodge, and F.T. Kyte

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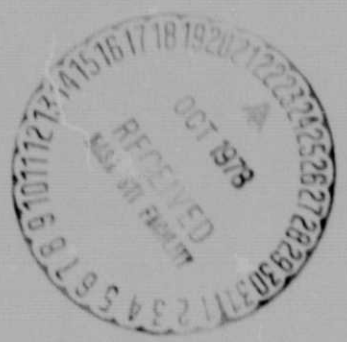

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M.B. Blanchard, Ames Research Center, Moffett Field, California
D.E. Browniee, California Institute of Technology, Pasadena, California
T.E. Bunch, Ames Research Center, Moffett Field, California
P.W. Hodge, University of Washington, Seattle, Washington
F.T. Kyte, San Jose State University, San Jose, California

NASA
National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035

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M.B. Blanchard*

D.E. Brownlee**

T.E. Bunch*

P.W. Hodge***

and

F.T. Kyte†

*NASA Ames Research Center

Moffett Field, California 94035

**California Institute of Technology

Pasadena, California 91125

***University of Washington

Seattle, Washington 98195

†San Jose State University

San Jose, California 95192

ABSTRACT

This paper describes analyses of spheres which were magnetically extracted from mid-Pacific abyssal clays ranging in age from 0 to 500,000 years. The concentration of spheres larger than 200 microns was found to be a few times 10 ppb. The spheres were readily divided into three groups using their dominant mineralogy. These groups are named iron, glassy, and silicate. Most of the spheres were formed from particles that completely melted and subsequently recrystallized as they separated from the parent meteoroid bodies. However, some of the silicate spheres contain occasional relict grains of the parent metoroids that did not experience any melting. Typically, these relict grains are olivine crystals whose cores are Mg-rich, ranging from Fo_{89-99}. Commonly the outer rim of these relict grains was altered during heating. Other relict mineral grains include enstatite, ferrous spinel, chromite, and pentlandite.

The three groups of spheres (iron, glassy, and silicate) may possibly have some genetic significance. It seems reasonable to expect iron-rich spheres to be produced during ablation of iron and metal-rich silicate meteoroids. Metal spheres are probably not produced by ablation of predominantly silicate meteoroids because studies of fusion crusts and laboratory ablated silicate materials have never yielded separate metal spheres, but rather have produced spheres with intergrown iron oxide and silicate phases. The iron spheres recovered possess identical mineralogy with the fusion crusts of Boguslavka, Norfork, and N'Kandhla iron meteorites as well as with the ablation debris created in the laboratory using metallurgical samples of iron and nickel-iron. The combination of several

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iron oxide phases and Ni segregation in individual spheres is convincing evidence of ablation from metallic Fe-rich meteoroids.

The glassy spheres are considerably more Fe-rich than the silicate spheres. They consist of magnetite and a Fe glass which is relatively low in Si. This combination is most likely produced by ablation of metal-rich silicate meteoroids.

The silicate spheres are undoubtedly derived from ablation of stony meteoroids. The olivine-magnetite-glass and sulfide mineral assembleges occurring in these spheres are identical to those described in the natural fusion crusts of Allende, Orgueil, and Murchison meteorites, ablation debris created in the laboratory, and melted interplanetary dust collected from the stratosphere. Bulk compositions and relict grains are useful for determining the parent meteoroid types for the silicate spheres. Bulk analyses of recrystallized spheres have shown that nonvolatile elemental abundances are similar to chondrite abundances. Analyses of relict grains (found in a few percent of the spheres) have identified numerous high temperature minerals which often occur as larger crystals in a fine-grained matrix that is characterized by numerous circular voids. These voids were caused by escaping volatiles (e.g., water, sulfur) produced by decomposition of hydrated and other low temperature minerals during ablation. Because larger crystals of higher temperature minerals are associated with fine-grained, low temperature, volatile-rich matrix, the obvious candidates for parent meteoroids of these silicate spheres are carbonaceous chondrites.

1. Introduction

Over a century ago, Murray and Renard [1] discovered microscopic magnetic spheres in deep-sea sediments. Finding both "stony" and "iron" types, they suggested that the spheres were produced by the melting of meteoroids as they entered the atmosphere. Since their discovery, deep-sea spheres have been subjected to a variety of investigations, but their importance to the science of meteoritics has not been fully recognized. Reviews of much of the early work on the spheres were given by Schmidt [2] and Parkin and Tiller [3]. Most of the previous work has concentrated on the "iron" spheres which are reasonably well characterized and understood; their credibility as extraterrestrial particles is now well established. Evidence is strong that the "iron" spheres were produced by atmospheric melting of iron meteoroids [4,5]. The "stony" spheres have only been studied by a few investigators [6,7,8], and they are only now being extensively examined with modern analytical techniques [9,10]. The "stony" particles have not generated much interest because their properties were not understood, and there was no real evidence that the particles were, indeed, extraterrestrial. The "stony" spheres have been interpreted as droplets produced by ablation of stony meteoroids [6,7] and mistakenly identified as "rounded bodies in space" not altered by atmospheric entry [8]. In this paper we direct most of our efforts to the "stony" spheres because they are the least understood and potentially the most interesting. It is the purpose of this paper to show that the "stony" spheres are extraterrestrial and are generated by ablation of parent meteoroids similar to chondritic meteorites.

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The major technique we have used for identification and interpretation of ablation spheres is a detailed comparison with natural and laboratory ablated materials. Previous work has established a set of criteria for identifying debris produced by atmospheric ablation of meteoroid bodies. These criteria were derived from analyses of meteorite fusion crusts [11-13], ablation debris in the stratosphere [14], and material produced by laboratory ablation of olivine [11], metallic Fe and Ni-Fe [12], Fe-oxides [15], and a carbonaceous chondrite (Murchison) [13]. The criteria useful for identifying ablated extraterrestrial material are as follows:

(1) Occurrence of disequilibrium mineral phases (e.g., wüstite, glass and zoned olivine) due to melting and rapid cooling.

(2) Distinctive textures (e.g., zoned olivine surrounded by magnetite crystals in a groundmass of glass) produced by intergrown dissimilar phases.

(3) Depletion and migration of volatile elements (e.g, S, P, C, Cl, Na, H_2O) due to heating.

(4) Fractionation and concentration of less volatile elements in some mineral phases according to their affinity for oxygen (e.g., Ni-rich metal cores surrounded by Ni-poor oxides).

For iron meteoroid parent bodies, the metal is oxidized, and wüstite, magnetite, and hematite are formed. Since nickel is not as easily oxidized as iron, it concentrates in a metallic core. For chondritic materials (e.g., Allende, Murchison, and Orgueil), two melt phases are formed. The dominant phase is a silicate melt which crystallizes to form grains of zoned euhedral olivine and magnetite in a Ca,Fe,Al,Si-glass matrix. The

other phase, containing Fe, Ni, and S, crystallizes to form iron sulfides (pyrrhotite and/or pentlandite) and iron oxides (magnetite and/or wüstite). Both phases produce spheres when sprayed off an ablating meteoroid, and it is common for silicate spheres to contain inclusions of sulfide minerals.

2. Experimental Procedure

Because studies of fusion crusts and samples ablated in the laboratory produce magnetite from iron-bearing materials, we expect most meteor ablation debris to be ferromagnetic. For a meteoroid to ablate without producing magnetite, it must have a very low iron content. Therefore, the spheres in this study were separated by magnetic extraction from 3 kg of globigerina ooze and 100 kg of Pacific red clay. The samples came from box cores taken from the top 50 cm of mid-Pacific abyssal clays in water depths of 5,000 m. Assuming an average sedimentation rate of 100 cm per 10^6 years [16], the spheres in these sediments range in age from 0 to 500,000 years. The separation process used a magnetic extractor suspended in an agitated slurry of sediment and water. The magnetic fraction was sieved to remove particles larger than 100 μm and ultrasonically agitated to break down fecal pellets. Spheres were hand picked from the larger size fraction. This process was efficient for separating weakly magnetic (i.e., silicates) spheres larger than 100 μm.

Over 700 spheres in the size range 0.1 to 1 mm were selected, mounted, and analyzed with the scanning electron microscope (SEM) to study surface morphology and elemental composition. One hundred and fifty spheres were sectioned and polished for quantitative electron microprobe analysis and

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SEM studies of internal textures and individual crystals. Over thirty spheres were subjected to X-ray diffraction, using a Debye-Scherrer powder camera, for major mineral identification.

3. Results

The concentration of spheres larger than 200 μm was found a few times to be 10 ppb in the red clay and about 1 ppb in the globigerina ooze. It appears, however, that other clay samples and different extraction techniques (work in progress) may produce yields of spheres of as much as 400 ppb of dry sediment weight for this same size range. The spheres were readily divided into three groups using their dominant mineralogy. Based on their distinctive mineral and chemical compositions, these groups are name iron, glassy, and silicate. On the surface, the iron spheres were black and shiny, the silicate spheres were rough and dull, and the glassy spheres could not be distinguished optically from either the iron or silicate spheres. Any smooth surface the silicate and glassy spheres may have once possessed had been etched away by seawater action (Figs. 1, 2, and 3). Sphere shapes ranged from true spheres to spheroidal and button-shaped objects with protuberances (Fig. 4); some irregular fragments, presumably from partially decomposed spheres, were also recovered. (All particles are collectively referred to in this paper as spheres.) Several spheres contain relict grains from the parent meteoroid body. Since some relict grains have not been altered, they provide a basis for deducing the nature of the meteoroid bodies from which the deep-sea spheres were derived.

3.1 Iron spheres

The general abundance of the iron spheres ranged from 25 to 50% of the number recovered, depending upon the core sampled and the magnetic extraction procedures employed. The elemental content of these spheres is mostly iron with varying amounts of nickel and occasionally small amounts of other elements (e.g., Al, Si). The mineralogy of these spheres includes various iron oxides with or without metal. Spheres always contain magnetite (Fe_3O_4), usually contain magnetite and wüstite (FeO), and occasionally contain magnetite and hematite (Fe_2O_3, may be either primary or secondary). When present, the metal phase associated with these iron oxides is taenite (γNi-Fe). The magnetite and wüstite commonly form oriented, multi-crystalline, interlocking aggregates as in Fig. 5. Cell dimensions of the magnetite crystals are usually small, indicating it is often a ferrous trevorite. Wüstite cell dimensions are variable but in one case it is nearly stoichiometric FeO.

Several iron spheres contain eccentric Ni-rich cores which are usually metal (taenite) but may be partially or completely oxidized. The sphere in Fig. 6 contains three phases: an outer shell of magnetite (Ni-rich, containing about 25% trevorite molecule); an inner metallic core (crescent shaped) of Ni-Fe, containing 89% Ni; and an inner oxidized core (circular) containing 50% NiO and 7.5% SiO_2. This oxidized core has been identified as a siliceous, nickleiferous trevorite with a composition of $Ni(Ni_{.28}Si_{.15}Fe_{.57})_2O_4$. The oxidized portions of other cores commonly contained some Si. In some spheres there is no Ni-rich

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core, the significance of which will be discussed later. Iron spheres of this type have been previously described [1,3,8,17-23].

3.2 Glassy spheres

Less than 10% of the deep-sea spheres is characterized by a dendritic network of oriented skeletal magnetite crystals with an interstitial glass composed principally of Fe, a minor amount of Si, together with smaller amouts of Mg, Al, and Ca. One of these spheres, shown in Fig. 7, possesses an eccentric Ni-Fe core containing 38% Ni. These spheres show a strong resemblance to spheres recovered from manganese nodules by Finkelman [17,23].

3.3 Silicate spheres

The silicate spheres are the most dominant group; when viewed with the SEM, their surfaces show euhedral olivine and magnetite standing out in bold relief (Fig. 8). Olivine and magnetite crystals are often aligned in a brickwork fashion over large portions of the sphere surfaces.

The interior of the silicate spheres is composed mainly of olivine and magnetite crystals surrounded by interstitial glass or voids. Grain size is variable for the olivine and magnetite. Olivine crystals range from about 1 μm to 40 μm in diameter while magnetite crystals range from submicron to only a few microns in diameter. The two most common textures for these spheres are larger equant (unoriented) olivine crystals with smaller magnetite crystals surrounded by interstitial glass, or voids, or parallel bars of euhedral olivine crystals with magnetite

and glass occupying the interstitial region (Fig. 10). This latter type resembles "barred" chondrules in chondritic meteorites except for the presence of magnetite. The composition of the olivine in the spheres ranges from Fo_{55}-Fo_{80}. This olivine is always zoned and Fe-rich along the boundaries. The magnetite may be pure Fe_3O_4 or contain several percent Ti, Cr, or Al, substituting for the Fe. Composition of the glass varies among the spheres. The glass is an Fe-rich silica with minor amounts of Al and Ca and virtually no Mg. Usually most of the Ca in the spheres occur in the glass, whereas the Al occurs in both glass and magnetite. This glass contrasts with that in the glassy spheres (described earlier) because it is enriched in Si, Ca, and Al and contains considerably less Fe. Other mineral phases usually occurring in the silicate spheres are pentlandite, Ni-rich troilite, and chromite (relict?). Figure 11 illustrates a sulfide-bearing silicate sphere.

Occasionally spheres are encountered having a matrix of very fine-grained material, including olivine, magnetite, pentlandite, and glass with numerous vesicles that were apparently produced by volatile gases leaving the matrix. One of these spheres is illustrated in Fig. 12.

Nearly all of the silicate spheres have experienced etching by seawater. For some spheres, not only has the surface been severely etched, but the interstitial glass has also been completely dissolved away. In extreme cases, as illustrated in Fig. 9, even the Mg-rich cores of olivine crystals have been dissolved leaving only an Fe-rich olivine crystal boundary held together by a skeletal framework of magnetite.

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Elemental compositions for the silicate spheres show an affinity toward chondritic meteorites. Although the surface compositions of these spheres often strongly deviate from chondritic abundances, the interior portions of the spheres agree more favorably. Nineteen spheres possessing glass, a low void space, minimal alteration by seawater, and containing no relict grains were selected for bulk analyses with the electron microprobe. The results of broad beam analyses of polished sections are shown in Table 1.

3.4 Relict grains

Most of the silicate spheres were formed from grains that completely melted and subsequently recrystallized as they separated from the parent meteoroid body. However less than 10% of these spheres contain occasional relict grains of the parent meteoroid that did not experience any melting. Typically, these relict grains are olivine crystals whose cores are Mg-rich, ranging from Fo_{89} to Fo_{99}. Commonly, the outer rim of these relict olivine grains was altered during heating. These altered rims have compositions as low as Fo_{50}. Other relict mineral grains include enstatite, ferrous spinel, chromite, and pentlandite. Quantitative microprobe analyses of some of the relict olivine grains are given in Table 2. One of these spheres, shown in Fig. 13, contains a large (>100 μm) olivine grain (Fo_{99}) which has a Ni-Fe inclusion with 7.3% Ni. Surrounding this relict grain are the typical recrystallized phases of olivine and magnetite. Another sphere, shown in Fig. 14, contains an assemblage of relict grains which include olivine (Fo_{97}), enstatite (En_{99}), a vein of Al-rich material

(30% Al_2O_3, 15% FeO, and 52% MgO), and numerous micron-sized grains of pentlandite (relict?) in a fine-grained vesicular matrix. The outer rim of this sphere consists of recrystallized olivine and magnetite grains (the glass has been dissolved away).

4. Discussion

4.1 Comparison with chondritic abundances

The compositions of the relict olivine grains and the recrystallized silicate spheres are similar to chondritic meteorites. The results of electron microprobe analyses of relatively unaltered silicate spheres are shown in Table 3, which lists the principle elements in atomic percent ratioed to Si. This table compares the composition of these silicate spheres with that of C1, C2, H, and L chondrite meteorites. All of the elements are within the chondritic range, except Ni which shows a strong depletion (up to 100). The trace element analyses by neutron activation, performed by Ganapathy [24], of single silicate spheres from this collection have also shown a chondritic pattern for the following nonvolatile siderophile elements: Ir, Os, Sb, Ru, Sr, Ni, Co, Cr, and Sc.

There are several possible causes for the differences in elemental content between the spheres and the chondritic norm. These include the following:

(a) Inherent elemental and mineralogical differences among the parent meteoroids producing the spheres (e.g., comets versus asteroids).

(b) Fractionation and volatilization caused by different melting temperatures of various minerals during the ablation process. Volatile

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elements, such as S, are vaporized when iron sulfide minerals (i.e., pentlandite, troilite) melt. There is a marked absence of iron sulfide minerals in most of the recrystallized silicate spheres. Laboratory ablation of a carbonaceous chondrite (Murchison) produced small quantities of a sulfide phase as well as the ubiquitous recrystallized silicate phase [13]. Studies of the fusion crust and ablation debris revealed that nearly all of the Ni and some of the Fe of this meteorite was entering the sulfide phase and producing Fe,Ni,S-rich spheres. Similar spheres, usually 10 μm in size, have also been collected from the stratosphere [14]. It appears that during ablation Fe, Ni, and S combine to form small spheres; this may possibly account for some of the Ni deficiency in the deep-sea silicate spheres.

Fractionation produced by differences in density may possibly separate metal droplets from silicate droplets. While much of the metal Fe is being oxidized, other siderophile elements (especially Ni) could become concentrated in the core and subsequently be thrown out of the silicate melt (due to rapid rotational forces) or fall through the silicate melt as the sphere decelerates in the atmosphere. Even for silicate minerals containing small amounts of Ni, the Ni could migrate into the coexisting metal phase and ultimately become separated. Because silicate minerals in chondrites are usually Ni-free, the spheres would be depleted in Ni. The Ni depletions shown in Table 3 and Fig. 15 perhaps are best explained in the above manner.

(c) Grain size of the parent meteoroid could also produce mineralogical fractionation in spheres. Parent bodies having very small grain size (relative to sphere diameter) and few volatile constituents would have a

tendency to produce chemically homogenous spheres. Parent bodies having very large grain size (relative to sphere diameter) and few volatile constituents would tend to produce a variety of spheres with different mineralogy. Both metallic and silicate spheres could be produced by fragmentation and ablation from only one coarse-grained metal-rich silicate parent meteoroid.

(d) Chemical dissolution and etching are responsible for removing the glass phase and the Mg-rich core of olivine crystals in the recrystallized spheres. Undoubtedly, the seawater action will change the relative amounts of Mg, Si, Al, and Ca. Since the Al and Ca are concentrated in the glass (the phase most readily affected by etching), bulk analyses showing depletions of these two elements probably do not reflect the original sphere compositions. This effect is illustrated in Fig. 16 where Ca and Al contents of silicate spheres are compared with chondritic meteorite values. All but five of the spheres fall on the Ca/Al line and have abundances consistent with chondrites. These five spheres show depletions of Al and/or Ca from chondritic values probably because of seawater etching.

4.2 Origin of the iron spheres

The three groups of spheres (iron, glassy, and silicate) may possibly have some genetic significance. It seems reasonable to expect iron-rich spheres to be produced during ablation of iron- and metal-rich silicate meteoroids. Metal spheres are probably not produced by ablation of predominantly silicate meteoroids because studies of fusion crusts and laboratory ablated silicate materials have never yielded separate metal spheres, but

have produced spheres with intergrown iron oxide and silicate phases. Even though there is a relatively low abundance of iron- and metal-rich silicate meteorites, it is not too surprising that such a large quantity (25 to 50%) of iron spheres was found. Laboratory ablation experiments have shown that metal samples produce an overwhelming amount of spheres (>90%) whereas silicate samples produce a much smaller quantity (~25%). The iron spheres recovered possess identical mineralogy with the fusion crusts of iron meteorites (i.e., Boguslavka, Norfork, and N'Kandhla) as well as with the ablation debris created in the laboratory using metallurgical samples of iron and nickel-iron [12]. The combination of several iron oxide phases and Ni segregation in individual spheres is convincing evidence of ablation from metallic Fe-rich meteoroids. The most common mineralogy is an assoication of the various Fe-rich minerals (i.e., taenite (Ni-Fe), wüstite (FeO), magnetite (Fe_3O_4), and hematite (Fe_2O_3)) several of which are often in a single sphere. In the absence of industrial contaminants, the presence of the metastable mineral wüstite is accepted as sufficient proof of an ablation product [12, 25]. Another equally important recognition feature is the formation of a metallic core enriched by Ni.

4.3 Origin of the glassy spheres

The glassy spheres are considerably more Fe-rich than the silicate spheres. Glass in these spheres is relatively low in Si, and the spheres do not contain any silicate minerals. This combination is most likely produced by ablation of metal-rich silicate meteoroids.

4.4 Origin of the silicate spheres

The silicate spheres are undoubtedly derived from ablation of stony meteoroids. The olivine-magnetite-glass and sulfide mineral assemblages occurring in the spheres are identical to those described in the natural fusion crusts of Allende, Orgueil, and Murchison [11,13,26], ablation debris created in the laboratory from a carbonaceous chondrite [13], and melted interplanetary dust particles collected from the stratosphere [14]. Of the several ways to deduce information about possible parent meteoroids producing silicate spheres, we will discuss using both relict grains and bulk sphere chemistry. Analyses of relict grains have identified the following minerals: Mg-rich olivine, enstatite, ferrous spinel, pentlandite, troilite, Al-rich spinel(?), chromite, and Ni-Fe metal. Most of these minerals occur as larger crystals in a fine-grained matrix that is characterized by numerous circular voids. These voids were caused by escaping volatiles (e.g., water, sulfur) produced by decomposition of hydrated and other low temperature minerals during ablation. Because larger crystals of high temperature minerals are associated with a fine-grained, low temperature, volatile-rich matrix, the obvious candidates for parent meteoroids are carbonaceous chondrites.

Bulk analyses of spheres showing little or no signs of chemical weathering by seawater and not containing relict grains may also be useful for deducing possible parent meteoroids. One such attempt is shown in Table 4. In this method the assumption is made for spheres which are unaltered (seawater etching would change the Ca/Al ratio because some of the Al is in the magnetite as well as the Ca-bearing glass) and show no sign of gas vesicles, that if the Ca/Al ratios fall within the chondrite

range of 1.0 to 1.25 [27,28], then other elements have not been depleted and will correlate with the bulk chemistry of the parent chondritic meteorite type. In Table 4, spheres #25 and 33 have the proper Ca/Al ratio. The Fe, Mg, Ca, Al, and Si contents for these spheres match the mean composition of the type H and enstatite chondrite meteorite groups. A more rigorous study will be necessary before it can be determined if this method is a meaningful way to correlate bulk sphere chemistry with possible parent meteoroid types.

5. Conclusions

The mineralogy and chemistry of the deep-sea spheres are identical in many respects to the meteorite fusion crusts, laboratory created ablation debris, and the ablated interplanetary dust particles in the stratospheric collection. The principal differences are the unusual textures (e.g., barred olivine "chondrules") and the relict crystals. All of the spheres analyzed in this report appear to have been produced during ablation of larger meteoroids by melting, fragmentation, and vaporization.

Although these spheres are not abundant in deep-sea sediments, they were abundant (1 to 10% by weight) in the magnetic fraction larger than 200 μm in size in our samples. Because the natural sedimentation rate for abyssal clays is about 10^{-4} cm per year, the spheres are more concentrated in the clays than in any other terrestrial environment. There are very few magnetic terrestrial particles in the sediments in the same size range as the spheres, and extraction and identification is a relatively simple process.

The high abundance (25 to 50%) of the iron spheres was surprising, although we do have a possible explanation based on laboratory ablation experiments. However, if the nearly equal quantities of iron and silicate spheres do reflect pre-ablation abundance, there may have been a metal-rich component of the earth-crossing meteoroids during the last 500,000 years. Both the occurrence of relict grains and the bulk sphere compositions suggest parent meteoroids of chondritic composition for the silicate spheres. This is consistent with the analyses of lunar soils that indicate that the moon is accreting chondritic material [29]. The Ni deficiency in the silicate spheres is reasonably well understood and probably does not reflect a Ni deficiency in the parent meteoroids.

Meteor ablation spheres recovered from deep-sea sediments are valuable extraterrestrial material because they may (in some cases) represent samples of meteoroid types that are too fragile to survive atmospheric passage and become meteorites. A unique value of the spheres is that they provide a possible way to study the composition of the earth-crossing meteoroids as a function of time, perhaps as long as 2×10^8 years.

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References

1 J. Murray and A.F. Renard, Reports "Challenger" Exped. 4 (1891) 327.

2 R. Schmidt, NASA TN D-2719 (1965)

3 D.W. Parkin and D. Tilles, Science 154 (1968) 936.

4 H. Millard and R. Finkelman, J. Geophys, Res. 75 (1970) 2125.

5 R. Schmidt and K. Keil, Geochim Cosmochim. Acta 30 (1966) 471.

6 W. Hunter and D. Parkin, R. Soc. London Proc. 255 (1960) 382.

7 A. Bruun, E. Langer and H. Pauly, Deep Sea Research 2 (1955) 230.

8 D. Parkin, R. Sullivan and J. Andrews, Nature 266 (1977) 515.

9 D. Brownlee, The Sea, 7 (1978) (in press).

10 D. Brownlee, P. Hodge, M. Blanchard, T. Bunch and F.T. Kyte, 9th Lunar and Planetary Science Proc., Plan. Sci. Inst. (1978) 126.

11 M.B. Blanchard and G.C. Cunningham, J. Geophys. Res. 79 (1974) 3973.

12 M.B. Blanchard and A.S. Davis, J. Geophys. Res. 83 (1978) 1793.

13 F.T. Kyte, M.S. Thesis, San Jose State Univ. (1977); also NASA CR 152,075.

14 D.E. Brownlee, D. Tomandl, M.B. Blanchard, G.V. Ferry and F.T. Kyte, NASA TM X-73,152 (1976).

15 M.B. Blanchard, J. Geophys. Res. 77 (1972) 2442.

16 B. Heezen, I. MacGregor, H. Foreman, G. Forristall, H. Hekel, R. Hesse, R. Hoskins, E. Jones, A. Kaneps, A. Krashennikov, V. Okada and H. Ruef, Initial Rep. Deep Sea Drilling Proj. 20 (1973) 725.

17 R.B. Finkelman, Marine Tech. J. 6 (1972) 34.

18 R. Castaing and K. Fredrickson, Geochim. Cosmochim. Acta, 14 (1958) 114.

19 H. Fechtig and K. Uteck, Annals New York Acad. Sci. 119 (1964) 243.

20 J. Jedwab, Geochim. Cosmochim. Acta, 34 (1970) 447.

21 U. Marvin and M. Einaudi, Geochim. Cosmochim. Acta 31 (1967) 1871.

22 H. Pettersson and K. Fredriksson, Pacific Sci. 12 (1958) 71.

23 R. Finkelman, Science 167 (1970) 982.

24 R. Ganapathy, D. Brownlee and P. Hodge, Science (1978) (in press).

25 M.B. Blanchard, Meteoritics 5 (1970) 181.

26 D.E. Brownlee, M.B. Blanchard, G.C. Cunningham, R. Beauchamp and R. Fruland, J. Geophys. Res. 80 (1975) 3973.

27 H. VonMichaelis and L. Ahrens, Earth Plan. Sci. Letters 5 (1969) 387.

28 L. Ahrens and H. VonMichaelis, Earth Plan. Sci. Letters 5 (1969) 395.

29 E. Anders, R. Ganapathy, U. Krahenbuhl and S. Morgan, The Moon 8 (1973) 3.

TABLE 1

Bulk analyses with broad beam electron microprobe of 5 recrystallized silicate spheres which showed little or no signs of alteration by seawater dissolution. All Fe is expressed as FeO.

Composition	Recrystallized silicate spheres									
	2		8		25		26		33	
	*		*		*		*		*	
SiO_2	52.1	(24.3)	44.2	(20.7)	36.2	(16.9)	37.3	(17.4)	30.7	(14.4)
Al_2O_3	0.76	(0.4)	3.4	(1.8)	2.2	(1.2)	3.1	(1.2)	1.7	(0.9)
Cr_2O_3	0.61	(0.4)	0.60	(0.4)	0.71	(0.5)	0.22	(0.2)	0.55	(0.4)
"FeO"	25.0	(19.4)	22.9	(17.8)	33.4	(26.0)	32.7	(25.4)	44.7	(34.7)
MgO	18.4	(11.7)	27.5	(16.6)	24.2	(14.6)	23.4	(14.1)	18.0	(10.9)
CaO	1.02	(0.7)	3.1	(2.2)	1.9	(1.4)	3.5	(2.5)	1.34	(0.9)
MnO	1.07	(0.8)	0.28	(0.2)	0.29	(0.23)	<0.02	(--)	0.60	(0.4)
NiO	2.61	(2.0)	0.06	(0.1)	2.04	(1.6)	0.50	(0.4)	0.23	(0.2)
S	<0.03	(--)	<0.03	(--)	<0.03	(--)	<0.03	(--)	1.3	(1.4)
Totals	101.57		101.50		100.94		100.72		98.68	
Ca/Al	1.83		1.22		1.17		1.56		1.08	

* Elemental %.

TABLE 2

Analyses of one recrystallized and five relict meteoritic olivine grains occurring in silicate spheres. On two relict grains, values are included for heat altered rims as well as for their unaltered cores.

Composition	Recrystallized	Relict olivine grains						
	Sphere number							
	5	22	10	39		53		55
	core	core	core	core	rim	core	rim	core
SiO_2	38.9	42.1	42.4	46.5	38.6	42.4	41.9	40.9
Cr_2O_3	0.29	0.26	0.54	0.48	0.35	0.48	0.31	0.23
FeO	21.5	1.50	1.88	7.4	28.4	3.2	6.4	7.5
MgO	38.6	56.0	55.6	51.9	32.8	54.0	51.9	50.3
CaO	0.07	0.08	0.06	0.04	0.15	0.07	0.09	0.35
MnO	0.27	0.31	0.20	0.42	0.44	0.19	0.21	0.23
NiO	0.31	<0.03	<0.03	0.16	<0.03	<0.03	<0.03	0.12
Totals	99.94	100.25	100.68	100.90	100.74	100.34	100.81	99.63
Fo	76	99	99	93	67	97	94	92

TABLE 3

Average abundances of 19 silicate spheres compared with ordinary and carbonaceous chondrites.

	Deep-sea spheres ± 1 σ	C1	C2	H	L
Mg/Si	0.852 ± 0.160	1.06	1.04	0.97	0.94
Fe/Si	0.832 ± 0.532	0.901	0.841	0.812	0.577
Ca/Si	0.0544 ± 0.0267	0.0721	0.0719	0.0498	0.0484
Al/Si	0.0762 ± 0.0340	0.085	0.084	0.061	0.061
Ni/Si	0.0137*	0.051	0.046	0.049	0.030
Cr/Si	0.00825 ± 0.00479	0.0127	0.0124	0.0106	0.0109
Mn/Si	0.00634 ± 0.00332	0.0092	0.0062	0.0068	0.0068
Ti/Si	0.00214 ± 0.00064	0.0024	0.0024	0.0021	0.0021

*Three spheres did not contain detected Ni (<0.02%) and this table treats this upper limit as a measured value.

TABLE 4

Silicate spheres having Ca/Al ratios between 1.0 and 1.25 compared with mean elemental analyses for H-group and enstatite chondrites [27,28].

	Fe	Mg	Ca	Al	Si
Sphere #25	26.0	14.6	1.4	1.2	16.9
H-Group Chondrite (mean)	27.0	13.9	1.2	1.1	16.7
Sphere #33	34.7	10.9	0.9	0.9	14.4
Enstatite Chondrite (mean)	29.5	11.5	0.9	0.8	16.8

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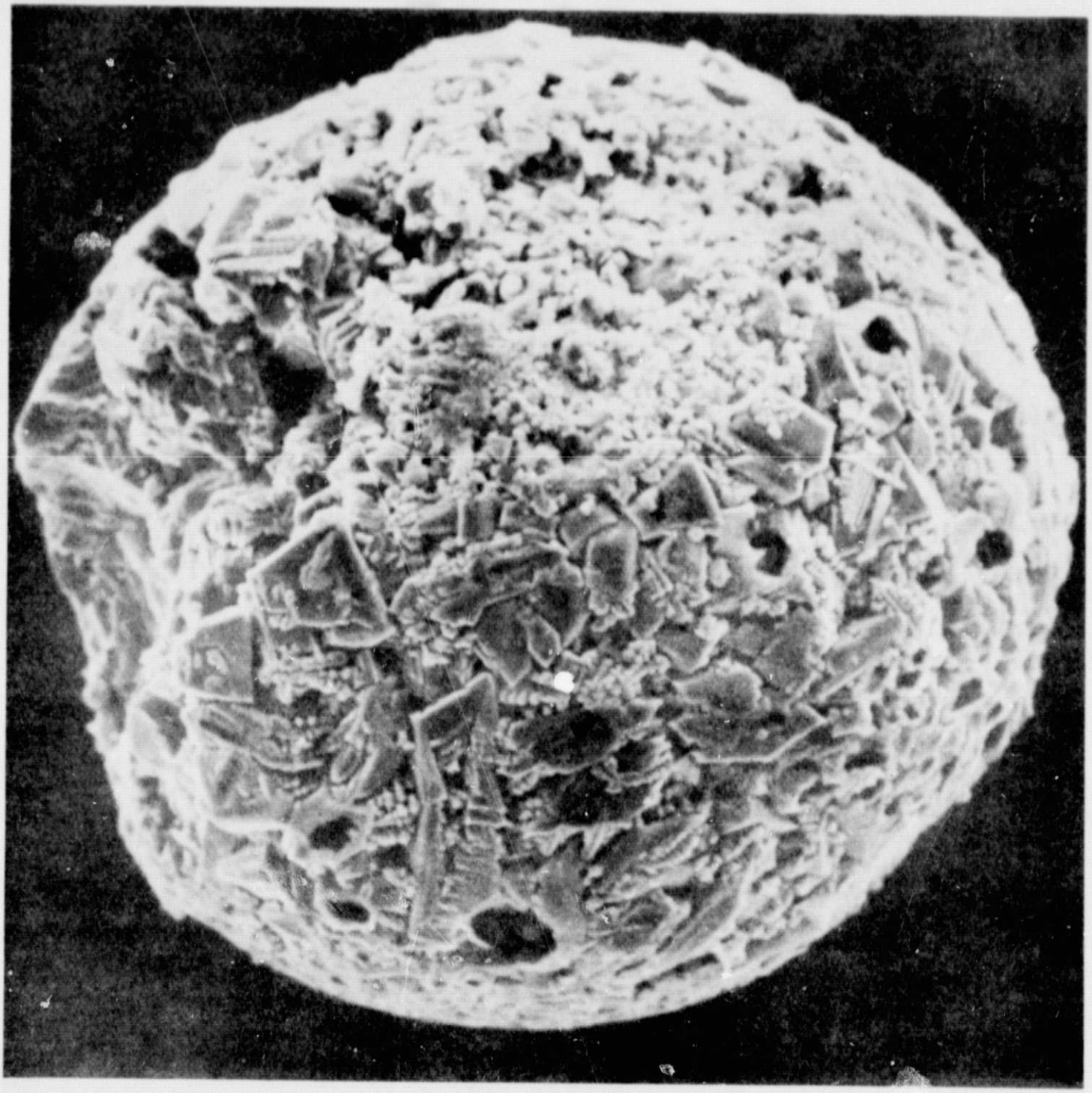

Fig. 1. An SEM image of a silicate sphere with surface etched away by seawater. Scale = 25 μm.

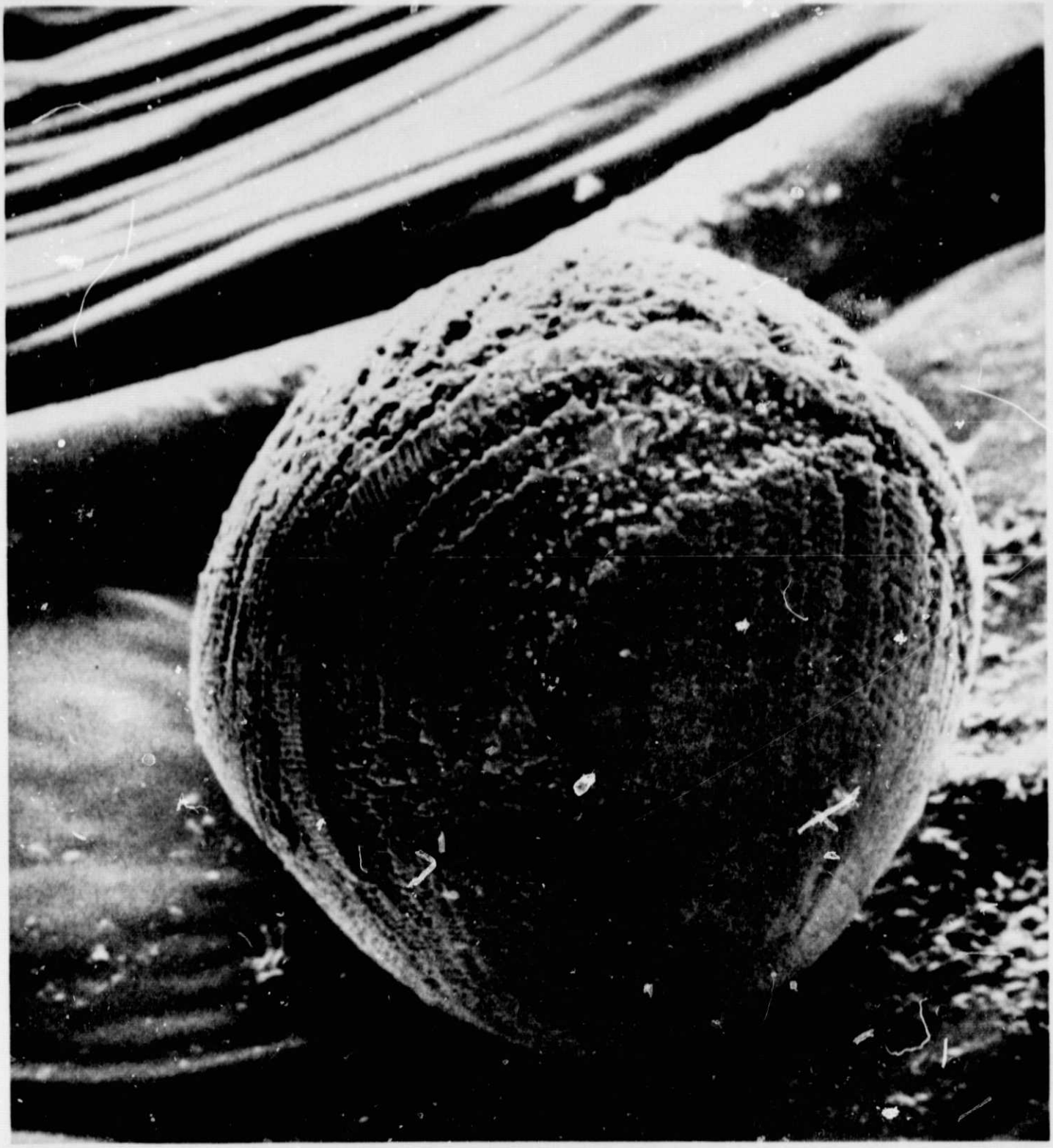

Fig. 2. An SEM image of a silicate sphere with surface etched away by seawater. Aligned olivine and magnetite crystals form brickwork-like patterns produced during ablation. Scale = 25 μm.

Fig. 3. An SEM image of a sphere with surface etched away by seawater. This is an iron type sphere revealing equigranular crystals of magnetite. Scale = 25 μm.

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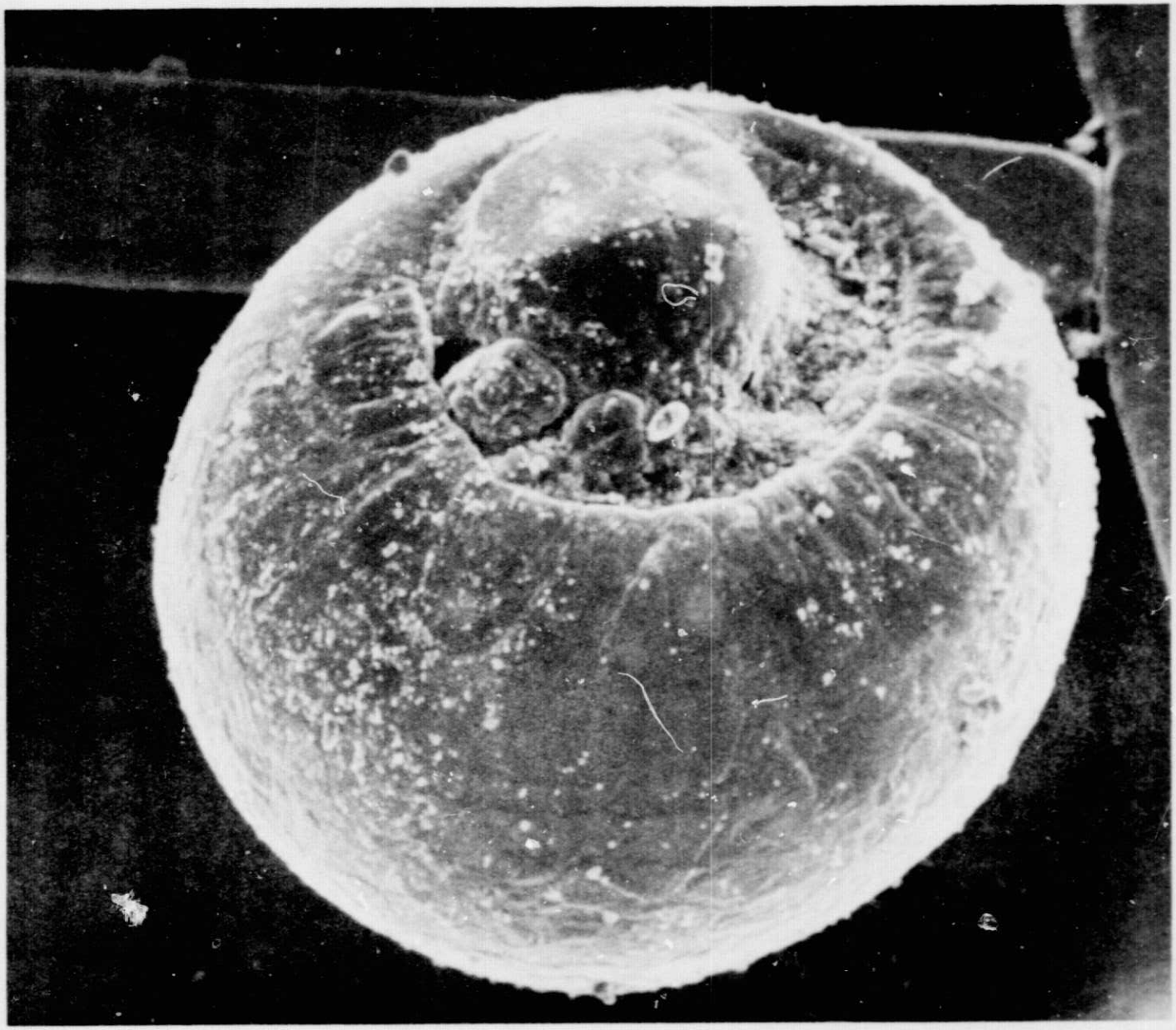

Fig. 4. An SEM image of a typical button-shaped iron sphere. Scale = 25 μm.

Fig. 5. An SEM image of an iron sphere with intergrowths of magnetite (dark) and wüstite (light) mineral phases. Scale = 25 μm.

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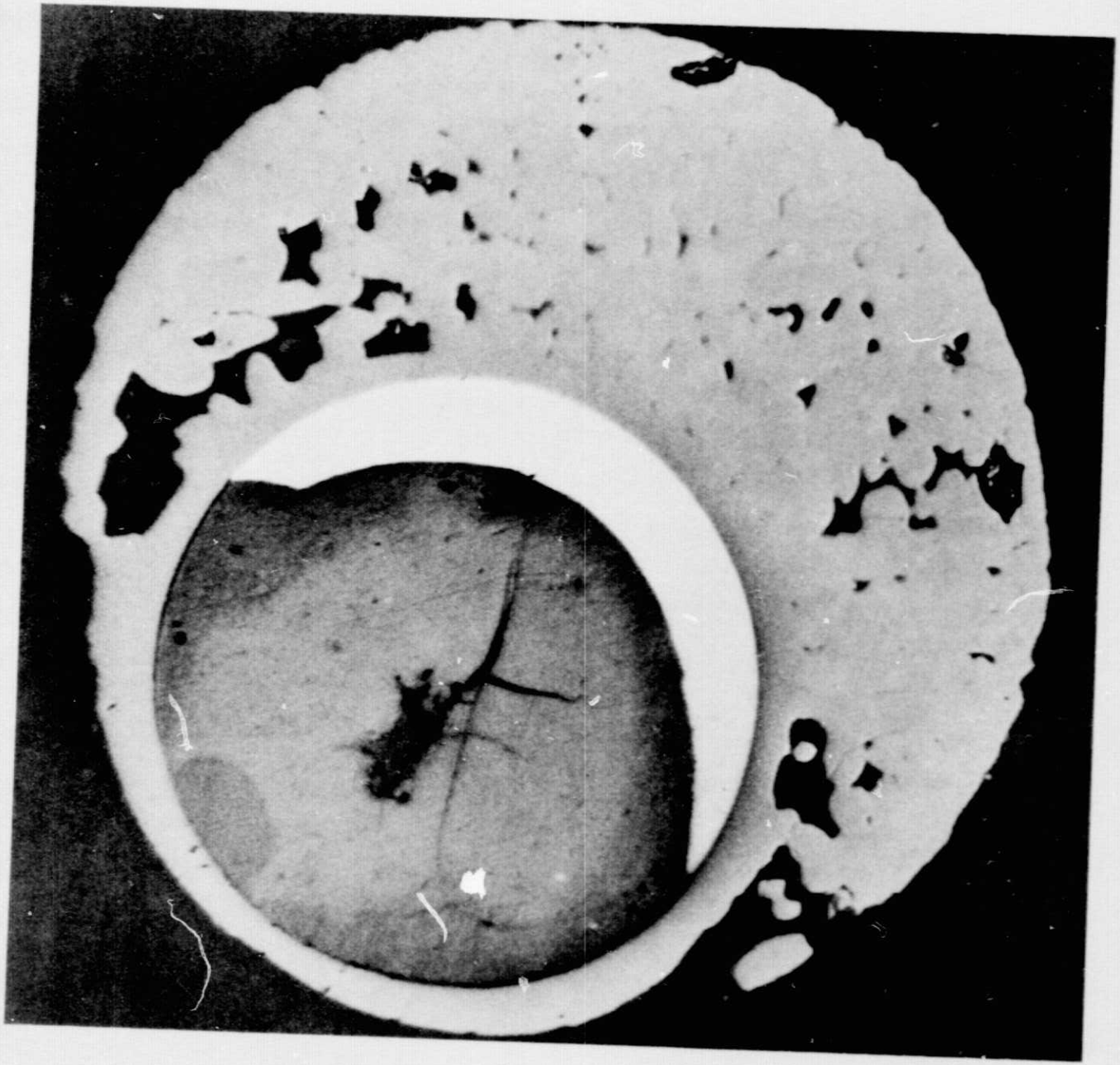

Fig. 6. An iron sphere with an eccentric Ni-rich core. The outer shell is magnetite. The bright rim of the core is Ni-Fe metal. The dark interior of the core is Si,Ni-rich trevorite. Scale = 25 μm.

Fig. 7. A glassy sphere. Bright skeletal magnetite crystals in a dendritic framework enclosing a dark, Fe,Si-glass. The bright eccentric core is Ni-Fe metal. A small patch of magnetite occurs at the edge of the Ni-Fe core where it intersects the sphere exterior. Scale = 25 μm.

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Fig. 8. Enlarged area of sphere shown in Fig. 1. Large crystals (gray) are olivine, small (bright) crystals often connected in chain-like fashion are magnetite, and groundmass areas are interstitial glass. Slightly above and to the right of the photo center is a hollow olivine crystal which has had its Mg-rich core dissolved away. Scale = 10 μm.

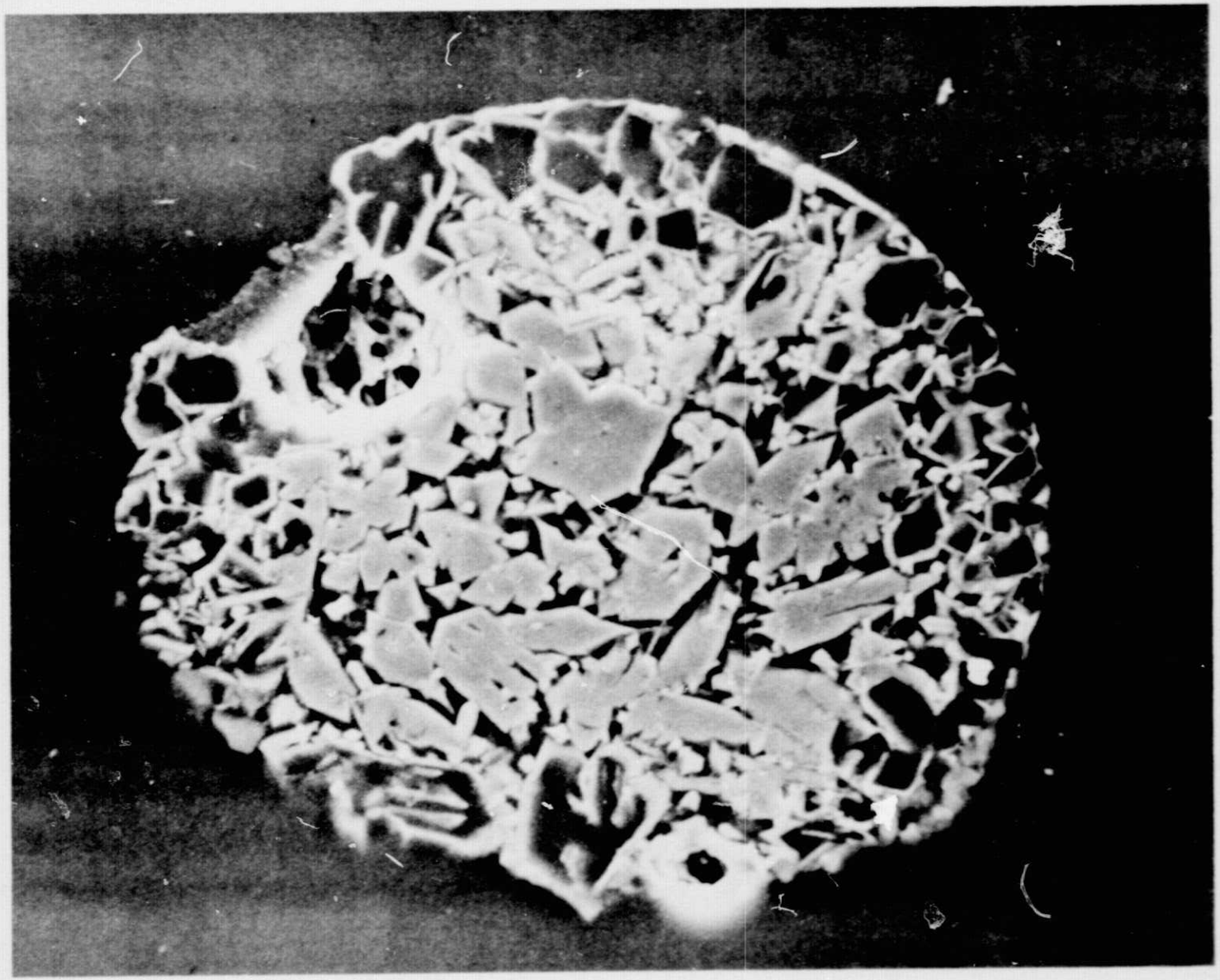
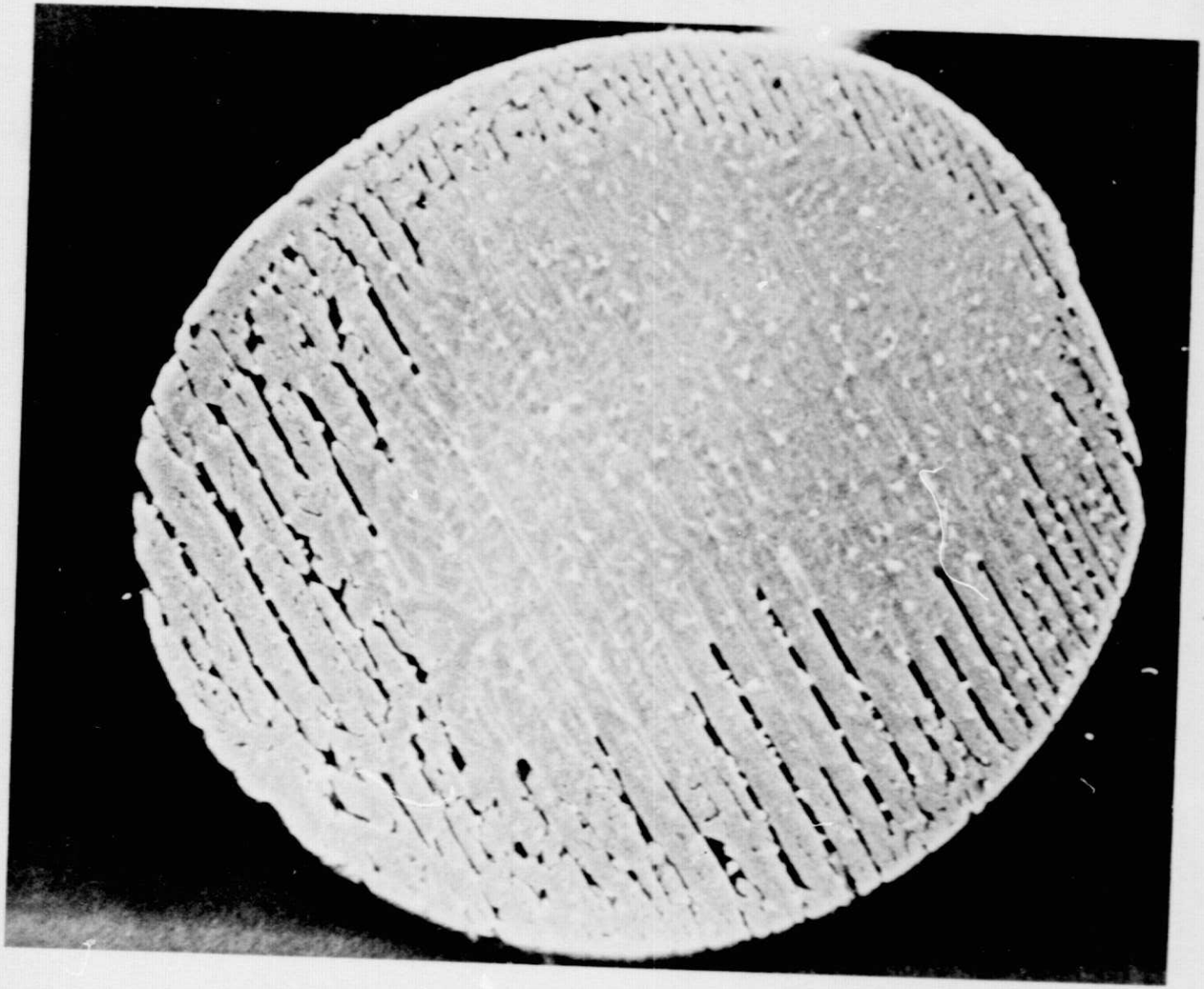


Fig. 9. An SEM image of a polished section of a silicate sphere, completely recrystallized, containing euhedral crystals of olivine (gray) and small magnetite crystals (bright). The dark crystals along the exterior of the sphere are actually voids filled with epoxy. The original Mg-rich cores of these olivine crystals were dissolved away by seawater, leaving only the Fe-rich rims. Scale = 25 μm.



(a) This sphere resembles a "barred" chondrule. Olivine forms parallel plates in between which are small crystals of magnetite and a glass composed of Ca, Al, Fe, and Si. Scale = 25 μm.

Fig. 10. SEM images of polished sections of silicate spheres which were completely melted and recrystallized. The glass occurs only in the central portions, elsewhere it has been dissolved away by seawater.

(b) A highly magnified image of another silicate sphere which shows the nature of the border between etched and glass-bearing portions of the spheres. Scale = 10 μm.

Fig. 10. Concluded.

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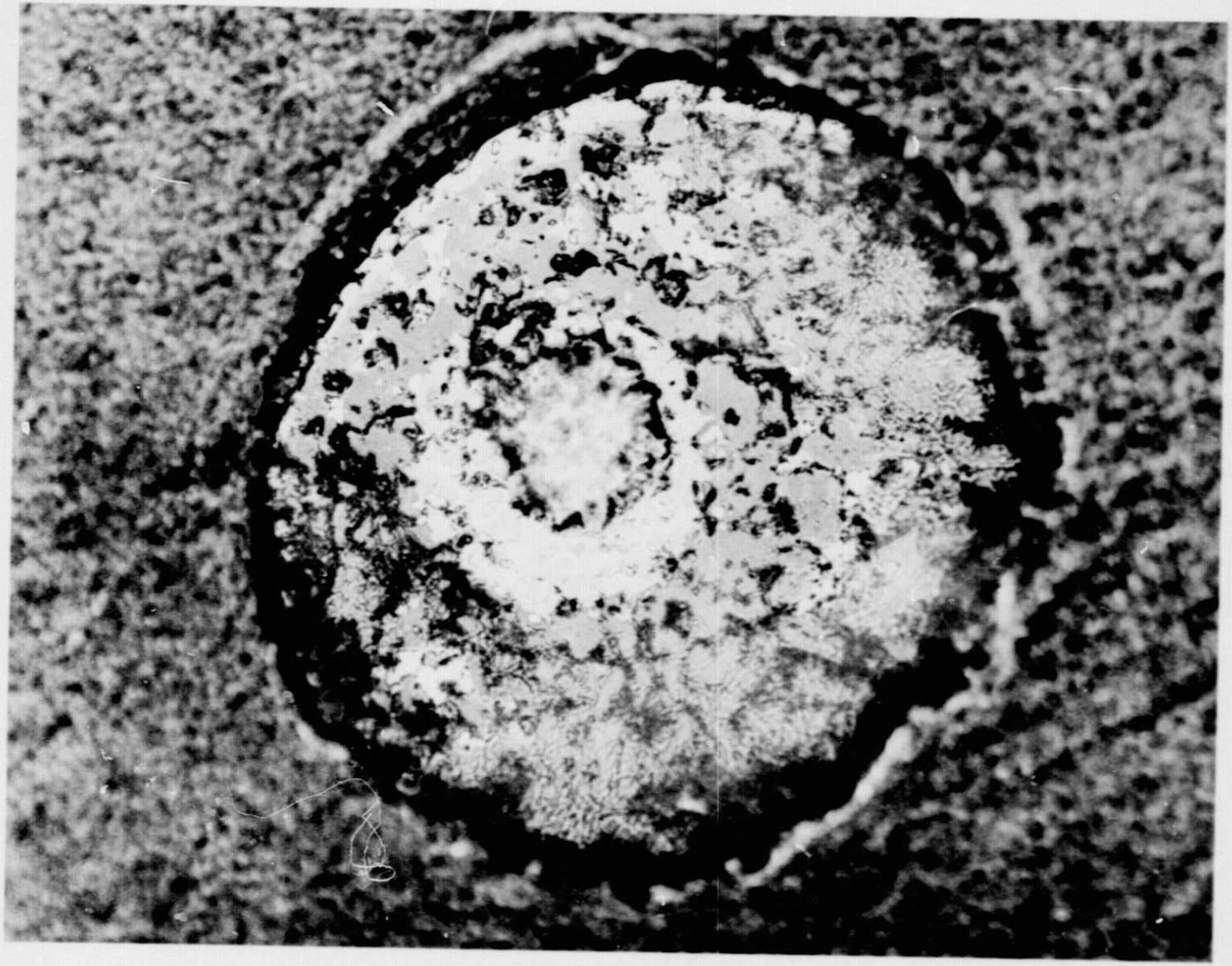

Fig. 11. A photomicrograph of a recrystallized silicate sphere containing sulfides. The center of the sphere is a void, surrounded by pentlandite (bright) and magnetite (light gray). The darker grains are olivine. Pentlandite and magnetite are dispersed throughout the sphere and along the rim. Where they occur together, magnetite was produced by vaporization of the sulfur and oxidation of the iron. Scale = 25 μm.

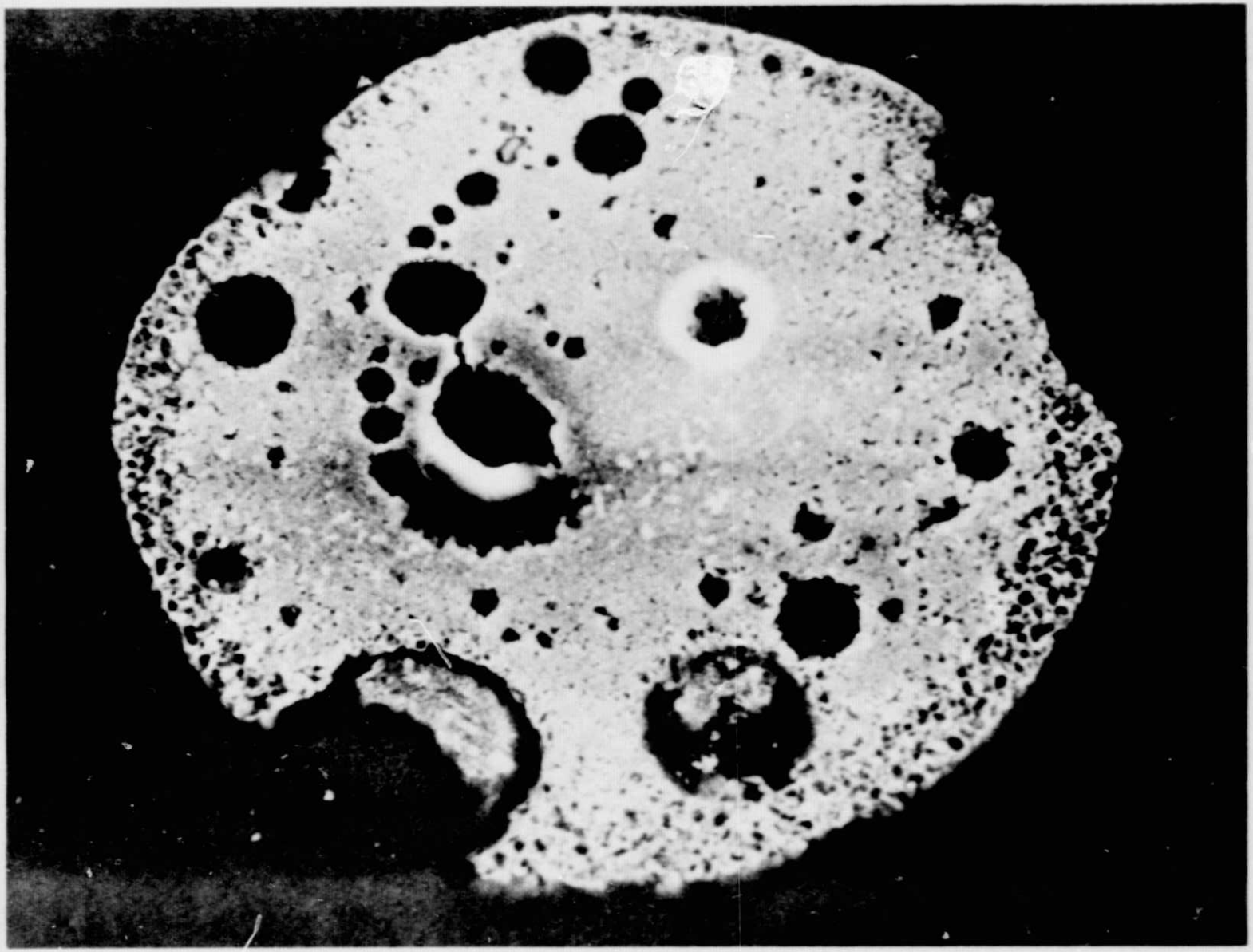

Fig. 12. An SEM image of a silicate sphere with a very fine-grained texture that contains numerous voids caused by escaping low temperature volatiles. Magnetite occurs only near the outer edges. The central interior contains numerous small bright grains of pentlandite and troilite. Scale = 25 μm.

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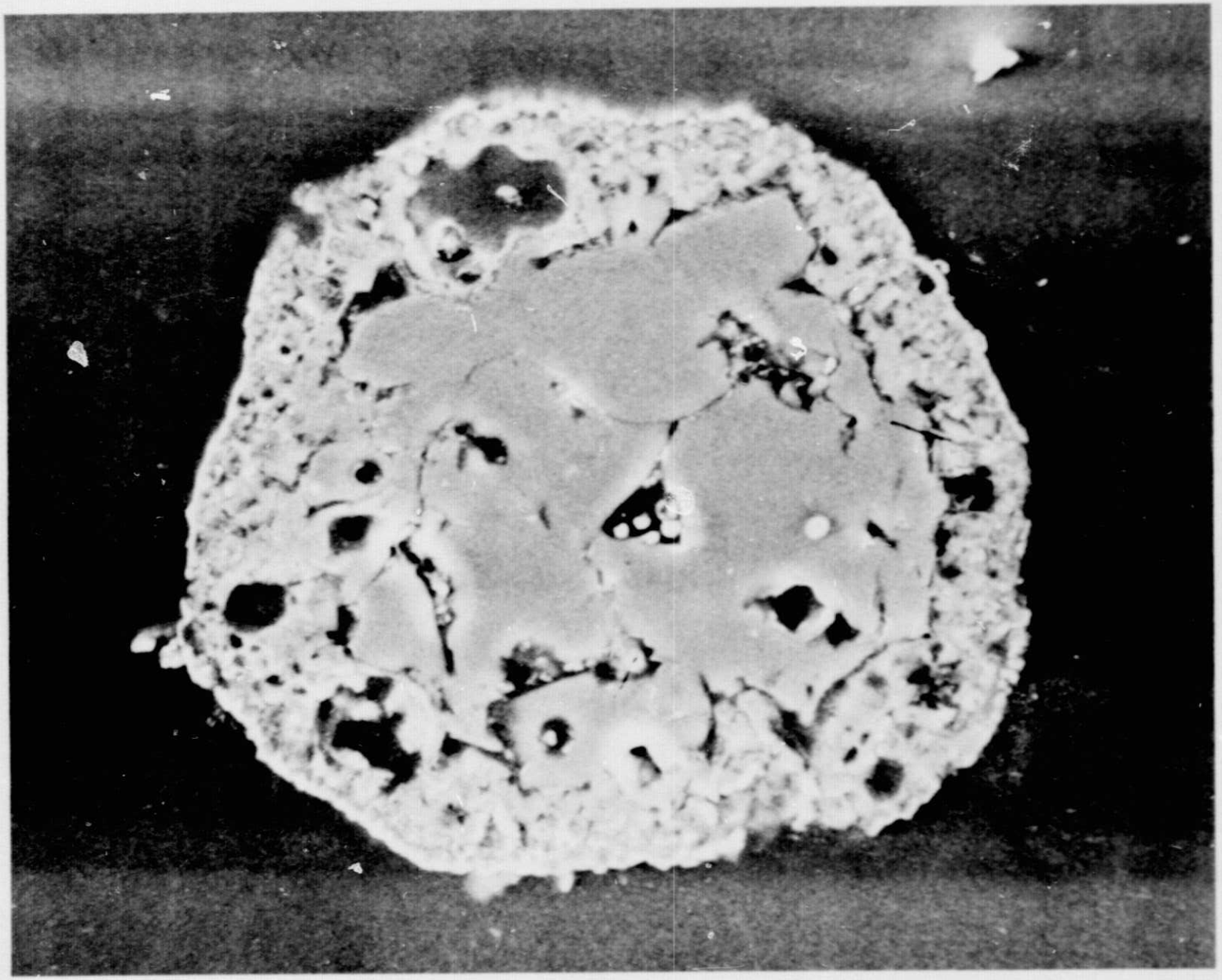

Fig. 13. An SEM image of a silicate sphere containing a large relict olivine grain (Fo_{99}) which has an Ni-Fe metal inclusion (bright). The outer portion of the sphere contains recrystallized olivine and magnetite grains. The dark gray spots are voids filled with epoxy. Scale = 25 μm.

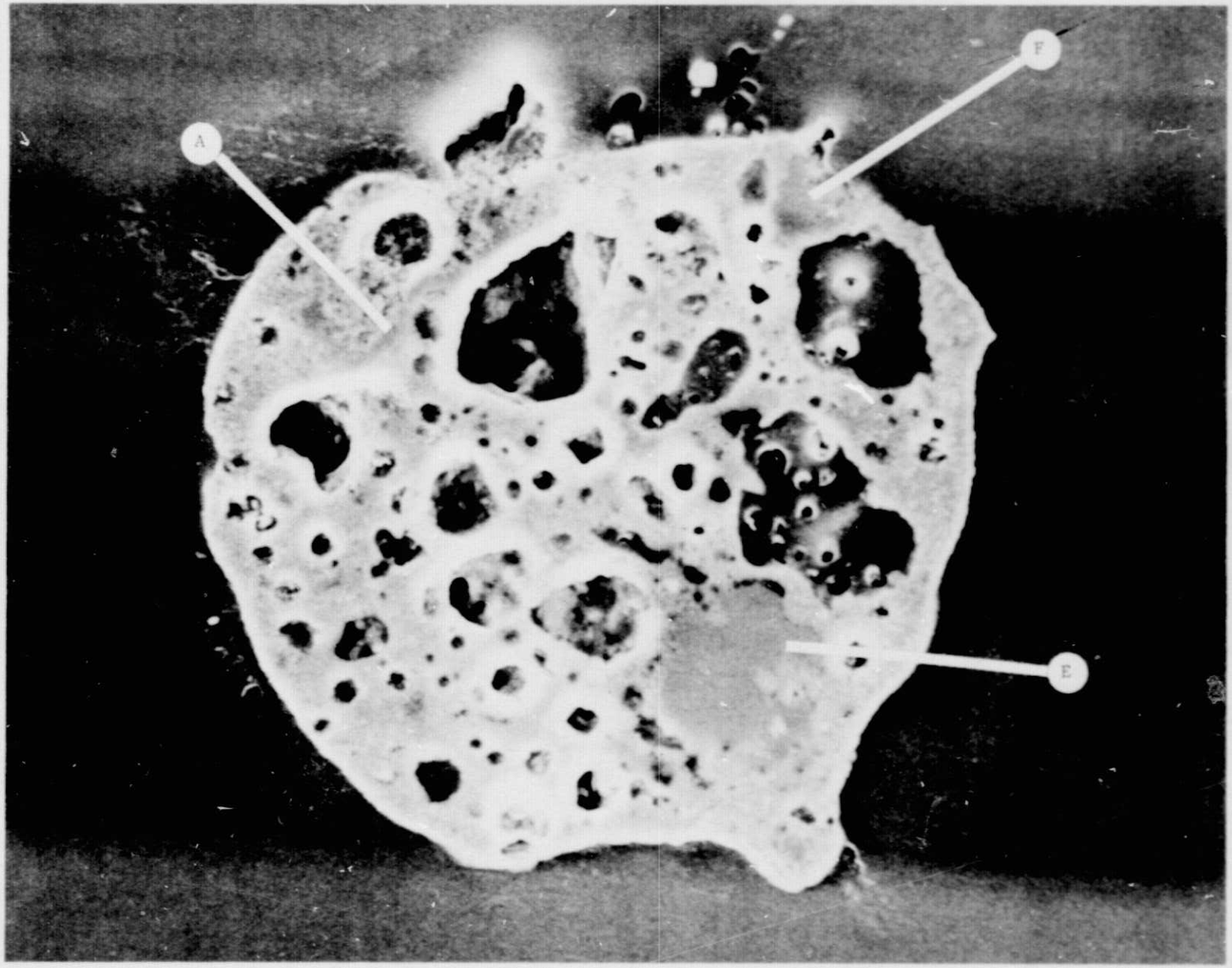

Fig. 14. An SEM image of a silicate sphere with relict grains of enstatite (E), forsterite (f), pentlandite (very small and bright), and an Al-rich vein (A) in a very fine-grained matrix filled with vesicles. Scale = 25 μm.

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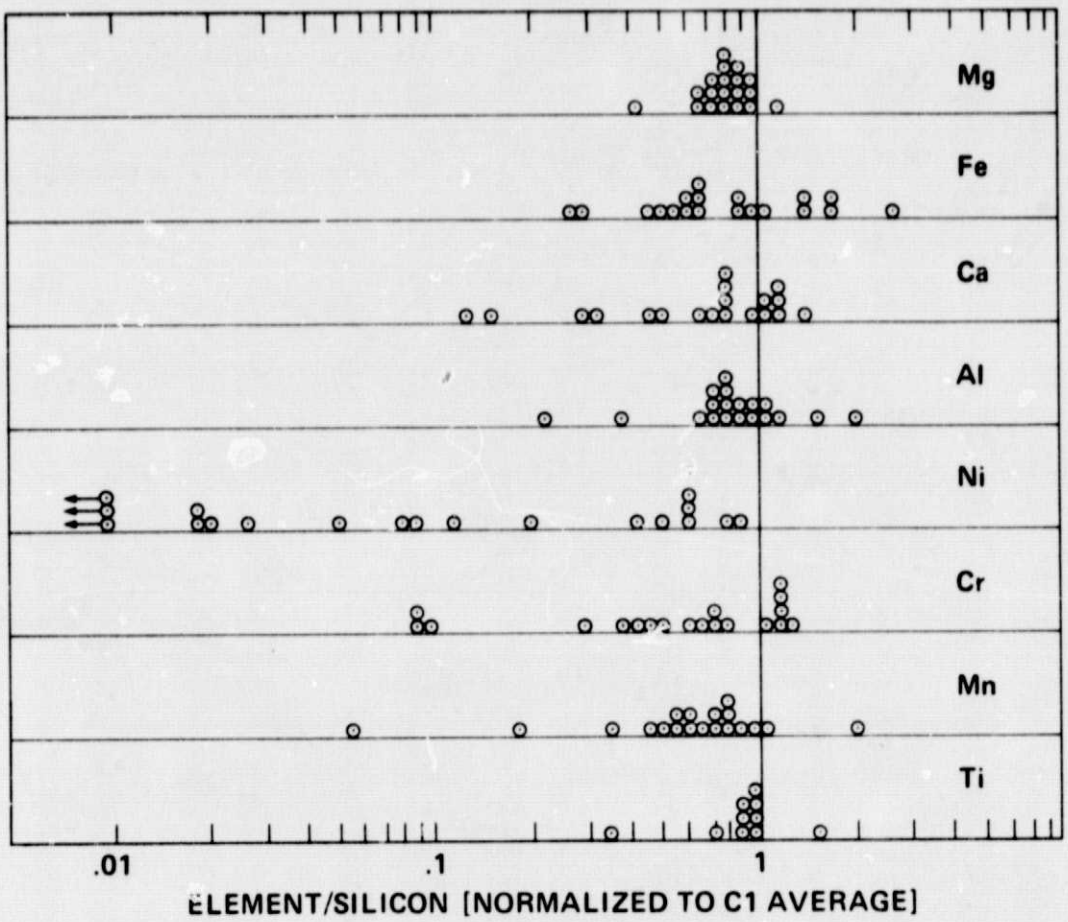

Fig. 15. Data compiled from 19 silicate spheres, comparing the elemental abundances of the spheres (normalized to Si) to the Cl average. The vaiues were obtained on the centers of spheres that did not show appreciable alteration of the glass phase.

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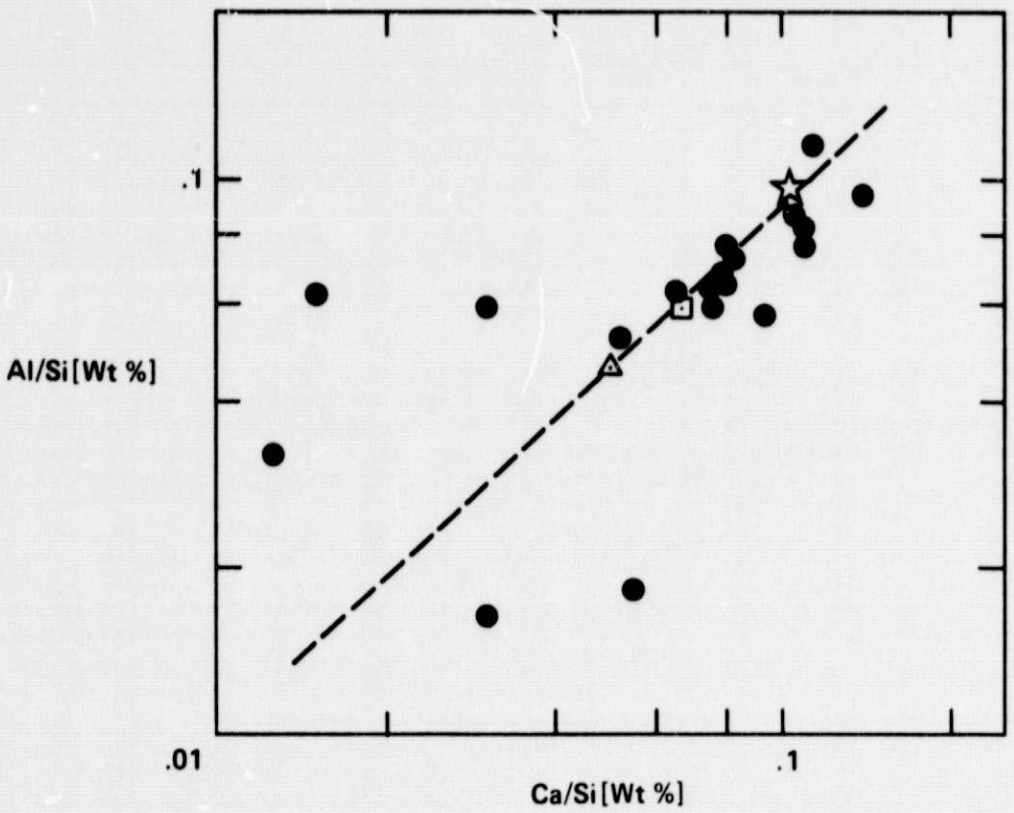

Fig. 16. Data compiled from bulk analyses of 19 silicate spheres showing the Ca/Al ratio of the silicate spheres to the C1 (☆), H and L (□), and enstatite (△) chondrites. The line is where the ratio of Al/Si to Ca/Si equals one.