On the genetic relationship and classification of Meteorites.[1]

By G. T. Prior, M.A., D.Sc., F.R.S.

Keeper of the Mineral Department of the British Museum.

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In a previous paper[2] attention was drawn to the close similarity in mineral and chemical composition of chondritic meteoric stones. In the case of about forty chondrites it was shown that, apart from variations in the amount of nickel-iron, not only are the constituent minerals present in very similar amounts, but their chemical compositions vary to no very great extent. In that paper sufficient importance was not attached to the variations in the amount of nickel-iron. The chemical investigations of the meteorites described in the paper immediately preceding show that this variation is of much greater significance than had been supposed. It was found that a progressive change in the chemical composition of the nickel-iron and of the magnesium silicates could be traced from chondritic stones like Daniel's Kuil containing over 20 per cent. of nickel-iron to those like Soko-Banja containing only small amounts. The analyses in fact indicate that *the less the amount of nickel-iron in chondritic stones, the richer it is in nickel and the richer in iron are the magnesium silicates.*

This interrelation between the amount and chemical composition of the nickel-iron and the chemical composition of the magnesium silicates

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

[2] G. T. Prior, 'On the remarkable similarity in chemical and mineral composition of chondritic meteoric stones.' Mineralogical Magazine, 1913, vol. xvii, pp. 33-38.

can be seen at a glance in the following table embodying the results of the analyses of the meteorites Daniel's Kuil, Cronstad, Baroti, and Soko-Banja, which contain, in order, decreasing amounts of nickel-iron:—

Type.	Percentage of nickel-iron.	Ratio of Fe to Ni in nickel-iron.	Ratio of MgO to FeO in olivine.	Ratio of MgO to FeO in pyroxene.	Ratio of total Fe atoms to Mg atoms.
(1) Daniel's Kuil	25½	13	—	∞	1·03
(2) Cronstad	18½	11	4	6	1·22
(3) Baroti	9	6½	3	4	1·46
(4) Soko-Banja	4	3	2½	3	1·80

As seen in the lists on pp. 28–31, most of the previously published analyses of chondritic stones supply convincing evidence in support of this interrelation.

The Classification of Chondrites.

Although the relationship indicated above is probably a perfectly continuous one, for purposes of classification it is convenient to make somewhat arbitrary divisions. It is proposed, therefore, to divide chondritic stones into four groups corresponding to the four types: (1) Daniel's Kuil (Hvittis), (2) Cronstad, (3) Baroti, and (4) Soko-Banja.

Group 1. *Daniel's Kuil (Hvittis) Type.*

In this group the structure is crystalline; chondrules are few and of ill-defined shape; a nickel-poor (Fe : Ni greater than 10) nickel-iron is in large amount (20 per cent. and over); the magnesium silicate is a nearly pure enstatite ($MgSiO_3$), practically free from iron and containing little or no lime; the felspar is near to oligoclase; and the sulphide of calcium, oldhamite, is a characteristic accessory constituent.

The following list gives for the four members of Group 1 at present known the percentage of nickel-iron, the ratio of Fe to Ni in the nickel-iron, the ratio of MgO to FeO in the magnesium silicates, the symbol in the Rose-Tschermak-Brezina classification, and the name of the analyst and date of publication:—

Group 1. Name.	Percentage of nickel-iron.	Ratio of Fe to Ni in nickel-iron.	Ratio of MgO to FeO in Mg silicates.	Symbol.	Analyst and date.
Daniel's Kuil (type)	25½	18	∞	Ck	G. T. Prior, 1916.
Hvittis	21	10	∞	Ck	L. H. Borgström, 1903.
Khairpur	18	18	∞	Ck	G. T. Prior, 1916.
Pillistfer	21½	10	30	Ck	C. Grewingk and C. Schmidt, 1868.

To this list should probably be added St. Marks,[1] and more doubtfully Indarch,[2] for both contain oldhamite, in both pyroxene constitutes the main mass of the magnesium silicates, and in St. Marks this is an enstatite almost free from iron.

Group 2. *Cronstad Type.*

In this group chondrules are more plentiful and more sharply defined; a nickel-iron, poor in nickel (Fe : Ni generally as high as 10), is in large amount (over 10 per cent.); olivine is present as well as pyroxene, both containing iron in such amount that the ratio of MgO : FeO is generally from 4–6; the pyroxene is mainly bronzite, but a lime-poor monoclinic pyroxene[3] generally accompanies it in small amount; the felspar is oligoclase.

The following is a list of chondritic stones which the data, drawn from the published analyses,[4] indicate belong to this group:—

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[1] E. Cohen, Ann. South African Museum, 1906, vol. v, p. 1.

[2] G. P. Merrill, Proc. U. S. Nat. Museum, 1915, vol. xlix, p. 109.

[3] W. Wahl, 'Die Enstatitaugite.' Min. Petr. Mitt., 1907, vol. xxvi, p. 1.

[4] In the following lists are included, besides other more recent analyses, all those quoted by O. C. Farrington in 'Analyses of Stone Meteorites'. Field Museum of Natural History, 1911, Publication 151, Geol. Series, vol. iii, No. 9. The original references have been consulted, for in Farrington's list it is not always possible to determine whether the iron for the sulphur is to be taken from Fe or FeO. Where the chemical composition of the olivine and bronzite have been determined, the ratio of MgO to FeO has been calculated from them. The numbers in brackets placed in some cases after this ratio is the ratio for the insoluble alone, for, when the separation of the metallic iron has been imperfect, more reliance can be placed upon this ratio than upon that for the soluble.

Group 2. Name.	Percentage of nickel-iron.	Ratio of Fe to Ni in nickel-iron.	Ratio of MgO to FeO in Mg-silicates.	Symbol.	Analyst and date.
Cronstad (type)	18½	11	4½	Cg	G. T. Prior, 1916.
Allegan	28	12	5	Cco	H. N. Stokes, 1900.
Baldohn	18	12	3½	Cc	E. Johanson, 1892.
Beaver Creek	17	10	4½	Cck	W. F. Hillebrand, 1894.
Blansko	17	15	3½ (5)	Cga	J. J. Berzelius, 1834.
Cabarrus County	13½	14	5	—	J. E. Whitfield, 1916.
Cape Girardeau	18	12	4½	Cc	S. L. Penfield, 1886.
Carcote	10	10	3 (4)	Ck	W. Will, 1889.
Cléguérec	20	13	4	Ck	F. Pisani, 1869.
Cullison	19	10	5	—	J. E. Whitfield, 1913.
Dundrum	20	18	5	Ck	S. Haughton, 1866.
Estacado	16	9	3½ (4½)	Ckb	J. M. Davison, 1906.
Gnarrenburg[1]	23	12	9	Ccb	F. Wöhler, 1856.
Gopalpur	20	11	8 (4)	Cc	A. Exner, 1872.
Hedjaz	11	9	4	—	F. Pisani, 1912.
Hessle	19	8	4	Cc	G. Lindström, 1870.
Khetri	17	18½	4½	Cgb	D. Waldie, 1869.
Klein-Wenden[1]	23	9	7	Ck	C. Rammelsberg, 1844.
Linn County	10½	9	3½	Cwa	C. Rammelsberg, 1870.
Linum[1]	13	22	32	Cw	A. Lindner, 1904.
Lixna	15	8	4 (5)	Cga	A. Kuhlberg, 1867.
Molina[1]	15	10	10 (75)	Cw	S. Meunier, 1869.
Mount Browne	18	9	5	—	H. P. White, 1902.
Nash County	14	11	4	Cgb	J. L. Smith, 1875.
Ogi	17	10	5	Cw	T. Shimidzu, 1882.
Orvinio	21	9	5	Co	L. Sipöcz, 1875.
Pultusk	10	13	3½ (4½)	Cga	G. vom Rath, 1869.
Rochester	10	17	3½ (4)	Cc	J. L. Smith, 1877.
Searsmont	14	10	3½	Cc	J. L. Smith, 1871.
Sevrukovo	16½	8	4½	Cs	A. Eberhard, 1882.
Stålldalen	18	11	4½	Cga	G. Lindström, 1877.
Stavropol[2]	10	—	4 (3½)	Ck	H. Abich, 1860.
Utah	17	11	4 (5)	—	S. L. Penfield, 1886.
Winnebago County	19	15	4½	Ccb	L. G. Eakins, 1890.

[1] Doubtful; if correct, these analyses, in which the ratio MgO : FeO is so high, suggest a passage to Group 1. In the case of Klein-Wenden, as in some others of his analyses, Rammelsberg appears to have rather over-corrected for the NiO in the unattracted part.

[2] The numbers given depend on Abich's statement that the stone contains over 10 per cent. of nickel-iron, instead of the much lower amount indicated by the bulk-analysis.

Group 3. Baroti Type.

Chondrites of this group contain from 6–10 per cent. of nickel-iron, rich in nickel (Fe : Ni generally from 6–8); the ferromagnesium minerals are olivine and pyroxene in which the ratio of MgO to FeO is generally 3–4; the pyroxene is mainly bronzite but, as in group 2, a lime-poor monoclinic pyroxene may also be present; the felspar or glass has the composition of oligoclase.

The following is a list of chondrites which the published analyses indicate belong to this group:—

Group 3. Name.	Percentage of nickel-iron.	Ratio of Fe to Ni in nickel-iron.	Ratio of MgO to FeO in Mg-silicates.	Symbol.	Analyst and date.
Baroti (type)	9	6½	3½	Cw	G. T. Prior, 1913.
Ausson	8	7	3	Cc	E. P. Harris, 1859.
Bjurböle	7	8	3½	Cca	W. Ramsay & L. H. Borgström, 1902.
Chantonnay	8	6	3½	Cgb	C. Rammelsberg, 1870.
Coon Butte	8½	8	4 (3)	Cib	J. W. Mallet, 1906.
Farmington	7	7	3½	Cs	L. G. Eakins, 1892.
Launton	8½	6	3½	Cia	G. T. Prior, 1916.
Lesves	8	7½	3	Cw	A. F. Renard, 1896.
Meuselbach	8	6	3 (3½)	Ccka	G. Linck, 1899.
Mezö-Madaras	9	5	3 (3)	Cgb	C. Rammelsberg, 1871.
Modoc	7	9½	3½	Cwa	W. Tassin, 1906.
Muddoor	9	7	3	Cc	F. Crook, 1868.
Parnallee	6½	5	4	Cga	E. Pfeiffer, 1863.
Pickens County[1]	9	7	3	—	E. Everhart, 1909.
Rakovka	7	4	3½	Ci	P. Grigorieux, 1880.
Richmond	8	7	3½ (3)	Cck	C. Rammelsberg, 1870.
St. Christophe	9	5	3½	Cg	A. Lacroix, 1906.
St. Denis-Westrem	8	6	3½	Cca	C. Klement, 1886.
St. Michel	8½	7	3½	Cw	L. H. Borgström, 1912.
Stewart County	7	7	3½ (2½)	Cck	J. L. Smith, 1870.
Tourinnes-la-Grosse	8½	5½	3	Cw	F. Pisani, 1864.
Utrecht	9	7	3	Cca	E. H. von Baumhauer, 1845.
Warbreccan	7	6	3½	Cwa	G. T. Prior, 1916.
Wittekrantz	8	7	3½	Cw	G. T. Prior, 1913.
Zomba	8½	7	3½	Cw	L. Fletcher, 1901.

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[1] Doubtful, as it contains nearly 11 per cent. of Fe_2O_3.

Group 4. Soko-Banja Type.

In this group the nickel-iron is in small amount (less than 6 per cent.) and is very rich in nickel (Fe : Ni less than 5); the ferromagnesium minerals are olivine and pyroxene as in groups 2 and 3 but are still richer in iron, the ratio MgO : FeO being less than 3; the felspar is oligoclase.

The published analyses indicate that the following chondrites belong to this group:—

Group 4. Name.	Percentage of nickel-iron.	Ratio of Fe to Ni in nickel-iron.	Ratio of MgO to FeO in Mg-silicates.	Symbol.	Analyst and date.
Soko-Banja (type)	4	3	2½	Cc	G. T. Prior, 1916.
Albareto	5	6	2	Cc	P. Maissen, 1880.
Alfianello	7	5	2½	Ci	P. Maissen, 1884.
Bachmut[1]	6½	4	3 (4½)	Cw	A. Kuhlberg, 1867.
Binda	½	—	2	—	J. C. H. Mingaye, 1913.
Bluff[2]	5½	5	2½	Ck	J. E. Whitfield, 1888.
Buschhof	5	2	2½	Cwa	C. Grewingk & C. Schmidt, 1864.
Cold Bokkeveld	0	—	1	K	E. P. Harris, 1859.
Eli Elwah[3]	—	—	2	C	A. Liversidge, 1903.
Ergheo	1	3	3	Ckb	G. Boeris, 1898.
Honolulu[1]	4	1½	2 (4½)	Cwa	A. Kuhlberg, 1867.
Kaba	4	2½	1½	K	F. Wöhler, 1858.
Knyahinya	5	4	2½	Cg	E. H. von Baumhauer, 1872
Krähenberg	3½	5	2	Cho	G. vom Rath, 1869.
Long Island[4]	3	4	3 (9)	Cia	H. W. Nichols, 1902.
Makariwa	5	4	3	Cgb	L. Fletcher, 1894.
Mauerkirchen[5]	4	4	2	Cw	F. Crook, 1868.
Mocs	5	3	1½	Cwa	F. Koch, 1883.
Nerft[1]	6	4	3 (4½)	Cia	A. Kuhlberg, 1869.
Ngawi	3	5	2	Ccn	E. H. von Baumhauer, 1884.
Orgueil[6]	0	—	2	K	F. Pisani, 1864.
Ornans[7]	2	—	2 (5)	Cco	F. Pisani, 1868.
Saline Township	6	4	2	Cck	H. W. Nichols & E. W. Tillotson, 1911.
Uden	2	—	1½	Cwb	E. H. von Baumhauer & F. Seelheim, 1862.
Waconda	5	7	2	Ccb	J. L. Smith, 1877.
Zavid	0	—	2	Cia	C. Hödlmoser, 1901.

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[1] These possibly belong to Group 3, for the MgO : FeO ratio for the insoluble is as high as 4½, and the specific gravities of the stones are all over 3·5, which

[Foot-notes continued on p. 32.]

The analyses from which the data given in the preceding lists have been calculated date back as far as 1884 and are doubtless of very unequal value especially as regards the determination of the nickel-iron and its content of nickel. It is only to be expected, therefore, that, where three conditions have to be satisfied, some analyses will present discrepancies which make it difficult to fix with certainty the groups to which the stones belong. In order to test by means of the older analyses the principles suggested by the writer's own work, it was decided, as the most satisfactory proceeding, to consider every analysis in Farrington's pamphlet, rather than to make a selection of those which might be regarded as the most accurate. In the preparation of such a list as Farrington's the work of choosing the most satisfactory must have been a difficult one. It is not surprising therefore to find (see footnotes) that it includes many which a critical examination suggests are inaccurate or incomplete, and omits some which are beyond reproach.[8]

The following list of the remaining chondritic stones referred to in Farrington's pamphlet contains those of which the analyses appear to be most at variance with the principles which the preceding lists serve to support:—

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suggests a somewhat higher percentage of nickel-iron than that given in the analyses.

[2] Doubtful, for the soluble contains nearly 3 per cent. and the insoluble nearly 2 per cent. of NiO, indicating that the separation *by means of iodine* of the metal was imperfect.

[3] Doubtful, as the analysis was incomplete, the nickel-iron not being determined. It possibly belongs to Group 3.

[4] Doubtful, as it is supposed to contain 10 per cent. of limonite; the ratio for the bronzite is so high owing to the large amount of FeO required for the extraordinarily high percentage of chromite (nearly 10 per cent.).

[5] Doubtful: on Crook's analyses, see G. Tschermak, Sitzber. Wien. Akad., 1872, vol. lxv, p. 134.

[6] Doubtful, as it contains nearly 8 per cent. of Fe_2O_3.

[7] Doubtful, owing to high MgO : FeO ratio for the insoluble and the presence of nearly 3 per cent. of NiO in the soluble. It possibly belongs to Group 2, like Allegan, which belongs to the same class (Cco), as does also Warrenton, which so closely resembles Ornans in external appearance.

[8] The omission of some of the most detailed and accurate analyses of meteoric stones we possess, such as those of Zomba and Makariwa by L. Fletcher, was due probably to the results being given as analyses of the individual constituents and not as bulk-analyses.

Name.	Percentage of nickel-iron.	Ratio of Fe to Ni in nickel-iron.	Ratio of MgO to FeO in Mg-silicates.	Symbol.	Probable Group.	Analyst and date.
Adare	19	6	3½	Cga	3	R. Apjohn, 1874.
Amana	12	5	1½	Cgb	4	C. W. Gümbel & A. Schwager, 1875.
,,	12½	8	1⅔	—	—	J. L. Smith, 1875.
Borkut[1]	22	8	3 (2½)	Cc	3	J. Nuricsany, 1856.
Chandakapur	6	10	2 (4½)	Cib	3	H. E. Clarke, 1910.
Château-Renard	8½	4	1 (2)	Cia	4	A. Dufrénoy, 1841.
Cynthiana	6	11	3 (4)	Cg	3	J. L. Smith, 1877.
Dhurmsala	8	4	4½	Ci	4	S. Haughton, 1866.
Drake Creek	11½	6½	3½	Cwa	3	E. H. von Baumhauer, 1845.
Ensisheim	9	7	2½	Ckb	—	F. Crook, 1868.
Felix	3	7	1½ (16)	Kc	—	P. Fireman, 1901.
Gnadenfrei	26	5½	2 (2½)	Cc	4	J. G. Galle & A. von Lasaulx, 1879.
Hendersonville	2½	11	4 (5)	Cc	2	W. Tassin, 1907.
Heredia	26	15	2 (2½)	Ccb	—	I. Domeyko, 1859.
Jerome	4	9	1 (5)	Cck	2	H. S. Washington, 1898.
Kakowa	8	6	2 (∞)	Cga	—	E. P. Harris, 1859.
Lundsgård	12	5	3½	Cw	3	O. Nordenskjöld, 1891.
Middlesbrough	9	3	1½ (1)	Cw	4	W. Flight, 1882.
New Concord	10½	7	1½	Cia	—	J. L. Smith, 1861.
Shelburne	8	10	3	Cg	3	L. H. Borgström, 1904.
Shytal	10	6	2	Cib	3	T. Hein, 1866.
Tadjera	8	11	3 (½)	Ct	—	S. Meunier, 1868.
Takenouchi	13	7	2½	Ck	—	A. Lindner, 1904.
Tieschitz	8½	5½	2	Cc	4	J. Habermann, 1879.
Travis County	2	8	4 (5)	Cs	2	L. G. Eakins, 1891.
Warrenton	2	9	3 (4)	Cco	2	J. L. Smith, 1877.

In ten of the stones in this list (viz. Adare, Amana, Château-Renard, Drake Creek, Gnadenfrei, Hendersonville, Lundsgård, Middlesbrough, Tieschitz, and Travis County) the discrepancy occurs only in the amount of nickel-iron. In some cases this may be accounted for by variations in the amount of nickel-iron in different parts of the stone, the portion analysed not being a fair sample. This appears to have been the case with Amana, for Lawrence Smith remarks that 'the specimen analysed had a vein running through it which was much richer in iron than the mass to which it belonged'. Hendersonville and Jerome show discrepancies owing to their having been much oxidized. In the case of Jerome, Felix, and Warrenton, also, the presence of from 1–3 per cent. of NiO in

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[1] Wadsworth's calculation of the bulk-analysis, as quoted by Farrington, is not in agreement with the details of the analyses.

the soluble suggests imperfect separation of the nickel-iron. In Chandakapur the nickel has probably been under-estimated, since the separation from iron was by means of ammonia. As regards Dhurmsala, examination of specimens and sections in the British Museum Collection suggests that the metallic iron, as well as the sulphur and chromium, have been over-estimated.

CLASSIFICATION OF NON-CHONDRITIC STONES.

Turning now to the non-chondritic meteoric stones, we should expect, if the same principle which governs the variation in chemical composition of chondritic stones applies also to them, that those containing large amounts of nickel-iron, like the siderolites, would have that iron poor in nickel and their ferromagnesium minerals correspondingly poor in iron, whereas those with little or no iron should have that iron rich in nickel and their ferromagnesium minerals rich in iron. The published analyses of these stones, data from which are given in the following lists, show that this is generally the case.

Achondrites containing large amounts of nickel-iron.

Taking first the case of the non-chondritic stones containing large amounts of nickel-iron, the following list gives the ratio of Fe to Ni in the nickel-iron, and the ratio of MgO to FeO in the ferromagnesium silicates for various siderolites (including under that name also lithosiderites):—

Name.	Ratio of Fe to Ni.	Ratio of MgO to FeO in olivine.	Ratio of MgO to FeO in pyroxene.	Class.	Analyst and date.
Admire	15	7	—	Pallasite	W. Tassin, 1902.
Brahin	11	7	—	,,	A. A. Inostranzeff, 1869.
Brenham Township	9	8	—	,,	L. G. Eakins, 1890.
Eagle Station	5	4	—	,,	J. B. Mackintosh, 1887.
Imilac	9	7	—	,,	F. v. Kobell, 1851.
Marjalahti	12	7	—	,,	L. H. Borgström, 1903.
Mount Dyrring	19	7	—	,,	J. C. H. Mingaye, 1904.
Mount Vernon	6	4	—	,,	W. Tassin, 1905.
Pallas Iron	9	6	—	,,	J. E. Whitfield, 1916.
South Bend	10	—	—	,,	H. W. Nichols, 1906.
Breitenbach	9	—	5	Siderophyre	C. Winkler, 1878.
Estherville	13	6	2	Mesosiderite	J. L. Smith, 1880.

Name (*cont.*).	Ratio of Fe to Ni.	Ratio of MgO to FeO in olivine.	Ratio of MgO to FeO in pyroxene.	Class.	Analyst and date.
Hainholz	10	3	3	Mesosiderite	F. Wöhler, 1857.
Llano del Inca	10	$\frac{1}{12}$	2	,,	L. G. Eakins, 1890.
Taney County	$12\frac{1}{2}$	7	3	,,	J. L. Smith, 1865.
Morristown	12	$\frac{1}{2}$	8	Grahamite	L. G. Eakins, 1893.
Powder Mill Creek	7	—	4	,,	J. E. Whitfield, 1887.
Lodran	7	7	5	Lodranite	G. Tschermak, 1870.

The list shows that, on the whole, the siderolites, in the poorness in nickel of the nickel-iron and the poorness in iron of the ferromagnesium minerals, correspond to Group 2 (Cronstad type) of chondritic stones. In the pallasites, with the exception of Mount Vernon and Eagle Station, the ratio of MgO to FeO is remarkably constant at about 7. The grahamites (including some mesosiderites), containing a felspar near to anorthite, appear to have relations with the eucrites, since they are richer in lime and alumina than most chondritic stones (see p. 37). Further analyses, however, of the individual minerals of these felspar-bearing siderolites are needed before their place can be definitely fixed. Where this has been done, as in the case of Estherville and Taney County by Lawrence Smith, the ratio of the MgO to FeO for the olivine was found to be about 7 as in the pallasites, and that of the pyroxene about 3. In other cases (e.g. Morristown and Llano del Inca) where the separation has been made into parts soluble and insoluble in acids, although the ratio for the pyroxene is still about 3, that of the olivine sinks to less than unity; possibly owing to admixture with metallic iron not separated by the magnet, for the soluble in Morristown contains over 1 per cent. of NiO, and that of Llano del Inca nearly 3 per cent.

Achondrites containing little or no nickel-iron.

In these non-chondritic stones (with the exception of the bustites and ureilites) it is found, according to expectation, that the ferromagnesium minerals are rich in iron, and the small amount of nickel-iron, when present, is correspondingly very rich in nickel. The following list gives the percentage of nickel-iron, the ratio of Fe to Ni in this iron, and the ratio of MgO to FeO in the ferromagnesium silicates for most of these stones:—

Name.	Percentage of nickel-iron.	Ratio of Fe to Ni in nickel-iron.	Ratio of MgO to FeO in Mg-silicates.	Class.	Analyst and date.
Ibbenbühren	—	—	2½	Chladnite (Diogenite)	G. vom Rath, 1872.
Manegaum	—	—	2	,,	N S. Maskelyne & W. Flight, 1870.
Shalka	—	—	2	,,	N. S. Maskelyne & W. Flight, 1871.
Chassigny	—	—	2	Chassignite	A. Damour, 1862.
Jelica	1½	2	2	Amphoterite	S. M. Losanitch, 1889.
Manbhoom	2	1½	2½	,,	H. von Foullon, 1888.
Bandong	3	2	1	Rodite	— Vlaanderen, 1872.
Roda	—	—	2½	,,	F. Pisani, 1874.
Vavilovka	3	2	2½	,,	P. Melikov, 1893.
Angra dos Reis	—	—	2½	Angrite	E. Ludwig & G. Tschermak, 1909.
El Nakhla	—	—	1	Nakhlite	G. T. Prior, 1911.
Frankfort	—	—	2	Howardite	G. J. Brush & W. J. Minter, 1869.
Mässing	—	—	1	,,	A. Schwager, 1878.
Petersburg	—	—	1	,,	J. L. Smith, 1861.
Constantinople	—	—	½	Eucrite	G. Tschermak, 1872.
Juvinas	—	—	⅔	,,	J. E. Whitfield, 1916.
Peramiho	—	—	⅔	,,	E. Ludwig, 1903.
Stannern	—	—	½	,,	C. Rammelsberg, 1851.
Sherghotty	—	—	⅚	Sherghottite	E. Lumpe, 1871.
Bustee	—	24	∞	Bustite	N. S. Maskelyne, 1870.
Bishopville	—	—	∞	,,	J. L. Smith, 1864.
Alatyr (Novo-Urei)	5½	26	Olivine 5 Pyroxene 8	Ureilite	M. Jerofejeff & P. Latschinoff, 1888.
Goalpara	8½	—	Olivine 4 Pyroxene 12	,,	N. Teclu, 1870.

As seen in this list, the chladnites (diogenites), chassignites, amphoterites, and rodites have a ratio of MgO to FeO of 2 to 2½ and a nickel-iron, when present, extremely rich in nickel. Felspar when present, as e.g. in Jelica and Manbhoom,[1] is oligoclase and not anorthite. In chemical composition therefore these stones correspond to Group 4 (Soko-Banja type) of chondritic stones.

The angrites, nakhlites, howardites, eucrites, and sherghottites, besides

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[1] H. Michel, 'Plagioklase der Meteoriten.' Min. Petr. Mitt., 1913, vol. xxxii, p. 170.

having for the most part ferromagnesium silicates still richer in iron, are richer in lime, and (with the exception of El Nakhla) also in alumina, than chondritic stones generally. These chemical characters manifest themselves in most of the stones by a fairly high content of felspar which is near to anorthite instead of to the oligoclase of chondritic stones, and also in all of them by an increased amount of monoclinic pyroxene, which in the case of the eucrites is the enstatite-augite of Wahl (see p. 28), of small optic axial angle and poor in lime as compared with most terrestrial augites, but containing more than the orthorhombic pyroxenes of the chondrites. In chemical characters, therefore, these stones extend rather beyond the limits of the Soko-Banja group and are not at present represented with certainty amongst chondritic stones, for the so-called howardite-chondrites present no very striking resemblance to howardites under the microscope, and chemically appear to belong mostly to the Soko-Banja group.

Now to the increase of ferrous oxide in the ferromagnesium minerals in stones containing little or no nickel-iron, there are two notable exceptions, viz., the bustites (Bustee, Aubres, and Bishopville), and the ureilites (Alatyr (Novo-Urei), Dyalpur and Goalpara), but these appear to be, *par excellence*, exceptions which prove the rule.

Bustites in the character of their pyroxenic and felspathic constituents differ essentially from the chladnites (diogenites), Shalka, Manegaum, and Ibbenbühren, with which one of them (Bishopville) has hitherto been confused. They consist mainly of a nearly pure enstatite practically free from iron, with oldhamite and an acid plagioclase felspar (near to oligoclase) instead of anorthite, as accessory constituents. Examination of specimens in the British Museum Collection shows that Bustee and Aubres only differ from Bishopville in being rather more clastic, and Bustee also in containing, but for the most part only in the neighbourhood of the nodule rich in oldhamite, a monoclinic pyroxene, rich in lime, and nearly free from iron. Of the two published analyses of Bustee, the one by Dancer, which is very similar to that of Bishopville, probably represents more closely the chemical composition of the main mass of the stone than that of Maskelyne which was made on exceptional material from the neighbourhood of the oldhamite nodule. Although the name 'chladnite' was originally applied to Bishopville, it has become so associated in the Rose-Tschermak classification, as modified by Brezina, with the very different stones, the diogenites of Tschermak, Shalka, Manegaum, and Ibbenbühren, that it may be advisable to retain it for them, while Bishopville is included with Bustee and Aubres in the bustite class.[1]

Except that they contain so little nickel-iron, bustites, in chemical and mineral composition, are precisely similar to the Daniel's Kuil (Hvittis) type of chondritic stone, for in both oldhamite occurs in fair amount, the nickel-iron (as seen from Maskelyne's analysis) is very poor in nickel, and the enstatite and felspar are similar in chemical composition. Bustites probably separated from the same magma which gave rise to Group 1 of chondritic stones, but under more deep-seated conditions which allowed of a partial segregation of the nickel-iron.

The ureilites consist of a coarsely crystalline aggregate of olivine and monoclinic pyroxene cemented together by a film of nickel-iron and carbonaceous matter. As already pointed out by Wahl,[2] they are not chondritic, but in structure are very similar to the pallasites, the nickel-iron although in small amount forming a similar sort of mesh round the other constituents. The analyses show that the iron is poor in nickel and the ferromagnesium silicates correspondingly poor in iron, the ratio of MgO to FeO for the olivine being about 4–5, and for the pyroxene from 8–12. In spite of their poorness in iron, the ureilites therefore are similar in general composition to Lodran, and correspond to Group 2 (Cronstad type) of chondritic stones, just as the bustites do to Group 1.

THE GENETIC RELATIONSHIP OF METEORITES.

As pointed out by L. Fletcher,[3] the general similarity of structure and chemical composition and the almost universal presence of nickel-iron suggest a common source for all meteorites. As regards the chondritic stones, the published analyses show that for stones of all four groups the percentage of magnesia varies within only narrow limits. The variations in the amount of ferrous oxide, on the other hand, are considerable, for a stone like Daniel's Kuil belonging to Group 1 contains practically none, whereas stones of the other Groups 2–4 have ferromagnesium silicates increasingly rich in ferrous oxide. This distinction between the groups however becomes almost evanescent when, instead

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[1] An alternative plan would be to retain the name Chladnite for Bishopville as a stone consisting mainly of pure enstatite without diopside, and to revive Tschermak's name of diogenite for the bronzite stones, Shalka, Manegaum, and Ibbenbühren.

[2] W. Wahl, Min. Petr. Mitt., 1907, vol. xxvi, p. 90.

[3] Sir L. Fletcher, 'An Introduction to the Study of Meteorites' (British Museum Guide-Book), eleventh edit., 1914, p. 50.

of oxides, atoms are considered. A. E. Nordenskiöld[1] many years ago, and W. Wahl[2] more recently, have shown in the case of several chondritic stones that the atomic composition is very similar, and the latter has drawn the conclusion that the difference between the enstatite-chondrite, Hvittis, and the other chondrites depends only upon the different amounts of oxygen the stones contain. If, in the case of the four type specimens of chondritic stones, the total Mg and Fe atoms be compared instead of only the oxides, the ratio of Mg to Fe shows much less variation than might be expected from the differences in the amount of nickel-iron. As seen in the table on p. 27, for Daniel's Kuil containing 25 per cent. of nickel-iron this ratio is about 1, and for Soko-Banja containing only 4, it is about 1·8. This is a direct result of the interrelationship between the amount and composition of the nickel-iron and the amount of oxide of iron in the magnesium silicates which we have sought in the preceding pages to establish, not only for the chondrites but for meteoric stones generally. It leads at once to the conclusion *that all meteorites have had a common origin from a single magma which is most nearly represented by that which gave rise to the Bustee and the Daniel's Kuil (Hvittis) types of meteoric stone, and that from this magma all other types have been produced by progressive oxidation of the nickeliferous iron.*

In a magma such as would produce stones of the Daniel's Kuil type the amount of oxygen was sufficient to form oxides with the elements silicon, magnesium, aluminium, sodium, but only partially with calcium and chromium,[3] and scarcely at all with iron. No chemical action therefore was possible which could lead to the production of iron-bearing pyroxenes or of more basic ferriferous olivines. As soon, however, as the magma came under the further influence of oxidizing agents, some of the iron would also be converted into oxide, and a reaction would then be possible by which part of the magnesium silicate would be reduced to a ferriferous olivine, and part converted into a bronzite. In this reaction the nickel took no part, for the ferromagnesium minerals of chondritic stones contain practically no oxide of nickel.[4] Consequently,

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[1] A. E. Nordenskiöld, Geol. Fören. Förh. Stockholm, 1878, vol. iv, p. 56.

[2] W. Wahl, 'Beiträge zur Chemie der Meteoriten.' Zeit. Anorg. Chemie, 1910, vol. lxix, p. 67.

[3] Part of the Ca and Cr are in the form of sulphides, oldhamite and daubreelite.

[4] This fact, which has given rise to much comment, has been explained by Wahl (l. c. p. 70) as due to the lower heat of production of oxide of nickel as compared with that of oxide of iron.

the residual iron, according to the degree to which the oxidation was carried, would become progressively more and more enriched in nickel. The production in this way of the particular olivine and bronzite and the nickel-rich iron of Soko-Banja from a magma having the composition of Daniel's Kuil may be represented approximately by the following equation:—

$$\underset{\text{Enstatite}}{19\,\mathrm{MgSiO_3}} \;+\; \underset{\text{Nickel-iron}}{9\,(\mathrm{Fe} + \tfrac{1}{13}\,\mathrm{Ni})} \;+\; \underset{\text{Oxygen}}{7\mathrm{O}}$$

$$= \underset{\text{Olivine}}{2\,(5\,\mathrm{MgO.2\,FeO.3\tfrac{1}{2}\,SiO_2})} + \underset{\text{Bronzite}}{3\,(3\,\mathrm{MgO.FeO.4\,SiO_2})} + \underset{\text{Nickel-iron}}{2\,(\mathrm{Fe} + \tfrac{9}{2.6}\,\mathrm{Ni})}.$$

On the left in this equation the proportion by weight of the enstatite and nickel-poor nickel-iron is about the same as in Daniel's Kuil, and on the right the relative amounts and chemical composition of the olivine and bronzite are about what they are in Soko-Banja, and the nickel-iron is considerably reduced in amount and proportionately enriched in nickel.

It is just conceivable that to some such action as this we must look for the explanation of the formation of chondrules. In the Daniel's Kuil (Hvittis) type chondrules are of rare occurrence and consist almost solely of fibrous pyroxene. If, as suggested by Wahl (l. c. p. 92), chondritic stones were produced under surface conditions like terrestrial volcanic tuffs, it may be that the oxidation of the nickel-iron, with the resultant production of the olivine and bronzite, was of such a violent nature that drops were thrown out in a hot and rarefied atmosphere[1] and consolidated sufficiently slowly to form the crystalline chondrules.

METEORITES AND THE EARTH'S INTERIOR.

Although no very general support has been given to Sir Robert Ball's[2] suggestion that meteorites falling upon the earth from outer space are only returning to their original home from which they were ejected at an early stage of its history when the moon was separated, there is a widely accepted idea that the earth's interior is composed of material very similar to meteorites. In accordance with the genetic relationship of meteorites suggested above, the earth's core may be regarded as consisting mainly of iron, with other metals, principally Ni, Mg, Ca,

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[1] L. H. Borgström, 'Der Meteorit von St. Michel.' Bull. Comm. Géol. Finlande, 1912, No. 34, p. 88.

[2] Sir Robert Ball, 'Speculations on the Source of Meteorites.' Nature, 1879, vol. xix, p. 493.

Na, Al, and Cr, and non-metals, principally Si, S, and C, by the progressive oxidation of which the more superficial formations of the earth's crust have resulted. Above this core it may be imagined is an oxidized zone in which the Mg, Si, Na, Al, and Ca occur more and more in the form of oxides, but the iron and nickel are still in the metallic state. The upper part of such a zone would correspond to a magma such as gave rise to the nickel-poor hexahedrite type of meteoric iron, and the Bustee and Daniel's Kuil types of meteoric stone, in which calcium is still partly in the form of sulphide and the magnesium silicates contain no iron. Above this zone, it is conceivable, is one of further oxidation, in which part of the iron is also in the state of oxide, but that only in the ferrous condition. This zone would correspond to the other meteoric stones containing ferriferous olivine and bronzite, and a nickel-iron increasingly rich in nickel as it decreased in amount. In this connexion the occurrence in New Zealand and Canada of nickel-iron (awaruite and josephinite) extremely rich in nickel, in association with serpentine and peridotite, is of some significance. In a zone of still higher oxidation, in which all the iron is in the form of oxide, the higher oxides should occur besides the ferrous, and magnetite should be a prominent constituent. Such a zone would correspond to basalt, which recent researches claim as the magma from which all other igneous rocks of the earth's surface have been derived, whether by absorption of sedimentary rocks,[1] or by differentiation controlled by crystallization.[2]

THE GENERAL CLASSIFICATION OF METEORITES, SHOWING THEIR MUTUAL RELATIONS.

The Rose-Tschermak-Brezina scheme of classification now generally adopted, in the case of the chondrites is somewhat complicated and divides them into groups which do not appear to have much relation to their chemical and mineral composition.

The following scheme of classification, according to which all the three main classes of meteorites, viz. Chondrites, Achondrites, and Irons, are divided into five groups, each having some characters common to all three classes, serves to express the genetic relationship of meteorites demonstrated in the preceding pages, and also to exhibit their chemical and mineral distinctions. The groups from 1 to 5 may be

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[1] R. A. Daly, 'Igneous Rocks and their Origin.' 1914.

[2] N. L. Bowen, 'The later stages of the evolution of the Igneous Rocks.' Journ. Geol., 1915, vol. xxiii, No. 8, Supp.

Class.	Group 1. Iron, poor in Ni. Mg-silicates (Enstatite) almost free from Fe and Ca. Felspar, oligoclase.	Group 2. Iron, less poor in Ni, generally in large amount. Mg-silicates (Bronzite and Olivine) poor in Fe and Ca (MgO : FeO = 4–7). Felspar, oligoclase in chondrites, anorthite in siderolites.	Group 3. Iron, rich in Ni, in less amount. Mg-silicates (Bronzite and Olivine) poor in Ca, but richer in Fe (MgO : FeO = 3–4). Felspar, oligoclase.	Group 4. Iron, richer in Ni, in still less amount. Mg-silicates (Bronzite and Olivine poor in Ca, but still richer in Fe (MgO : FeO = 2–3). Felspar, oligoclase.	Group 5. Iron, little or none. Mg-silicates (Bronzite, Olivine, and Augite) richer in Ca as well as in Fe. Felspar, anorthite.
Chondrites	Daniel's Kuil (Hvittis) Type.	Cronstad Type.	Baroti Type.	Soko-Banja Type.	—
Symbol	C 1	C 2	C 3	C 4	C 5
Achondrites (non-chondritic stones)	Bustites (including Bishopville).	Siderolites (including Lithosiderites). Ureilites.	—	Chladnites (Diogenites). Chassignites. Amphoterites. Rodites.	Angrite. Nakhlite. Howardite. Eucrite. Sherghottite.
Symbol	A 1	A 2	A 3	A 4	A 5
Irons (Siderites)	Hexahedrites. Nickel-poor Octahedrites. Nickel-poor Ataxites.	Most Octahedrites. Nickel-poor Ataxites.	Nickel-rich Octahedrites. Nickel-rich Ataxites.	Ataxites still richer in Ni.	—
Symbol	S 1	S 2	S 3	S 4	S 5

regarded as corresponding to different magmas progressively richer in oxygen, each of which has given rise to members of all three classes of meteorites.

According to this scheme, which may be used as subsidiary to the present classification in all cases where the chemical composition of the meteorite has been determined, the chondritic stones are divided into four groups corresponding to the Daniel's Kuil (Hvittis), Cronstad, Baroti, and Soko-Banja types, and may be distinguished by the symbols C1–C4. Under these same four groups can be arranged the meteoric irons (Siderites), with symbols S1–S4, according to their richness in nickel, and also most of the non-chondritic stones, with symbols A1–A4, according to the richness in iron of their magnesium silicates. A fifth group (A5) is added for the remainder of the non-chondritic stones (angrites, nakhlites, howardites, eucrites, and sherghottites), in which the magnesium silicates are richest in iron, since they are also richer in lime, and (with the exception of El Nakhla) in alumina, than any chondritic stones of which the chemical composition has been determined.

The main principle of classification of the meteoric stones is the ratio of MgO to FeO in the magnesium silicates, and its interrelation with the richness in nickel of the nickel-iron. The further interrelation with the amount of nickel-iron is true for most stones, but is liable to a few exceptions amongst the achondrites (see list on p. 36), and possibly also amongst the chondrites (see list on p. 33).

CONCLUSIONS.

The source of all meteorites, and possibly by analogy of all terrestrial rocks, was a nickel-poor nickel-iron containing originally also other unoxidized metals, principally Mg, Al, Ca, Na, and Cr, and non-metals, principally Si, S, and C. In the magma which gave rise to such meteorites as the rare Bustee type of non-chondritic stone and the Daniel's Kuil (Hvittis) type of chondritic stone, sufficient oxygen had been added to the original nickel-iron to form oxides with the Mg, Si, Al, Na, but only partially with Ca and Cr, and scarcely at all with Fe. These meteorites therefore consist mainly of a metasilicate of magnesium, enstatite, free from iron, a nickel-poor nickeliferous iron, a sulphide of iron, troilite, a sulphide of calcium, oldhamite, a sulphide of chromium and iron, daubreelite, and an acid soda-lime felspar. By a further accession of oxygen, part of the iron also became converted into oxide, and a reaction was then possible which led to the production of iron-bearing olivine and bronzite instead of pure enstatite. Under surface conditions this action may have given rise to the chondrules of chondritic stones. In this process the nickel escaped oxidation so long as any iron remained in the metallic state, and consequently this residual iron became increasingly enriched in nickel. Therefore, *in meteoric stones generally, the poorer they are in nickel-iron, the richer that iron is in nickel, and the richer in iron are the magnesium silicates.*

The classification proposed in order to illustrate this genetic relationship of meteorites divides the chondritic stones into four groups corresponding to the four types (1) Daniel's Kuil (Hvittis), (2) Cronstad, (3) Baroti, (4) Soko-Banja, which contain in order decreasing amounts of nickel-iron increasingly rich in nickel, and magnesium silicates increasingly rich in ferrous oxide. Under the same four groups fall the meteoric irons according to their richness in nickel, and most of the non-chondritic stones according to the richness in ferrous oxide of their magnesium silicates. A fifth group is added for the remaining non-chondritic stones, which are somewhat richer in lime and generally also in alumina than any chondritic stones of which the chemical composition is known.