IMPACT-MELT ORIGIN FOR THE SIMONDIUM, PINNAROO, AND

HAINHOLZ MESOSIDERITES: IMPLICATIONS FOR IMPACT

PROCESSES BEYOND THE EARTH-MOON SYSTEM

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ABSTRACT

The Simondium, Pinnaroo, and Hainholz mesosiderites are interpreted
to be clast-laden impact melts that crystallized from immiscible sili-
cate, metallic (Fe-FeS) liquids. The existence of silicate melts is
shown by intergranular basaltic textures. Metallic melts are inferred
on the basis of smooth boundaries between metal and troilite and the
occurrence of troilite as anastomosing areas that radiate outward into
the silicate fractions. These relations suggest that troilite crystal-
lized after silicates, concentrating as a late-stage residuum. Evidence
for impact melting includes: diversity and abundance of clast types
(mineral, metal, lithic) in various stages of recrystallization and
assimilation; differences in mineral chemistries between clasts and
igneous-textured matrix silicates; unusual metal plus silicate bulk
composition. Silicate clasts consist primarily of orthopyroxene and
minor olivine with a range of Fe/Fe+Mg ratios, anorthitic plagioclase,
and rare orthopyroxenite (diogenite) fragments. Substantial amounts of
Fe-Ni metal were melted during the impact events and minor amounts were
incorporated into the melts as clasts. The clast populations suggest
that at least four rock types were melted and mixed: (a) diogenite,
(b) a plagioclase-rich source, possibly cumulate eucrite, (c) dunite,
and (d) metal. Most orthopyroxene appears to have been derived from
fragmentation of diogenites. Orthopyroxene (En_{82-61}) and olivine
(Fo_{86-67}) clasts include much material unsampled as individual
meteorites and probably represent a variety of source rocks.

Differences in whole-rock modal abundances between Pinnaroo, and Simondium and Hainholz are due primarily to variable proportions of the silicate and metal + troilite fractions. Very little chemical variability is evident when the compositions of clast-free portions of silicate melt are compared. The data are consistent with, but do not prove, a common origin during the same cratering event for Simondium and Hainholz, and possible Pinnaroo. Relatively coarse grain size and deficiency of clasts suggest that Pinnaroo may have been generated during a major cratering event.

Comparisons between the three mesosiderites and terrestrial, lunar clast-laden impact melts indicate that similar impact processes were operative on distant planetary bodies. A scenario for the formation of these meteoritic clast-laden melts, based partly on terrestrial cratering models, is presented that is believed to be compatible with observed structural and textural relationships. During crystallization of the coexisting silicate and metal liquids partial segregation occurred on a cm scale. Lack of more complete separation may have been due to (1) high viscosity of the clast-laden melts, (2) sheetlike form of the impact-melt layers, (3) homogenization of melted material followed by unmixing of silicate and metallic liquids on a μ scale, and (4) weak gravitational field of the parent body.

INTRODUCTION

Impact-melt breccias with igneous-textured matrices are very common in the lunar highlands and are described from many terrestrial craters (S   ds et al., 1976; Phinney and Simonds, 1977). In contrast, inferred impact melts of meteoritic origin have been reported only as rare lithic fragments in chondrites (Fodor and Keil, 1975; 1976a,b; Wilkening, 1978) and howardites (Bunch, 1975). No individual meteorite has been described as an impact melt, although such a possibility has been raised for the Shaw chondrite (Fodor and Keil, 1975). In this paper we present textural, mineralogical, and chemical evidence supporting an impact-melt origin for the Simondium, Pinnaroo, and Hainholz mesosiderites; a preliminary petrologic report has been given in Floran et al. (1978a). Similarities as well as differences between these meteorites and possible lunar-terrestrial analogs provide a framework for comparison of impact processes on planetary bodies with grossly different bulk surface chemistries. A petrographic reconnaissance survey of the remaining 17 mesosiderites reveals that the Estherville mesosiderite may be a highly metamorphosed impact melt, and that breccia clasts of impact-melt origin are present in Patwar and Crab Orchard (Floran and Prinz, 1978; Floran, 1978). Further petrographic studies of individual mesosiderites are likely to reveal the presence of additional impact-melted clasts.

Mesosiderites, including Simondium and Hainholz, consist of roughly equal amounts by weight of silicate and metal, although some mesosiderites contain a considerably higher or lower proportion of

metal. All three of these mesosiderites display the fragmental
structure that is typical of the group as a whole. The textures of
their matrices are atypical, however, because they provide evidence of
crystallization from a melt. Although diagnostic shock features
considered definitive evidence for shock melting during a hypervelocity
event are rare, petrographic data are consistent with such an origin.
In other mesosiderites variable recrystallization of the matrices
appears to have obliterated all traces of a pre-metamorphic history
except for a variety of igneous and metaigneous-textured lithic clasts
(Floran, 1978).

Previous studies of these three meteorites are few. No modern
petrologic descriptions exist with the exception of Hainholz which was
studied by Powell (1971) as part of a broader investigation of the
entire group. Prior described both Hainholz (Prior, 1918) and Simondium
(Prior, 1910; 1918; 1921) and emphasized the strong textural similari-
ties between the silicate fractions of these two meteorites and their
resemblance to terrestrial basalts. The only published data on
Pinnaroo are a brief description of its find together with a bulk
chemical analysis (Alderman, 1940) and selected trace element
determinations on two metallic separates (Wasson et al., 1974).

ANALYTICAL TECHNIQUES

Two polished thin sections of Simondium, and three each of Pinnaroo
and Hainholz were used for petrographic studies and microprobe analysis.
Hand specimens of the three meteorites were examined visually and
additional photographic material was kindly made available by Dr. Roy
C. Clarke of the U.S. National Museum.

Microprobe analyses were collected on a fully automated, 9 channel ARL-SEMQ instrument using appropriate standards and correction procedures for silicates (Bence and Albee, 1968) and metals (Colby, 1968). Metal data was reduced using a MAGIC IV program modified for the ARL-SEMQ microprobe. A modal analysis computer program was developed to calculate a volume % mode for point counts on selected areas of thin sections with the microprobe. An area linearly defined by 20 points or less was sampled by a square grid for a desired number of measurements. Nine elements (Si, P, Ti, Al, Cr, Fe, Mg, Ca, Ni) were measured (2 sec counting time) and examined with a "filter" of abundances and ratios to determine the phase at the measuring point. The data of all 9 elements for each point were printed and reexamined to check for consistency. The modes were then recomputed excluding all unidentifiable points. All modal analyses are based on approximately 1,000 corrected measurements.

HAND SPECIMEN PETROLOGY

Examination of hand specimens of Simondium, Pinnaroo, and Hainholz in the meteorite collection of the American Museum of Natural History reveals that all are moderately weathered. A significant fraction of the metal has been oxidized, which is not surprising since the three meteorites are finds: Hainholz appears to be the least altered.

An etched, polished slab of Pinnaroo (Fig. 1) provides fascinating insights into how the various physical (clasts, matrix) and mineralogical (silicate, metal) components were aggregated and

juxtaposed together to form coherent meteorites. Centimeter-sized silicate clasts and metal nodules interpreted to be clasts are both present, suggesting that the parent material consisted of a heterogeneous mixture of discrete silicate and metal source regions. The outer portions of metal clasts consist of kamacite plates ("swathing kamacite") that nucleated and grew in the subsolidus state parallel to the interface with dark silicate matrix (Fig. 1). The observational evidence indicates that these plates grew _in situ_ after metal-silicate mixing and after the clasts had acquired their irregular shapes. Large silicate clasts are rounded to subangular, compact masses while the large metal clasts, which are also associated with the silicate fraction, have grossly rounded but, in detail, highly irregular shapes. This suggests that the physical states of the two clast types were grossly different at the time they were mixed with matrix material. The metal clasts were soft and malleable, and possibly in a partially molten state. If these metal clasts were aggregated liquid globules we would not expect them to resemble fragmental material, which they clearly do. On the other hand, if rigid solids, these clasts should have retained a smooth angular boundary with the matrix. The very delicate and intricate boundaries of the smaller but more abundant, irregular metal masses (Fig. 1) suggest a different origin from that of the metal clasts. Nevertheless, there appears to be a continuum between recognizable, coherent metal clasts on a cm scale, to irregular, swirling metal masses on a mm scale which do not appear to be clastic in origin.

Based on available hand specimens and photographs, we conclude that the large, rounded areas of metal in Pinnaroo were incorporated into the meteorite as solid, plastically-deformed clasts. This conclusion can be extended to Hainholz where large well-defined metal clasts have been identified, and possibly to Simondium which did not contain obvious metal clasts in the material examined. In both of these meteorites the bulk of the metal occurs as irregular masses, similar to those present in Pinnaroo. The melt origins of the silicate matrix and the smaller, irregular metal masses (as well as troilite, which is not visible in Fig. 1) become apparent only when microscopic textural relationships are examined (see below).

PETROGRAPHY

Silicate matrix

Petrographic data for the silicate fractions of Simondium, Pinnaroo, and Hainholz are summarized in Table 1. The silicate textures of Simondium and Pinnaroo (Figs. 2a, b) are unequivocally igneous, while Hainholz appears to have undergone a metamorphic event of moderate intensity following crystallization from a melt. Hainholz has been classified as a metaigneous mesosiderite (Floran, 1978) because portions of the meteorite retain a primary basaltic texture (Fig. 2c). No directional fabric was observed in any of the three mesosiderites.

The silicate matrix of Simondium has a well-developed intergranular basaltic texture (Fig. 2a) dominated by anhedral to subhedral,

rounded granules of orthopyroxene which fill the interstices between a network of fine, lathy, subhedral plagioclase. Plagioclase laths generally have a length/width ratio of 10:1 or greater and rarely exhibit albite twinning. Orthopyroxene matrix grains are difficult to distinguish from small pyroxene clasts. Both clast and matrix orthopyroxenes often contain tiny inclusions which tend to be concentrated at their borders; many appear to be troilite but some are composed of unidentified silicate material. Minor and accessory phases, which generally occur in the interstices between orthopyroxene and plagioclase include tridymite, clinopyroxene (augite), troilite, chromite, merrillite ("whitlockite"), and rare metal.

The silicate portion of Pinnaroo is coarsely intergranular (Fig. 2b) with incipient development of a subophitic or poikilitic texture where pyroxenes are locally intergrown with coarser grained plagioclase laths. As in Simondium and Hainholz, pyroxene forms rounded granules. These grains are considerably coarser, highly variable in size, may have thin exsolution lamellae or blebs of calcic pyroxene, and contain numerous small inclusions uniformly distributed throughout individual grains. Most of these inclusions are troilite, a minor amount are chromite, and some may be crystallized silicate melt; metal appears to be absent. Larger pyroxene grains consist of orthopyroxene with minor pigeonite concentrated at their rims. The boundary between the two pyroxene phases is typically irregular and some of these grains have cloudy interiors that may represent relict clasts. Plagioclase forms stubby subhedral laths up to 1.5 mm long with well-developed

albite twinning and occasionally encloses small rounded anhedral
pyroxenes. Tridymite is an abundant minor constituent which forms
stubby prismatic crystals often in contact with troilite; minor amounts
of euhedral merrillite also tend to be associated with troilite at the
metal-silicate boundary.

Hainholz retains remnants of an original basaltic texture
(Fig. 2c) similar to that of Simondium but it is observed only locally;
the average grain size of the matrix constituents is slighter coarser,
however (Table 1). Matrix pyroxenes are similar in morphology to those
of Simondium but have a somewhat mottled appearance due to the presence
of numerous, uniformly distributed, tiny inclusions. The distinction
between matrix and small clasts is even more difficult to discern than
in Simondium. Plagioclase occurs as subhedral to anhedral tablets that
only rarely occur as well-formed laths. Tridymite and opaque phases
(troilite, minor chromite, rare metal) occur either in the interstices
between the silicates or as inclusions within matrix silicates.

Silicate clasts

Simondium and Hainholz have similar clast populations that are
dominated by monomineralic crystal fragments. Virtually all clasts
have ragged edges indicative of reaction with the melt (Fig. 2a, c)
and, in the case of Hainholz, suggestive of further modification by
recrystallization. Clasts, generally ranging in size from tens of
microns to several millimeters, are very abundant and, in Simondium,
consist primarily of orthopyroxene ($\sim$90%), minor plagioclase ($\sim$10%),
and accessory olivine ($\sim$0.5%). Some clasts are zoned near their rims,

suggesting that partial equilibration with the melt took place. Very small grains of clinopyroxene and other trace mineral constituents in both meteorites may be clastic in origin but this is uncertain. Many pyroxene clasts contain tiny inclusions of troilite and chromite giving a spongy or sieve-like appearance; others are inclusion-free or very rarely contain fine exsolution lamellae of calcic pyroxene. Some pyroxene fragments in Simondium display "checkerboard melting", a common petrographic feature of terrestrial impact melts (Grieve, 1975; Floran et al., 1978b; Simonds et al., 1978). Plagioclase clasts occur as clear anhedral fragments with scalloped borders and as spongy relics that appear to have been recrystallized as a result of shock-induced thermal heating. A few large plagioclase grains exhibit broad, well-formed albite twinning that may be indicative of a plutonic source rock. As is typical for most mesosiderites, olivine often occurs as large clasts so that, relative to plagioclase, its volumetric abundance is greater than its numeric abundance. In the polished thin sections examined, olivine was much more abundant in Hainholz than in Simondium. Olivine clasts in both meteorites sometimes have broad kink bands but are not surrounded by the reaction coronas present in many of the metamorphosed mesosiderites (Powell, 1971; Nehru et al., 1978).

In contrast to Simondium and Hainholz, Pinnaroo has relatively few but large mineral clasts. The silicate clast population consists of orthopyroxene and rare olivine. Most orthopyroxene fragments are relatively free of troilite and chromite but some resemble the opaque-filled pyroxene of the matrix. Large olivine grains form irregular, ophitic-like intergrowths at their borders with matrix plagioclase,

suggesting that a minor amount of recrystallization took place after olivine was incorporated into the melt. Relict plagioclase in Pinnaroo is present only as mottled, complexly zoned cores near the centers of a few subequant matrix plagioclase grains. By analogy with identical relations in the Manicouagan and other terrestrial impact melts (Floran et al., 1978b; Grieve, 1975), these are interpreted to be extensively digested clasts that served as nuclei for growth of plagioclase from the melt.

Lithic fragments are rare or absent and were positively identified only in Hainholz where several fine-grained recrystallized ortho-pyroxenite clasts (diogenites) and a single plagioclase-rich fragment were observed. Several dark cm-sized fragments that are clearly visible in the slab of Pinnaroo (Fig. 1) are almost certainly lithic clasts and probably represent the source rocks of the mineral clast population.

Metal-troilite-silicate relations

Textural relationships among metal, troilite, and silicates are similar in Simondium, Pinnaroo, and Hainholz. Because these are best displayed in Pinnaroo we emphasize this meteorite. Figs. 3a-c illustrate the nature of the metal-troilite-silicate boundary. Metallic clasts such as those identified in Fig. 1 were not observed in any of the polished thin sections of the three meteorites because of their large size and relative scarcity. The smaller metal masses (Figs. 1 and 3) have smooth round outlines and are often in contact with troilite; direct contact between metal and silicates is somewhat rare in Pinnaroo, common in Simondium, and very common in Hainholz. The

reason for this is a marked increase in the abundance of troilite as evidenced by the increase in the troilite/metal ratio from Hainholz to Simondium to Pinnaroo (see Tables 8 and 9). Troilite occurs principally in anastomosing irregular areas that radiate outward from metal into the silicate material, and as small anhedral to subhedral grains within and interstitial to orthopyroxene (Fig. 3). These relations suggest that the bulk of the troilite crystallized after the silicate fraction, concentrating as a late-stage residuum somewhat analogous to the felsic residue of quartz-rich terrestrial basalts. The smaller grains within orthopyroxene may represent sulfide-rich liquid trapped during crystallization.

The preferential occurrence of troilite at the boundary between the metallic and silicate fractions appears difficult to explain if the bulk of metal was mixed into the silicate melt as a solid, especially in view of the fact that the smoothly curved boundaries between metal and troilite suggest crystallization from an Fe-Ni-S melt (Smith and Goldstein, 1977). These relations appear to be best explained by assuming the coexistence of two immiscible liquids--a metallic melt rich in Fe, Ni and S, and a silicate melt within which were suspended numerous silicate clasts and a smaller number of metal clasts. In terrestrial impact melts, silicate clasts often act as nuclei for solid phases crystallizing from the melt or influence the nucleation and growth of phases in the nearby melt due to thermal disequilibrium between relatively cold clasts and melt (Simonds et al., 1976; Floran et al., 1978b). We may expect the same to be true of the mesosiderite

impact melts except that the metal clasts, being grossly different from the bulk of the silicate melt in composition and physical properties, would have remained effectively isolated from the crystallizing silicates. Consequently, nucleation and growth from the silicate melt would have been concentrated near silicate clasts. The bulk of the iron sulfide apparently did not crystallize until after complete solidification of the silicate melt and most of the Fe-Ni metal. The remaining voids left to be filled would have been concentrated at the boundary between metal and solid silicates. This sequence of events is supported by the textures and is consistent with phase relations in the Fe-Ni-S system (Kullerud, 1963), as discussed below.

An additional feature worth noting is that the metal clasts like their silicate counterparts may have served as nuclei for crystallizing metal, although they are now physically separated from the metallic melt fraction. If so, these clasts have a composite, solid-melt origin as is true of the silicate clasts with equilibrated rims. Although we favor a largely solid origin for these metal bodies, the possibility remains that they may have been substantially if not entirely liquid. A detailed petrographic and microprobe investigation of these nodules, which was not done in this study, should resolve their origin.

MINERAL CHEMISTRY

Pyroxene

Pyroxene matrix compositions for Simondium, Pinnaroo, and Hainholz are plotted in Fig. 4a and average compositions are tabulated in

Table 2. These data indicate that orthopyroxene exhibits a very narrow compositional range within each meteorite and that the average compositions for all three meteorites are similar. Restricted ranges in pyroxene compositions are characteristic of large terrestrial melt sheets such as Manicouagan (Floran et al., 1978b). Although most low-Ca pyroxenes are hypersthene there is a cluster of analyses in Simondium and Hainholz trending toward augite. These fall on a mixing line between orthopyroxene and calcic pyroxene and probably represent sub-microscopic intergrowths of the two pyroxene phases. Some pyroxene analyses in Pinnaroo have pigeonitic compositions ($Wo_{10-11}En_{54-59}Fs_{31-36}$) and some in Simondium and Hainholz near Wo_6En_{54} may be pigeonites (Fig. 4a).

Representative analyses of orthopyroxene clasts are shown in Fig. 4b and Table 3. These illustrate that (1) clasts have a wide range in Fe/Fe+Mg ratio (En_{61-82}) and (2) individual grains typically have magnesian cores; many of the latter are homogeneous and have iron-enriched rims that are equilibrated with matrix pyroxenes. Although minor zoning is indicated, the distinction between cores and rims is relatively abrupt. In all three meteorites, many clasts have compositions approaching or exceeding En_{80}. Others are more iron-rich than the matrix, although such grains are rare.

Plagioclase

Differences in composition between plagioclase clasts and matrix is not as pronounced as with the pyroxenes, but clast-matrix relations follow the same general trends. Matrix plagioclases in the three

meteorites are predominantly anorthitic with limited variability (Fig. 5a, Table 2). Individual laths in Simondium and Hainholz show only minor zoning. The smaller variability of matrix compositions in Hainholz may reflect, in part, metamorphic homogenization. As with the pyroxenes, plagioclase clasts tend to be more refractory (i.e., more calcic) than matrix plagioclase (Table 4). Microprobe analyses of two relict cores in Pinnaroo yielded compositions of An_{97} and An_{94} and rim compositions of An_{92} and An_{91} respectively, in agreement with the results from Simondium and Hainholz.

Olivine

The compositional range of olivine in Simondium and Hainholz is considerable, Fo_{88-67} (Fig. 4b, Table 5). Olivine appears to be much more abundant in Hainholz, but the compositional range of analyzed clasts is very similar. The range for Hainholz is consistent with that obtained by Powell (1971), although we found no evidence of zoning in individual grains. Pinnaroo olivines have similar compositions to one another, but the data are limited because few grains are present. The most magnesian-rich olivine compositions are similar in all three meteorites.

Other phases

Selected analyses of chromite, merrillite, tridymite, and rutile are shown in Table 6. Except for rutile which was found in Pinnaroo only, these occur as minor or accessory constituents in the silicate melt portions of all three mesosiderites. Examination of the chromite analyses indicate that the percentages of various end-member components

do not vary significantly. Analysis 4 from Pinnaroo and both analyses 5 and 6 from Hainholz are very similar to those reported by Bunch and Keil (1971) for the same meteorites. Similarly, merrillite (formerly reported as whitlockite; Dowty 1977) shows little variation. To our knowledge these analyses represent the first reports of fluorine in meteoritic occurrences of this phase. Rutile is extremely rare in Pinnaroo, nearly pure TiO_2, and compositionally very much like rutile reported by El Goresy (1971) in the Vaca Muerta mesosiderite.

METAL CHEMISTRY

Average abundances and ranges of Fe, Ni, Co, and P for the metal phases in Simondium, Pinnaroo, and Hainholz are shown in Table 7. Also shown are compositional data for small metallic blebs associated with the silicate fraction in Hainholz. The data for the "metallic fraction" indicate a close correspondence in the metal compositions of the three meteorites except for a Ni enrichment in taenite from Pinnaroo. Abundances of phosphorus and cobalt are uniformly low and near detection limits. Consequently, these elements should have negligible effects on phase relations in the Fe-Ni-S system.

The compositions of the metal phases (excluding the blebs) are not unusual when compared with other mesosiderites and are consistent with previous studies: (1) the Ni ranges given for taenite and kamacite in Hainholz are essentially the same as recorded for this meteorite by Powell (1969) in microprobe step scans, (2) although bulk compositions of metal grains were not measured in this study, the bulk Ni content of

Hainholz metal is 8.63% (Powell 1969), which is very similar to other
mesosiderites, and (3) Bulk Ga, Ge, and Ir contents in metal from
Hainholz and Pinnaroo are both similar to the average determined for 17
mesosiderites (Wasson et al. 1974).

Compositional differences between the small metal blebs and the
larger metal masses may be due to any of a number of factors including
(a) size of the grains analyzed, (b) crystallization from the silicate
rather than the metal portion, or (c) analytical problems due to the
finite size of the electron beam. The first explanation is favored
here, since the size-compositional relationships follow those predicted
by cooling-rate studies (Powell 1969).

Microprobe analyses of troilite have not been tabulated but it is
appropriate to mention here that a survey of this phase was carried out
in all three meteorites. This revealed that the typical coarse grained
troilite at metal-silicate boundaries is stoichiometric and generally
contains less than 0.01% other constituents.

MODEL MINERALOGY AND BULK CHEMISTRY

The modal mineralogies of Simondium, Hainholz, and Pinnaroo, as
determined by microprobe analysis are compared in Table 8. The whole-
rock data indicate that major differences exist in the modal abundances
of some phases. Simondium and Hainholz are a rather close match for
all mineral phases except olivine. However, Simondium is significantly
enriched in troilite while Hainholz is enriched in total iron. Both
meteorites consist volumetrically of 2/3 silicates and 1/3 metal and

troilite. In contrast, the silicate and metallic fractions are about equal in our sample of Pinnaroo. Relative to the other two mesosiderites, the silicate component in Pinnaroo is significantly poorer in orthopyroxene and chromite but contains more Ca-rich pyroxene and two to seven times more troilite.

The silicate melt-rock data show a greater degree of homogeneity than the whole rock data. Despite obvious differences in modal abundances of some phases, the silicate fractions of Simondium, Pinnaroo, and Hainholz are surprising similar, given the uncertainties associated with sampling and data collection. A good example of these uncertainties is the abundance of Ca-rich pyroxene (augite). The relative abundances of clastic augite and augite that crystallized from the melt is difficult to ascertain because this phase commonly occurs as minute grains in the silicate matrix and therefore could easily be overestimated or underestimated. Nevertheless, the abundances of phosphate and troilite and the lack of metal in Pinnaroo appears to set this meteorite apart from Simondium and Hainholz.

In summary, the whole-rock data indicate (1) a general resemblance in modal mineralogy between Simondium and Hainholz and (2) an overall dissimilarity between these two meteorites and Pinnaroo. The silicate melt-rock data for the three mesosiderites are more similar to one another than are the bulk meteorites, a conclusion consistent with the presence of a heterogenous, polymict clast population in the bulk meteorites.

Bulk chemical analyses of the silicate portions of Simondium, Pinnaroo, and Hainholz were calculated from the modal data of Table 8. These data, along with previously published, recalculated analyses of the three mesosiderites are presented in Table 9A. An overall comparison between literature analyses and our analyses of the same meteorite is satisfactory for most oxides. Discrepancies exist (e.g. CaO in Simondium), but the most glaring differences are in total iron content which is reflected in the Fe/Fe + Mg ratio. The greater abundances of FeO in the silicate fractions of the older analyses may be due to the difficulty of obtaining pure metal and silicate separates, as suggested by their relatively high nickel contents (c.f. Prior, 1918; Alderman, 1940). It should be noted that the close correspondence between the two silicate analyses of Simondium may be somewhat fortuitous. Before recalculation, Prior's analysis contained more than 10% water and more than 5% Fe_2O_3, suggesting the possibility that major changes in chemical composition other than simple hydration and oxidation may have taken place. The potential for such alterations affecting the chemical analyses of Pinnaroo (0.87% H_2O; Alderman, 1940) and Hainholz (2.38% H_2O, 5.48% Fe_2O_3; Prior, 1918) would have been much less, however.

Although the proportions by weight % of the metallic and silicate fractions are nearly identical in all of the determinations, large comparative discrepancies exist for most elements. Apparently it may be more difficult to obtain a representative sample of the metallic fraction. These disparities point out some of the problems in obtaining accurate and representative compositional data for the mesosiderites

due to the effects of textural and mineralogical heterogeneities on sampling.

In Table 9B the clast-free portions of silicate melt are compared. Since these compositions are calculated from the modal data the same conclusions apply: (1) general correspondence between Simondium and Hainholz with some minor differences, and (2) overall similarity between Pinnaroo and the other two mesosiderites, with some important exceptions e.g., higher amounts of FeS and P_2O_5, and lower content of Cr_2O_3. The discrepancy in P_2O_5 can be rationalized by assuming that most phosphate formed by oxidation of phosphorus originally dissolved in the metallic fraction (Powell, 1971). Differences in the other two oxides, however, are not easily dismissed particularly the large amounts of FeS and lack of associated Fe, Ni metal.

DISCUSSION

Evidence for impact melting

The confident identification of an igneous-textured rock as an impact melt is based on a combination of field, geophysical, petrographic, and chemical criteria (Dence, 1971; Irving, 1975; Floran et al., 1976a, 1978b; Winzer et al., 1977). In the absence of field relations and geophysical information for meteorites, we must rely on petrochemical data together with comparisons of appropriate lunar and terrestrial analogs inferred to have originated by impact melting.

The impact-melt origin of Simondium, Pinnaroo, and Hainholz is based on textural (von Englehardt, 1978) and chemical arguments for clast-laden melts. Textural criteria include the presence of abundant

mineral (± lithic) clasts of varying composition and texture in an
igneous or metaigneous matrix, and disequilibrium between clast-matrix
components. Chemical criteria focus primarily on the unusual bulk com-
positions of these mesosiderite melts.

Arguments as to whether mineral clasts represent xenocrysts rather
than phenocrysts have been presented previously (Grieve, 1975; Floran
et al., 1978b) and will not be repeated here. The extraordinarily
thorough mixing of clasts on a submillimeter scale as observed in
Simondium and Hainholz has been emphasized by Simonds et al. (1976) as
a unique characteristic of impact-melted debris. Evidence for
disequilibrium within the clast-laden melts is shown by the physical
states of the clasts, most of which show no evidence of reaction with
the melt. Some clasts, however, are in various stages of recrystal-
lization and assimilation. These effects are due to shock damage and
accompanying residual heating, and to the variable compositions of
individual clasts which were out of chemical equilibrium with the
silicate melt. As previously noted, clasts are generally more refac-
tory than crystallizing phases of the melt, and many have equilibrated
rim compositions similar to the matrix. The less refractory clasts
(e.g., iron-rich orthopyroxenes) as well as the more strongly shocked
clasts were unstable in the melt and underwent selective or "partial"
melting.

The bulk compositions of the impact-melted mesosiderites (Table
9A) is indeed unusual because of the coexistence and apparent non-
reactivity between large amounts of metal and silicate. These
abundances, together with the intimate macroscopic and microscopic

association of metal, silicate, and troilite are difficult if not impossible to account for by a partial-melt model. Partial melting at depth of mesosiderite-like material will not result in metal-silicate magmas. In fact, Stolper (1975) has proposed a primitive mesosiderite source as the possible parental material that partially melted to form metal-poor, eucritic magmas. The silicate fractions of these mesosiderites alone, with their polymict clast populations are sufficiently unique to set them apart from the clast-free, achondritic meteorites and their brecciated (monomict) equivalents that crystallized from a melt.

The igneous textures of the silicate matrices, the diversity and abundance of xenocrysts, the differences in mineral chemistry of clasts vs. matrix silicates, and metal-silicate-troilite textural relationships all support the contention that Simondium, Hainholz and Pinnaroo are the products of impact melting. For each mesosiderite, intimate unmixing of a metal, sulfur-bearing melt and a clast-rich silicate melt saturated with Fe metal and sulfur, without subsequently segregating, is readily explainable by impact total melting of a heterogeneous metal-silicate target followed by relatively rapid cooling within a thin sheet-like layer.

Although shock deformation features have not been unambiguously identified from any of these meteorites, this does not compromise the impact-melt model. Shock features are relatively abundant in detrital impact formations (von Englehardt, 1971) but relatively rare in clast-laden melts where they tend to be obliterated by thermal reactions between the shock-heated clasts and superheated melt (Grieve, 1975). Most clasts incorporated into terrestrial and lunar impact melts did

not experience pressures greater than 100 kb or temperatures in excess of 200-300°C (Simonds et al., 1976). As a result, highly shocked clasts are rare in impact melts. Those that are present are usually partially assimilated by the melt.

Crystallization of the metallic-sulfide fraction

Observed textural relations among taenite, kamacite, and troilite are compatible with phase relations in the Fe-Ni-S system (Kullerud, 1963). Metal with about 8% Ni and negligible amounts of phosphorus would begin to crystallize under equilibrium conditions as taenite at $\sim 1500°C$ (Powell, 1971) although the presence of sulfur in the melt should lower this temperature. In these three meteorites taenite continued to crystallize and coexist with liquid and vapor to below 1000°C, during which time the silicate melt would have been extensively, if not entirely, crystallized. Further cooling led to precipitation of troilite and taenite at the Fe-FeS eutectic. Thus, continued crystallization of taenite over a wide temperature range led to a residual sulfur-rich metallic melt that crystallized below the temperature at which the last silicates crystallized.

The troilite blebs associated with the silicate fraction and often accompanied by metal appear to have had a different origin. The presence of these tiny dispersed grains suggests that the silicate melts were saturated with sulfur and, in Simondium and Hainholz, with metal also.

Of the three impact-melted mesosiderites, a cooling rate has been determined for the metal in Hainholz only. The extremely slow rate of 0.1°C/10^6 yr between 500-350°C determined by Powell (1969) is the same as those calculated by him for many other mesosiderites. In addition, Hainholz has been moderately metamorphosed, probably at temperatures considerably in excess of 500°C, causing extensive recrystallization of the silicate matrix. Simondium and Hainholz may have experienced a less severe reheating episode, though textural evidence is lacking.

Comparison with lunar-terrestrial analogs

As already noted, there are a number of similarities between meteoritic, terrestrial, and lunar impact melts. Differences in bulk composition among these melts, especially the abundances of metal, reflect the nature of the target material and the surface chemistries of their respective parent bodies. Gross similarities in appearance (i.e., brecciated structure) and texture between lunar-terrestrial impact melts and the silicate portions of Simondium, Pinnaroo, and Hainholz unequivocally demonstrate that the same kinds of processes were operative in the past outside the earth-moon system. This conclusion is predicated on the assumption that these mesosiderites, like most differentiated meteorites, formed in the asteroid belt. Recently, Wetherill (1976, 1977) has raised the possibility that the basaltic achondrites (and by extension the eucrite clast-bearing mesosiderites) are fragments of ancient earth planetesimals. It is not clear where the impact-melted mesosiderites fit into this scheme, but they do appear

to be compositionally related to the metamorphosed mesosiderites which
in turn have affinities with the basaltic achondrites and diogenites,
based on their clast populations (Floran, 1978) and oxygen isotopes
(Taylor et al., 1965; Clayton et al., 1976).

Figures 6a and 6b are examples of fine-grained, clast-laden and
medium-grained, clast-poor impact melts. The former was collected
during the Apollo 16 mission and is texturally analogous to the sili-
cate portions of Simondium and Hainholz (prior to metamorphism) while
the latter is from Manicouagan Crater, Quebec, and is roughly equiva-
lent to Pinnaroo. Although representing different impact events these
crystallized melts demonstrate the progressive textural changes that
take place within a single, large melt sheet. With increasing distance
above the basement-melt contact there is an inverse relationship between
matrix grain size and clast content, so that fine grained impact melt
rich in clasts is gradually replaced by coarser melt with few or no
recognizable clasts. Because of this relationship, textural
variability cannot be used for or against a genetic relationship
between any of the igneous-textured mesosiderites. However, the fine
to medium grain size of Pinnaroo is comparable to the transition between
the middle clast-bearing, and upper clast-poor units at Manicouagan,
suggesting that the formation of Pinnaroo represented a major cratering
event. Relatively coarse, clast-deficient melt rocks occur on earth
typically within craters with diameters exceeding 20 km. If the present
grain size and clast content of Pinnaroo can be used as a rough qualita-
tive guide of the magnitude of the "Pinnaroo impact event," we must
allow for the possibility that considerably coarser grained rocks coul

have been formed during the same impact. An interesting feature of the mesosiderite impact melts is their high clast contents relative to lunar and terrestrial analogs. Impact melts with 25-67% clasts are rare in the lunar highlands (Simonds et al., 1976) but both Simondium and Hainholz fall within this category. Pinnaroo contains far fewer clasts but compared with equivalent silicate textures and grain sizes at Manicouagan, it is significantly enriched in fragmented debris.

Paragenesis: A scenario

Petrochemical studies of terrestrial and lunar impact melts (Grieve, 1975; Floran et al., 1976a,b, 1978; Irving, 1975; Winzer et al., 1977) have shown that melt rocks formed during the same event occur in a variety of textures but exhibit only limited chemical variability. Textural inhomogeneities can be related to stratigraphic position within a melt sheet and to the initial abundance of clasts; these in turn determine cooling rates and degrees of supercooling which control textural development (Floran et al., 1978b). The gross similarity in bulk chemistry, mineral chemistry, and mineralogy coupled with observed variations in grain size in the three impact-melted mesosiderites is consistent with a common origin during a single impact event in which Simondium and Hainholz cooled more rapidly than the coarser-grained Pinnaroo. However, despite approximate equivalence in the bulk compositions of the silicate melt portions, sufficient differences exist to cast doubt on a common origin for all three mesosiderites. The data are consistent with, but do not prove a common origin for Simondium and Hainholz. Because of compositional differences

previously discussed, the evidence is less compelling for a genetic relationship between Pinnaroo and the other two mesosiderites. Perhaps the most serious difficulties to be reconciled if a common origin is proposed for the three meteorites, is the large enrichment of the metallic fraction in Pinnaroo (2/3 of the entire meteorite vs 1/2 for Simondium and Hainholz), and the high abundance of troilite (14% vs 9% and 2%). A possible explanation is provided by the much smaller chemical variations encountered in terrestrial impact-melt sheets. Although these melts are remarkably well mixed chemically, they are not perfectly homogenized. For example, in the Manicouagan impact melt, incomplete homogenization of local concentrations of one of several basement rocks that were melted and mixed during the impact event, has resulted in slight but detectable differences in the Al_2O_3 content of the melt in different areas of the crater (Grieve and Floran, 1978). Whether differences of the magnitude observed among the three meteorites could be accounted for in this manner, remains an intriguing question.

It would seem logical to assume that cratering events causing impact melting should not be rare, isolated occurrences outside the earth-moon system (i.e., the asteroid belt). This line of reasoning suggests that at least two impact events may well have been involved in the generation of Simondium, Pinnaroo and Hainholz.

Based on the above information, several reasonable inferences can be made:

(1) Hypervelocity impacts (i.e., velocities > several km/s) with enough energy to cause extensive though localized melting, occurred at various times on one or more parent bodies with similar, stony-iron

surface compositions. The craters that formed during these impact
events were at least several kilometers in diameter, and in the case of
Pinnaroo, may have been tens of kilometers across.

(2) Assuming that the parent bodies formed in the asteroid belt
and are still located there, as suggested by spectral reflectance
studies (Gaffey and McCord, 1977), collisional events causing impact
melting are likely to have occurred with other asteroids at velocities
much greater than the present average relative velocity of 5 km/s
(Chapman 1976) which appears to be insufficient to form extensive
impact-melt sheets. Less likely alternatives include impact melting
caused by collisions with other objects traversing the asteroid belt
such as comets, or formation of the mesosiderite parent bodies and
their impact melts outside the main belt. Wherever they formed, the
presumed occurrence of these melts as extensive sheets and the presence
of a silicate clast population of achondritic parentage argues strongly
for an origin on relatively large differentiated bodies, probably
several hundreds of kilometers in diameter or greater. Such bodies
must have had sufficient gravity fields to retain their impact-melt
products.

(3) For each mesosiderite the lack of separation between dense
molten metal and a lower density silicate melt may have been due to a
combination of factors including the very high viscosity of the clast-
laden melt, the extreme sheetlike form of the melt layer, and the
intimate mixing of the two immiscible liquids on a cm and mm scale. At
the 65 km diameter Manicougan Crater in Quebec the high viscosity of
the melt-clast mixture prevented meter-sized blocks more dense than the

melt from settling to the base (Simonds et al., 1976) and the melt layer within the crater is truly a sheet, having a preerosional diameter:depth ratio of ~150:1 (Floran et al., 1978b). The present intricate structural relationships observed in Pinnaroo (Fig. 1) were probably established after unmixing of an homogenous superheated (super-critical?) fluid into micron-sized globules of immiscible silicate and metal liquids. At some point, these coexisting melts may have briefly had the physical characteristics of an emulsion. Unmixing of these liquids was slow enough to permit partial segregation on a cm scale but not rapid enough to allow complete separation by gravity. Alternatively, the lack of separation may reflect rapid cooling of small bodies of impact melt. While perhaps possible for Simondium and Hainholz, this alternative is less attractive in accounting for the much slower cooling history implied by the coarser grain size of Pinnaroo.

(4) The presence of various mineral clasts with diverse compositions, metal clasts, and rare lithic fragments indicate that the targets were heterogenous. The clast populations suggest that at least four rock types were melted and mixed during one or more impact events: (a) orthopyroxenite (diogenite), (b) a plagioclase-rich source (plagioclase cumulate eucrite?), (c) dunite, and (d) metal. Other rock types may have been involved but are not identifiable. For example, basaltic eucrites may have been a source of some of the plagioclase component but textural evidence for their existence as clasts is lacking. Pre-existing mesosiderites may also have been a target rock but, again, textural evidence is absent. The wide compositional range of

coarse-grained mineral clasts of likely plutonic origin (i.e.,
orthopyroxene, olivine) indicate that a variety of rock types were
present within the target area. Pyroxene clasts with compositions more
magnesian than $\sim En_{75}$ probably represent unsampled diogenite material not
found as individual meteorites; pyroxene more iron-rich than $\sim En_{70}$
may have been derived from Fe-rich diogenites or Mg-rich cumulate
eucrites. Although individual olivine grains are typically coarse
grained and unzoned, the compositional range in two of the three impact
melts (Fo_{86-67}) suggests that several dunitic bodies, also unsampled
as meteorites, were target rocks. Alternatively, these compositionally
distinct clasts may represent debris from previous impacts transported
to the impact site and mixed into the impact melts.

(5) Most of the metal component was present as a solid on the
surface of the planet at the time of the impact, either in discrete
metal-rich bodies or as a dispersed phase associated with silicates.
Only a very small amount of the metal is likely to have been derived
from the projectile. For typical terrestrial and lunar impact
velocities the projectile is largely vaporized (Dence, 1971) and
dispersed over a wide area. Metal could have been deposited onto the
surface in the solid state by previous, low-velocity impacts.

These inferences lead to the following scenario for the origin of
these mesosiderites, based in part on impact-melt models developed for
terrestrial craters (Grieve, 1975; Grieve et al., 1977; Phinney and
Simonds, 1977; Grieve and Floran, 1978). Hypervelocity impacts on one
or more large, differentiated asteroids with stony-iron surfaces caused
impact melting and minor vaporization of heterogeneous silicate-metal

targets near the point of impact. Chemical homogenization of melted and vaporized material occurred due to the dynamic conditions of the melted volume as it moved radially outward into the rapidly expanding crater cavity. Conditions for chemical homogenization included a high degree of superheat, internal velocity gradients, an initially low viscosity, and extremely turbulent flow (Grieve et al., 1977). During this violent mixing stage disequilibrium prevailed, as relatively cold unshocked silicate and metal clasts were engulfed by the outward motion of the melt. The superheat of the melt was absorbed almost instantaneously by the clasts, some of which were assimilated or selectively melted leaving behind a refractory clast population. The ability of silicate clasts to rapidly absorb the superheat of an impact melt is well established (Simonds et al., 1976). This general property should be true of metal clasts also, but to a much greater degree because of their larger heat capacity and thermal conductivity. As a result of clast-melt interactions, the viscosity of the melt volume (now in the form of a subhorizontal sheet on the crater floor) increased dramatically with a correspondingly sharp decrease in temperature. Initially a single silicate-metal melt phase was formed but as an approach to thermal and chemical equilibrium was established, the melt split into two immiscible fractions, possibly as micron-sized particles. In Simondium and Hainholz clast-melt interactions caused supercooling of the silicate melt below their liquidii, thereby initiating widespread nucleation of plagioclase and pyroxene. The silicate and metal-rich liquids crystallized under tranquil conditions, independent of one another. Intricate structural relationships between the crystallizing

melts (Fig. 1) were established at this time due to failure of the melts to completely segregate. The last phase to crystallize was troilite which formed from the metallic melt at the boundaries between solidified silicate and metal. At this point the evolutionary history of Hainholz deviated from the other two meteorites. Hainholz may have been deeply buried for an extended period of time. This would explain its recrystallized texture and possibly its extremely slow metal cooling rate. Ultimately, all three fragments were ejected from their respective parent bodies or from different areas of the same body into orbits that resulted in collision with the earth where they were recovered as meteorites.

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FIGURE CAPTIONS

Fig. 1. Photograph of polished, etched surface of Pinnaroo. Both
         silicate (black) and metal (white) clasts are present. Matrix
         material consists of finer grained silicate material (dark
         grey) and swirling metal in sharp contact. Irregular lobate
         borders of metal clasts suggest flowage in a plastic or
         partially molten state. Clast at upper right is ∿ 4 cm in
         diameter (USNM neg. #1052 D).

Fig. 2. Basaltic, intergranular textures of silicate portions of
         mesosiderite impact melts. (a) Simondium, plane polarized
         light, longest dimension (l.d.) = 1.3 mm, (b) Pinnaroo,
         partially crossed nicols, l.d. = 4.2 mm, (c) Hainholz, plane
         polarized light, l.d. = 1.3 mm.

Fig. 3. Silicate - troilite - metal relations of mesosiderite impact
         melts, reflected light, longest dimension = 4.2 mm, silicates
         (dark grey), troilite (light grey), metal (white), (a)
         Simondium, (b) Pinaroo, (c) Hainholz. Metal in Simondium is
         partially oxidized. Opaque phases within silicate portions
         are troilite and metal in Simondium and Hainholz, and troilite
         in Pinnaroo.

Fig. 4. Pyroxene compositions for Simondium, Pinnaroo, and Hainholz
         plotted on a Wo-En-Fs diagram (mol %). Olivine compositions
         are shown on a Fo-Fa plot. (A) matrix, (B) clasts.

Fig. 5. Plagioclase compositions for Simondium, Pinnaroo, and Hainholz
plotted on an An-Ab-Or diagram (mol %). (A) matrix, (B)
clasts. Only a small portion of feldspar diagram is shown.

Fig. 6. Lunar and terrestrial impact melts. (A) 67025, plane
polarized light, longest dimension (l.d.) = 1.3 mm, (b) MAN
74-157 from Manicouagan crater, Quebec, partially crossed
nicols, l.d. = 5.2 mm.

Table 1. Petrographic features of silicate portions
of impact-melted mesosiderites

| | "IGNEOUS" | | "METAIGNEOUS" |
	Simondium	Pinnaroo	Hainholz
TEXTURE	intergranular, basaltic	intergranular, basaltic	granoblastic locally intergranular
GRAIN SIZE (avg.) Pyroxene Plagioclase	fine 250µ 150µ	fine to medium 0.5-1.2 mm 0.5-1.0 mm	fine 0.25-1.0 mm 250µ
CLAST CONTENT	40-50%; primarily opx, minor plag, ol	~5-10% primarily opx, minor ol	40-50% primarily opx, minor plag, ol
LITHIC CLAST TYPES PRESENT	none recognizable	none identifiable	diogenite; plag cumulate eucrite(?)
APPROXIMATE TERRESTRIAL/ LUNAR TEXTURAL ANALOG	Apollo 16 basaltic impact melts	Manicouagan impact melt; middle-upper unit transition	—

Table 2. Average compositions (wt %) of matrix pyroxenes (columns 1-3) and plagioclases (columns 4-6) froi. Simondium, Pinnaroo, and Hainholz as determined by electron microprot. analysis

	Simondium		Pinnaroo		Hainholz		Simondium		Pinnaroo		Hainholz	
	1	1σ	2	1σ	3	$1o$	4	1σ	5	1σ	6	$1o$
SiO_2	53.51	0.63	52.51	0.75	53.46	0.51	46.84	0.85	46.85	0.70	47.58	0.79
TiO_2	0.33	0.09	0.29	0.13	0.28	0.12	<0.01	-	<0.02	-	<0.02	-
Al_2O_3	0.68	0.25	0.89	0.32	0.81	0.25	33.85	0.70	33.48	0.52	33.08	0.79
Cr_2O_3	0.45	0.14	0.56	0.17	0.51	0.12	n.d.	-	n.d.	-	n.d.	-
FeO	18.61	0.98	20.82	1.79	19.66	0.83	0.58	0.13	0.56	0.23	0.69	0.16
MnO	0.87	0.08	0.82	0.10	0.88	0.12	n.d.	-	n.d.	-	n.d.	-
MgO	24.41	1.14	21.86	1.36	23.40	0.90	0.09	0.02	0.15	0.04	0.20	0.05
CaO	1.15	0.47	1.78	0.58	1.58	0.37	18.16	0.48	18.51	0.46	17.75	0.29
Na_2O	0.01	-	0.02	-	-	-	1.02	0.19	0.89	0.15	1.11	0.09
K_2O	n.d.	-	n.d.	-	n.d.	-	0.06	0.02	0.05	0.02	0.08	0.01
BaO	n.d.	-	n.d.	-	n.d.	-	<0.01	-	<0.01	-	<0.01	-
Total	100.02		99.55		100.58		100.62		100.52		100.52	
Wo	2.3	1.0	3.6	1.2	3.2	0.8	An 90.4	1.8	91.7	1.4	89.4	0.9
En	68.3	2.4	62.8	3.3	65.8	1.9	Ab 9.2	1.7	8.0	1.4	10.2	0.9
Fs	29.4	1.8	33.6	3.1	31.0	1.5	Or 0.4	0.1	0.3	0.1	0.4	0.1
No. analyses	28		46		33		34		38		21	

n.d. = no data

Table 3. Representative analyses (wt %) of orthopyroxene clasts

	Simondium				Pinnaroo			Hainholz			
	1	2	3	4	5	6	7	8	9	10	11
SiO_2	55.5	54.6	54.1	52.9	55.1	52.1	51.9	55.3	55.2	54.0	54.3
TiO_2	0.03	0.06	0.03	0.11	0.84	0.22	0.22	0.05	0.10	0.33	0.34
Al_2O_3	0.24	0.60	0.16	0.71	0.15	0.88	0.99	0.30	0.52	0.89	0.65
Cr_2O_3	0.73	0.65	0.59	0.34	0.63	0.53	0.56	0.49	0.48	0.50	0.34
FeO	11.6	15.4	18.8	20.8	15.2	20.1	23.0	13.2	15.7	18.6	19.8
MnO	0.39	0.50	0.64	0.76	0.44	0.80	0.82	0.36	0.52	0.83	0.76
MgO	30.8	28.0	25.2	22.7	27.2	22.9	20.8	28.8	27.3	24.5	22.8
CaO	0.48	0.48	1.04	1.04	1.09	1.31	0.90	0.72	1.13	1.36	1.72
Na_2O	0.03	0.01	0.02	0.01	-	-	0.02	0.01	-	-	-
Total	99.8	100.3	100.6	99.4	100.7	98.8	99.2	99.2	101.0	101.0	100.7
Wo	0.9	0.9	2.1	2.1	2.2	2.6	1.8	1.4	2.2	2.7	3.5
En	81.8	75.7	69.0	64.7	74.5	65.2	60.6	78.5	74.0	68.3	64.9
Fs	17.3	23.4	28.9	33.2	23.3	32.2	37.6	20.1	23.8	29.0	31.6

Cores of grains: 1, 2, 3, 4(?), 5, 7, 8, 9

Rims of grains: 6, 10, 11

Table 1. Representative analyses (wt %) of plagioclase clasts

	Simondium				Pinnaroo		Hainholz			
	1a core	1b rim	2a core	2b rim	3a core	3b rim	4a core	4b rim	5a core	5b rim
SiO_2	45.3	47.9	45.0	46.9	44.6	45.9	44.5	47.6	44.1	46.8
TiO_2	0.01	0.05	-	0.02	0.04	0.07	0.01	0.04	0.03	0.05
Al_2O_3	35.9	32.9	34.9	34.5	34.7	33.9	35.7	33.2	35.6	32.9
FeO	0.24	0.97	0.33	0.38	0.17	0.47	0.22	0.58	0.24	0.33
MgO	0.06	0.09	0.06	0.09	0.12	0.17	0.07	0.17	0.07	0.17
CaO	19.0	17.1	19.4	18.1	18.8	18.1	19.4	17.4	19.5	17.8
Na_2O	0.52	0.96	0.42	0.78	0.61	0.89	0.41	1.21	0.34	1.10
K_2O	0.03	0.08	0.01	0.06	0.07	0.08	0.05	0.10	0.07	0.09
BaO	0.01	-	-	0.05	-	-	-	-	-	-
Total	101.1	100.1	100.1	100.9	99.1	99.6	100.4	100.3	100.0	99.2
An	95.1	90.4	96.1	90.2	94.1	91.3	96.0	88.2	96.5	89.5
Ab	4.7	9.2	3.8	9.4	5.5	8.2	3.7	11.2	3.1	10.0
Or	0.2	0.4	0.1	0.4	0.4	0.5	0.3	0.6	0.4	0.5

Table 5. Representative analyses (wt %) of olivine clasts

	Simondium			Pinnaroo		Hainholz			
	1	2	3	4	5	6	7	8	9
SiO_2	40.3	38.9	37.4	40.7	39.8	40.2	38.9	38.7	37.1
TiO_2	<0.03	<0.03	<0.03	-	-	<0.03	<0.05	<0.03	<0.05
Al_2O_3	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
FeO	11.6	19.9	29.4	11.1	15.0	12.7	18.8	22.4	28.4
NiO	<0.02	<0.04	<0.03	<0.03	<0.03	<0.01	<0.04	<0.02	<0.05
MnO	0.25	0.54	0.87	0.32	0.40	0.34	0.54	0.59	0.82
MgO	48.6	41.4	33.4	47.9	44.8	47.6	42.4	39.3	34.1
CaO	0.02	0.10	0.06	0.02	0.03	0.07	0.04	0.04	0.06
Total	100.8	100.9	101.2	100.1	100.1	101.0	100.8	101.1	100.6
Fo	88.2	78.7	67.0	88.4	84.2	87.0	80.1	75.8	68.1

Table 6. Representative analyses (wt %) of chromite (columns 1-6), merri rutile (column 13)

	Simondium		Pinnaroo		Hainholz		Sim
	1	2	3	4	5	6	7
SiO_2	0.15	0.08	0.13	0.13	0.10	0.18	0.02
TiO_2	0.75	3.00	2.97	1.04	0.66	1.35	n.d.
Al_2O_3	8.3	7.6	9.5	12.8	10.9	9.6	<0.01
Cr_2O_3	52.0	52.1	50.5	50.5	52.9	52.3	n.d.
V_2O_3	0.49	0.32	0.73	0.65	0.69	0.56	n.d.
FeO	34.2	33.8	31.6	32.0	29.0	31.2	0.45
MnO	1.01	0.78	1.82	1.59	1.28	0.92	0.19
MgO	2.47	2.34	2.63	2.46	3.2	2.57	3.6
CaO	0.58	0.25	0.17	0.22	0.49	0.20	47.1
ZnO	0.21	0.22	0.20	0.18	0.20	0.18	n.d.
Na_2O	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.76
K_2O	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
P_2O_5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	46.3
Cl	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	<0.02
F	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.70
Y	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.15
La	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	<0.01
Ce	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	<0.01
Nd	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.05
Total	100.2	100.5	100.2	101.6	99.4	99.1	99.4
						O≡F	0.29
							99.1
Us	2.2	8.3	8.0	2.8	1.7	3.7	
Cm	79.1	75.4	72.2	70.6	75.1	75.7	
Sp	14.0	12.7	14.3	12.8	17.3	13.9	
Hc	4.7	3.6	5.5	13.8	5.9	6.7	

Us = ulvöspinel ($FeTi_2O_4$), Cm = Chromite ($FeCr_2O_4$), Sp = spinel ($MgAl_2O_4$), He = hercynite ($(Fe,Mn,Zn)Al_2O_4$); after Busche et al. (1972).

*Includes 0.19% Nb_2O_5 and 0.07% ZrO_2.

Pinn	Hain	Sim	Pinn	Hain	Pinn
8	9	10	11	12	13
0.04	0.04	98.7	99.6	99.7	0.20
n.d.	n.d.	0.13	0.18	0.22	98.3
<0.01	<0.01	0.07	0.14	0.16	0.01
n.d.	n.d.	n.d.	n.d.	n.d.	0.12
n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
0.77	0.37	0.48	0.49	0.55	0.76
0.24	0.18	n.d.	n.d.	n.d.	0.05
3.65	3.7	<0.01	<0.01	<0.01	0.03
47.7	48.4	0.05	0.05	0.07	0.32
n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
0.86	0.82	<0.01	<0.01	<0.01	n.d.
n.d.	n.d.	0.02	0.07	0.06	n d.
45.6	45.9	n.d.	n.d.	n.d.	n.d.
<0.03	<0.03	n.d.	n.d.	n.d.	n.d.
0.74	0.80	n.d.	n.d.	n.d.	n.d.
0.16	0.15	n.d.	n.d.	n.d.	n.d.
0.05	0.05	n.d.	n.d.	n.d.	n.d.
0.06	<0.03	n.d.	n.d.	n.d.	n.d.
<0.02	0.06	n.d.	n.d.	n.d.	n.d.
99.8	100.5	99.5	100.6	100.8	100.1[*]
0.31	0.34				
99.5	100.2				

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Table 7. Average compositions and ranges (wt %) of metal phases

A. Taenite

	Simondium		Pinnaroo		Hainholz		Hainholz[*]	
	Avg	Range	Avg	Range	Avg	Range	Avg	Range
Fe	57.3	(47.7-64.2)	51.0	(47.2-61.4)	57.6	(44.3-63.2)	48.0	(46.9-49.5)
Ni	41.4	(34.5-51.1)	46.7	(37.5-51.9)	41.6	(36.2-54.6)	51.4	(50.2-53.4)
Co	0.04	(0.00-0.09)	0.06	(0.00-0.17)	0.07	(0.02-0.13)	0.05	(0.00-0.12)
P	0.02	(0.00-0.08)	<0.01	-	0.02	(0.00-0.08)	0.02	(0.00-0.08)
Total	98.8		97.8		99.3		99.5	
No. analyses	19		12		22		10	

B. Kamacite

	Simondium		Pinnaroo		Hainholz		Hainholz[*]	
Fe	91.7	(90.9-92.3)	92.0	(91.0-92.5)	93.5	(92.2-95.0)	95.2	(94.7-95.7)
Ni	6.2	(5.3-6.9)	6.2	(5.3-6.4)	6.2	(5.0-6.8)	4.0	(2.5-5.0)
Co	0.52	(0.47-0.58)	0.69	(0.62-0.86)	0.50	(0.37-0.59)	0.84	(0.70-1.31)
P	0.03	(0.00-0.13)	0.02	(0.00-0.03)	0.02	(0.00-0.10)	0.03	(0.00-0.13)
Total	98.5		98.9		100.2		100.1	
No. analyses	38		10		50		5	

[*]Analyses of small blebs associated with silicate fraction; all other analyses are from metallic fraction.

Table 8. Model analyses (vol %) of whole-rock and silicate-melt portions as determined by microprobe analysis

	Whole rock			Silicate melt		
	Sim	Pinn[*]	Hain	Sim	Pinn	Hain
Plagioclase	21.2	17.5	19.8	36.1	32.5	34.9
Orthopyroxene	40.9	25.1	39.5	53.3	54.0	57.9
Ca-rich pyroxene	0.2	0.7	0.1	3.0	1.6	0.8
Olivine	0.3	0.9	1.0	-	-	-
Chromite	0.9	0.1	0.5	0.6	0.3	0.8
Tridymite	3.0	3.2	3.5	4.3	5.7	3.6
Phosphate	1.4	1.8	2.3	1.4	3.6	1.6
Kamacite	19.0	32.1	28.1	0.2	-	0.4
Taenite	5.0	3.6	3.3	0.2	-	-
Troilite	8.1	15.0	1.9	0.9	2.3	tr[†]
Silicates	67.9	49.4	66.7	98.7	97.7	99.6
Metal + Troilite	32.1	50.6	33.3	1.3	2.3	0.4

[*]Includes 0.1% rutile.

[†]Petrographic studies suggest a somewhat greater abundance.

Table 9A. Bulk chemical analyses (wt %) of silicate (melt + clasts) and metallic portions

	Simondium		Pinnaroo		Hainholz		
	This work	Prior (1918)	This work	Alderman (1940)	This work	Prior (1918)	Powell (1971)
Silicates (to 100%)							
SiO_2	51.3	53.1	49.9	48.5	51.1	48.8	50.8
TiO_2	0.25	n.d.	0.48	-	0.10	n.d.	0.40
Al_2O_3	9.7	9.6	11.2	10.0	9.5	10.6	9.2
Cr_2O_3	1.24	1.05	0.46	n.d.	0.94	0.78	n.d.
FeO	12.4	13.9	12.3	19.9	11.7	14.7	18.5
MnO	0.58	tr	0.48	n.d.	0.35	tr	0.47
MgO	16.6	17.7	14.3	14.5	16.8	16.8	13.6
CaO	6.7	3.4	8.9	6.6	7.6	7.0	5.9
Na_2O	0.23	0.12	0.31	0.54	0.23	0.51	n.d.
K_2O	0.02	n.d.	0.02	0.05	0.02	n.d.	-
P_2O_5	0.98	1.13	1.65	n.d.	1.66	0.81	1.13
Metallic							
Fe	36.3	47.8	48.7	58.3	47.7	42.1	n.d.
Ni	6.2	3.2	5.6	5.7	5.4	4.0	8.6
Co	0.18	-	0.27	0.10	0.24	0.41	n.d.
P	0.04	n.d.	0.03	n.d.	-	n.d.	n.d.
FeS	8.8	2.56	13.9	7.8	2.00	3.96	4.30
Sch	-	n.d.	-	n.d.	-	0.69	n.d.
Subtotal (metallic)	51.5	53.5	68.5	71.8	55.3	51.2	57.7
Subtotal (silicates)	48.5	46.5	31.5	28.2	44.7	48.8	42.3

n.d. = no data, tr = trace

H_2O, SO_3, Fe_2O_3, and NiO in silicate portions from Prior (1918) and Alderman (1940) were removed before recalculation to 100%; Cr_2O_3 + Na_2O + H_2O component (2.96% total) from Powell (1971) was removed before recalculation to 100%.

Table 9B. Compositions of clast-free portions of silicate melt rocks (wt %)

	Sim	Pinn	Hain
SiO_2	51.8	50.4	52.9
TiO_2	0.24	0.20	0.10
Al_2O_3	11.3	10.2	10.6
Cr_2O_3	0.72	0.38	0.94
FeO	11.3	13.1	11.1
MnO	0.53	0.51	0.33
MgO	15.3	14.6	15.8
CaO	7.9	8.6	7.3
Na_2O	0.26	0.29	0.23
K_2O	0.02	0.01	0.02
P_2O_5	0.69	1.76	0.75
Subtotal	97.6	96.5	99.1
Fe	0.76	-	0.90
Ni	0.25	-	0.10
Co	-	-	-
P	-	-	-
FeS	1.37	3.50	-
Scn	-	-	-
Subtotal	2.4	3.5	1.0