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The Barea, Dyarrl Island, and Emery meteorites, and a review of the mesosiderites

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SUMMARY. Barea and Emery are typical mesosiderites, whereas Dyarrl Island[1] is unique in having the lowest metal content and the highest FeO/(FeO+MgO) ratio of any meteorite of this class. Average pyroxene compositions have been determined for the individual mesosiderites, and show a sequential increase in $FeSiO_3$ content, ranging from a mean of 21 mole % for Veramin to 45 mole % for Dyarrl Island. Steinbach may possibly be classed as a mesosiderite, since its mineralogy is identical except for the absence of plagioclase. Dalgaranga and Mt. Padbury may be a paired fall. The chemical and mineralogical composition of the silicate material of the mesosiderites is similar to, but not identical with the howardites; the overall range of composition is greater in the mesosiderites.

THE mesosiderites form a small but interesting class of meteorites. The name was introduced by Rose (1863), who defined these meteorites as 'ein körniges Gemenge von Meteoreisen und Magnetkies mit Olivin und Augit', and used the name mesosiderite to indicate that they consisted of approximately equal amounts of metal and silicate phases and thus fell midway between the major groups of iron and stony meteorites. He described two representatives of this class, Hainholz and Vaca Muerta. Tschermak (1885) proposed an additional class, which he named grahamites, defining them as consisting of plagioclase, bronzite, augite, and nickel-iron, i.e. mesosiderites with plagioclase. However, Prior (1918) showed that there was no real distinction between the grahamites and the mesosiderites, since all contained plagioclase, and recommended that the term grahamite be dropped. In a later paper (Prior, 1920), he defined the mesosiderites as hypersthene–anorthite stony-irons, 'consisting of nickel-iron enclosing patches of stony matter composed of hypersthene (and clinohypersthene) and anorthite: olivine is also present but generally as separately enclosed crystals, often of fairly large size'. This definition adequately describes these meteorites, with the proviso that Prior's clinohypersthene is more precisely described as pigeonite (the augite of Rose and Tschermak). Some twenty mesosiderites are known (table II), of which six are observed falls. Powell (1969, 1971) has recently provided much data on several of these meteorites, and has discussed the whole group.

Although a considerable amount of mesosiderite analytical data is available, much of it is incomplete or inadequate for a number of reasons. Their frequently irregular textures, and the presence of much nickel-iron, sometimes in coarse lumps, makes representative sampling an extremely difficult task. The complex mixture of minerals requires a careful selection and sometimes the modification of analytical methods for

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[1] The actual place of fall is Dyaul Island; see below.

accurate results. Further, many of the analysed mesosiderites have been extensively weathered, which compounds the already intricate problem of apportioning total iron between metal, sulphide, and oxidic phases.

In the hope of improving this situation, we have investigated three previously unanalysed mesosiderites: Barea, Dyarrl Island, and Emery. Barea is the first mesosiderite observed to fall, on 4 July 1842, at Barea in the province of Logroño in northern Spain. Dyarrl Island fell on 31 January 1933; the place of fall is in fact Dyaul Island, a small island off the coast of New Ireland in the Territory of New Guinea. The locality was misspelt as Dyarrl Island in the original description (Hodge-Smith, 1933) and this has been perpetuated in the literature; it is customary to retain the original spelling of meteorite names even when it is incorrect (e.g. Queng-gouk, Durala, Dyalpur). Emery was found in the spring of 1962 in a field four miles west of Emery, Hanson County, South Dakota, by Larry Plucker, a twelve-year-old boy. It was recognized as a meteorite in 1968 and acquired by the American Meteorite Laboratory in Denver, Colorado, the weight being 16·7 kg (Clarke, 1972). A slice of this meteorite was purchased from the American Meteorite Laboratory. Although somewhat rusted on the surface, the meteorite is completely fresh in the interior, and therefore well-suited for analysis. Specific gravities were determined on pieces of these meteorites by weighing in air and in carbon tetrachloride; the results were (weight of piece in parentheses): Barea (70 g), 4·25; Dyarrl Island (94 g), 3·87; Emery (18 g), 4·63.

Sampling and analysis. The definition of a representative sample of a meteorite has always been a subject of discussion and frequent disagreement. It is generally agreed that 10–15 grams of an ordinary chondrite can be considered a fairly representative sample. In fact, it has been our experience that (with a few exceptions where the metal is coarse-grained) this is true. Obtaining a representative sample of a mesosiderite, because of its gross inhomogeneity, is obviously a very difficult task. As in most cases, there are some practical aspects one must consider in the selection of a sample for analysis; these are: first, and most important, the availability of material and second, the amount of material that can be handled conveniently during an analysis.

For this work, 15 grams of Barea, 9 grams of Dyarrl Island, and 15 grams of Emery were taken for analysis. These quantities may not be representative of the meteorites as a whole, but nevertheless we can determine an accurate composition of the metal and silicates in these particular samples and hopefully in the whole meteorite, even though the proportions of those two phases could vary from one sample to another.

Each sample was crushed in a diamond mortar, giving fine silicate powder and silicate-rich metallic grains up to 2 to 3 mm. There was a 5 gram silicate-rich metal fragment in the Barea sample that could not be crushed, and it appeared that this sample would contain proportionately a much larger amount of metal than the Emery sample, though preliminary optical and microprobe investigation indicated that these two meteorites are rather similar in composition. The bulk chemical analysis and proportions of acid-soluble and acid-insoluble fractions, nevertheless, compared well with estimates from hand specimens and polished thin sections. Perhaps this would serve as an example, for this class of meteorites, that even though it appears that there is a large silicate or metal inclusion, it still may contain fairly representative portions of both phases.

The whole sample was then dissolved in bromine water and nitric acid. The solution was evaporated to dryness, dissolved in dilute hydrochloric acid and filtered. Thus an acid-soluble fraction was obtained containing primarily nickel-iron, troilite, plagioclase, olivine, and phosphates, and an acid-insoluble portion containing chromite, pyroxene, and silica. A little sulphur, phosphorus, and nickel were found in the acid-insoluble fraction, most likely derived from minute inclusions in pyroxene grains.

Appropriate aliquots were then taken for the various determinations. The analysis was performed according to the general procedure given by Hillebrand *et al.* (1953) and Peck (1964), and adopted for meteorite analysis by Jarosewich (1966). In short, silica was separated by double dehydration and then volatilized with HF. The R_2O_3 group was separated by ammonia and dissolved with pyrosulphate. Iron was determined on an aliquot of this solution by reduction on a silver reductor followed by titration with potassium dichromate. Interfering ions were removed from a second aliquot of the R_2O_3 solution, and titanium was determined with tiron and aluminium precipitated by 8-hydroxyquinoline. The R_2O_3 filtrate was used for the determination of calcium and magnesium, by precipitation with oxalate and ammonium phosphate respectively. Phosphorus was determined colorimetrically on a separate sample with molybdovanadate, cobalt with nitroso-R-salt, and chromium was oxidized to chromate. Sulphate was precipitated with barium chloride and nickel with dimethylglyoxime. Sodium and potassium were determined using the flame photometer. A separate sample was taken for carbon and analysed with a Leco carbon analyser.

We attempted to determine quantitatively the amount of phosphate and phosphide. A two-gram sample was dissolved in dilute hydrochloric acid, assuming that the phosphate is soluble in dilute acid and the phosphide is not. There was no significant difference in the phosphorus content between this and the bulk acid-soluble sample, indicating that the amount of phosphide phosphorus must be very small.

Interpretation. Table I presents the results of these analyses and the norms calculated therefrom. Phosphate is calculated as whitlockite, since this is the only phosphate mineral detected by microprobe analysis. Free SiO_2 is reported as tridymite, this mineral being present in all three meteorites. The calculated norm should agree well with the observed mineralogical composition, since the normative minerals correspond closely to those actually present.

The same minerals are present in all three meteorites, although their proportions differ. Major minerals ($> 10\,\%$) are nickel-iron (kamacite, with minor taenite), plagioclase, and pyroxene (mostly hypersthene). Minor minerals (1 to 10 %) are troilite, tridymite, ilmenite in Dyarrl Island, olivine in Barea, and whitlockite in Emery and Barea. Trace constituents ($< 1\,\%$) include schreibersite, graphite, chromite, ilmenite (Barea and Emery), and whitlockite, schreibersite, chromite, and graphite (Dyarrl Island). Of these minerals the only ones that show marked compositional differences are plagioclase and pyroxene. Plagioclase is uniformly calcic, but specific grains range from An_{80} to An_{98} within the individual meteorites. The average composition from microprobe analyses is about An_{90} for all three meteorites, in close agreement with the normative composition. Pyroxene compositions vary widely; microprobe analyses of about forty grains from each meteorite gave:

Barea	23–37 Fs	0·8–3·8 Wo	60–76 En	Mean:	30 Fs	2·0 Wo	68 En
Emery	30–37	2·5–10·5	59–64		35	3·4	61
Dyarrl I.	34–51	1·4–11·7	44–63		45	5·5	50

TABLE I. *Analyses and norms of the Barea, Emery, and Dyarrl Island meteorites*

	Barea (NMNH 1468)			Emery (NMNH 5604)			Dyarrl I. (NMNH 5655)		
	Acid-sol. (64·62 %)	Acid-insol. (35·38 %)	Bulk	Acid-sol. (64·87 %)	Acid-insol. (35·18 %)	Bulk	Acid-sol. (29·42 %)	Acid-insol. (70·58 %)	Bulk
Fe	77·74	—	50·24	69·62	—	45·12	53·57	—	15·76
Ni	9·56	0·04	6·19	7·65	0·02	4·92	5·50	0·04	1·65
Co	0·18	< 0·01	0·12	0·79	< 0·01	0·11	0·26	< 0·01	0·08
FeS	2·39	0·22	1·62	11·24	0·14	7·34	6·96	0·38	2·32
SiO_2	—	61·35	21·71	—	63·61	22·38	—	56·82	40·10
TiO_2	< 0·01	0·32	0·11	0·01	0·40	0·15	0·04	1·08	0·77
Al_2O_3	5·79	0·89	4·01	6·53	0·91	4·55	20·20	0·72	6·45
Cr_2O_3	< 0·01	1·05	0·37	< 0·01	0·96	0·34	0·02	0·75	0·54
FeO	—	15·86	5·61	—	13·86	4·88	—	20·70	14·61
MnO	0·02	0·65	0·24	0·01	0·66	0·24	0·02	0·67	0·48
MgO	0·53	17·76	6·62	0·05	16·54	5·85	0·47	15·22	10·88
CaO	3·08	1·52	2·54	3·89	1·61	3·09	11·17	2·97	5·39
Na_2O	0·18	< 0·01	0·12	0·25	< 0·01	0·16	0·72	0·02	0·22
K_2O	0·01	< 0·01	0·01	0·02	< 0·01	0·01	0·04	< 0·01	0·01
P_2O_5	0·01	0·01(P)	0·53	1·10	0·01(P)	0·72	0·81	0·01(P)	0·26
C	—	—	0·04	—	—	0·03	—	—	0·14
Total	—	—	100·08	—	—	99·89	—	—	99·66
Total Fe	79·26	12·47	55·63	76·76	10·86	53·58	57·99	16·33	28·59

Norm		Norm		Norm	
Nickel-iron	56·6	Nickel-iron	50·2	Nickel-iron	17·5
Troilite	1·6	Troilite	7·3	Troilite	2·3
Albite	1·0	Albite	1·4	Albite	1·8
Anorthite	10·4	Anorthite	11·7	Anorthite	16·5
Hypersthene	26·6	Hypersthene	23·3	Diopside	7·2
Tridymite	2·6	Tridymite	4·1	Hypersthene	49·4
Whitlockite	1·2	Whitlockite	1·7	Tridymite	1·9
Chromite	0·5	Chromite	0·5	Ilmenite	1·7
Ilmenite	0·3	Ilmenite	0·4	Chromite	0·8
				Whitlockite	0·6

It is possible to arrive at two other estimates of mean pyroxene composition: the acid-insoluble material consists almost entirely of pyroxene (tridymite and the small amounts of chromite and ilmenite will hardly affect the calculated composition); and the norm calculation also provides an estimate of mean pyroxene composition. The results are:

	Microprobe analysis			Acid-insoluble			Norm		
Barea	30 Fs	2·0 Wo	68 En	32 Fs	3·9 Wo	64 En	32 Fs	0 Wo	68 En
Emery	35	3·4	61	30	4·5	65	31	0	69
Dyarrl I.	45	5·5	50	40	7·4	53	40	6·4	54

On the whole, the agreement is good, and the discrepancies have a reasonable explanation. The non-appearance of Wo in the normative pyroxene of Barea and Emery results from the complete utilization of CaO in the calculation of whitlockite and plagioclase, whereas some of the phosphorus calculated as whitlockite may be present as schreibersite and in solid solution in the metal phase, and some of the aluminium calculated as plagioclase is contained in the pyroxene and in the chromite. This has the effect of over-committing CaO to whitlockite and plagioclase, leaving less available for pyroxene. The Wo content in acid-insoluble pyroxene is consistently higher than determined by microprobe analyses; the microprobe analyses were programmed to exclude analyses showing more than 12 % Wo, these being usually of exsolved augite from inverted pigeonite. The Fs content of the pyroxene in Emery and Dyarrl Island is consistently higher in the microprobe analyses than in the acid-insoluble and the norm calculation; however, the difference is not great, and may be within the experimental error involved.

Normative ilmenite and chromite will be somewhat greater than the amounts actually present, because of the presence of titanium and chromium within the pyroxenes. Microprobe analyses gave the average contents of TiO_2, Cr_2O_3, and Al_2O_3 in the pyroxene:

	TiO_2	Cr_2O_3	Al_2O_3
Barea	0·23 %,	0·66 %,	0·28 %
Emery	0·37	0·39	0·19
Dyarrl I.	0·34	0·34	0·19

These figures indicate that pyroxene accounts for about 40 % of the titanium in Barea, 45 % in Emery, and 20 % in Dyarrl Island; and 50 % of the chromium in Barea, 25 % in Emery, and 40 % in Dyarrl Island. Conversely, normative chromite is somewhat diminished relative to actual chromite by being calculated as $FeCr_2O_4$, whereas chromite in the mesosiderites contains appreciable amounts of aluminium: microprobe analyses gave 8·1 % Al_2O_3 in chromite from Barea, 10·4 % in that from Emery, and 7·8 % in that from Dyarrl Island. The chromite also contains *titanium*: 2·0 % TiO_2 in Barea chromite, 1·7 % in that from Emery, and 4·7 % in that from Dyarrl Island. The data are consistent with analyses of mesosiderite chromite published by Bunch and Keil (1971), although the Dyarrl Island chromite is higher in TiO_2 than any other mesosiderite.

Some interrelations within the mesosiderites

The complex brecciated structure of the mesosiderites suggests that sequential interrelationships between individual meteorites, if present, would be difficult to recognize. However, this is not altogether the case. These meteorites do show some sequential relationships, and some uniform features, which may indicate a common origin, or at least an origin in a relatively few closely related events.

Some of the parameters that may have significance in this discussion are enumerated in table II. Of these, the average composition of the pyroxene seems to have particular utility. Pyroxene is the dominant silicate mineral in all these meteorites. We have determined the relative proportions of Fs, Wo, and En in twenty to forty grains of pyroxene in each mesosiderite. Powell (1971) has provided similar data for several of these meteorites, and our results are generally in excellent agreement. While there is an extensive range of composition over the whole group (Fs_{18} to Fs_{52}), the range within a single meteorite is much more limited (fig. 1), and the average composition probably has some significance in establishing a compositional sequence for this group of meteorites. As the Fs content increases, the Wo content of the pyroxene also tends to increase.

TABLE II. *Some compositional parameters of the mesosiderites*

	Pyroxene comp. (*mean*)			*Metal*		Ca/Al (weight)	*Source of metal and* Ca/Al *data*
	Fs	Wo	En	wt %	Ni %		
Veramin	21	1·6	77	49	7·60	0·88	Powell (1971)
Chinguetti	26	1·8	72	80	8·28*	0·97	Lacroix (1924)
Bondoc	27	2·2	71	44	7·40	0·63	Powell (1971)
Estherville	29	1·7	69	56	8·57	0·90	Powell (1971)
Budulan	29	1·9	69	70	8·4	0·63	Kirova+Dyakonova (1966)
Simondium	29	1·5	69	—	—	—	
Mincy	29	2·8	68	—	8·41	—	Powell (1971)
Barea	30	2·0	68	57	11·0	0·85	This paper
Łowicz	31	3·1	66	60	7·52	0·84	Powell (1971)
Patwar	32	2·3	66	38	11·1	0·84	Jarosewich+Mason (1969)
Hainholz	32	2·4	65	53	8·63	0·87	Powell (1971)
Crab Orchard	33	3·2	64	55	8·83	0·90	Powell (1971)
Clover Springs	34	3·6	62	37	10·4	0·61	Wiik (1969)
Mt. Padbury	34	2·7	63	57	9·0	0·74	Wiik (1969)
Dalgaranga	35	3·0	62	—	8·63	—	Simpson (1938)
Vaca Muerta	35	2·5	62	47	8·50	0·96	Powell (1971)
Emery	35	3·4	61	50	9·8	0·92	This paper
Pinnaroo	36	4·5	60	64	8·9	0·89	Alderman (1940)
Morristown	41	4·0	55	50	8·55	0·89	Powell (1971)
Dyarrl Island	45	5·5	50	17	9·5	1·12	This paper

* E. Jarosewich, unpublished.

The amount of metal shows a rough correlation with the pyroxene composition. Dyarrl Island, with the most iron-rich pyroxenes, has the lowest metal content of any mesosiderite (and correspondingly the highest silicate content). At the other extreme, Chinguetti, with the most magnesium-rich pyroxenes except for Veramin, has a very high metal content, estimated as 80 % by Lacroix (1924). Budulan also resembles Chinguetti in these features. However, the correlation is not very close, and for most of these meteorites the metal content is rather uniform in the range 40 to 60 %.

In an earlier paper (Jarosewich and Mason, 1969), we suggested that Prior's rules (the smaller the amount of nickel-iron, the higher the Ni/Fe ratio, and the higher the FeO/MgO ratio in the silicates), established for the chondrites, might also apply to the mesosiderites. Our suggestion was based largely on the high nickel content of Patwar metal (11·1 %) relative to that in Chinguetti metal (4·97 %, according to Lacroix). However, a redetermination of the nickel content of Chinguetti metal gave 8·28 %, and a study of the data in table II shows no correlation between nickel content of the metal and the FeO/MgO ratio in the silicates given by the pyroxene composition. In fact, the relative uniformity of nickel content in the metal of the mesosiderites may have important genetic significance. Wasson (unpublished) has shown that for six of the mesosiderites (Chinguetti, Crab Orchard, Dalgaranga, Estherville, Patwar, and Vaca Muerta) this relative uniformity of nickel content also extends to the trace elements Ga, Ge, and Ir. If this should prove to be true for all mesosiderites, it strongly suggests a single source for this metal phase. It may be significant that the Ni, Ga, Ge, and Ir contents of mesosiderite metal fall within the range given for nickel-iron from the H-group (olivine-bronzite) chondrites (Chen-Lin Chou, 1972).

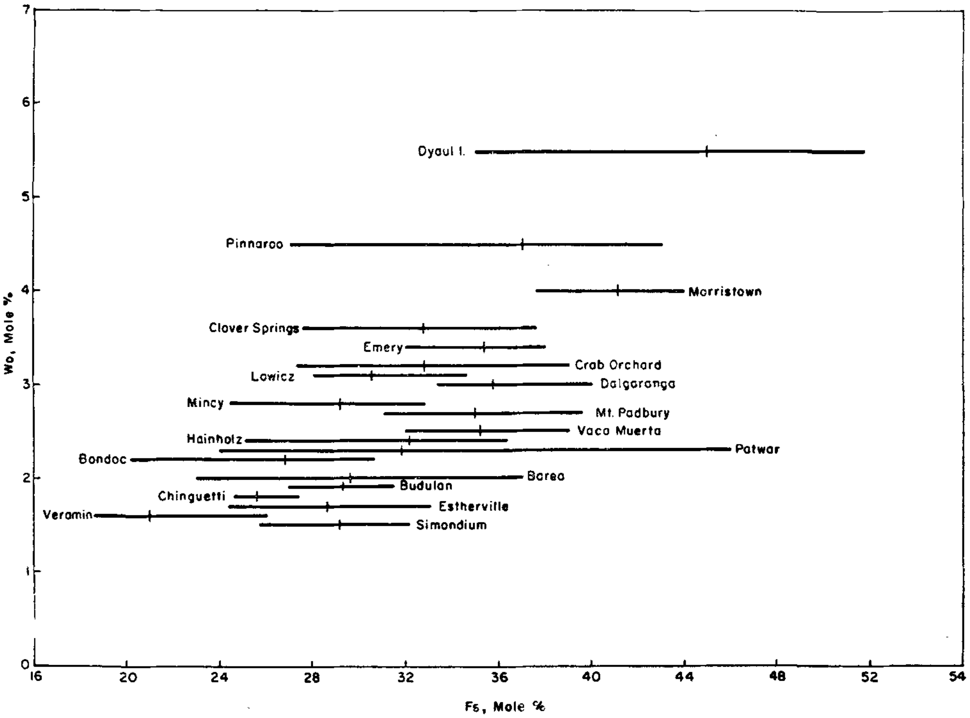

Fig. 1. Range and mean of pyroxene compositions in the mesosiderites.

Ahrens has written extensively on inter-element relationships in meteorites, and has recently discussed the Ca/Al ratio in mesosiderites (McCarthy and Ahrens, 1971). Using our data for Patwar, and the data of Powell (1971) for Vaca Muerta, Patwar, Morristown, Crab Orchard, Hainholz, Estherville, Lowicz, Veramin, and Bondoc, McCarthy and Ahrens arrive at an average Ca/Al ratio of 0·88, with relatively little variation (see table II), except for Bondoc. They comment that the sample of Bondoc analysed by Powell was weathered, so the result is suspect; however, other meteorites analysed by Powell were weathered, so this explanation seems contrived. Weathering is unlikely to affect the Ca/Al ratio unless the feldspar is decomposed, which is contrary to our experience in these meteorites; the silicates remain unaltered even when the metal has been totally oxidized. Possibly unrepresentative sampling is the explanation for the aberrant Ca/Al ratio in Bondoc, or analytical error. Analytical error seems indicated, since it is impossible to reduce the Ca/Al ratio in any mesosiderite below about 0·75 (the mineral containing most of the Ca and Al, plagioclase of composition around An_{90}, has a Ca/Al ratio of 0·70, and is always accompanied by considerable amounts of pyroxene in which this ratio is 2 or greater).

The data in table II shows that the Ca/Al ratio, while it averages close to 0·88 as established by McCarthy and Ahrens, does show considerable variation. Sampling difficulties and analytical error probably account for some of this variation, but certainly not all. The Ca/Al ratio is related to the relative amounts of plagioclase and pyroxene in the meteorite, and the average calcium content of the pyroxene. Since the plagioclase contains much higher concentrations of calcium and aluminium than pyroxene, a small amount of plagioclase has a much greater effect on the Ca/Al ratio than a larger amount of pyroxene, hence sampling difficulties can have a significant influence on this ratio. However, sampling difficulties are probably not the problem for the seemingly most aberrant meteorite, Dyarrl Island. The pyroxene in this meteorite is notably richer in calcium than any other mesosiderite (table II and fig. 1), but this pyroxene has about the same aluminium content as that in other mesosiderites. As a result the Ca/Al ratio in Dyarrl Island pyroxene is 5·5, compared to about 2 in the more typical mesosiderites, Barea and Emery. This high Ca/Al ratio in the pyroxene, coupled with a somewhat higher pyroxene–plagioclase ratio in Dyarrl Island than in most mesosiderites, is responsible for the relatively high Ca/Al ratio in the bulk analysis.

McCarthy and Ahrens use the average Ca/Al ratio in the mesosiderites to argue against the theory, proposed by Prior (1918) and reiterated by later investigators, that the mesosiderites are mixtures of nickel-iron with material of howardite or eucrite composition. They point out that the Ca/Al ratio for all varieties of common stony meteorites (chondrites, howardites, and eucrites) is uniform or nearly so, averaging 1·09.

McCarthy and Ahrens make a good case that the Ca/Al ratio for the mesosiderites is consistently lower than that for other stony meteorites, and their conclusion, that the mesosiderites cannot be regarded simply as mixtures of metal and howardite, is probably valid. However, the differences between howardite and mesosiderite silicates are not great. The minerals are essentially identical, but their proportions are somewhat different. In general, the plagioclase/pyroxene ratio is somewhat greater in the mesosiderites than in the howardites, this being reflected in their somewhat lower Ca/Al ratios. The mesosiderite silicate compositions show a broader range than the howardites; for example, the FeO/(FeO+MgO) molecular per cent ranges from 22 (Veramin) to 43 (Dyarrl Island), and in the howardites from 32 (Frankfort) to 47 (Brient). Some meteorites in the two groups match up fairly closely; compare, for example, the silicate composition of Dyarrl Island with that of the howardite Kapoeta (Mason and Wiik, 1966). One interesting feature of the mesosiderites relative to the howardites and eucrites is the considerably higher phosphate content of the mesosiderites; phosphate minerals are common accessories in the mesosiderites, whereas they are practically absent in the eucrites and howardites. Fuchs (1969) has noted that the phosphate minerals in the mesosiderites are closely associated with the metal phase, and has suggested that they originate by reaction of phosphorus in solid solution in the metal with the silicate minerals. Our own examination of Barea, Emery, and Dyarrl Island confirm Fuchs's observations.

It thus appears that while the howardites and the mesosiderites may not have a common source, the silicate material in the mesosiderites has had a parallel evolution to that in the howardites.

Dalgaranga and Mt. Padbury—a paired fall?

The mesosiderites appear to show a random geographical distribution, being known from all the continents except Antarctica. It is therefore intriguing when a pair that are relatively close together geographically shows a marked compositional similarity. Dalgaranga and Mt. Padbury are contiguous in table II, the average and range of pyroxene compositions for these two meteorites being very similar. These meteorites were found 140 miles apart in Western Australia. Dalgaranga is associated with a crater, but only small and sparse fragments have been recovered. Mt. Padbury was a large mass, over 600 pounds. Because of the fragmentary nature of Dalgaranga it is not possible to compare the textural features of the two meteorites. However, Mt. Padbury contains slugs of metal up to 2 cm across, and comparable slugs have been found at Dalgaranga (Nininger and Huss, 1960). Further investigation such as trace element determinations on the metal, and (if possible) dating of the two meteorites, is called for in order to prove their identity or non-identity. If their identity can be proved, search for additional specimens along the Dalgaranga–Mt. Padbury line is indicated. However, Wasson and his co-workers conclude from their data on minor and trace elements in mesosiderite metal (Meteoritical Society Meeting, 1972) that Mt. Padbury and Dalgaranga are not a paired fall.

Steinbach a mesosiderite?

Steinbach is a meteorite consisting of nickel-iron and pyroxene, with minor amounts of tridymite. It has been classified as a siderophyre, a unique member of the stony-irons. However, all that distinguishes it mineralogically from the mesosiderites is the absence of plagioclase, and structurally it is similar to these meteorites. The pyroxene is more magnesian than that in any of the mesosiderites; our microprobe analysis gave an average composition of $Fs_{16}Wo_{0\cdot4}En_{84}$, with very little variation from grain to grain. Since the amount of pyroxene relative to plagioclase in the mesosiderites increases in the more magnesium-rich meteorites (e.g. Chinguetti, Veramin, Estherville) it is conceivable that eventually a plagioclase-free type could occur. Steinbach may be such a type.

A possible common origin for the mesosiderites

Several compositional features seem to argue for a possible common origin for the mesosiderites. Specifically these are: the sequential range in composition of the pyroxenes; the almost constant Ca/Al ratio (reflecting uniform plagioclase composition, and no great variation in the plagioclase/pyroxene ratio); and the relative uniformity of metal composition, both in Ni content and in the trace elements.

Omitting for the present the accessory olivine present in many mesosiderites, we can consider the silicate material in terms of the system anorthite–tridymite–pyroxene (hypersthene and pigeonite), in which the principal variable is the FeO/(FeO+MgO) mole percentage in the pyroxene; this ranges from 18 to 52, or if we include Steinbach with the mesosiderites, from 16 to 52. The pyroxene/plagioclase ratio is fairly uniform within the mesosiderites at around 2/1; however, Steinbach contains no plagioclase, and in the mesosiderites with lowest FeO/(FeO+MgO) mole percentages, Veramin and Chinguetti, pyroxene is much more abundant than plagioclase. These facts suggest a common magmatic source for mesosiderite silicates—a slightly oversaturated magma, which began crystallizing magnesium-rich pyroxene and tridymite (as in Steinbach). Crystallization of the magnesium-rich pyroxene increased the concentration of Ca and Al in the magma, resulting in the eventual crystallization of anorthite; at the same time the FeO concentration in the magma increased, and the crystallizing pyroxene became successively richer in iron. With the incoming of plagioclase there ensued essentially cotectic crystallization of plagioclase, pyroxene, and tridymite in approximately constant proportions, with the pyroxene becoming progressively richer in iron as crystallization proceeded.

We must now consider the accessory olivine. Prior (1918) showed that the olivine in the mesosiderites he analysed (Vaca Muerta, Hainholz, Simondium) was magnesium-rich, in the range Fa_{9-13}. This is the common composition of pallasitic olivine, and was the basis for Prior's thesis that the mesosiderites are mixtures of howarditic and pallasitic material. However, olivine of this composition could also have crystallized at an earlier stage from a magma that produced the silicates of Steinbach and the mesosiderites, since magnesium-rich olivine can crystallize from a magma slightly oversaturated with silica. Alternatively, the crystallization and removal of olivine from a saturated or undersaturated magma will increase the SiO_2 concentration of the magma and lead to the eventual crystallization of tridymite or some other SiO_2 polymorph. The situation is, however, somewhat more complicated than was indicated by Prior's work. Different olivine grains in the Patwar mesosiderite show a wide range in composition, from Fa_9 to Fa_{30} (Jarosewich and Mason (1969)), and this has been confirmed by Powell (1971); in the mesosiderites he examined the olivine ranged from Fa_{14} to Fa_{48}. Thus the mesosiderite olivine is not uniformly magnesian, as indicated by Prior, but shows essentially the same range of Fe/Mg ratios as the pyroxenes. A possible explanation is variation in magma composition during fractional crystallization, whereby local undersaturation leading to the occasional crystallization of olivine was produced.

The relative uniformity of metal composition in the mesosiderites suggests a single source. Two possibilities may be envisaged: the mesosiderites represent the product of the collision of two asteroids, one providing the metallic material and the other the silicate material; or the mesosiderites are the debris from the breakup of a single asteroid, which contained both silicate and metallic material. A piece of evidence in favour of the latter hypothesis is that the mesosiderites, while brecciated, are not extremely shocked, as would be expected from the impact hypothesis; they contain no glass, and the plagioclase is not altered to maskelynite. The relatively high metal content of the magnesium-rich mesosiderites Chinguetti and Budulan, and the low metal content of Dyarrl Island at the other extreme, suggests that the postulated asteroid may have had an incipient gravitational segregation, with metal accumulating with the early formed silicates.

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