SILICATE PETROGRAPHY AND ORIGIN OF THE MESOSIDERITES: A PRELIMINARY INVESTIGATION OF THEIR RELATIONSHIPS TO THE HOWARDITE-EUCRITE-DIOGENITE SUITE

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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 primarily of orthopyroxene, plagioclase, and olivine. Lithic clasts provide important information on the surface and near-surface distribution of magmatic differentiates and polymict breccias on the mesosiderite parent body; lithic clast types include diogenites, plagioclase 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. The mesosiderites were variably recrystallized, possibly near the base of a hot megaregolith layer after major differentiation events which produced the diverse suite of volcanic-plutonic rock associations found as clasts. Although many of the same clast types are also present in howardites, important differences exist between the two meteorite groups: howardites lack appreciable metal, olivine, troilite and phosphate, all integral constituents of mesosiderites, but contain various glasses and rare chondritic clasts not found in mesosiderites. These differences may reflect origins on different planetary bodies or localized origins on the same, heterogeneous planet. The mesosiderite

parent body, if still intact, may be either (1) asteroid 4 Vesta or (2) one or more of the 12 large asteroids with inferred mesosiderite or pyroxene stony-iron surfaces.

INTRODUCTION

The mesosiderites (Table 1) 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 (Hewins et al., 1977; Floran and Prinz, 1978, Floran et al., 1978a; Nehru et al., 1978) 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 individual mesosiderites, each of which is a breccia containing numerous clast types within a variably recrystallized or igneous-textured matrix. Powell studied 10 of the mesosiderites and although the scope of his investigation remains impressive, many first-order unanswered 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), and probably a significant fraction of the larger asteroids. Recent attempts by Chapman (1976), Gaffey and McCord (1977), and others to relate the spectrophotometric properties of differentiated (as well as undifferentiated meteorites) to specific asteroids emphasizes the important role that impact events have played in the accretion and collisional fragmentation of these bodies.

As with other meteorites, early studies of mesosiderites were limited to descriptions of the circumstances surrounding their fall or discovery, often accompanied by a brief discussion of their mineralogy and gross chemistry. The first 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 all but 2 of the then-known 9 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 (1965) touched upon the petrology and origin of the mesosiderites but both of these 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 trace element studies of 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, 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 ^{40}Ar-^{39}Ar systematics of Estherville.

In this paper previous data and hypotheses of origin are reviewed and evaluated in the light of new information obtained from a petrologic reconnaissance survey of all 20 mesosiderites. 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 enigmatic 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 parent body (or bodies).

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 Powell's interpretation is assumed to be correct for the bulk of the mesosiderites. This assumption may not be valid for all of the metamorphosed mesosiderites, nor for the finer-grained metal in the impact-melts. However, the relatively large metal "nodules" that occur in virtually all mesosiderites (Floran *et al*., 1978a) are clearly clasts that were intimately mixed as solids (Fig. 1). Wilson (1972) described a lineation of metal nodules and large pyroxene clasts in Bondoc which he attributed to solid-state shaping during deposition. A directional fabric is also observed for metal clasts in Estherville (see Fig. 3, Powell, 1971), but it 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 may be a gradation in some mesosiderites, especially the highly recrystallized ones, from metal clasts with silicate inclusions to metal-rich silicate clasts.

PETROGRAPHY OF MATRIX

Mineralogically, the mesosiderites are low-Ca pyroxene, plagioclase, olivine-bearing, stony iron meteorites consisting of $\sim$ 50% silicates and $\sim$ 50% Ni-Fe metal. Minor and accessory mineral phases generally present in all mesosiderites include, in approximate decreasing order of abundance: troilite, tridymite, chromite, whitlockite (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). Lawrencite appears to have been originally present in 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 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, 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. Additional information such as the nature of the clast population further elucidate the petrogenesis of these meteorites and more clearly delineate differences as well as similarities among subgroups.

In Table 2 a revised classification is presented that incorporates the main elements of Powell's scheme. 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 metamorphosed meteorites, Clover Springs and Veramin, represent an intermediate level of textural reorganization and appear to represent textural precursors of the PX POIK and PLAG POIK mesosiderites respectively. A new major subgroup, subgroup 4, has been added (Table 2) to accomodate clast-laden, igneous-textured mesosiderites with petrographic features consistent with an impact-melt origin. A detailed mineralogic and petrologic report of these mesosiderites is given elsewhere (Floran _et al_., 1978b). Although Hainholz and possibly Estherville are impact melts, both have been recrystallized during a later metamorphic event; they are thus designated as special members of subgroups 2 and 3 (i.e., 2*, 3*) depending on the intensity of recrystallization.

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, however, are absent, largely because of the recrystallized nature of most mesosiderites. McCall (1966) has described fine-grained mosaic plagioclase within a cumulate eucrite clast of Mount Padbury that may be thermally recrystallized maskelynite. 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 Myr) and cosmic ray exposures ages (∿ 150 Myr) (Carver and Anders, 1976). Of uncertain significance is the widespread kink banding and undulatory extinction that is present in olivines of many mesosiderites. Carter et al. (1968), concluded that these probably formed by plastic deformation under static conditions, thus implying a non-shock origin.

The silicate textures of representative mesosiderites of each subgroup are illustrated in Figs. 2, and 3. Members of subgroup 1 are characterized by very fine-grained matrices and angular clasts (Fig. 2a). Except for the metal component these meteorites resemble slightly recrystallized, lunar clastic-matrix breccias. However, the nature of the matrix from a mineralogic and textural point of view is not easily discernible. 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 medium grade metaigneous mesosiderite. The distinctive textures of Veramin (Fig. 2b) and Clover Springs are essentially identical to the slightly coarser grained PX POIK and PLAG POIK textures of subgroup 3. PX POIK mesosiderites are characterized by mm sized orthopyroxene poikiloblasts (Fig. 2c), both as coarse anhedral overgrowths optically continuous with the inclusion-poor cores of clasts, and as smaller, irregular recrystallized matrix grains. The poikiloblasts contain numerous inclusions of anhedral plagioclase, tridymite, chromite, troilite and metal; exsolved augite, often associated with orthopyroxene that has inverted from pigeonite, is ubiquitous in the poikiloblasts but is rare or absent in clast cores. Variations in the size of the poikiloblasts is, to some extent, controlled by the abundance of metal; in Emery, metal forms a connecting network between pyroxenes which tends to limit the size of the poikiloblasts, while in Lowicz most metal occurs in a few discrete masses, allowing pyroxene poikiloblasts to achieve cm-sized dimensions (see Fig. 4, Powell, 1971). In the PLAG POIK mesosiderites orthopyroxene occurs as numerous, small rounded granules often poikilitically enveloped within polysynthetically twinned plagioclase (Fig. 2d). 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. 3; Floran et al. 1978a,b). The high clast content of Hainholz and Simondium and the highly variable response of clasts to the thermal effects of the melt (i.e., little or no recrystallization, extensive recrystallization, partial checkerboard melting) is typical of terrestrial and lunar impact melted rocks (Floran et al., 1978c). Of the two mesosiderites that are classified as metaigneous, only Hainholz partially retains an igneous texture, that is very similar to the intergranular basaltic texture of Simondium. In contrast, Estherville is a highly recrystallized clast-laden mesosiderite with a granoblastic texture; it is tentatively identified as an impact melt based on the preservation of "relict" plagioclase laths ($\sim$ 150 microns long) which are suggestive of a basaltic texture prior to metamorphism.

PETROGRAPHY OF CLASTS

Table 3 lists clast types that have been identified in each mesosiderite based primarily on petrographic examination of one or more polished thin sections. 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.

A general relationship which 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 3:

(1) The mineral clast population consists of 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 3 meteorites have PLAG POIK textures (Table 2). Other minerals may occur in trace amounts as clasts but these were not positively identified.

(2) The most common lithic clast type is diogenite (orthopyroxenite). Probably all coarse single crystal fragments of orthopyroxene are derived from the fragmentation of diogenites.

Plagioclase-rich lithic clasts are also abundant and generally indicate the presence of feldspar cumulate eucrite fragments* rather than anorthosite. Cumulate eucrites, with high modal plagioclase content, are numerically the dominant lithic clasts 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 best 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. 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 selectively or "partially" melted silicate clasts invaded by matrix metal.

(3) Metal clasts have been identified in every mesosiderite except Dyarrl Island, Budulan, and Simondium. The significance of this observation is difficult to assess, as the lack of metal fragments may be due to sampling bias since only four polished thin sections of these meteorites were available for study.

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*In this paper the term (feldspar) cumulate eucrite refers broadly to all medium and coarse grained, generally feldspathic fragments with gabbroic or granulitic textures; similarly, metaeucrites are basaltic eucrite clasts whose igneous textures, while recognizable, have been largely recrystallized to granoblastic aggregates. Other clast types are defined on the basis of their textural resemblance to meteoritic, lunar, or terrestrial analogs.

(4) Lithic clasts are best preserved and therefore most abundant in subgroup 1 mesosiderites. This is consistent with the view that increasing recrystallization tends to obliterate the igneous textures of lithic clasts, leading to a recognizable clast population dominated by large single crystals and monomineralic, polycrystalline fragments. However, some of the differences in the clast population are related to pre-metamorphic abundances. For example, the PX POIK and PLAG POIK mesosiderites have distinctly different lithic clast contents; the PLAG POIKS lack eucrite fragments and are remarkably free of lithic clasts except for diogenites. In contrast, the PX POIK mesosiderites apparently contain a variety of clast types not found in Bondoc, Budulan, and Mincy.

DISCUSSION AND CONCLUSIONS

Like lunar breccias, the mesosiderites are fragmental rocks. The variety of textures and clast types, particularly lithic clasts, and the overall brecciated appearance of the mesosiderites indicate that they accumulated in a near-surface environment 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 mesosiderites as impact melts (Floran et al., 1978a,b) indicates a multiple origin for this group that is even more complex than suggested by Powell (1971).

The inferred sequence of increasing recrystallization within the metamorphosed mesosiderites is somewhat analogous to the succession of petrologic types in the C1 → C6 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. 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. Although Warner (1972) recognized a progressive metamorphic sequence in the Apollo 14 samples, restudy of these breccias indicates that most of the originally defined groups are no longer considered valid (Simonds et al., 1977).

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 (Table 3). Extensive recrystallization of clast + matrix pyroxene of subgroup 1 mesosiderites could easily 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 mesosiderites (Table 2) is not well established, despite Powell's (1971) classification of Mincy (the only PLAG POIK he studied) as a subgroup 3 mesosiderite. The absence of 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. Conceivably, intense recrystallization of a clast-deficient, igneous-textured mesosiderite such as Pinnaroo could have resulted in formation of the PLAG POIK texture. Although the silicate fraction of this meteorite has an intergranular diabasic texture, isolated plagioclase laths occasionally enclose small, rounded pyroxene grains. If recrystallization of a Pinnaroo-like precursor were limited primarily to plagioclase, a PLAG POIK texture might result.

In contrast to the PLAG POIK mesosiderites, Clover Springs and the related PX POIK mesosiderite Crab Orchard, have abundant plagioclase cumulate eucrite and "anorthosite" clasts. This is especially true of Clover Springs (Table 3) and is supported by the low REE abundances and positive Eu anomalies obtained by Wanke et al. (1972) for both meteorites. The REE patterns are essentially identical to the plagioclase-rich cumulate eucrite, Serra de Mage (Schnetzler and Philpotts, 1969). It should be noted that the apparent rarity of true anorthositic clasts in any of the mesosiderites indicates that plagioclase did not play as prominant 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 may exist linking the metamorphosed and impact melted mesosiderites. This sequence extends from igneous-textured mesosiderites of subgroup 4 to more evolved meteorites with metaigneous textures (subgroups 2* and 3*). An intriguing question is whether the silicate matrices of subgroup 1 have a clastic, clastic + melt, or melt origin. The extremely fine grain size of this subgroup, coupled with the tendency toward textural obliteration induced by recrystallization, hinders the resolution of this problem. If vestiges of an igneous texture exist, then these mesosiderites are related to the impact melts. The SEM techniques developed by Phinney et al. (1976) for lunar breccias might indicate whether the matrices of subgroup 1 are entirely clastic or have a silicate melt component.

Such studies could shed much light on the bonding mechanism responsible for the coherency of the mesosiderites.

In addition to petrologic characteristics, radiometric dating techniques can be potentially useful in understanding the evolutionary history of the mesosiderites. Unfortunately, few data are available except for cosmic ray exposure ages. Begemann et al. (1976) studied 13 mesosiderites and found no apparent clustering of exposure ages which ranged from 10 to 160 Myr. However, a closer examination of their data indicates that six age groups may be tentatively distinguished: (1) 9 Myr (Barea), (2) 30 Myr (Clover Springs, Morristown), (3) 40 Myr (Budulan, Mincy), (4) 55-60 Myr (Lowicz, Estherville, Crab Orchard), (5) 85-90 Myr (Patwar, Varamin), and (6) 130-140 Myr (Vaca Muerta, Emery, Bondoc). The relatively large uncertainty in most ages suggests that the number of collisional events may have been larger, although these groupings are consistent within assigned error limits. In general, there is a lack of correspondence between exposure ages and petrologic subgroup. An exception is Budulan and Mincy, PLAG POIK mesosiderites with exposure ages of 36 ± 8 and 43 ± 5 Myr respectively. This age overlap and identity of petrologic type strongly suggests that both meteorites were involved in the same collisional event and very probably were located on the same parent body or the same fragment of an originally larger body. The same conclusion applies to Clover Springs (28 ± 3 Myr) and Morristown (33 ± 4 Myr). Morristown has a PX POIK texture, which is very similar to that of Clover Springs. The partial overlap in these two age groups indicates that until the exposure ages of individual mesosiderites are better resolved, their interpretation must be treated with caution.

Relationships to the howardites, eucrites and diogenites

The lithic clast types within individual mesosiderites (Table 3) provide a powerful tool with which to determine endmember mixing components. Further petrographic studies together with modal and bulk chemical analyses on 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. 4): (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. This simplifies possible quantitative comparisons. For example, on a triangular plot with apices of eucrite, cumulate eucrite, and diogenite + dunite, Clover Springs and Emery would plot near the cumulate eucrite corner while Dyarrl Island and Patwar would plot within the eucrite-rich portion of the diagram.

Although similar clast types occur in mesosiderites and howardites there are some important differences which make a close genetic relationship uncertain. The clast population of howardites includes minor amounts of clast types not found in mesosiderites such as carbonaceous chondrites, and various glasses (Bunch, 1975). Howardites are little or unmetamorphosed and lack appreciable metal, olivine, troilite, and phosphate, each of which are integral components of mesosiderites. Many of these phases have been reported as accessory mineral fragments in howardites (Bunch, 1975; Dymek et al., 1976). However, the common occurrence of diogenites, eucrites, and various types of breccias as major clastic components in both meteorite groups (Fig. 5) is a strong argument favoring an origin on the same, albeit heterogeneous planetary body. Supporting this contention is the overall similarity in mineral chemistry between the eucrites, cumulate eucrites, diogenites, and equivalent clast types in howardites and the slightly recrystallized mesosiderites (Powell, 1971). However, 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 should be present on the mesosiderite parent body. Perhaps Vesta is dominated by metal-poor regions (eucrites) interspersed with metal-rich patches (mesosiderites) or else the metal-rich source areas of the mesosiderites are hidden beneath younger eucritic flows. The extended time span of partial melting at depth within the eucrite parent body as proposed by Stolper (1977) may be compatible with the extremely slow cooling rates of $\sim 0.1^\circ$ C/10^6 yrs below 500°C that have been calculated for the metal in nine mesosiderites studied by Powell (1969), as well as Bondoc (Axon and Nasir, 1977) and Emery

(Hewins et al., 1977). The occurrence of metal nodules and various lithic clasts indicates that these meteorites 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, possibly within the eucrite parent body. Formation and extrusion of multiple cycles of eucritic melts followed by continued partial melting of the same source regions within plutonic rather than near-surface environments would have resulted in a hot crust that remained near or at its liquidus for perhaps tens to hundreds of million years. The absence of indigenous glass in the mesosiderites, the presence of variably recrystallized breccia clasts, and the slow cooling rates indicate that these meteorites must have undergone shallow burial metamorphism for an unusually long period of time. They may therefore represent the lower portions of a megaregolith that was metamorphosed by continued magmatic activity at depth. If so, the slightly recrystallized mesosiderites were stratigraphically above the highly recrystallized mesosiderites and were farther away from internal heat sources. 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 melted mesosiderites must have formed at the surface but these too were buried at shallow depths. They suggest 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). This is consistent with the relative rarity of impact melts among the mesosiderites. The high metal content of these meteorites indicates that metal must have been abundant at one time near or at the surface. Subsequent eucritic flows, however, could have obliterated any evidence for a major metal component on the surface, and spectral reflectance studies (e.g. McCord et al., 1970) would be consistent with a basaltic, metal-poor surface.

Alternatively the mesosiderites may be derived from one or more of the 12 large asteroids identified by Gaffey and McCord (1977) as having "mesosiderite" or "px stony-iron" surfaces. Of these, 6 Hebe and 8 Flora merit special attention because of their occurrence near the V_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. The ultimate origin of these asteriods is an interesting question. 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. However, oxygen isotope data indicate that the earth is more closely related to the chondrites than to the basaltic achondrite-diogenite-mesosiderite suite (Taylor et al., 1965).

The extremely narrow range of Ni contents found by Begemann et al. (1976) in the metal of 12 of 13 mesosiderites (Ni/Ni + Fe = 8.0 ± 0.4) may indicate a common origin for most mesosiderites on a single body or a relatively few bodies that formed in the same region of the solar nebula. This range is considerably smaller than that found by Wasson et al. (1974) and Powell (1969), but is considered to be more accurate because relatively large amounts of sample were analyzed (generally between 10 and 30 g).

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FIGURE CAPTIONS

Fig. 1. Photograph of polished, etched surface of Pinnaroo impact melt showing metal-silicate and clast-matrix relationships. Note irregular lobate boundaries of smaller metal masses, possibly indicative of plastic flowage. Most of this metal including large metal clast at upper right displays widmanstatten structure. Metal clast is 4.4 cm long (USNM neg. #1052E).

Fig. 2a-d. Photomicrographs illustrating textural and mineralogical features of mesosiderites. (a) slighly recrystallized mesosiderite, Crab Orchard. Two cumulate eucrite fragments are visible (upper left, center right). Olivine clast surrounded by fine-grained corona is present at lower right; width = 2.6 mm. (b) moderately recrystallized mesosiderite, Veramin, showing incipient development of plagioclase poikiloblastic texture. Plagioclase in interstitial to irregular, rounded orthopyroxene grains; width = 1.1 mm. (c) highly recrystallized mesosiderite, Lowicz, with pyroxene poikiloblastic texture. Note optical continuity between pyroxene clasts (left, center right) with inclusion-rich overgrowths. Entire field of view consists of three pyroxene crystals, partially crossed nicols; width = 2.6 mm. (d) highly recrystallized mesosiderite with plagioclase poikiloblastic texture, Budulan. Numerous rounded granules of orthopyroxene are enclosed within coarser plagioclase crystals; width = 2.3 mm.

Fig. 3. Clast-laden impact melted mesosiderite with integranular basaltic texture, Simondium. Silicate clasts are orthopyroxene; width = 1.1 mm.

Fig. 4. 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.

Fig. 5. A comparison between the clastic portions of mesosiderites and howardites. All clast types shown are found in both groups except carbonaceous chondrites and glasses which are not present in mesosiderites, and metal and dunite which are generally absent from howardites.

Table 1. The mesosiderites

Meteorite	Find or Fell	Powell's subgroup	This study
Barea	Fell, 1842		1
Bondoc	Find, 1956		1
Budulan	Find, 1962		3
Chinguetti	Find, 1920		1
Clover Springs	Find, 1954		2
Crab Orchard	Find, 1887	1	1
Dalgaranga	Find, 1923		3?
Dyarrl Island	Fell, 1933		1
Emery	Find, 1962		3
Estherville	Fell, 1879	1	3*
Hainholz	Find, 1856	2	2*
Lowicz	Fell, 1935	3	3
Mincy	Find, 1857	3	3
Morristown	Find, 1887	3	3
Mount Padbury	Find, 1964	1	1
Patwar	Fell, 1935	1	1
Pinnaroo	Find, 1927		4
Simondium	Find, 1907		4
Vaca Muerta	Find, 1861	1	1
Veramin	Fell, 1880	2	2

Table 2. Classification of the mesosiderites (silicate portion)

Metamorphic			Metaigneous (Impact melts)		Igneous (Impact melts, relatively unmetamorphosed)
Subgroup 1	Subgroup 2	Subgroup 3	Subgroup 2*	Subgroup 3*	Subgroup 4
Barea Chinguetti Crab Orchard Dyarrl Island Mt. Padbury Patwar Vaca Muerta	A. Clover Springs	A. [Px Poiks] Emery Lowicz Morristown †(West Point)	Hainholz	Estherville?	Simondium Pinnaroo several clasts within Patwar and Orchard
	B. Veramin	B. [Plag Poiks] Bondoc Budulan Mincy			

Not classified: Dalgaranga, due to weathered nature of available specimen.

†Unidentified mesosiderite, originally part of West Point meteorite collection.

Table 3. Clast types in mesosiderites (mineral >> lithic > metal)

	Mineral			Lithic								Metal
	Px	Pl	Ol	Di	E	EC	ME	A	Du	RB	IMB	-
Low Grade												
Barea (2)	X	X	X					X				X
Chinguetti (1)	X	X	X									X[1]
Crab Orchard (3)	X	X	X	X	X	X		X		X	?X	X
Dyarrl Island (1)	X	X	X		*			X	X	X		
Mt. Padbury (1)	X	X	X	X	X	X	X	X	X[2]	?X[3]		X
Patwar (2)	X	X	X		*	X		X		X	X	X
Vaca Muerta (3)	X	X	X	X	X	X				X		X
Medium Grade												
Clover Springs (3)	X	X	X			*	X	*		X		X
Veramin (2)	X	X	X						X			X
High Grade												
Bondoc (2)	X		?X	X								X
Budulan (1)	X			X								
?Dalgaranga (1)	X	X	X	X	X							X[4]
Emery (4)	X	X	X	*	X	*		X	X	X		X
Lowicz (1)	X	X	X	X				X				X
Morristown (1)	X	X	X					X	X			X
Mincy (1)	X		X	X								X
Unknown, Wt Pt (1)	X	X	X	X		X		X				
Impact Melts												
?Estherville (3)	X	X	X	X		X		X	X			X
Hainholz (3)	X	X	X	X				X				X
Pinnaroo (2)	X	X	X	?X								X
Simondium (2)	X	X	X									

Based on studies of polished thin sections (number examined in parentheses) and hand specimens with supportive data, where noted, from the literature; [1]Lacroix (1924), [2]McCall (1966), [3]Wasson (1974), [4]McCall (1965).
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; * denotes lithic clast types that are especially abundant. For the purposes of this table, Dalgarange is tentatively classified as a high grade mesosiderite.