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On the mesosiderite-grahamite group of Meteorites: with analyses of Vaca Muerta, Hainholz, Simondium, and Powder Mill Creek.[1]

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IN the Rose-Tschermak-Brezina classification of meteorites the intermediate class of stony-irons, in which iron and stony matter occur in approximately equal amounts and to which Maskelyne gave the name siderolites, is divided into (1) siderolites proper, including the groups of the pallasites and the siderophyres, and (2) lithosiderites, comprising the groups of the mesosiderites, grahamites, and lodranites. Mesosiderites are defined as consisting of iron and crystalline olivine and bronzite, and grahamites of the same constituents with the addition of plagioclase-felspar. As seen in the following pages, chemical and microscopic

[1] Communicated by permission of the Trustees of the British Museum.

examination of typical members of these two groups fails to reveal any real distinction between them based on the amount of felspar they contain. For the combined group, all the members of which contain abundant felspar, it is proposed to retain the earlier name of mesosiderite, which was first given to them by Rose.[1]

As pointed out in a previous paper,[2] from the author's point of view of a genetic relationship of meteorites, this group of mesosiderites is somewhat anomalous. The results of most of the published analyses showed that, although the nickeliferous iron and olivine had chemical compositions similar to those they have in the pallasites and thus served to place these meteorites in group A 2, the anorthite-felspar and the pyroxene, fairly rich in ferrous oxide, gave them a close relationship also to the eucrites and howardites of group A 5. Further analyses therefore of members of the group appeared to be desirable. The meteorites chosen for investigation were Vaca Muerta which has been classed as a grahamite, Hainholz a mesosiderite, and Simondium which presented many points of similarity with Hainholz.

Vaca Muerta (= Sierra de Chaco).

In Domeyko's original description of this meteorite[3] the locality was given as the Sierra de Chaco, but in a later communication[4] this was changed to the 'Quebrada (ravine) of Vaca Muerta, a dozen leagues from the small bay of Guanilla'. The uncertainty as to the precise place of fall has been discussed by L. Fletcher,[5] who gave reasons for supposing that specimens labelled as being from Taltal, Sierra de Chaco, Chili, Janacera (Jarquera) Pass, and Mejillones were all to be referred to Vaca Muerta. That these specimens all belong to one fall is most probably true, but some doubt must still remain as to whether the Vaca Muerta, 15 leagues to the south-east of Taltal, is the real place of fall. In view of this uncertainty, and for similar reasons to those advanced by

[1] G. Rose, Monatsber. Akad. Berlin, 1863, p. 34.

[2] G. T. Prior, On the genetic relationship and classification of meteorites. Mineralogical Magazine, 1916, vol. xviii, p. 35.

[3] I. Domeyko, Anal. Univers. d. Chili (Santiago), 1864, vol. xxv, p. 289.

[4] I. Domeyko, Compt. Rend. Acad. Sci. Paris, 1875, vol. lxxxi, p. 599.

[5] L. Fletcher, On the Meteorites which have been found in the Desert of Atacama and its neighbourhood. Mineralogical Magazine, 1889, vol. viii, p. 234.

Fletcher, Llano del Inca and Doña Inez should certainly be added to the above synonyms; for specimens of these meteorites in the British Museum Collection are under the microscope precisely similar to specimens of Vaca Muerta. These two meteorites were found by the Chilian and Bolivian Boundary Survey in 1888, and specimens which were obtained by the late Professor Henry A. Ward at Santiago in the following year were described by E. E. Howell, M. E. Wadsworth, A. C. Lane, and H. B. Patton.[1] In that paper Llano del Inca is stated to be about 35 leagues to the south-east of Taltal, and according to the maps Cerro de Doña Inez is also about 100 miles to the south-east of Taltal, so that the distance between the two localities cannot be very great. As in the case of many other Chilian meteorites, the specimens may have been transported to the place of find, which does not therefore represent the place of fall; and support to this idea is lent by Howell's remark (loc. cit., p. 95) that 'the breaking up of both meteorites . . . into such small, solid angular fragments with sharp corners . . . is doubtless the work of man'.

The following specimens in the British Museum Collection are referred to Vaca Muerta:

35124. A piece, weighing 493 grams, from 'Sierra de Chaco, Atacama Desert', presented in 1863 by W. Taylour Thomson, to whom it had been given by Domeyko.

46200. A piece, weighing 1850 grams, 'found 40 leagues inland near the low range of the Cordilleras of the Andes', obtained from F. Pini in 1873.

52234. A piece, weighing 551 grams, from 'Chili' (see L. Fletcher, loc. cit., p. 241), obtained from Mr. Cutter of London in 1879.

54721. A piece, weighing 4370 grams, from 'Desert of Atacama' (see L. Fletcher, loc. cit., p. 343), presented by F. A. Eck in 1882.

For the chemical analysis, a fragment weighing about 13 grams was taken from specimen 52234. The material was crushed in an iron mortar and was separated by the magnetic comb into an attracted portion weighing 5·7705 grams and an unattracted portion weighing 6·9030 grams. In order that the unattracted portion might be free from all but traces of metal, more than fifty separations were made with the magnetic comb in the fine powder left after the removal of the coarser pieces of iron. The results of the analyses are as follows:

[1] E. E. Howell, Proc. Rochester Acad. Sci., 1890, vol. i, p. 93.

	Attracted.	Unattracted.	Bulk-analysis.	
Fe	84·00	—	38·25	41·51
Ni	6·38	—	2·90	
Co	0·79	—	0·36	
Fe	0·07	2·38	1·37	2·16
S	0·04	1·37	0·79	
Fe	0·78*	1·62*	1·27	2·32
Ni	0·41*	0·90	0·70	
P	0·21	0·45	0·35	
SiO_2	0·90	45·47	26·02	
Al_2O_3	0·59	9·96	5·87	
Fe_2O_3	—	2·41	1·36	
Cr_2O_3	—	0·80	0·45	
FeO	—	12·48	7·03	
MnO	—	0·43	0·24	
CaO	0·83	7·04	4·35	
MgO	trace	13·07	7·36	
Na_2O	—	0·32	0·18	
H_2O	—	0·96	0·54	
Insoluble	4·11	—	—	
	99·11	99·66	99·39	

The analysis of the attracted shows that the ratio of Fe to Ni in the nickel-iron is about 13.

Separate analyses of the portions soluble and insoluble in hydrochloric acid of the unattracted material gave the following results:

	Soluble in HCl.	Molecular ratios.
SiO_2	12·15	0·202
Al_2O_3	8·76	0·086
FeO	1·42	0·020
MnO	—	
CaO	5·64	0·100
MgO	1·38	0·034
Troilite, Schreibersite, Fe_2O_3, H_2O	10·09†	
	39·44	

* These amounts are taken to correspond to the formula Fe_2NiP for schreibersite, but in the analysis of the unattracted, part of the phosphorus is probably in the form of phosphate, and thus the total amount of schreibersite may be over-estimated.

† From the analysis of the total unattracted portion.

	Insoluble in HCl (direct determinations).	Insoluble in HCl (by difference between total unattracted and soluble).	Molecular ratios.
SiO_2	33·22	33·32	0·555
Al_2O_3	1·15	1·20	0·012
Cr_2O_3	0·80*	0·80	0·005
FeO	11·38†	11·06	0·154
MnO	—	0·43	0·006
CaO	1·53†	1·40	0·025
MgO	11·64	11·69	0·292
Na_2O	0·32	0·32	0·005
	60·04	60·22	

These analyses show that the soluble portion consists mainly of anorthite with some troilite and only a little olivine; and the insoluble of a pyroxene (containing very little lime and having approximately the composition $2\,MgSiO_3.FeSiO_3$) and a little felspar which escaped decomposition by the acid. From the molecular ratios of the insoluble there would appear to be rather more silica than is required for the pyroxene and felspar, and the close agreement between the direct and indirect determinations seems to preclude the idea that this is due to errors in the analysis. The free silica thus indicated may possibly be present in the form of asmanite (tridymite) which is recorded by Tschermak as occurring in this meteorite,[1] although the author has not succeeded in identifying it with certainty in the thin slices in the British Museum Collection.

The amount of olivine in the sample analysed was so small, as shown by the low percentage of magnesia, that no reliable deduction as to its composition could be made from the analysis of the soluble part of the unattracted material. A separate analysis was therefore made of material broken from a patch of the mineral on the specimen. The result of the analysis, made on 0·5583 gram of material, is as follows:

		Molecular ratios.
SiO_2	39·89	0·665
FeO	8·98	0·125
MgO	49·50	1·237
Insoluble	1·95	
	100·32	

The olivine, therefore, has approximately the composition

$$10\,Mg_2SiO_4.Fe_2SiO_4.$$

* From the analysis of the total unattracted portion.

† Including some MnO.

[1] G. Tschermak, Sitzungsber. Akad. Wiss. Wien, 1884, vol. lxxxviii, (1), p. 352.

The approximate mineral composition of the meteorite deduced from the analyses is as follows:

Nickel-iron	41½	(in which Fe : Ni is about 13).
Troilite	2	
Anorthite	17	
Pyroxene	32	(in which MgO : FeO is about 2).
Olivine	1½	(in which MgO : FeO is about 10).
Chromite	1	
Rust	2	
Schreibersite, &c. ...	3	
	100	

Analyses of specimens referable to Vaca Muerta have been made by I. Domeyko on one of the original specimens of Vaca Muerta[1]; by C. A. Joy on a specimen from the 'Janacera' (really Jarquera) Pass, 50 miles S.E. of Copiapo[2]; by J. M. Davison on a specimen of Doña Inez[3]; and by L. G. Eakins on a specimen of Llano del Inca.[4] The numbers given in these analyses, except the last two, are not easily interpreted in terms of the mineral contents of the meteorite. Domeyko appears to have been unaware of the presence of felspar, while Joy, on the other hand, concluded that the silicate portion consisted mainly of felspar with some olivine but no pyroxene. Domeyko, Joy, and Eakins agree fairly closely as regards the composition of the nickel-iron in making the ratio of Fe to Ni about 10.

The results of Eakins's analyses of the soluble and insoluble parts of the stony matter of Llano del Inca are as follows:

	Soluble.	Molecular ratios.		Insoluble.	Molecular ratios.
SiO_2 ...	28·08	0·47	SiO_2 ...	53·11	0·88
Al_2O_3 ...	12·74	0·12	Al_2O_3 ...	2·32	0.02
FeO ...	42·52	0·59	Cr_2O_3 ...	0·90	—
NiO ...	2·90	0·04	FeO ...	18·82	0·26
MnO ...	0·20	—	CaO ...	1·75	0·03
CaO ...	9·33	0·16	MgO ...	23·10	0·58
MgO ...	1·98	0·05		100·00	
P_2O_5 ...	2·25	—			
	100·00				

[1] I. Domeyko, Compt. Rend. Acad. Sci. Paris, 1864, vol. lviii, p. 551.
[2] C. A. Joy, Amer. Journ. Sci., 1864, ser. 2, vol. xxxvii, p. 243.
[3] E. E. Howell, Proc. Rochester Acad. Sci., 1890, vol. i, p. 93.
[4] Ibid., p. 94.

The numbers obtained for the soluble portion suggest that the greater part consists of oxides of iron and nickel from the rusting of the meteorite, together with anorthite and only a little olivine. The molecular ratios for the insoluble portion correspond quite closely to 58 $MgSiO_3$. 26 $FeSiO_3$. $CaSiO_3$ + 2 $CaAl_2Si_2O_8$, i. e. (as in the analysis of the British Museum specimen) to a pyroxene in which the ratio of MgO to FeO is about 2, together with a little felspar which has escaped decomposition.

Davison's analysis of the total mass of Doña Inez is as follows:

				Molecular ratios.
SiO_2	...	18·41	...	0.30
FeO	...	58.91	...	0·82
Al_2O_3	...	6·39	...	0.06
P_2O_5	...	0.32	...	—
NiO	...	5.28	...	0.07
CoO	...	0.34	...	—
CaO	...	3·56	...	0·06
MgO	...	4.92	...	0·12
S	...	1·06	...	0.03
Cu	...	trace		
		99·24		

The molecular ratios correspond fairly closely with $6\frac{1}{2}$ $CaAl_2Si_2O_8$ + 12 $MgSiO_3$. 6 $FeSiO_3$ + 3 FeS + 7 $Fe_{10}Ni$ (oxidized), i. e. to a mixture of oxidized nickel-iron in which the ratio of Fe to Ni is about 10, a pyroxene in which again the ratio of MgO to FeO is about 2, anorthite, and some troilite. The numbers he obtained for the soluble and insoluble parts are not so readily interpreted in terms of the minerals present.

Under the microscope, thin sections of Vaca Muerta (35124 and 46200), Llano del Inca (66206), and Doña Inez (66203) in the British Museum Collection are indistinguishable from each other. They all show a marked cataclastic structure, for the anorthite-felspar occurs only in sharp-edged broken fragments and the pyroxene shows little in the way of crystal outline. The iron is present for the most part as an irregular net-work enclosing felspars and pyroxene, and was obviously the last constituent to consolidate. The pyroxene is mainly bronzite giving straight extinction, but with this orthorhombic pyroxene are some grains with oblique extinction: there appears to be no reason, however, for supposing any of it to be of the nature of diallage, as suggested by Lane (loc. cit., p. 96). Olivine is not to be detected with certainty except in the case of one fairly large rounded section in one of the slides of Vaca Muerta. In the actual specimens of the meteorite olivine is seen rather sparsely distributed but occasionally in fairly large patches.

HAINHOLZ.

This meteorite was found near Minden, in Westphalia, in 1856, was first described by Wöhler [1] in 1857, and was analysed by C. Rammelsberg [2] in 1870. According to his analysis it consisted of nickel-iron in which the ratio of Fe to Ni was about 10, and of soluble and insoluble silicates in both of which the ratio of MgO to FeO was about 3. He appears to have completely overlooked the presence of felspar and makes no record of any Al_2O_3 or CaO in his analysis of the soluble silicates. A determination of the composition of the nickel-iron, made by E. Priwoznik,[3] in 1892, gave a ratio of Fe to Ni of about 13, as in Vaca Muerta.

For the present analysis a piece weighing about 17 grams was taken from a specimen (33911) in the British Museum Collection, which had been obtained from Dr. A. Krantz in 1862. It was separated by the magnet into an attracted portion weighing 9·1269 grams and an unattracted portion weighing 8·3268 grams. The results of the analyses are as follows:

	Attracted. (1)	Attracted. (2)	Unattracted.	Bulk-analysis.[4]	
Fe	78·74	83·65	—	42·13	46·54
Ni	7·48	7·83	—	4·00	
Co	(0·76)*	0·80	—	0·41	
Fe	—	—	4·99	2·52	3·96
S	—	—	2·86	1·44	
Fe	0·67†	—	—	0·36	0·69
Ni	0·43†	—	—	0·23	
P	0·19	trace	—	0·10	

[1] F. Wöhler, Ann. Phys. Chem. (Poggendorff), 1857, vol. c, p. 342.

[2] C. Rammelsberg, Monatsber. Berlin. Akad. 1870, p. 322.

[3] E. Priwoznik, Österr. Zeits. Berg- u. Hüttenwesen, 1892, No. 39.

[4] In the calculation of the bulk-analysis, analysis (1) of the attracted, with the loss evenly distributed over the constituents, was used.

* Calculated from result in (2).

† The amounts of Fe and Ni are taken to correspond to the formula Fe_2NiP for schreibersite.

	Attracted. (1)		Attracted. (2)		Unattracted.		Bulk-analysis.
SiO_2 ...	2·05	...	1·07	...	40·73	...	21·69
Al_2O_3 ...	0·91	...	0·67	...	8·89	...	4·99
Fe_2O_3 ...	—	...	—	...	5·48	...	2·77
Cr_2O_3 ...	—	...	—	...	0·65	...	0·33
FeO ...	—	...	—	...	12·24	...	6·19
MnO ...	—	...	—	...	trace	...	trace
NiO ...	—	...	—	...	0·95*	...	0·48
CaO ...	1·04	...	0·58	...	5·80	...	3·49
MgO ...	trace	...	trace	...	13·98	...	7·07
P_2O_5 ...	—	...	—	...	0·67*	...	0·34
Na_2O ...	—	...	—	...	0·42	...	0·21
H_2O ...	—	...	—	...	2·38	...	1·20
Insoluble	5·46	...	4·32	...	—	...	—
O, C, &c.	(2·27)	...	(1·08)	...	—	...	—
	100·00		100·00		100·04		99·95

Analysis (1) of the attracted was made on the original material from the 17 gram piece. The low summation is probably partly due to loss owing to spurting during the solution of the metal in aqua regia and the subsequent expulsion of nitric acid by evaporation. Analysis (2) was made on another fragment of the meteorite weighing about 5 grams, which was separated by the magnet into 2·3081 grams of attracted and 2·7169 of unattracted. In this analysis there is still a low summation, although every precaution was taken to avoid any loss. Low summation, in the author's experience, occurs almost invariably in the analysis of the attracted portion of meteorites, and may be due to the non-determination of some volatile constituent or of carbonaceous matter. In the present case it may be partly attributed to oxygen, as the iron was rather rusted.

The numbers given under the unattracted are the combined result of separate analyses of the portions soluble and insoluble in hydrochloric acid, the individual numbers for which are as follows:

* The Ni and P are taken as oxidized, since in the analysis of the soluble below there is no excess of Fe beyond that determined as Fe_2O_3 to form schreibersite.

	Soluble.	Molecular ratios.	Insoluble.	Molecular ratios.
SiO_2 ...	10·91 ...	0·18 ...	29·82 ...	0·50
Al_2O_3 ...	7·37 ...	0·07 ...	1·52 ...	0·015
Fe_2O_3 ...	5·48* ...	— ...	— ...	—
Cr_2O_3 ...	— ...	— ...	0·65* ...	0·004
FeO ...	0·58 ...	— ...	11·66 ...	0·16
MnO ...	— ...	— ...	trace ...	—
NiO ...	0·95 ...	— ...	— ...	—
CaO ...	4·73 ...	0·08 ...	1·07 ...	0·02
MgO ...	1·77 ...	0·04 ...	12·21 ...	0·30
Na_2O ...	— ...	— ...	0·42* ...	0·007
P_2O_5 ...	0·67*			
H_2O ...	2·38*			
{Fe ...	4·99			
{S ...	2·86*			
	42·69		56·93	

The analyses show that, as in the case of Vaca Muerta, the nickel-iron is poor in nickel, but with a ratio of Fe to Ni of about 10½ rather less than in the Chilian meteorite; that the soluble portion of the stony material consists of anorthite, with some troilite and rust, and only a little olivine; and that the insoluble is mainly composed of a pyroxene, poor in lime, in which the ratio of the MgO to FeO is again about 2, together with a little chromite and undecomposed felspar.

Since in the case of this meteorite also no reliable deduction could be drawn as to the composition of the small amount of olivine in the soluble portion of the unattracted material, a separate analysis was made on material taken from a small patch of the mineral on the specimen. The result of the analysis, made on only 0·1087 gram of material, is as follows:

		Molecular ratios.
SiO_2	40·48	0·67
FeO	11·59	0·16
MgO	42·97	1·07
Insoluble	2·76	
Loss and O	(2·20)	
	100·00	

* These determinations were made on separate portions of the total unattracted.

The ratio of MgO to FeO in the olivine is therefore between 6 and 7, perhaps nearer 7 than 6, since the material was slightly oxidized. The lower ratio as compared with Vaca Muerta corresponds to the lower ratio of the Fe to Ni in the nickel-iron.

The approximate mineral composition of the meteorite, deduced from the analyses, is as follows:

Nickel-iron ...	46½	(in which Fe : Ni is about 10½)
Troilite	4	
Anorthite	14½	
Pyroxene	27	(in which MgO : FeO is about 2)
Olivine	1½	(in which MgO : FeO is about 7)
Chromite	½	
Rust	4	
Schreibersite, &c.	2	
	100·0	

Hainholz, a typical mesosiderite, is thus seen to have a chemical and mineral composition very similar to that of the grahamite Vaca Muerta, from which certainly it cannot be distinguished as regards the amount of felspar.

Under the microscope in a thin section of the British Museum specimen the structure is seen to be finer grained and less cataclastic than that of Vaca Muerta, for the felspar occurs more in laths and less as broken fragments, although a few of these are prominent in the slide[1]; it is in fact much more basaltic in character and thus strikingly resembles that of the meteorite Simondium described below. The section shows one rounded olivine precisely similar to the one in the section of Vaca Muerta. The iron occurs in more detached grains.

Simondium.

A short description of this meteorite, which was found in gravel near Simondium Station on the Paarl to French Hoek line, Cape Colony, has been previously given by the author.[2] It has unusual characters and resembles in some parts a terrestrial basalt perhaps more closely than any other n eteorite (see loc. cit., Plate VII). As it contained olivine as well as bronzite and plagioclase-felspar and in some parts only little nickel-iron, it was referred to the howardite group. In many respects,

[1] See G. Tschermak, 'Die mikroskopische Beschaffenheit der Meteoriten,' 1883–1885, p. 22 and pl. XXIV, fig. 4.

[2] G. T. Prior, Mineralogical Magazine, 1910, vol. xv, p. 312.

however, it differed from any member of that group, for some fragments contained nodules of troilite and olivine up to 2 inches in length, while others showed fairly plentifully distributed grains of nickel-iron. As the meteorite was in such a bad state of oxidation, no attempt was made in 1910 to analyse it as a whole, but an analysis was made of the olivine which showed that its chemical composition was similar to that of the olivine in most pallasites, for the ratio of MgO to FeO was as high as 10, instead of about 2 as it is in the olivine of the howardites, Luotolacs and Mässing.

The meteorite therefore presents, from the author's point of view, a similar anomalous composition to that of the mesosiderites, and, in spite of its altered condition, a chemical analysis which might lead to a determination, at any rate, of the composition of the pyroxenic constituent, seemed desirable. For this purpose a fragment weighing about 9 grams was taken from the interior of one of the specimens (**1909, 149**) which, from its colour, appeared to be less oxidized than the rest, although, as seen in thin section under the microscope, even in this part the nickel-iron was mainly represented by red and black alteration products. From the powdered fragment 0·5533 gram of black attracted material was separated by the magnet from 8·4658 grams of unattracted. The results of the analyses are as follows:

	Attracted.	Unattracted.
Fe	47·76	—
Ni	3·18	—
Co	undetd.	—
Fe	—	1·63
S	—	0·93
SiO_2	9·65	39·36
Al_2O_3	2·40	7·10
Cr_2O_3	—	0·78
Fe_2O_3	—	5·22
FeO	—	10·30
NiO	—	5·02
MnO	—	trace
CaO	0·61	2·51
MgO	0·24	13·14
Na_2O	—	0·10
H_2O	—	10·77
P_2O_5	—	0·85
SO_3	—	2·71
Insoluble	7·92	
S, O, &c.	(28·24)	
	100·00	100·42

The figures given under the unattracted are the combined result of separate analyses of the portion soluble in water, and, after its separation of the portions soluble and insoluble in hydrochloric acid. The results of these three analyses are as follows:

	Soluble in water.	Molecular ratios.
NiO	1·28	0·017
CaO	0·91	0·017
SO_3	2·71	0·034
H_2O	undet.	
	4·90	

	Soluble in HCl.	Molecular ratios.	Insoluble in HCl.	Molecular ratios.
SiO_2	11·23	0·19	28·13	0·47
Al_2O_3	5·47	0·05	1·63	0·015
Cr_2O_3	—	—	0·78	0·005
Fe_2O_3	5·22*	0·03	—	—
FeO	1·38	0·02	8·92	0·13
NiO	3·74	0·05	—	—
MnO	—	—	trace	—
CaO	0·72	0·013	0·83	0·015
MgO	1·44	0·036	11·70	0·29
Fe	1·63	0·03	—	
S	0·93*	0·03	—	
Na_2O	—	—	0·10*	
P_2O_5	0·85*	0·006	—	
H_2O	10·77*	—	—	
	43·38		52·14	

From the results of the analyses the following conclusions may be drawn:

(1) In the small attracted portion the iron and nickel are almost wholly in the oxidized condition, but the original nickel-iron was one poor in nickel with a ratio of Fe to Ni well above 10, as in most of the pallasites.

(2) The part of the unattracted soluble in water consists of hydrated sulphates of lime and nickel. The presence of sulphate of lime in the part soluble in water of a meteorite has been often, though perhaps somewhat rashly, supposed to indicate the original presence of oldhamite.

* These determinations were made on separate portions of the total unattracted material. A large amount of the H_2O is to be referred to the part of the unattracted soluble in water.

In the present case it has resulted almost undoubtedly from the decomposition of troilite and felspar.

(3) After the removal of the part soluble in water, the portion of the unattracted soluble in hydrochloric acid is made up partly of some anorthite and troilite and a little olivine, but mainly of decomposition products consisting of hydrated oxides and silicates of iron, aluminium, and nickel.

(4) The part of the unattracted insoluble in hydrochloric acid consists mainly of a pyroxene in which the ratio of MgO to FeO is about 2 as in the mesosiderites, together with a little chromite and felspar.

There is little doubt that the original constituents of the meteorite were mainly anorthite, pyroxene, nickel-iron, and olivine, all having chemical compositions very similar to those of the same minerals in Vaca Muerta and Hainholz. In the few fragments of Simondium which have been preserved the iron has been for the most part oxidized, so that they present very much the same appearance as the rusted specimens of Doña Inez and Llano del Inca. That in parts of the meteorite the amount of nickel-iron was much more plentiful and conspicuous than in the much weathered and oxidized fragments in the British Museum Collection seems probable from the fact that the large stones, a foot in diameter, originally discovered, were broken up by the finders, as in the case of many Chilian meteorites, under the mistaken idea that the metal was silver.

The three meteorites, Vaca Muerta (including Llano del Inca and Doña Inez), Hainholz, and Simondium thus present such similar characters that they must all be referred to the same group, to which the earlier name of mesosiderite is given. In the case of Vaca Muerta and Hainholz any distinction between mesosiderite and grahamite as regards the amount of felspar breaks down altogether. Examination of the microscopic characters and consideration of the analyses which have been published of other members of this group, as described below, indicate that all have very similar characters to those of Vaca Muerta and Hainholz, and that in their case also no real distinction as regards the amount of felspar can be drawn between them.

Taney County (= Mincy).

This meteorite, which is reported to have fallen in Taney Co., Missouri, in 1857, was first analysed by Lawrence Smith[1] in 1865

[1] J. L. Smith, Amer. Journ. Sci., 1865, ser. 2, vol. xl, p. 213.

under the name of Newton County, Arkansas (to which place a fragment had been transported), and later in 1887 by J. E. Whitfield[1] under the name of Mincy.

Lawrence Smith determined the compositions of the nickel-iron, the olivine, and the pyroxene (so-called 'hornblende') separated mechanically from the meteorite, and was quite unaware of the presence of felspar. According to his analyses, the ratio of Fe to Ni in the nickel-iron is about $12\frac{1}{2}$, and the ratio of MgO to FeO in the olivine about 7, and in the pyroxene about 3. These three constituents therefore have chemical compositions very similar to those of the same minerals in Vaca Muerta.

Whitfield's analyses were made on the nickel-iron, the total stony matter from which the iron had been separated, and the portion of the stony matter insoluble in hydrochloric acid, and by them the presence of abundant anorthite in the meteorite is made very evident. For the nickel-iron he obtained a ratio of Fe to Ni of about 9. His results for the stony matter are as follows:

	Total stony matter.	Molecular ratios.	Insoluble in HCl.	Molecular ratios.
SiO_2	45·88	0·76	52·39	0·87
Al_2O_3	7·89	0·08	7·11	0·07
FeO	19·73	0·27	14·68	0·20
CaO	6·02	0·10	4·49	0·08
MgO	17·96	0·45	21·33	0·53
NiS	1·67	0·02	—	
FeS	0·54	0·01	—	
	99·69		100·00	

The molecular ratios of the insoluble correspond very closely to a mixture of $53\,MgSiO_3 . 20\,FeSiO_3 . 2\,CaSiO_3$ and $7\,CaAl_2Si_2O_8$, i.e. of a pyroxene in which the ratio of MgO to FeO is about 2, as in Vaca Muerta, and some anorthite. Making use of this composition of the pyroxene in the interpretation of the results of the analysis of the total stony matter, the molecular ratios are seen to correspond fairly closely to a mixture of the molecules

$$42\,MgSiO_3 . 16\,FeSiO_3 . 2\,CaSiO_3 + 8\,CaAl_2Si_2O_8$$

(i.e. of pyroxene and anorthite), together with some FeS, only a very little olivine, and oxides of Fe and Ni either from rusted nickel-iron or from nickel-iron which had not been separated from the

[1] J. E. Whitfield, Amer. Journ. Sci., 1887, ser. 3, vol. xxxiv, p. 467.

stony matter, for it is improbable that any of the nickel is in the form of sulphide as given in the analysis.[1]

Under the microscope a thin section of a specimen (40886) in the British Museum Collection shows a structure much less cataclastic than that of Vaca Muerta but coarser grained than that of Hainholz. The pyroxene occurs in rounded grains forming a sort of mosaic with the interstices filled with bladed felspar: this was obviously the last mineral to consolidate before the nickel-iron, which occurs in strings enclosing felspar and pyroxene.

Thus neither chemical analysis nor microscopic examination suggests any reason why this meteorite as regards the amount of felspar should have been classed as a 'mesosiderite' rather than a 'grahamite'.

ESTHERVILLE.

This meteorite, of which several large masses and many small fragments fell in Emmet Co., Iowa, on May 10, 1879, has been analysed by Lawrence Smith.[2] As in the case of Taney County, separate analyses were made of the nickel-iron, olivine, and pyroxene, picked out from the crushed meteorite, and the presence of felspar was again undetected, although it had been already recorded by C. U. Shepard.[3] The analyses show that the chemical compositions of these constituents are very similar to those in Vaca Muerta, the ratio of Fe to Ni in the nickel-iron being about 18, the ratio of MgO to FeO in the olivine about 6, and in the pyroxene about 2.

In later accounts of the meteorite the presence of felspar is mentioned by Tschermak,[4] Wadsworth,[5] and Meunier.[6]

Under the microscope thin sections prepared from specimens (58764 and 65575) of the meteorite in the British Museum Collection show abundant anorthite-felspar, not only as groundmass as in Taney County, but also as broken sharp-edged fragments, intermixed with rounded grains and larger sections of pyroxene, most of which give straight

[1] There is no justification for G. P. Merrill's suggestion (see Handbook and Descriptive Catalogue of the Meteorite Collections in the United States National Museum. U.S. Nat. Mus. Bull. 94, 1916, p. 106) that in Kunz's original description the analyses of the soluble and insoluble were reversed.

[2] J. L. Smith, Amer. Journ. Sci., 1880, ser. 3, vol. xix, p. 459.

[3] C. U. Shepard, Amer. Journ. Sci., 1879, ser. 3, vol. xviii, p. 188.

[4] G. Tschermak, 'Die mikroskopische Beschaffenheit der Meteoriten,' 1883–1885, pp. 22 and 23, pl. XXIV. fig. 1.

[5] M. E. Wadsworth, 'Lithological Studies,' 1884, pp. 92–101.

[6] S. Meunier, 'Révision des Lithosidérites,' 1895, pp. 30–32.

extinction, but some oblique. In the two slides only three rounded sections could be doubtfully referred to olivine.

Estherville, therefore, as regards its constituents and their chemical compositions, differs in no way from the other previously described members of the group of mesosiderites. The fact that the felspar, which is seen so prominently in thin sections, was originally overlooked, doubtless accounts for the meteorite having been classed as a 'mesosiderite' instead of a 'grahamite'.

POWDER MILL CREEK (= Rockwood = Crab Orchard).

This meteorite, which was found in Cumberland Co., Tennessee, in 1887, was analysed by J. E. Whitfield,[1] and described by G. F. Kunz[2] in the same year. The analysis by Whitfield of the stony material is difficult to interpret in terms of the constituents since he was unable to make separate determinations of the soluble and insoluble portions. He states, however, that the soluble contained only traces of MgO, and concludes from this the absence of olivine. A separate analysis of a nodule, containing only about 6 per cent. of soluble material, gave a ratio of MgO to FeO of about 3. The composition of the pyroxene is, therefore, not very different from that in Vaca Muerta. In the nickel-iron the ratio of Fe to Ni was found to be about 7, and is thus rather low for an iron showing such coarse octahedral structure as is figured (loc. cit., p. 388), but the material analysed may have been a small exceptional piece not typical of the main mass. A re-determination of the composition of the nickel-iron therefore seemed desirable. Accordingly a fragment weighing about 11 grams from the specimen (63547) of the meteorite in the British Museum Collection was crushed and separated by the magnet into an attracted portion weighing 6·0186 grams and an unattracted portion weighing 4·6306 grams. The result of an analysis of the attracted portion is as follows:

Fe	73·15
Ni	5·61
Insoluble	11·58
Anorthite, &c.	(9·66)
	100·00

[1] J. E. Whitfield, Amer. Journ. Sci., 1887, ser. 3, vol. xxxiv, p. 387.
[2] G. F. Kunz, ibid., p. 476.

The soluble material besides the nickeliferous iron consisted mainly of anorthite, for only traces of MgO and S were found.

The analysis shows that the fragment contained about 42 per cent. of nickel-iron in which the ratio of Fe to Ni is about 13, as in Vaca Muerta.

Although olivine may not be present in many samples of the meteorite, on a polished slice it is seen to occur sparsely distributed just as it does in other mesosiderites. As its composition has not hitherto been determined, an analysis was made of material picked out from a patch of the mineral on the slice (63547) of the meteorite in the British Museum Collection. The result of the analysis is as follows:

		Molecular ratios.
SiO_2	40·18	0·666
FeO	9·15	0·127
MgO	48·91	1·213
Insoluble (Chromite)	1·42	
	99·66	

The composition of the olivine corresponds approximately to the formula $10\,Mg_2SiO_4 . Fe_2SiO_4$, as in Vaca Muerta. The insoluble proved to consist mainly of chromite, probably from inclusions in the olivine.

Now the analysis by Whitfield of the nodule referred to on p. 167 gave the following result:

		Molecular ratios.
SiO_2 ...	49·96 ...	0·88
Al_2O_3 ...	4·75 ...	0.045
FeO ...	15·97 ...	0·22
CoO + NiO ...	trace ...	—
CaO ...	1.15 ...	0·02
MgO ...	28·15 ...	0·70

The fact that the amount of silica is too low in order to form only metasilicates with the bases suggests that olivine is present. By introducing the composition of the olivine as determined above the molecular ratios correspond approximately to the following:

$$44\,MgSiO_3 . 20\,FeSiO_3 + 13\,Mg_2SiO_4 . 1\tfrac{1}{3}\,Fe_2SiO_4 + 3\,CaAl_2Si_2O_8,$$

i. e. to a mixture of pyroxene in which the ratio of MgO to FeO is about 2 with olivine in which this ratio is about 10, and a little anorthite.

A thin section of the British Museum specimen shows a sharp division into two parts, one of which contains much iron while the other is free from it. The latter part consists of a coarse-grained mosaic of anorthite and pyroxene just like a gabbro, and the other part of much iron with anorthite and pyroxene broken into irregular fragments. This slide apparently gives a picture in miniature of what has happened in the main mass of this and other mesosiderites, viz. the invasion and breaking up of a pyroxene-anorthite rock by nickeliferous iron (see p. 171).

The results of analyses and microscopic examination show that, in chemical and mineral composition, Powder Mill Creek is very similar to other mesosiderites.

MORRISTOWN (= Hamblen County).

This meteorite, which was found in September, 1887, in Hamblen Co., Tennessee, has been analysed by L. G. Eakins[1] and described by G. P. Merrill.[2] According to Eakins's analysis, in the nickel-iron the ratio of Fe to Ni is about 12, as in Vaca Muerta. His results for the soluble and insoluble portions of the stony material are as follows:

	Soluble in HCl.	Molecular ratios.	Insoluble in HCl.	Molecular ratios.
SiO_2 ...	45·61 ...	0·76 ...	50·67 ...	0.84
Al_2O_3 ...	22·62 ...	0.22 ...	14.89 ...	0.15
Cr_2O_3 ...	— ...	— ...	1.32 ...	0.01
FeO ...	11.73 ...	0.16 ...	10·55 ...	0.15
MnO ...	— ...	— ...	0.76 ...	0.01
NiO ...	1.06 ...	0.01 ...	— ...	—
CaO ...	14.09 ...	0.25 ...	3.61 ...	0.07
MgO ...	3.64 ...	0.09 ...	17.98 ...	0.45
K_2O ...	— ...	— ...	0.08 ...	—
Na_2O ...	— ...	— ...	0.19 ...	—
P_2O_5 ...	1·25 ...	0.01 ...	— ...	—
	100.00		100.00	

These analyses are difficult to interpret in terms of the constituent minerals. The soluble, however, as in other analyses of mesosiderites, appears to consist mainly of anorthite, with only a little olivine, most of the oxide of iron and nickel being derived probably either from rust or from nickel-iron and troilite not separated from the stony material. In the insoluble the ratio of MgO to FeO is about 3.

The microscopic characters of the meteorite have been well described by Merrill. He states that the felspar occurs, as in other members of the group, in broken fragments, and that the structure is strongly cataclastic, not like that of a clastic rock, but rather of a crystalline variety which had been subjected to dynamic agencies. Olivine was not

[1] L. G. Eakins, Amer. Journ. Sci., 1893, ser. 3, vol. xlvi, p. 283.
[2] G. P. Merrill, Amer. Journ .Sci., 1896, ser. 4, vol. v, p. 149.

detected with certainty. Two pyroxenes were distinguished, one cloudy with inclusions and giving straight extinctions, the other clear and pellucid and giving oblique extinctions as high as 30°.

In a thin section from the specimen (81008) in the British Museum Collection the two pyroxenes are not easily distinguishable in appearance: most sections which are fairly clear give straight extinctions, but a few occur with oblique extinctions. There appears to be no reason for supposing the latter to be diallage-like, as suggested by Merrill, whose micro-chemical test for alumina is not very convincing considering the intimate association of the mineral with anorthite. In the author's experience, in no analysis of a meteorite has he found it necessary to attribute any alumina to a pyroxenic constituent. In parts of the slide the pyroxene occurs in irregular ophitic-like patches enclosing the broken felspars. One fairly large section in the slide may be doubtfully referred to olivine. In a polished slice of the meteorite a few small patches of brown olivine are visible, but they did not afford sufficient material for analysis.

Conclusions.

The results of the analyses of the preceding members of the mesosiderite group of meteorites may be summarized in the following table, which is a corrected form of that given in a previous paper:[1]

Mesosiderites.

Name.	Ratio of Fe to Ni in nickel-iron.	Ratio of MgO to FeO in olivine.	Ratio of MgO to FeO in pyroxene.	Analyst and date.
Vaca Muerta (including Llano del Inca and Doña Inez)	13	10	2	G. T. Prior, 1918.
Hainholz	$10\frac{1}{2}$	7	2	,,
Simondium	over 10	10	2	,,
Taney County	$12\frac{1}{4}$	7	3	J. L. Smith, 1865.
Estherville	13	6	2	,, 1880.
Powder Mill Creek	18	10	2	J. E. Whitfield, 1887, and G. T. Prior, 1918.
Morristown	12	—	3	L. G. Eakins, 1893.

[1] G. T. Prior, Mineralogical Magazine, 1916, vol. xviii, pp. 34-35.

The preceding investigation has shown that no real distinction can be drawn between so-called 'mesosiderites' and 'grahamites' as regards the amount of felspar they contain. For the combined group the earlier name mesosiderite is proposed.

The members of this group are remarkably uniform in character. They consist mainly of pyroxene and felspar, with nickel-iron in large amount but rather unevenly distributed, and nodules of olivine somewhat sparsely distributed but occasionally of considerable size. Accessory constituents are troilite, chromite, and schreibersite. The felspar is a nearly pure anorthite; the pyroxene is fairly rich in ferrous oxide with a ratio of MgO to FeO about 2; the olivine, on the other hand, is poor in ferrous oxide with a ratio of MgO to FeO from 6 to 10; and the nickel-iron is poor in nickel with a ratio of Fe to Ni from 10 to 18. The curiously uneven distribution of the iron and the rather sporadic occurrence of the olivine suggest that both these constituents are in some way foreign to the main mass of stony matter consisting of anorthite and pyroxene, and to this idea the peculiar structural features of these meteorites lends support. In structure, in the parts rich in iron, they are highly cataclastic, the felspars occurring in sharp-edged broken fragments. In the parts freer from iron, however, this cataclastic structure is less apparent, and sometimes, as in Powder Mill Creek, the stony matter consists of a granular aggregate of anorthite and pyroxene like a gabbro, or, as in Hainholz and Simondium, it shows a more basaltic character with the felspar in laths. In this connexion Merrill's description of the structure of Morristown (loc. cit., p. 153) may be quoted. He says, 'The coarser portions of the rock, and particularly those in immediate juxtaposition with the metallic iron, have a strongly marked cataclastic structure, the felspars existing mainly as angular fragments. . . . All structural features point to the injection of the metallic iron, or at least to its reduction to the metallic state, subsequently to the solidification of the stone, the same being accompanied by a shattering and more or less displacement of the minerals in the near vicinity. In the more siliceous portions the iron exists only in small blebs, and seems to have been wholly without effect on the structural features; but where existing in masses of some size . . . the appearance is at once suggestive of subsequent injection and consequent disruption of particles'.

From the author's point of view of a genetic relationship of meteorites, therefore, there is considerable a priori evidence in favour of the idea that the characters of this group of meteorites may be most reasonably explained as the result of a mixture of two types, to one of which belong the pyroxene and anorthite, and to the other the iron and olivine; a eucritic magma, i.e. according to the theory, one of higher oxidation, having been invaded by a pallasitic magma, i.e. by a, terrestrially speaking, more 'deep-seated' one of lower oxidation.