Silicate petrography, classification, and origin of the mesosiderites: Review and new observations

R. J. FLORAN*
Department of Mineral Sciences, American Museum of Natural History
New York, New York 10024

Abstract—The classification of mesosiderites proposed by Powell (1971) is modified and expanded to include impact melts. A petrographic study of all 20 mesosiderites reveals that most contain a complex assemblage of mineral, lithic, and metal clasts. Mineral fragments dominate the clast population and consist of orthopyroxene, plagioclase, and olivine. Lithic clasts, which provide information on the distribution of magmatic differentiates and polymict breccias on the mesosiderite parent body, include diogenites, cumulate eucrites, basaltic eucrites and dunites, as well as secondary or modified rock types such as metaeucrites, recrystallized breccias, and impact-melt breccias. A majority of mesosiderites contain both diogenitic and eucritic clasts. The occurrence of lithic fragments in most mesosiderites and the subsequent metamorphism of the group indicate that they are highly evolved meteorites. Variable recrystallization of silicate matrices occurred after major differentiation events produced the diverse suite of volcanic-plutonic rock associations found as clasts.

A comparison with inferred lunar analogs indicates that the bulk of the mesosiderites can be considered annealed crystalline matrix breccias and may be meteoritic equivalents of granulitic impactites described by Warner et al. (1977). Textural observations suggest that the matrices of the metamorphosed mesosiderites lack a significant melt component indicating that the silicate and metallic fractions were mixed as solids. Although similar clast types occur in mesosiderites and howardites, a close genetic relationship is uncertain. Differences in the Ca/Al ratios of howardites and mesosiderites can be related to variations in the plagioclase/pyroxene ratio as well as the clast population of individual mesosiderites.

INTRODUCTION

The mesosiderites comprise a relatively small but important group of meteorites (6 falls, 14 finds) that can potentially shed much light on the early evolutionary history of differentiated planetary bodies. Within their brecciated silicate and metallic portions are preserved a succession of events involving magmatic differentiation, brecciation, metal-silicate mixing, and burial metamorphism (Powell, 1969, 1971). Ongoing petrologic studies (Nehru et al., 1978; Floran et al., 1978b) support this complex record of events. However, the origin of the mesosiderites and their relationships to other meteorite groups is poorly understood. Much additional petrochemical data is required to understand the
evolution of the group as a whole as well as that of individual mesosiderites, each of which is a breccia containing numerous clast types within a variably recrystallized or igneous-textured matrix. Powell (1969, 1971) studied ten of the mesosiderites and although the scope of his investigation remains impressive, many unanswered first-order questions remain, especially the role of impact processes including impact melting, and the parent-source bodies for these meteorites. Impact cratering is now recognized as a fundamental process that resulted in primordial melting and igneous differentiation of the moon and planets (Wetherill, 1976), but the accretional energy accompanying such impact events was probably insufficient to cause total or even partial melting of the larger asteroids—the presumed source bodies of differentiated meteorites. The dominant role that impact processes have played in the evolution of the asteroid belt is shown by the present size distribution of the asteroids which is controlled by collisional-fragmentation processes (Chapman, 1976).

The first modern attempts to discuss the origin of the mesosiderites as a coherent group were given by Prior, who in a series of papers (Prior, 1910; 1918; 1921), provided excellent and perceptive petrographic descriptions of seven of the then-known nine mesosiderites. During the next 50 years none of the mesosiderites were examined in detail except Mount Padbury (McCall, 1966). Lovering (1962) and Duke and Silver (1967) touched upon the petrology and origin of the mesosiderites but both studies were primarily concerned with other meteorite groups. Our knowledge of mesosiderites was significantly advanced by Powell's (1969, 1971) detailed textural, mineralogical, chemical, and cooling rate data, which were later complemented by Ni, Ga, Ge and Ir data on metal in 17 mesosiderites, including all of those that Powell had examined (Wasson et al., 1974). Most recently, Mittlefehldt (1977) has determined REE patterns for several mesosiderites. Recent studies of individual mesosiderites include those of Hewins et al. (1977) and Nehru et al. (1978) on the petrology of Emery; Kulpecz and Hewins (1978) on the cooling history of Emery; Floran et al. (1978a,b) on the impact-melt origin of Simondium, Hainholz, and Pinnaroo; and Murthy et al. (1977, 1978) on Rb/Sr, and 40Ar-39Ar systematics of Estherville.

This paper presents the results of a petrographic reconnaissance survey, extends and modifies the classification scheme proposed by Powell (1971) to all 20 mesosiderites, and offers some tentative conclusions regarding relationships among mesosiderites, related meteoritic groups, and lunar breccias. Emphasis is placed on the clast-laden nature of the mesosiderites, the impact-melt origin for several of them, and the distribution and relative abundances of clast types as a key to unravelling the history of this group. The nature of the clast population is especially critical in determining the relative importance of various rock types existing in plutonic and volcanic environments within the mesosiderite parent body (Floran and Prinz, 1978).

**Silicate-Metal Relations**

As noted by Powell (1969), textural and other data are not definitive in
settling the question as to whether the metal component of mesosiderites was in a solid or liquid state at the time of mixing with silicate material, although he later favored a solid-state origin (Powell, 1971). The 3-dimensional interconnection of metal observed by Powell (but not observed in the Bondoc mesosiderite; Wilson, 1972) is compatible with either a metallic liquid, or extreme plastic deformation in the solid state. For the purposes of the present discussion and for reasons given below, Powell's interpretation of a solid-state origin for the metallic component is assumed to be correct for the bulk of the mesosiderites. This assumption may not be valid for all metamorphosed mesosiderites, and is not true of the mesosiderites interpreted to be impact melts. However, the relatively large metal “nodules” that occur in virtually all mesosiderites (Floran et al., 1978a) appear to be clasts that were intimately mixed as solids (Fig. 1). Wilson (1972) has shown that the random magnetic polarity of metal nodules in Bondoc, first reported by Nininger (1963), and their well-sorted nature are indicative of a solid state at the time this meteorite was formed. These clasts have a directional lineation that was formed during deposition of the metal. A directional fabric is also observed for metal clasts in Estherville (see Fig. 3, Powell, 1971), but is is uncertain whether this is depositional in origin or due to metamorphic reorganization. Metal clasts often contain silicate inclusions (Fig. 1; Axon and Nasir, 1977; Powell, 1971) and there is a gradation in some mesosiderites, especially the highly recrystallized ones, from metal clasts with silicate inclusions to metal-rich silicate clasts (Fig. 1).

PETROGRAPHY OF MATRIX AND CLASSIFICATION

Mesosiderites are low-Ca pyroxene, plagioclase, olivine-bearing, stony-iron meteorites consisting of roughly one-half silicates and one-half Ni-Fe metal by weight. Considerable variation in the proportions of metal and silicates exist, however, as pointed out by Mason and Jarosewich (1973). Minor and accessory mineral phases generally present in all mesosiderites include, in approximate decreasing order of abundance: troilite, tridymite, chromite, merrillite (and/or apatite)*, augite, schreibersite, ilmenite, and rutile; the latter two phases are typically present in trace amounts (Powell, 1971). In addition, graphite was found in Barea, Dyarrl Island and Emery (Mason and Jarosewich, 1973) and also in Crab Orchard, Vaca Muerta, Veramin, and Dalgaranga (Ramdohr, 1965); magnetite (Powell and Weiblen, 1967) and copper (Ramdohr, 1965) in Patwar; stanfieldite in Estherville (Fuchs, 1969) and Bondoc (Wilson, 1972); farringtonite in Mincy (Malissa, 1974); sphalerite in Pinnaroo (Ramdohr, 1965); and zircon in Vaca Muerta (Marvin and Klein, 1964). Magnetite is probably a secondary mineral formed by terrestrial weathering, as is lawrencite which has been reported from Crab Orchard, Mount Padbury, Pinnaroo, Vaca Muerta (Ramdohr, 1965), and Bondoc (Wilson, 1972). The presence of lawrencite, possibly in all mesosiderites, is a major factor contributing to the steady and

*As suggested by Dowty (1977), the term merrillite is used in preference to whitlockite.
Fig. 1. Photograph of polished surface of Emery mesosiderite. Matrix consists of intimate mixture of fine-grained metal (white) and silicates (dark). Visible clasts include metal (right) and large diogenite fragment with thin metalliferous vein (left). Most silicate clasts do not exhibit sharp boundaries with matrix and some contain numerous minute inclusions of metal. Maximum dimension: about 10 cm.
continued disintegration of many members of this meteorite group. For detailed petrographic descriptions of individual phases the reader is referred to Powell (1971) and Ramdohr (1965).

On the basis of various petrographic criteria, dealing primarily with matrix relationships, Powell divided the mesosiderites into three metamorphic subgroups representing an implied sequence of increasing recrystallization. These criteria included (1) degree of preservation of brecciated texture, (2) silicate grain size, (3) grain boundary contacts, (4) scale of textural heterogeneity, (5) low-Ca pyroxene relations, and (6) extent of coronal development around olivine clasts. In general, the same criteria have been used in this study. Additional information such as the nature of the clast population further elucidates the petrogenesis of these meteorites and more clearly delineates differences as well as similarities among subgroups.

In Table 1A a revised classification for all 20 mesosiderites is presented that incorporates the main elements of Powell's scheme. Silicate textures of the various subgroups and other petrographic features are illustrated in Figs. 2–4. Subgroups 1, 2, and 3 remain essentially intact as defined by Powell (1971) except that subgroup 3, which is highly recrystallized, has been further subdivided on textural grounds into the pyroxene poikiloblastic (PX POIK) and plagioclase poikiloblastic (PLAG POIK) mesosiderites. Moderately metamor-

<table>
<thead>
<tr>
<th>Table 1A. Classification of the mesosiderites (silicate portion).*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subgroup 1</td>
</tr>
<tr>
<td>slightly recrystallized</td>
</tr>
<tr>
<td>Barea</td>
</tr>
<tr>
<td>Chinguetti</td>
</tr>
<tr>
<td>Crab Orchard (1)</td>
</tr>
<tr>
<td>Dyarrl Island</td>
</tr>
<tr>
<td>Mount Padbury (1)</td>
</tr>
<tr>
<td>Patwar</td>
</tr>
<tr>
<td>Vaca Muerta (1)</td>
</tr>
</tbody>
</table>

*Powell's (1971) subgroups given in parentheses.
†Unidentified mesosiderite, part of West Point collection, U.S. National Museum; this meteorite is either a new mesosiderite or possibly a fragment of Morristown (found, 1887); the West Point mesosiderite cannot be related to either Lowicz or Emery because both of these meteorites came to light (1935, 1962 respectively) well after the West Point collection was donated to the USNM (R. Clarke, pers. comm., 1978).

Not classified: Dalgaranga due to weathered nature of available specimen.
Fig. 2. Photomicrographs illustrating textures of metamorphosed mesosiderites. (a) Slightly recrystallized mesosiderite, Mount Padbury. Silicate matrix is extremely fine-grained and contains numerous angular to subrounded clasts including diogenite fragment at right. Metal forms irregular masses that are probably connected in the third dimension; transmitted light; width = 3.0 mm. (b) Moderately recrystallized mesosiderite, Veramin, showing incipient development of plagioclase poikiloblastic texture. Plagioclase is interstitial to irregular, rounded orthopyroxene grains; reflected light; width = 1.1 mm.
(c) Highly recrystallized mesosiderite, Lowicz, with pyroxene poikiloblastic texture. Note optical continuity between pyroxene clasts and inclusion-rich overgrowths (left, lower right). Most of the field of view consists of a single pyroxene crystal. Former olivine clast, outlined by chromite (black) is present at upper right; partially crossed nicols; width = 3.0 mm. (d) Highly recrystallized mesosiderite with plagioclase poikiloblastic texture, Budulan. Numerous rounded granules of orthopyroxene are enclosed within coarser anhedral plagioclase; transmitted light; width = 2.3 mm.
Fig. 3a. Clast-laden impact-melt mesosiderite with intergranular basaltic texture, Simondium. Orthopyroxene clast at center left has a sieved, "checkerboard" appearance; crossed nicols; width = 1.1 mm.

Fig. 3b. Metaeucrite (?) clast, Clover Springs. Plagioclase (white) and pyroxene (dark grey) have been recrystallized but original basaltic texture is still recognizable in places; transmitted light; width = 3.0 mm.
Fig. 3c. Silicate clast-rich area in Clover Springs. Plagioclase-rich lithic fragment, probably a cumulate eucrite, is at center. Other clasts include plagioclase (white) and low Ca pyroxene (grey); transmitted light; width = 2.3 mm.

Fig. 3d. Metal-rich matrix in Emery illustrating recrystallization and replacement of four clasts and surrounding matrix (center) by a single orthopyroxene poikiloblast. Widespread exsolution of augite is visible. Another orthopyroxene poikiloblast is present at upper left; crossed nicols; width = 2.3 mm.
Fig. 4a. Poikiloblastic orthopyroxene pseudomorphous after olivine in Emery. Original olivine grain is outlined by distribution of chromite; transmitted light; width = 3.0 mm.

Fig. 4b. Same view, crossed nicols. Olivine is completely replaced and fine-grained reaction corona is recrystallized to several coarse pyroxene poikiloblasts. Dark grains at left and center are in optical continuity; width = 3.0 mm.
Fig. 4c. Recrystallized breccia clast in Emery. Plagioclase (light grey) and pyroxene (dark grey) have xenoblastic shapes. Note irregular borders of clasts, which have partially reacted with metal-poor matrix of breccia fragment; width = 3.0 mm.

Fig. 4d. Impact-melt breccia clast in Patwar. Note comb structure of plagioclase crystallites and metal-poor matrix of breccia clast. Boundary between clast and metal-rich matrix of meteorite is at right; reflected light; width = 3.0 mm.
phosed meteorites, Clover Springs and Veramin, represent an intermediate level of textural reorganization and appear to be textural precursors of the PX POIK and PLAG POIK mesosiderites respectively. A new major subgroup, subgroup 4, has been added to accommodate clast-laden, igneous and metaigneous textured mesosiderites as well as individual clasts with petrographic features consistent with an impact-melt origin. A detailed mineralogic and petrologic report of three of these mesosiderites, Simondium, Hainholz and Pinnaroo, is given elsewhere (Floran et al., 1978b).

Although largely successful in categorizing similarities and differences among the mesosiderites, there are problems with this classification. First, many of Powell’s criteria are potentially influenced by pre-metamorphic textures and mineral abundances; thus observed relationships may only partly reflect recrystallization processes. Another problem is failure of the classification to allow for the possibility that some of the subgroup 1 mesosiderites may eventually be shown to be recrystallized, clast-laden impact melts.

At least one of Powell’s criteria, the extent of reaction coronas around olivine, is not a consistent indicator of progressive recrystallization. Powell (1971) noted that these mantles are clearly developed in subgroup 1, extensively developed in subgroup 3, but absent from his subgroup 2. In actuality, the development of coronas is variable within each group and within individual mesosiderites. Coronal development observed in subgroup 1 ranged from slight (Barea, Mount Padbury), to variable (Patwar), to clearly developed (Chingueiti, Crab Orchard, Vaca Muerta). In subgroup 3, extensive coronas are present but variable (Emery, Lowicz), highly variable (Morristown) or not observed (Mincy). This variability appears to be related to concentration gradients at the olivine-matrix boundary. Spectacular development of these mantles occurs in Emery where often only tiny remnants of olivine remain. Some olivine grains, along with surrounding matrix, are completely replaced by one or more mm-sized orthopyroxene poikiloblasts (Fig. 4a,b). Outlines of former olivine clasts, however, are perfectly preserved by the distribution of chromite. As noted elsewhere (Floran et al., 1978b), coronal development is absent in the impact-melt mesosiderites (Simondium, Pinnaroo, Hainholz), although it is highly variable in Estherville. In these meteorites olivine has ragged, irregular outlines suggestive of an unstable phase undergoing dissolution. Powell (1971) drew attention to the close resemblance between these reaction rims and similar coronas around olivine in terrestrial metamorphic rocks. Coronal development, especially in subgroup 1, is very similar to olivine-matrix reactions in Apollo 14 crystalline matrix breccias (Cameron and Fisher, 1975). These “metamorphosed breccias” have been reinterpreted as clast-rich impact melts (Simonds et al., 1977), though the olivine-matrix reaction is generally acknowledged to represent subsolidus reequilibration.

An alternate classification is presented in Table 1B which anticipates the possibility that members of subgroup 1 may be shown to be recrystallized impact melts. In this scheme, metaigneous mesosiderites such as Hainholz are grouped according to their metamorphic characteristics; the inferred melt history of these meteorites and that of recrystallized impact-melt clasts is disregarded. The
Table 1B. Alternate classification of the mesosiderites (silicate portion).

<table>
<thead>
<tr>
<th>Metamorphic</th>
<th>Igneous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subgroup 1</td>
<td>Subgroup 2</td>
</tr>
<tr>
<td>slightly</td>
<td>moderately</td>
</tr>
<tr>
<td>recrystallized</td>
<td>recrystallized</td>
</tr>
</tbody>
</table>

- Barea
- Chinquetti
- Crab Orchard (1)
- Dyar Island
- Mount Padbury (1)
- Patwar (1)
- Vaca Muerta (1)
- several clasts within Patwar and Crab Orchard

- Hainholz (2)
- A. Clover Springs
- A. [Px Poiks]
- Emery
- Lowicz (3)
- Morristown (3)
- †West Point

- Estherville (1)
- B. Veramin (2)
- B. [Plag Poiks]
- Bondoc
- Budulan
- Mincy (3)

- Pinnaroo
- Simondium

The moderately recrystallized nature of Hainholz would place it in subgroup 2 as originally suggested by Powell (1971).

In the alternate classification, Estherville is tentatively assigned to subgroup 3 rather than to subgroup 1 (cf., Powell, 1971, Table 4) for the following reasons:

1. A pronounced clastic texture, as observed in the slightly recrystallized mesosiderites is not evident and many clasts are subrounded rather than angular,
2. Extremely fine-grained comminuted silicates are not present,
3. Grain boundary contacts tend to be sutured,
4. Textural heterogeneity, while present, is not as obvious as in the subgroup 1 mesosiderites,
5. Pigeonite appears to be rare, and
6. Reaction coronas around olivine are highly variable, as previously noted, and do not resemble the fine-grained mantles of subgroup 1. It is interesting to note that some olivines lack coronas and have ragged edges as in the impact melts while others appear to have been completely replaced, the only evidence for their former existence being a concentration of tiny chromite grains within pyroxene. These observations are compatible, though not entirely satisfactory, with a subgroup 3 designation (Table 1B). In the preferred classification, Estherville tentatively is included with the impact melts (Table 1A).

Members of subgroup 1 are characterized by very fine-grained matrices and angular clasts (Fig. 2a). The fine-grained matrices of some mesosiderites such as Crab Orchard have partially recrystallized to plagioclase, opaque-filled orthopyroxene grains that may represent incipient development of the PX POIK texture. In addition, some of the pyroxene clasts have narrow, inclusion-filled rims that are highly irregular in shape but optically continuous with the inclusion-poor cores or clasts.
Subgroup 2 has two members as it did in Powell’s classification, but Clover Springs is new and Hainholz, although also moderately recrystallized, has been removed and reclassified as a subgroup 4 metaigneous mesosiderite. The distinctive textures of Veramin (Fig. 2b) and Clover Springs (Fig. 3c) are similar to the slightly coarser grained PX POIK and PLAG POIK textures of subgroup 3 but poorly developed.

Pyroxene POIK mesosiderites are characterized by mm-sized orthopyroxene poikiloblasts (Fig. 2c), both as coarse anhedral overgrowths optically continuous with the inclusion-poor cores of rounded clasts, and as smaller irregular recrystallized matrix grains. The poikiloblasts contain numerous inclusions of anhedral plagioclase, tridymite, chromite, troilite and rare metal; exsolved augite associated with orthopyroxene that has inverted from pigeonite is common in the poikiloblasts but is rare or absent in clast cores. Variations in the size of the poikiloblasts is, to some extent, controlled by metal abundance; in Emery, metal forms a connecting network between pyroxenes which tends to limit the size of the poikiloblasts, while in Lowicz and Morristown most metal occurs in a few discrete masses, allowing pyroxene poikiloblasts to achieve cm-sized dimensions (see Fig. 4, Powell, 1971). The silicate portions of the PX POIK mesosiderites should not be confused with the Apollo 16 pyroxene poikiloblastic rocks described by Bence et al. (1972). Despite an inferred metamorphic origin, these lunar breccias have been convincingly demonstrated by Simonds et al. (1972) to be impact melts and hence are more accurately termed poikilitic-matrix breccias. In the PLAG POIK mesosiderites orthopyroxene occurs as numerous, small rounded granules often poikilitically enveloped within polysynthetically twinned plagioclase (Fig. 2d). Plagioclase poikiloblasts up to 5 mm in length have been observed in Bondoc. This texture is not always obvious in transmitted, plane-polarized light but is well displayed in reflected light.

The silicate fractions of subgroup 4 mesosiderites, and to a lesser extent that of Hainholz, display igneous textures similar to those of terrestrial basalts (Fig. 3a; Floran et al. 1978a,b). The high clast contents of Hainholz and Simondium and the highly variable response of clasts to thermal effects of the melt (i.e., little or no recrystallization, extensive recrystallization, partial checkerboard melting) is typical of terrestrial and lunar impact-melt rocks (Floran et al., 1978c). Of the two mesosiderites classified as metaigneous, only Hainholz partially retains a recognizable igneous texture, similar to the intergranular basaltic texture of Simondium. In contrast, Estherville is a highly recrystallized clast-laden mesosiderite with a unique texture that does not resemble either the PX POIK or PLAG POIK mesosiderites. Many of the larger pyroxene grains contain both anhedral and subhedral mineral inclusions including tiny plagioclase laths, ~100–200 microns long. Other grains consist of microophitic intergrowths of pyroxene and lathy plagioclase. However, it is not clear whether these grains are clasts or part of the matrix. Much of the coarser plagioclase contains tiny inclusions, and pyroxene “necklaces” are occasionally observed near the rims of plagioclase clasts.
Silicate petrography, classification, and origin of the mesosiderites

Petrography of Clasts

Shock-deformation features, considered definitive evidence of origin during a hypervelocity impact event, are not abundant in the mesosiderites but have been tentatively identified within a number of mineral and lithic clasts. These features include fracturing; undulose extinction; mosaicism and recrystallization in pyroxene, plagioclase, and olivine; planar lamellae in orthopyroxene; and rare checkerboard melting of orthopyroxene. Strong shock effects are invariably absent, probably because of the recrystallized nature of most mesosiderites. McCall (1966) described fine-grained mosaic plagioclase within a cumulate eucrite clast of Mount Padbury that may be thermally recrystallized maskelynite. A similar clast was observed in Crab Orchard, in which mosaic pyroxene is accompanied by devitrified plagioclase. Jain and Lipshutz (1973) estimated on the basis of deformation features in kamacite that Dalgaranga had experienced shock pressures of between 130 to 400 kilobars, and Axon and Nasir (1977) concluded that the occurrence of unmelted to completely melted silicate inclusions within metallic clasts in Bondoc was due to reheating below 450°C following a shock event of unknown magnitude. Reheating by a late impact is supported by concordancy of fission track ages (140 ± 40 m.y.) and cosmic ray exposures ages (150 m.y.) (Carver and Anders, 1976). Of uncertain significance is the widespread kink banding and undulatory extinction that is present in olivine clasts of many mesosiderites. Carter et al. (1968), concluded that these probably formed by plastic deformation under static conditions, thus implying a non-shock origin.

Table 2 lists clast types that have been identified in each mesosiderite based largely on petrographic examination of one or more polished thin sections of each mesosiderite. Hand specimen examination, when available, and literature references were used as complementary data sources. It should be noted that these data are preliminary and that study of additional samples is likely to add heretofore unrecognized clast types to individual mesosiderites. For example, the single polished thin section of Chinguetti that was examined measured only 5 mm X 7 mm and almost certainly is non-representative of the main mass; as a result, no lithic clasts were found although they may well be present in this meteorite.

Clast types (Table 2) include low-Ca pyroxene, plagioclase, olivine, various lithic fragments, and metal. Identification of lithic clasts is based on textural resemblance to meteoritic, lunar or terrestrial analogs, such as the equivalence of diogenite and eucrite to terrestrial orthopyroxenite and basalt respectively. Cumulate eucrite clasts are broadly defined as medium to coarse grained, generally feldspathic fragments with gabbroic textures; similarly, metaeucrites are basaltic eucrite clasts whose igneous textures, while recognizable, have been recrystallized to granoblastic aggregates (Fig. 3b). “Anorthositic” clasts have high modal abundances of plagioclase but are not typical of true anorthosite because of their generally small size and resemblance to feldspar-rich cumulate
Table 2. Clast types in mesosiderites (mineral > lithic > metal).

<table>
<thead>
<tr>
<th></th>
<th>Mineral</th>
<th>Lithic</th>
<th>Metal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Px</td>
<td>Pl</td>
<td>Ol</td>
</tr>
<tr>
<td>Subgroup 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barea (2)</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Chingetti (1)</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Crab Orchard (4)</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Dyarrl Island (1)</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Mt. Padbury (2)</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Patwar (2)</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Vaca Muerta (3)</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Subgroup 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clover Springs (3)</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Veramin (3)</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Subgroup 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bondoc (3)</td>
<td>x</td>
<td></td>
<td>?x</td>
</tr>
<tr>
<td>Budulan (2)</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mincy (2)</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Emery (5)</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Lowicz (2)</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Morristown (2)</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>?Dalgaranga (2)</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>UnKnown, Wt Pt (1)</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Subgroup 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>?Estherville (4)</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Hainholz (3)</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Pinnaroo (3)</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Simondium (2)</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>

Based on studies of 52 polished thin sections (number for each mesosiderite in parentheses) and hand specimens with supportive data, where noted, from the literature; 1Lacroix (1924); 2McCall (1966), 3Wasson (1974), 4McCall (1965), 5Prior (1918). Px = Ca-poor pyroxene; Pl = plagioclase; Ol = olivine, Di = diogenite; E = eucrite; EC = cumulate eucrite; ME = metaeucrite; A = "anorthosite" (plagioclase-rich lithic clasts); Du = "dunite" (olivine-rich lithic clasts); IMB = impact melt breccia; RB = recrystallized breccia. For the purposes of this table, Dalgaranga is tentatively classified as a high grade mesosiderite.

Eucrites. For these reasons they are best described as plagioclase-rich lithic clasts but may be considered non-representative, cumulate eucrite fragments. (Fig. 3c). However, coarse-grained plagioclase derived by the fragmentation of anorthosite may well be present in some mesosiderites. Dunite clasts are rather rare but are likely to be the source rocks of most olivine clasts. The distinction between fine-grained recrystallized and impact-melt breccia clasts is often indicated by an examination of their matrices in reflected light (Figs. 4c,d). An impact-melt origin for fragment-laden clasts is suggested by the presence of tiny plagioclase
Silicate petrography, classification, and origin of the mesosiderites

laths in their matrices. As noted by Phinney et al. (1977), feldspar morphology is a sensitive indicator of clastic vs. melt origin. In these clasts individual fragments commonly served as nuclei for the growth of matrix phases, producing a quench texture. Breccia clasts without obvious igneous-textured matrices are classified as metamorphosed breccias. Metal clasts are angular to subrounded, sharply defined nodules that are physically separated from finer grained matrix metal (Fig. 1).

A general relationship that appears to be true of every mesosiderite is that mineral clasts are far more abundant than lithic clasts which in turn are usually more numerous than recognizable metal clasts. This relationship, in part, reflects the present grain size relative to the coarse grained mineralogy of the source rocks prior to brecciation and mixing.

The following observations are apparent from an examination of Table 2:

(1) The mineral clast population is dominated by three phases: low-Ca pyroxene, plagioclase, and olivine. Orthopyroxene is the dominant clast type although pigeonite occurs in substantial amounts in several eucrite-rich subgroup 1 mesosiderites. Plagioclase and olivine clasts are present in most mesosiderites but the apparent lack of one or both in Bondoc, Budulan, and Mincy may be significant. Although their absence could be a sampling problem, it is worth noting that these three meteorites have PLAG POIK textures (Table 1). Other minerals may occur in trace amounts as clasts but these were not positively identified.

(2) The most common lithic clast type is diogenite. Most coarse single crystal fragments of orthopyroxene are probably derived from the fragmentation of diogenites. Plagioclase-rich lithic clasts are also abundant, as are cumulate eucrites with high modal plagioclase contents. These are common lithic clast types in Clover Springs and Emery, while finer grained, basaltic-textured eucrites are a major clast type in Dyarrl Island and Patwar. Rare, olivine-rich fragments (dunite) occur in several mesosiderites, the most thoroughly described of which are those in Mount Padbury (McCall, 1966). Recrystallized breccia clasts are found in all three metamorphic subgroups but are most prevalent in subgroup 1 mesosiderites. In Patwar, slightly recrystallized breccia clasts retain igneous-textured matrices suggestive of impact melting (Fig. 4d). At least 2 mesosiderites, Emery (Hewins et al., 1977) and Mount Padbury (Wasson, 1974, Fig. XIV-3), contain metal-silicate segregations that may be clasts of earlier-formed mesosiderites. However, these are more likely to be silicate clasts that were selectively replaced or invaded by hot matrix metal.

(3) Metal clasts have been identified in every mesosiderite except Dyarrl Island, Budulan, and Simondium. This indicates that solid metal was an important source (target) rock. The apparent lack of metal nodules in the above meteorites is difficult to assess but may be due to sampling.

(4) Lithic clasts are best preserved and therefore most abundant in subgroup
mesosiderites. This is consistent with the view that increasing recrystal-
ization tends to obliterate the primary textures of lithic clasts, leading to
a recognizable clast population dominated by large single crystals and
monomineralic, polycrystalline fragments. In some instances, however,
destruction of premetamorphic textures within highly recrystallized
mesosiderites is slight, despite extensive replacement (Fig. 3d). In Emery,
monomineral clasts as well as breccia clasts are completely replaced by
course pyroxene poikiloblasts but the original distinction between clastic
material and matrix is perfectly preserved.

(5) There are distinct differences in the clast populations of the PX POIK
and PLAG POIK mesosiderites; the PLAG POIKS lack recognizable
eucrite and cumulate eucrite fragments and are remarkably free of lithic
clasts except for diogenites. In contrast, the PX POIKS contain a variety
of clast types not found in the PLAG POIK mesosiderites.

DISCUSSION AND CONCLUSIONS

The variety of textures and clast types, particularly lithic clasts, and the overall
brecciated appearance of the mesosiderites indicate that they accumulated in
near-surface environments by the same kinds of processes that led to the
formation of lunar breccias and terrestrial impactites. A similar mode of origin is
necessary to account for the metal-deficient analogs of mesosiderites—the
howardites. However, the recognition of clast-laden, igneous textured mesosider-
ites as impact melts (Floran et al., 1978a,b) adds yet another dimension to the
complex history outlined by Powell (1971) for these meteorites.

The inferred sequence of increasing recrystallization within the metamor-
phosed mesosiderites is somewhat analogous to the succession of petrologic types
in the H, L, LL 3 → 6 chondrites (Van Schmus and Wood, 1967), with subgroup
4 possibly equivalent to the melted or ultrametamorphosed Shaw meteorite
(Dodd et al., 1975; Berkley et al., 1976) classified by Dodd et al. (1975) as an
LL7 chondrite. As with the chondrites, uncertainty exists as to whether a higher
grade mesosiderite can be derived from a lower grade mesosiderite solely by
recrystallization. Portions of Emery are informative in this regard because of
their near-perfect preservation of relict clast-matrix textures.

Petrographic observations suggest that two distinct paths of recrystallization
may be present which at high grade result in the formation of PX and PLAG
POIK textures. The matrix texture of Crab Orchard suggests that extensive
recrystallization of clast + matrix pyroxene of subgroup 1 mesosiderites could
have led to development of the PX POIK texture, but the low grade precursors of
the PLAG POIK texture are not represented among known mesosiderites. In
fact, their inferred equivalence in metamorphic grade to the PX POIK mesosid-
erites (Table 1) is not well established, despite the classification by Powell (1971)
of Mincy (the only PLAG POIK he studied) as a subgroup 3 mesosiderite. The
absence of recognizable plagioclase clasts in the PLAG POIK mesosiderites, the
lack of lithic clasts other than diogenites, and the unique texture suggest a fundamental difference with other mesosiderites.

In contrast to the PLAG POIK mesosiderites, Clover Springs and the related PX POIK mesosiderite Emery contain both cumulate eucrite and plagioclase-rich lithic clasts. This is especially true of Clover Spring and is supported by the low REE abundances and positive Eu anomaly obtained by Wänke et al. (1972). The REE pattern of Clover Springs (as well as that of Crab Orchard) is essentially identical to the plagioclase-rich cumulate eucrite, Serra de Magé (Schnetzler and Philpotts, 1969). The apparent rarity of true anorthositic clasts in any of the mesosiderites indicates that plagioclase did not play as prominent a role in the evolution of the mesosiderite parent body as it did in the evolution of the lunar highlands.

In addition to the divergent paths of recrystallization leading to the PX and PLAG POIK textures, a third sequence exists linking metamorphosed and impact-melted mesosiderites. This sequence extends from igneous-textured mesosiderites to more evolved meteorites with metaigneous textures such as Hainholz and possibly Estherville. Hainholz is an obvious link between the two major subdivisions of the mesosiderites but its moderately recrystallized silicate matrix does not resemble that of any other metamorphosed mesosiderite.

An intriguing question is whether the silicate matrices of the least thermally altered mesosiderites, subgroup 1, represent recrystallized clast-rich impact melts or are fragmental breccias that contained variable amounts of glass prior to recrystallization. Several lines of evidence suggest that the silicate matrices of these meteorites may never have contained a significant silicate melt component: (1) lack of igneous-textured matrices accompanied by preservation within the same mesosiderite of fine-grained impact-melt clasts with quench textures, (2) partial preservation of clast-laden igneous textures in mesosiderites that have experienced more intense recrystallization, as noted above for Hainholz, and (3) troilite-metal relationships. A detailed examination of troilite and metal was beyond the scope of this study but the textural occurrence of the metallic fraction bears on the origin of the silicate component and the meteorites themselves. In the impact-melt mesosiderites, most troilite occurs at the metal-silicate boundary; only a very minor amount is present as small disseminated grains surrounded by silicates. Curved metal-troilite borders and the anastomosing nature of troilite radiating away from metal into the silicate fraction suggested that both phases crystallized from a metallic melt (Floran et al., 1978b). In the recrystallized mesosiderites these relations are not observed, implying that most if not all metal and troilite may be fragmental in origin. Powell (1971) noted that in subgroup 1 mesosiderites troilite does not appear to be preferentially associated with either metal or silicates. In Veramin, troilite is physically separated from metal and in subgroup 3 "troilite is generally associated with silicates rather than metal . . . most sulfide masses are completely surrounded by silicates, although occasionally they are bordered partially by Ni-Fe metal" (Powell, 1971). These observations are supported by the present investigation and suggest that the silicate matrices and probably the entire metallic fraction were mixed as solids at the time of
breccia formation. Evidence of localized mobilization and migration of metal after formation is present in some mesosiderites (Fig. 1).

Relationships to lunar breccias

By analogy with lunar impactites the mesosiderites can be broadly characterized as crystalline matrix breccias. Table 3 lists various lunar breccia types and their approximate mesosiderite analogs. Some of the criteria that distinguish the breccia types are self-evident or listed in Table 3. A detailed discussion of these breccias is given in Simonds et al. (1977), Warner et al. (1977), and Phinney et al. (1977). Although the classification presented in the latter paper has since been revised (Phinney, 1978, pers. comm.), the petrographic features upon which rock types were defined remain largely intact. For the fragmental matrix breccias and impact melts these criteria include (Simonds et al., 1977): (1) correlated variations in clast content, (2) refractory nature of the clast population, (3) grain size and morphology of matrix feldspar (4) glass content, and (5) matrix texture. Of these criteria, differences in feldspar morphology are very useful for classification purposes and, in addition, have genetic significance.

Bickel and Warner (1978) subdivided the feldspathic granulite suite on the basis of grain boundary relationships and plagioclase grain size. The granulites, which appear to be analogous primarily to subgroup 3 mesosiderites, are granoblastic- and poikiloblastic-textured impactites with recognizable clast-matrix structure (Warner et al., 1977). Crystal shapes are anhedral and equant, and plagioclase grain boundaries tend to approach 120° triple junctions. Although the latter feature is not present in mesosiderites, matrix textures of the granulitic impactites and subgroup 3 mesosiderites are similar (compare Fig. 2c,d with Fig. 1 of Warner et al., 1977).

Similarities and differences between the granulites and mesosiderites are summarized in Table 4. Both are metamorphosed polymict breccias with a clast population dominated by plutonic rock types. The granulites are derived from ANT suite material; the mesosiderites appear to contain a somewhat more diverse clast population that includes plutonic (e.g., diogenite, cumulate eucrite, dunite), near-surface (eucrite, various breccias) and unknown (metal) environments of formation.

A major difference between the two groups is the dominance of plagioclase in the granulites, emphasized by the term feldspathic granulitic suite, and orthopyroxene in the mesosiderites. As a result, textural development is not identical. The PLAG POIK mesosiderites and the poikiloblastic-textured granulites are probably the closest textural analogs of the various subgroups and textural types that have been defined. Another difference between the two groups is the nature and possible duration of metamorphism. The lunar rocks were annealed at about 1000°C (Warner et al., 1977) whereas the silicate portions of mesosiderites appear to have recrystallized at lower temperatures, possibly 600–700°C (Powell, 1971). The slow cooling rate for the mesosiderites below 500°C may
Table 3. Generalized classification of lunar breccias (in part modified from Simonds et al., 1977; Phinney et al., 1977; Bickel and Warner, 1978) and mesosiderite equivalents.

<table>
<thead>
<tr>
<th>Very High Clast/Matrix Ratio</th>
<th>Lunar Breccia Type</th>
<th>~Mesosiderite Equiv. (see Table 1B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Fragmental Matrix Breccias; no recrystallization; variable amounts of glass present; anhedral matrix minerals; seriate grain size</td>
<td>none; but subgroups 1–3 (excluding Hainholz and Estherville) may be metamorphosed fragmental breccias</td>
<td></td>
</tr>
<tr>
<td>1. light matrix</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. dark matrix</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. devitrified-glass matrix</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B. Crystalline Matrix Breccias [Igneous]; lathy or subhedral matrix feldspar; little or no recrystallization</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>1. clast-rich impact melts (Fra Mauro breccias, Apollo 16 poikilitic matrix breccias)</td>
<td>subgroup 4 Simondium Pinnaroo</td>
<td></td>
</tr>
<tr>
<td>2. clast-bearing impact melts (Apollo 16 basaltic matrix breccias)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. clast-free impact melts (14310)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. Crystalline Matrix Breccias [Annealed]; equant or anhedral matrix feldspar; poikiloblastic; granulitic texture</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>1. Granulitic (fine grained)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. (medium grained)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Impactites (coarse grained), poikiloblastic, granulitic</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: while some Igneous Crystalline Matrix Breccias (i.e., clast-rich impact melts) may show evidence of recrystallization, no reheating episode is implied; in contrast, Annealed Crystalline Matrix Breccias may have undergone extensive reheating over a long but unknown period of time.
represent a rapid, decelerating cooling from elevated temperatures or a reheating episode in a new, slowly cooling environment (Powell, 1971).

Bickel and Warner (1978) interpret the granulites to be very old impactites that resided in early ejecta blankets on the lunar surface. The mesosiderites may have experienced a similar history on a different parent body. However, the exceedingly long period of time required for cooling below 500°C, makes it impossible for the silicates in mesosiderites to have experienced the same kind of prolonged, high temperature annealing history hypothesized for lunar granulites.

Table 4. Characteristics of feldspathic granulites and silicate portions of mesosiderites.

<table>
<thead>
<tr>
<th>A. Similarities</th>
<th>Granulites</th>
<th>Mesosiderites</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. impactites</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. polymict breccias with relatively fine-grained matrices</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. annealed (metamorphic) textures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. abundant clasts of plutonic origin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B. Differences</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mineral</td>
<td>plagioclase (70–80%)</td>
<td>orthopyroxene (55–70%)</td>
</tr>
<tr>
<td>Annealing</td>
<td>T ~ 1000°C for extended time span</td>
<td>unknown, but extremely slow cooling between 500°C and 350°C (0.1°C/10^6 yr)</td>
</tr>
<tr>
<td>Protolith</td>
<td>impact melts (and fragmental matrix breccias?)</td>
<td>fragmental matrix breccias</td>
</tr>
</tbody>
</table>

Arguments advanced previously suggest that the recrystallized mesosiderites may be metamorphosed fragmental breccias (Table 3). If true, these mesosiderites should have the characteristics of detrital impactites. Engelhardt (1971) noted important differences between lunar and terrestrial impact formations which should also be applicable to the mesosiderite parent body. For example, unlike single-stage impactites associated with terrestrial craters, the lunar surface is blanketed by a multi-impact formation, or regolith, produced by repeated impacts. Lack of an atmosphere and reduced gravitational field allow extensive transportation and mixing of impact debris. The validity of these characteristics for the mesosiderite parent body is supported by the polymict clast populations of mesosiderites, the large number of different clast types present and the apparent genetic relationships between the mesosiderites and the howardite-eucrite-diogenite suite. The variety of rock types occurring as clasts exceeds that of most lunar breccias implying very efficient mixing on the surface of a heterogeneous planet.
Relationships to the howardites, eucrites and diogenites

The lithic clast types within individual mesosiderites (Table 2) provide a powerful tool with which to determine endmember mixing components. Further petrographic studies together with modal and bulk chemical analyses of a large number of representative samples may be able to quantify the relative contributions of clast types, and hence the ratios of various mixing components as has been done with howardites (Dreibus et al., 1977). This is especially true of subgroup 1 mesosiderites. To a first approximation there are 6 silicate endmember components (Fig. 5): (1) eucrite, (2) cumulate eucrite, (3) diogenite, (4) dunite, (5) recrystallized breccias, and (6) impact-melt breccias. These can be consolidated into an igneous or primary component comprised of distinct, mafic and ultramafic meteorite types, and a sedimentary or secondary component consisting of a group of heterogeneous breccias. No mesosiderite contains all of the silicate endmember components and few contain most of them.

Future work may show that additional components are present in the mesosiderites. For example, mesosiderites tend to contain more SiO₂ than howardites (Powell, 1971), suggesting perhaps that a silica-rich component may be present. silica enrichment could be due to a siliceous clast type, previously unrecognized. The present investigation did not reveal the presence of such clasts in any of the mesosiderites. However, microprobe studies of Emery have shown that rare clasts exist with high modal abundances of tridymite; in addition, the matrix of Emery contains unusually high amounts of tridymite (M. Prinz, 1978, pers. comm.). The relative abundances of such clasts in other mesosiderites is

![Diagram](image)

Fig. 5. The 6 major clast components that comprise the silicate portions of mesosiderites. These include both igneous (primary) and sedimentary (secondary) contributions of mafic-ultramafic affinity.
unknown, but a search should be made for them. Excess silica might also result from oxidation of silicon in solid solution within metal. Such a source is speculative at this point, but might explain the tendency in some mesosiderites, such as Pinnaroo, for tridymite and plagioclase to be associated with Ca phosphate within large metal masses and at metal-silicate boundaries. A large irregular metallic area in Morristown contains this mineral association. These minerals are disseminated as randomly oriented, rodlike regions throughout the metal rather than concentrated in discrete patches. Admittedly, disseminated silicates are rare in the metallic fractions of mesosiderites. Nevertheless, some silicate material, like phosphate, may have originated by subsolidus metal-silicate reactions. Several workers (Fuchs, 1969; Powell, 1971; Mason and Jarosewich, 1973) noted that phosphate minerals occur preferentially at metal-silicate boundaries and within kamacite. Fuchs (1969) proposed that most Ca phosphate formed by subsolidus oxidation of P dissolved in the metal. A similar reaction relation between elemental Si in the metal and surrounding silicates may explain the observed distribution of tridymite and plagioclase in Morristown and Pinnaroo. Under appropriate reducing conditions, up to several weight % Si can be dissolved in kamacite (Keil, 1968). Magnetic separation procedures for chemical analysis would result in inclusion of this component with the silicate fraction, thus yielding "higher" silica contents. At least some of the tridymite found within the silicate matrix may ultimately have had the same origin, i.e., by repeated fragmentation, mixing, and subsolidus reaction between the silicate and metallic fractions prior to their aggregation as mesosiderites. An unknown amount of tridymite will have been also contributed by the fragmentation of eucritic debris.

Although similar clast types occur in mesosiderites and howardites, there are differences which make a close genetic relationship uncertain. In addition to differing silica contents, the silicate portions of mesosiderites contain a significantly higher TiO₂ content (Powell, 1971, Table 9). Perhaps the mesosiderite with the closest affinities to the metal-poor howardites is Dyarrl Island. This was pointed out to the author by Ed Stolper and also recognized by Mason and Jarosewich (1973) who noted the close chemical similarity between Dyarrl Island and the Kapoeta howardite. According to the bulk analysis given in Mason and Jarosewich (1973), Dyarrl Island has the lowest weight percent metal of any mesosiderite, 17%, and a Ca/Al ratio (1.12) significantly higher than all other mesosiderites but similar to the average howardite or eucrite (1.09) (McCarthy and Ahrens, 1971). This high ratio as well as Ti enrichment relative to Kapoeta probably reflects the observed abundance of eucrite fragments in Dyarrl Island and therefore its relatively low plagioclase/pyroxene ratio.

The Ca/Al ratios of mesosiderites and their comparison with howardites has been discussed by McCarthy and Ahrens (1971) and Mason and Jarosewich (1973). Several additional observations are worth noting in the light of clast data presented in Table 2. A low Ca/Al ratio can be considered indicative of a high plagioclase/pyroxene ratio or, alternatively, a large amount of plagioclase cumulate eucrite debris. Clover Springs has a very low Ca/Al ratio (0.61), which
silicate petrography, classification, and origin of the mesosiderites

is consistent with its observed high abundance of cumulate eucrite clasts and the near identity of its REE pattern with Serra de Magê. The relatively high Ca/Al of Serra de Magê (0.96) reported by McCarthy and Ahrens (1971) is unexpected but may be due to biased sampling of pyroxene-rich areas, a common experience with this coarse-grained meteorite (see Prinz et al., 1977). Alternatively, low Ca/Al ratios in mesosiderites may be accentuated by overestimation of Al in older published analyses (B. Mason, 1978, pers. comm.). Very low Ca/Al ratios in Bondoc and Budulan (0.63) are compatible with a high plagioclase/pyroxene ratio but are not related to the presence of recognizable plagioclase-rich lithic clasts. The much higher Ca/Al ratio of the related mesosiderite, Veramin (0.88), is consistent with very poor development of the plagioclase poikiloblastic texture in this mesosiderite.

Despite some obvious differences, the common occurrence of diogenites, eucrites, and various types of breccias as major clastic components in both mesosiderites and howardites is a strong argument favoring a common origin on the same, albeit heterogeneous planetary body. Supporting this contention is the overall similarity in mineral chemistry between eucrite, cumulate eucrite, diogenite and equivalent clast types in howardites and the slightly recrystallized mesosiderites (Powell, 1971). In highly metamorphosed mesosiderites such as Emery extensive chemical homogenization between clasts and matrix has apparently occurred, obliterating primary mineral compositions in many lithic clasts (Nehru et al., 1978). On the other hand, the tentative identification of asteroid 4 Vesta as the source of the basaltic achondrites based on spectrophotometry (McCord et al., 1970), phase equilibria (Stolper, 1977) and trace element studies (Consolmagno and Drake, 1977) is incompatible with metal-rich surface areas which might be expected on the mesosiderite parent body.

The occurrence of metal nodules and various lithic clasts indicate that the mesosiderites have sampled a very diverse spectrum of rock types that include, but are not limited to, differentiated liquids and cumulates produced by variable degrees of partial melting. The absence of indigenous glass in the mesosiderites, the presence of variably recrystallized breccia clasts, and the slow cooling rates indicate that these meteorites, unlike the howardites, must have undergone burial metamorphism for an unusually long period of time. Although all mesosiderites studied by Powell (1969) appear to have undergone the same slow cooling history below 500°C, the silicate textures indicate that they experienced different thermal histories above 500°C, resulting in the observed recrystallization sequence.

The impact-melt mesosiderites must have formed at the surface but these too may have been buried at shallow depths. They indicate that hypervelocity impacts of considerable magnitude were probably common on the mesosiderite parent body (Floran et al., 1978b). Such impact events on the earth and moon, however, always produce a much greater quantity of consolidated, polymict clastic debris rather than impact melts (Simonds et al., 1976). The high metal content of these meteorites indicates that metal must have been abundant at one time near or at the surface of the parent body.
Possible parent source bodies other than Vesta include the 12 large asteroids identified by Gaffey and McCord (1977) which have “mesosiderite” or “px stony-iron” surfaces. Of these, 6 Hebe and 8 Flora merit special attention because of their occurrence near the $\nu_6$ secular resonance (Wetherill, 1976). According to Wetherill, such asteroids may be important sources of differentiated meteorites because of the high probability that they produce earth-crossing fragments through collisions. Wetherill (1977) raises the possibility that some of the large S asteroids (Chapman, 1976) including Flora, might be residual earth planetesimals or their fragments that differentiated near the earth during the latter stages of terrestrial accretion. He concludes that the basaltic achondrites (and therefore the eucrite, clast-bearing mesosiderites) may have originated on the surfaces of such bodies. Oxygen isotope data (Clayton et al., 1976) are consistent with this supposition, since the earth and the basaltic achondrite-diogenite-mesosiderite suite all fall on the same mass-fractionation line.

**EPILOG**

If the analogies made in this paper between lunar breccias and mesosiderites are valid, they may serve as a framework for more detailed, quantitative studies. Lunar analogies may be ultimately proven wrong, but current models for lunar evolution provide us with an increasingly detailed glimpse of how other differentiated planets may have evolved, including the mesosiderite parent-body. In any event, before the paragenesis of mesosiderites can be fully understood, the paradox of extremely slow cooling rates (and by implication long periods of time required for cooling) coupled with relatively old ages (Begemann et al., 1976; Murthy et al., 1978) and evidence of formation in shallow near-surface environments must be resolved.

**Acknowledgments**—I wish to thank Roy Clarke Jr. of the Smithsonian Institution for the loan of polished thin sections of Barea (USNM #1468, two sections), Bondoc (USNM #2578), Budulan (USNM #2487), Chinguetti (USNM #3205), Clover Springs (USNM #1633), Crab Orchard (USNM #346), Dalgaranga (USNM #3233), Dyarrl Island (USNM #5725), Emery (USNM #5604), Estherville (USNM #1722), Lowicz (USNM #1409), Mincy (USNM #207), Morristown (USNM #2935), Mount Padbury (USNM #3203), Pinaroo (USNM #2312), Veramin (USNM #225) and an unknown mesosiderite specimen from the West Point collection (USNM #5770); Tom McGetchin and his associates for a visiting scientist appointment at the Lunar and Planetary Institute; Bill Phinney, Jeff Warner, Jeff Taylor, and Marty Prinz for stimulating discussions; Roger Kroodsma and E. G. Struxness of the Environmental Sciences Division, Oak Ridge National Laboratory, for their support and encouragement; and the American Museum of Natural History where this project was initiated. Constructive criticisms by J. Wood, M. Prinz, and especially E. Stolper have hopefully resulted in improvements of the original manuscript. This work was supported in part by NASA grant NSG-7258 (M. Prinz, Principal Investigator). A portion of this work was performed at the Lunar and Planetary Institute, which is operated by the Universities Space Research Association under contract No. NSR-09-051-001 with the National Aeronautics and Space Administration. This paper constitutes the Lunar and Planetary Contribution No. 335.

**REFERENCES**

Silicate petrography, classification, and origin of the mesosiderites


LaCroix A. (1924) Sur un nouveau type de fer meteorique trouve dans le desert de l'Adrare en
Lovering J. F. (1962) The evolution of meteorites—evidence for the existence of chondritic,
achondritic, and iron meteorites in a typical parent meteorite body. In Researches on Meteorites
Malissa H. (1974) Electron microprobe analysis of some minor and accessory components in
Mason B. and Jarosewich E. (1973) The Barea, Dyarrl Island, and Emery meteorites and a review of
McCall G. J. H. (1965) New material from, and a reconsideration of the Dalgaranga meteorite and
McCall G. H. J. (1966) The petrology of the Mount Padbury mesosiderite and its achondritic
Mittlefehldt D. W. (1977) REE and igneous differentiation of the howardite and mesosiderite parent
bodies. Meteoritics 12, 311–312.
Murthy V. R., Coscio M. R. and Sabelin T. (1977) Rb-Sr internal isochron and the initial 87Sr/86Sr
Prinz M., Nehru C. E., Berkley J. L., Keil K., Jarosewich E. and Gomes C. B. (1977) Petrogenesis of
the Serra de Magé cumulate eucrite. Meteoritics 12, 341.
Prior G. T. (1910) On a meteoritic stone from Simondium, Cape Colony. Mineral. Mag. 15,
312–314.
Prior G. T. (1918) On the mesosiderite-grahamite group of meteorites: With analyses of Vaca
Prior G. T. (1921) On the South African meteorites Mount Ayliff and Simondium and the chemical
Ramdohr P. (1965) Uber Mineralbestand von Pallasiten und Mesosideriten und einige genetische
Schnetzler C. C. and Philpotts J. A. (1969) Genesis of the calcium-rich achondrites in light of
D. Reidel, Dordrecht.


