The Bencubbin meteorite: Further details, including microscopic character of host material and two chondrite enclaves

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Summary. The Bencubbin meteorite and some of its enclaves have been studied in thin section under transmitted light: supporting X-ray diffraction and chemical data have been supplied by the Smithsonian Institution, Washington. These results show the host material to consist of clinoenstatite and a little olivine (both nearly pure magnesian varieties) set in an opaque (cryptocrystalline ?) base, which is, in turn, enclosed in a mesh-work of nickel-iron, of composition equivalent to a hexahedrite. Two enclaves are revealed as: an atypical olivine-hypersthene chondrite (in the mode, the olivine is Fa_{19}, and pigeonite takes the place of orthopyroxene, but the chemical analysis is typical except for a small but appreciable carbon content); and an enstatite chondrite displaying crudely formed chondrules (chemically typical, with a small but appreciable carbon content).

The chondrite enclaves are not recrystallized: though Lovering has referred to the first as 'thermally metamorphosed', and both are dark coloured, there seems to be little evidence of the effect of the metallic host, which must surely have been molten, on the chondrite enclaves, which seem to have been able to survive in this environment without mineralogical or textural modification.

Lovering has stressed the importance of this meteorite in its bearing on meteorite provenance and genesis, and the further implications of this present study are discussed briefly.

The Bencubbin meteorite was first described by Simpson and Murray (1932): a general description was provided and a fairly complete chemical analysis. The meteorite was included with the mesosiderites with some reservation. It was noted that thin sectioning was not found possible. Lovering (1962) realized that the meteorite did not rightly belong to the mesosiderite class of stony-irons, but he did not assign it to any other class or erect a new class. He described, briefly, three types of chondrite inclusions, and remarked on the importance of this association of chondrite inclusions with a metal/achondrite host, in respect to theories of meteorite provenance and genesis. He considered the association to weigh heavily against Urey's

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theory of primary and secondary bodies (Urey, 1956, 1958, 1959). Mason (written communication to the writer) has tended to favour regarding this meteorite as an iron with silicate inclusions, but, lately (Mason, 1967), though applying this classification to Woodbine (a meteorite consisting of an octahedrite reticulation enclosing silicate enclaves of chondrite composition but not, it appears, texture), has expressed doubts about the suitability of this classification being applicable to Bencubbin. McCall (Supplement to the Catalogue of Western Australian Meteorite Collections, prepared for publication 1966) proposed a new class of meteorites to cover Bencubbin: the meteorite should certainly be regarded as a stony-iron, for it contains about equal quantities of silicate and metal fractions; and though he was satisfied, in an earlier description of the find of a second and larger mass in 1959 from $\frac{3}{4}$ mile away from the original site, to follow Lovering by using the term 'stony-iron of mixed type' (McCall and de Laeter, 1965), he has lately come to regard the classification 'enstatite-olivine stony-iron with enstatite and hypersthene chondrite enclaves' more acceptable.

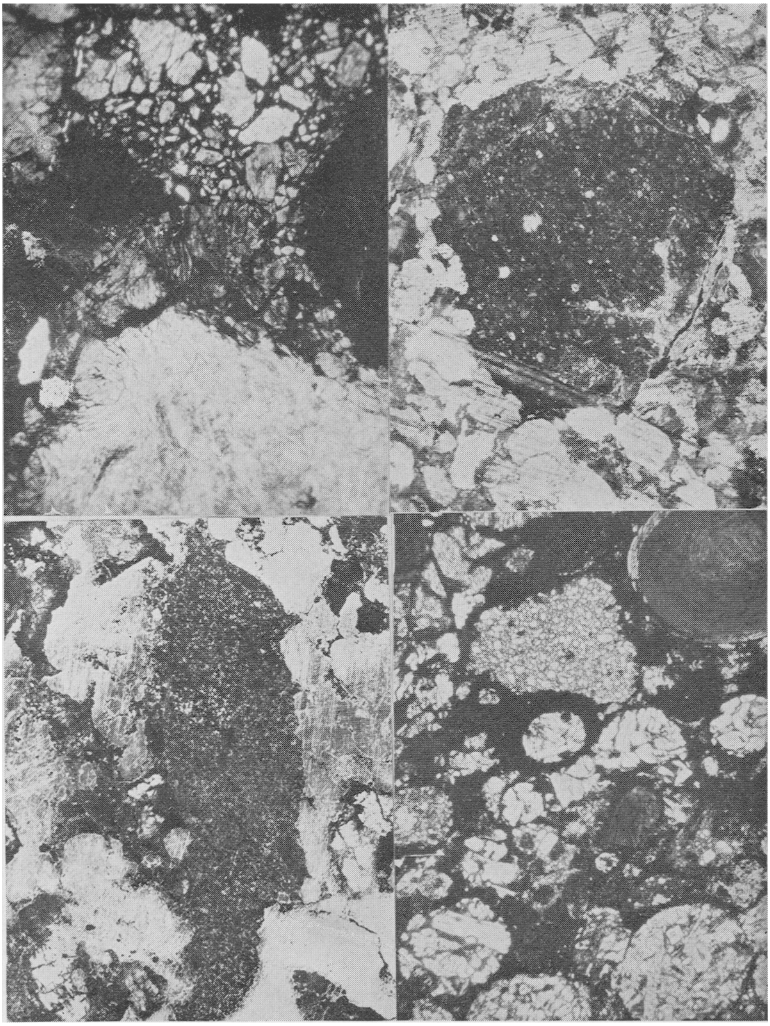
The classification, based on the results given below, has a precedent, for there are already two classes of stony-irons represented by unique meteorites. While Hey (1966) prefers to adopt a broad rather than strict definition for the mesosiderites, the writer finds this illogical, preferring the strict definition: though the basis for classification of stony-irons seems to involve modal mineralogy, texture, and possibly even analytical criteria, it does seem that if Lodran and Steinbach are to be distinguished by separate classes, so too should Bencubbin, following exactly the same reasoning.

Both the main masses of Bencubbin are held in the collections of the Western Australian Museum, and the writer, in 1966, decided to attempt a more detailed study with emphasis on thin sectioning, and the chemistry and modal mineralogy of the enclaves. Certain data had also accumulated in the Museum records in relation to the host material and this could, conveniently, be included in the results of this further study.

The technical difficulties in cutting this meteorite are considerable: neither a diamond saw nor a longitudinal abrasive saw could make the slightest impression, and a high-speed, rotary wheel, at the Railway Workshops, Midland, Western Australia, generated too much heat, blackening the cut surfaces, to be considered satisfactory. Again, the preparation of polished and thin sections is very difficult; in the case of the latter, chunks of metal become detached and soon gouge the thin section to pieces before it is complete. Extraction of samples of the chondrules presented another problem, surmounted by the construction by Mr. W. Smeed (Geological Technician at the University of Western Australia) of a 'mini-drill', which successfully extracted shallow cores about half a centimetre in diameter.

The host material. Lovering has described this material (1962), and all that is given here is a brief note on its appearance in thin section and the chemistry of the mineral components. The reticulation of metal consists of nickel-iron devoid of any distinct etch-pattern (though a fine mottling is produced with application of nital reagent). Simpson and Murray (1932) give values that are equivalent to an iron:nickel ratio of 15, or a content of *c.* 6·25 % Ni. The value is entirely consistent with the determination by Mason of the enstatite as Fs_0 and the olivine as Fs_{0-7} by diffractometer methods (McCall, in the press, op. cit.), according to Prior's Rules. The metal appears to be entirely kamacite. Troilite is not, in the main, aggregated with the metal, but rather tends to finely lace the silicate reticulations. The metal reticulation in the second mass shows a markedly directed fabric (McCall and de Laeter, 1965, p. 107, plate XVa), which suggests directed pressure, but no such texture was noted in the original mass.

The silicate reticulations are composed of patches of cream-coloured clinoenstatite forming islands within a dark, opaque, non-reflectant base, which is either a devitrified glass or a fine crush matrix: in view of the lack of evidence of clasis in the other components the former interpretation is preferred. The pyroxene is seen in thin section (fig. 1) to be fibrous, and to have shed narrow, discrete fibres from its margins. The texture of the core of these patches is one of compound fans, not unlike the texture of certain large orthopyroxene chondrules in chondrites (McCall, 1966, p. 58, fig. 9), but there is no trace of chondrule outlines and Lovering (1962) has, reasonably, referred to this material as achondritic. The fibres display straight to nearly straight extinction. The surround of dark, non-metallic material includes many shed fibres of clinoenstatite and a few small grains of olivine have been tentatively identified with these. The dark base shows a certain amount of oxide staining. No plagioclase has been identified modally; Simpson and Murray (1932) were also unable to detect it. Difficulties inherent in attempting a wide sampling of the masses prevent one from being sure that there is, in fact, no plagioclase at all present, but the plagioclase component revealed on analysis may well be entirely held within the cryptic base.

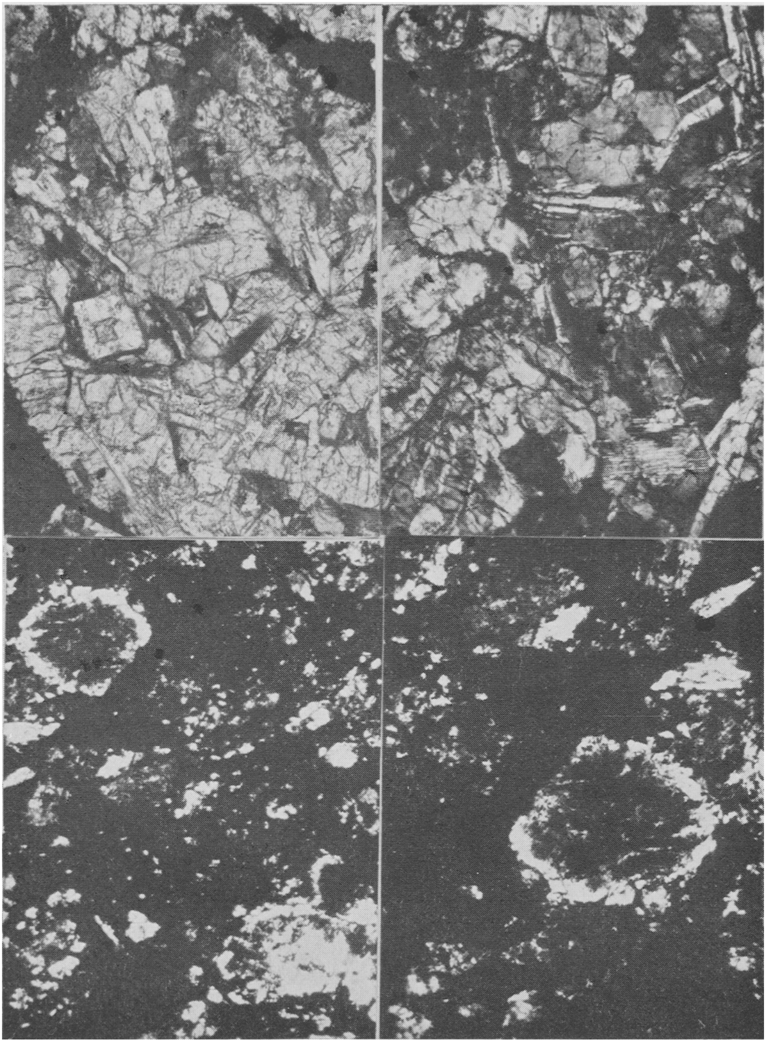


Figs. 1–4: Fig. 1 (top left). Microtexture of the host material: clinoenstatite (white, right); base of opaque, non-metallic material enclosing small grains of clinoenstatite and olivine; metallic reticulation (black). (×10, plane-polarized light.) Fig. 2 (top right). Enclave No. 1 (CHy), Bencubbin No. 1 mass. The fine spheroidal texture and the dark base enclosing the spheroids is apparent. The enclave is 3 cm across. Fig. 3 (bottom left). Enclave No. 2 (CEn), Bencubbin No. 2 mass. Lenticular, it is about 3 cm long, and is composed of a base of fine dark material inset with reflectant specks of metal. The host reticulation encloses a 'pool' of dark non-reflectant base material which in turn encloses clinoenstatite (white). Fig. 4 (bottom right). Enclave No. 1 (CHy): spheroidal texture: note the opaque base. (×25, plane-polarized light.)

In addition to the enstatite and olivine determinations by Mason (given above), Ringwood has told the writer (verbal communication) that there is free silica in the host material, a feature entirely consistent with the chemical nature of the silicates.

Two chondrite enclaves were studied in detail: A rounded area of chondritic material (fig. 2), type 1 of Lovering, 1962, and contained in the original mass, and a lenticular mass enclosed in the directed host reticulation of the second mass (1959 discovery); this (fig. 3) seems to resemble the type 3 of Lovering, 1962; this enclave is elongated parallel to the directed fabric.

Enclave No. 1. Round in shape and 3 cm in diameter, this is figured by Lovering (1962) and McCall and de Laeter (1965, pp. 108–109, plate XVIa). The enlarged photograph of the cut surface (fig. 2) clearly reveals a fine pattern of spherical chondrules set in a dark, fine base, which appears dark, purplish grey to black, to the naked eye. In thin section the appearance of the enclave material is not in any way dissimilar from that of many spherical chondrites: the chondrules are seen to include perfectly spherical types and do not show very marked brecciation: they are mostly of the textural type known as polysomatic, porphyritic, and are set in an opaque, cryptocrystalline base, which is almost identical with the base material of the achondritic (clinoenstatite) fraction already described. It is taken to be a devitrified glass rather than a crush material in view of the number of undeformed, perfect chondrules set in it (fig. 4). There are some irregular patches of minute silicate grains, olivine and lamellar twinned pigeonite in equal amounts and set in a sparse glass base (fig. 4); these could be regarded as very irregular chondrules. The spherical chondrules are, in fact, composed of the same minerals, subhedral to anhedral grains of olivine and lamellar-twinned pigeonite showing low birefringence, and resembling plagioclase except for its higher relief (figs. 5 and 6). The material differs from normal olivine-hypersthene chondrite material in that orthopyroxene is either absent altogether, or very sparingly represented; the writer has not been able to positively identify any; also the pigeonite is present as quite substantial grains, while pigeonite in such chondrites, though not uncommon as a pyroxene component subordinate to orthopyroxene in not-recrystallized chondrites, is commonly found only in the form of minute grains. There are some fibrous, radiating textures in the chondrules that could be orthopyroxene, but they are quite indeterminable without recourse to grain separations, not practicable because of the very meagre amount of material available for



FIGS. 5–8: FIG. 5 (top left). Enclave No. 1 (CHy): enlargement of a spherical chondrule: olivine (grey), pigeonite (white), glass (dark, turbid). (×100, plane-polarized light.) FIG. 6 (top right). Enclave No. 1 (CHy): another enlargement of the interior of a chondrule: olivine (grey, untwinned): pigeonite (laths, lamellar twinned). (×100.) FIG. 7 (bottom left). Enclave No. 2 (CEn): showing 'primitive' chondrules, with ill-formed cores: clinoenstatite (white): black non-silicate base and metal, opaque. (×63, plane-polarized light.) FIG. 8 (bottom right). Enclave No. 2 (CEn): the same under higher magnification. (×100, plane-polarized light.)

study. The polysomatic, porphyritic chondrules contain a little interstitial glass, light in colour but slightly turbid.

No plagioclase has been detected optically. There is no evidence whatever of recrystallization: as to the question of thermal metamorphism suggested by Lovering (1962), the writer does not feel qualified to judge whether it is a reality; all he can say is that this material does not look unlike that which makes up the entire mass of numerous spherical chondrites, entirely devoid of recrystallization.

Chemical analyses. A 2·5 g sample of this material was analysed by the Division of Meteoritics at the Smithsonian Institution as part of an exchange agreement, with the results included in table I. The MgO/FeO ratio is 2·0, which is within the range 2·0–4·0 specified for the olivine-hypersthene chondrites in Prior's classification. X-ray diffractometer determination by Dr. D. R. C. Kempe of the British Museum (Natural History) gave for the olivine, by the method of Yoder and Sahama (1957), Fa_{19}, and by the method of Jackson (1960), $Fa_{14·2}$. The former value is preferred as the peak is very sharp, while in the case of the latter it is somewhat diffuse: this is the olivine of an olivine-bronzite chondrite (Mason, 1962), not of an olivine hypersthene chondrite—another anomaly. The nickel/iron ratio is 22·5 % Ni, rather high, while the total nickel-iron is rather low. The total iron in the silicates is 13·9 and in the metal+sulphide 8·0; this places the material within the L group of Urey and Craig, amid the olivine-hypersthene chondrites (Mason, 1962, table, p. 77). The Mg/Si ratio is 0·8.

The enclave has the chemistry of the CHy group of common chondrites but anomalous mineralogy, both in the olivine variety and the presence of pigeonite; this was confirmed in substantial quantity in the diffractometer results, which recorded an iron-bearing clinopyroxene of the clinoenstatite–pigeonite isomorphous series.

Enclave No. 2. It is interesting to note that the polished surface (fig. 3) suggests that this chondritic material represents a patch originally included in the achondritic mass before crystallization of the metallic network. It appears as fine, black material, heavily speckled with nickel-iron and sulphide. In thin section (figs. 6 and 7), the picture is very simple: minute, anhedral to subhedral grains of lamellar-twinned clinoenstatite are inset in an opaque, iron-stained, cryptocrystalline, non-metallic base, which appears to contain a little finely divided carbon. A number of very 'primitive' chondrules are present: these consist of rims of clinoenstatite granules, sharply bounded on the outside but with hazliy defined boundaries against an opaque core of material identical

Table I. Analyses of two enclaves from the Bencubbin meteorite. E. Jaresowich anal. Cols. 1, 2, 3, acid-soluble, acid-insoluble, and bulk analysis respectively of No. 1 enclave, from Bencubbin I (olivine-hypersthene chondrite enclave); 4, average olivine-hypersthene chondrite, from Wood, 1963, p. 248; 5, 6, 7, acid-soluble, acid-insoluble, and bulk analysis respectively of No. 2 enclave, from Bencubbin II (enstatite chondrite enclave); 8, average enstatite chondrite, from Wood, *ibid.*

	1	2	3	4	5	6	7	8
	61·70 %	38·30 %			47·19 %	52·81 %		
Fe	—	—	4·03	7·13	—	—	22·12	19·82
Ni	—	—	1·28	1·07	—	—	2·22	1·66
Co	—	—	0·07	0·07	—	—	0·08	0·12
FeS	—	—	6·12	6·06	—	—	12·61	10·70
SiO_2	29·77	52·58	38·59	39·70	10·07	60·49	36·70	38·62
TiO_2	0·08	0·23	0·14	0·11	0·19	0·11	0·15	0·06
Al_2O_3	1·71	2·99	2·21	2·81	0·1	2·37	1·47	1·87
Cr_2O_3	—	—	0·44	0·41	—	—	0·40	0·35
FeO	—	—	17·88	14·33	—	—	1·34	1·69
MnO	—	—	0·30	0·26	—	—	0·26	0·14
MgO	25·33	22·64	24·30	24·58	5·54	31·84	19·43	21·01
CaO	0·98	3·13	1·81	1·92	2·03	0·44	1·19	0·97
Na_2O	—	—	0·60	0·94	—	—	0·61	1·00
K_2O	—	—	0·07	0·11	—	—	0·08	0·11
P_2O_5	—	—	0·28	0·22	—	—	0·38	0·20
$H_2O(+)$	—	—	1·25	0·24	—	—	0·72	0·62
$H_2O(-)$	—	—	0·25		—	—	0·11	
C	—	—	0·20	—	—	—	0·54	0·29
Total			99·82				100·41	
Total Fe	31·82	5·71	21·82		64·52	1·36	31·17	

with the opaque base, inset with only minute ragged microlites. The structure of the chondrules resembles the hollow growth of crystals seen in extremely rapidly cooled basaltic dyke rocks and lavas (it is perhaps significant that such rocks may show spherical glomerocrysts of pyroxene very like chondrules: Dunbar and McCall, unpublished results, The Mount Belches Area, Western Australia).

A 2-g specimen was analysed at the Division of Meteoritics, Smithsonian Institution, Washington, with the results included in table I.

The MgO/FeO ratio is 26, the Ni/Fe ratio in metal, 9·2 % Ni; total Fe in silicates 1·05 %, total Fe in metal+sulphide 30·1 %. This puts the enclave within the HH group (or H group) on the diagram of Urey and Craig as amended by Mason (1962, p. 77); it is very interesting to note that the values correspond with the position of the enstatite chondrites on the diagram representing falls only (i.e. fresh material) given by Mason (1962, p. 78). The Mg/Si ratio is 0·69. The clinoenstatite has been shown by diffractometer study by Mason to be an almost pure magnesian variety: Fe_{0-5}. These results indicate that this is in every way a typical enstatite chondrite fragment.

Discussion. The writer has discussed the implications of achondrite enclaves in a mesosiderite (Mt. Padbury) elsewhere (McCall, 1966*b*), with respect to theories of meteorite genesis. This and other fragmental associations in stony irons have also been discussed in another paper (McCall, 1966*c*), primarily concerned with discounting lunar provenance, still entertained by some authors for true meteorites. In that text, enclave No. 1 discussed here was erroneously referred to as of enstatite chondrite composition (it was not realized at the time of writing that more than one chondrite type was represented among these enclaves).

Lovering (1962) has discussed the significance of these chondrite inclusions, but without the additional evidence that enstatite chondrite and hypersthene chondrite material are represented, and with no knowledge of the details of the chemistry of the enclaves. The present study endorses Lovering's rejection of Urey's concept of primary and secondary objects (Urey, 1959), based mainly on evidence incompatible with this theory found in Cumberland Falls and Bencubbin.

In considering the implications of the evidence now available from Bencubbin, it seems apposite to start with the fact that the meteoritic irons can be accommodated in a model involving a single parent melt with about 11 % nickel content: all the irons could come from such a melt by the combination of fractionation and varying cooling histories (Mason, 1962, p. 143). Now we find virtually all known types of stony meteorite as inclusions in such alloys in stony iron-meteorites: howardite (McCall, 1965), eucrite, diogenite, olivine achondrite (McCall, 1966*b*), and enstatite achondrite, enstatite chondrite, and olivine-hypersthene chondrite (this paper). There can be little argument that all these inclusions represent material that solidified before the metallic host.

The evidence from Mt. Padbury gives us a picture of a patchy, heterogeneous mass representing an early crystallized fraction, predominantly composed of silicates, and entirely composed of achondritic material. The patches are not in equilibrium one with another: for example two anchondrite enclave types show excess silica in the form of tridymite and the other shows olivine. One achondrite enclave type, the eucrite, is demonstrably a product of crystallization from the melt, for it displays an ophitic texture: a second type, the diogenite, displays the same tridymite as a residual interstitial phase as does the eucrite, and may be inferred to represent crystallization from a melt.

Now the enclave material of Bencubbin represents an even earlier phase of crystallization, for it is enclosed in an achondrite host, which is in turn enclosed in a metal reticulation. In the case of Mt. Padbury, there seem to be represented successive crystallizations of silicate, metal, and sulphide phases, and one may reasonably regard these as immiscible phases, following the concept of Goldschmidt (McCall, 1966*b*). In the case of Bencubbin there is an early phase of chondritic crystallization preceding the achondrite phase.

Now, Lovering recorded thermal metamorphism of the chondrite enclaves (Lovering, 1962). Darkening was the main criteria for this metamorphism. This dark coloration is certainly evident in all the chondrite enclaves, but such a coloration may well accompany a very small carbon content such as is revealed in both analyses. Whether this metamorphism is real or not (and Lovering is far better qualified to judge than the writer, though he may not have seen thin sections), it is a feeble process: there is no trace of modification of the mineral components of the chondrite enclaves, nor of the texture; there is no recrystallization; indeed the first enclave is in every way a typical spherical chondrite such as is found in the form of discrete meteorites, possessed of a cryptic, opaque base, no modal plagioclase, and showing a little clear glass in the interstices of the chondrules, which show no trace of loss of outline by recrystallization; the enstatite chondrite shows a similar cryptic base, and very primitive, partly formed chondrules. When one comes to consider how such material could get included in a stony-iron host, which must represent the deep interior of the immediate parent body, one is impressed by three facts: The material seems entirely at home in its new environment, and modification in mineralogy and fabric is minimal; glass is still preserved and primitive chondrules; and the enclaves themselves obey the requirements of Prior's Rules as is shown by the analyses. Now Prior's Rules involve nickel-iron ratios that have been thought to reflect differentiation of a single 11 % parental melt, since the whole character of these meteoritic alloys is consistent with such a single, continuous molten parent in the first place. The rules also involve the chemical ratios of the silicate minerals and the total amount of metal alloy in stony meteorites. It seems absolutely critical that the achondrite and metal of the stony-iron conforms to these rules[1] in that the Mg/Fe ratio in the silicates and Ni/Fe ratio in the metal are just what are expected in an enstatite chondrite or achondrite: and also the chondritic enclaves conform to the same rules, including the nickel-iron ratio, which must surely, again, be determined by differentiation of the same parental melt as applies to the irons. As the chemistry of the chondrules and non-metallic cryptic base is systematically related to the metal chemistry, one cannot escape the conclusion that this too must be controlled by the same process as the determination of the metal ratio. It seems that the conformity to Prior's Rules of all the 'elements' in the Bencubbin meteorite can only be explained if the differentiation that controls these distributions took place before even the chondritic material of the enclaves was solidified, and if the chondritic material stems from a process of solidification under extraordinary conditions in the same parent body as the stony-iron material solidified. It seems quite impossible to envisage any process by which chondritic enclaves of such varied chemistry, showing so little modification and preserving glass and primitive character, could be brought into a molten host in the deep levels of the interior of a parent body; it seems even more difficult to see how such introduced material could be covered by a single set of rules such as Prior's Rules. If they were derived from an earlier body, disrupted before incorporation in the body represented by the stony-iron host material, surely they should not be covered by such a simple control of chemical distribution: more than one distributional pattern should be recognizable in enclaves and stony-iron host. This evidence virtually relegates theories such as those of Urey (1959) and Levin (1958) to the status of purely historical

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[1] Which mainly concern chondrites but have an obvious application to the genesis of all meteorites.

significance, and also discounts all other theories of prior origin of the chondrules.

The evidence is entirely compatible with the theory of Ringwood (1961), attributing chondritic material to 'volcanism' of a 'grand scale', in which degassing occurred on a very large scale, and which affected the greater part of the parent body. The evidence favours a single parent body, and, if anything, Ringwood's planetary model rather than Fish, Goles, and Anders's (1960) asteroidal model. The recognition of a time sequence from chondrite to achondrite crystallization, and the discovery of two of the major types of chondrites at a depth presumed to be equivalent to the Core:Mantle boundary, seems to favour an extensive 'volcanism' on a grand scale, followed by achondritic crystallization, a process in which chondritic material could be formed right down to such a deep level. The writer believes that Fish *et al.* are correct in referring achondrite material to such a deep level (McCall, 1966*b*), but he follows Ringwood in doubting if the chondritic material represents any concentric shell in the parent planet or asteroid. He himself regards restrictions on the size of the parent body due to the amount of asteroidal material now in orbit as possibly misleading (much of this material would surely have gone into the sun by now), and tends to favour a planetary rather than an asteroidal parent, while having no direct evidence as to size of the parent body stemming from this study. What the study does support is the single parent body favoured by both these authorities.

The study reveals that CEn, CBr, and CHy chondrites do not represent separate parent bodies: theories involving several coexistent parent bodies, such as that of Yavnel (1958) and Mason (1962, p. 199) must, surely, likewise be regarded now as of purely historic significance. The carbonaceous chondrites, though not covered by this restriction, are (at least in the case of type II) related to the enstatite chondrites, and it may be very far fetched to suggest, now, that they too come from anywhere but the same, single parent body. We can also restrict the H and L differentiation involving Low and High Iron Groups of Chondrites (Mason, 1962, p. 77) to an astronomical scale 'within the limits of a single parent body'. We have L and H (or HH) chondrites represented in the one meteorite, and, for reasons given above, the differentiation that controls this division into groups can surely not be attributed to processes outside the immediate parent: for the differentiation is related to the type of chondrite, and the type of chondrite is related to the differentiation covered by Prior's Rules.

Whether or not strong counter-arguments and other interpretations to the writer's are offered for these relationships, any future theory of meteorite genesis must take this evidence into account: there is far too much theorizing published that does not take into account the fundamental evidence of such physical associations in single meteorites. There is much to learn about the genesis of meteorites, but the writer believes that we have in this meteorite, and in the evidence from other such associations, a new point of departure, excluding a number of well-favoured models and genetic sequences, and bringing Ringwood's model to a status of inevitably broad acceptance. The evidence seems to favour Ringwood's (1966) auto-reduction *in situ* (though it has no direct bearing on the validity of the argument for the parental, primitive status of Cc type I meteorites): it is impossible to reconcile the application of Prior's rules to enclaves and host with any theory involving a single, continuous mass of melt of 11 % nickel content within the parent body and parental to all meteoritic iron. The nickel-iron ratios must surely have been produced by auto-reduction *in situ*, not fractionation of a single melt.

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