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The chemical classification of iron meteorites—II. Irons and pallasites with germanium concentrations between 8 and 100 ppm

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Abstract—We report the concentrations of Ni, Ga, Ge and Ir in sixty-one iron meteorites and six pallasites having 8–100 ppm Ge, and eight irons having less than 8 ppm Ge. A new resolved chemical group is described, which is composed of irons which appear to be genetically related. It has two distinct branches, which are designated IIIA (twenty-four irons) and IIIB (fourteen irons). Arguments are given which indicate that the pallasites form an additional resolved group. Three new members of group IVA and a single new member of group IVB are also reported. The remaining meteorites (including four studied previously) are classified into a tentative group of four irons, five doublets, sixteen apparently unique irons, and one mislabelled iron which had been studied previously. Strong correlations are found between the concentrations of the different elements within subgroups IIIA and IIIB. The former shows a positive correlation between Ge (or Ga) and Ni, whereas the latter shows a negative correlation. The compositional differences within resolved groups are discussed in terms of possible fractionation processes. It seems likely that the variations in composition within each group are associated with the original radial distribution within the parent body. The cosmic-ray ages of groups IIIA and IIIB are similar within each subgroup and between the subgroups, with no correlation between age and variations in chemical composition. Short discussions are given regarding the number of parent bodies, and the interpretation of available evidence on cooling rates.

INTRODUCTION

THIS is the second of a series of papers reporting the results of a study of the concentrations of Ni and of some interesting trace elements in the iron meteorites. The first paper in the series (WASSON, 1967a) was chiefly concerned with meteorites having low concentrations of Ge. This report deals with irons having intermediate concentrations of Ge, in the range of 8–100 ppm.

BROWN and co-workers (GOLDBERG *et al.*, 1951; LOVERING *et al.*, 1957) were the first to make measurements of trace elements in substantial numbers of iron meteorites. They showed that there appeared to be a "quantization" of the measured concentrations of the elements Ga and Ge, with some concentration ranges highly favored. On the basis of their results they classified the metorites into Ga–Ge groups which had limited ranges of each element. These four groups were believed to have genetic significance, and possibly to indicate that the iron meteorites originated in at least four parent bodies.

More recently, NICHIPORUK and BROWN (1965) and HERR *et al.* (1961) have determined noble-metal concentrations in iron meteorites. Their results show a rough quantization in the concentrations of these elements (Ru, Rh, Re, Os, Ir and Pt), but groups based on these elements are quite different in their membership from the four Ga–Ge groups. Further "quantizations" of other elements have recently been reported by SMALES *et al.* (1967) and COBB (1967).

The first paper of this series (WASSON, 1967a) was essentially an investigation of thirty-four irons expected to be members of Ga–Ge group IV. Improved techniques were used which allowed Ga and Ge to be determined in all irons, whereas LOVERING *et al.* (1957) had reported upper limits for a number of the objects they classified as group IV. The improved data allowed two new groups to be delineated, which were designated IVA and IVB. Each of these groups was composed of irons having very similar structures and Ni concentrations. It was noted that group I of LOVERING *et al.* was defined in a similar manner, whereas groups II and III each contained meteorites of widely differing structure and Ni content. The former groups were considered to be resolved, and it was proposed that such groups should contain only meteorites of a single structural type, and should have limited ranges of Ni as well as other siderophilic elements. There was some indication in the noble-metal data cited above that the latter requirement might be conserved for these elements, but the amount of data was much too small to allow more than a qualitative statement to be made.

On the basis of these considerations we have chosen to investigate the chemical characteristics of a large number of iron meteorites. In addition to Ga and Ge, procedures were developed which allowed the determination of Ni and Ir in the same samples. The present paper reports Ga, Ge and Ni concentrations in seventy-five irons, and Ir concentrations in thirty-five of these objects.

EXPERIMENTAL

A scheme has been developed which allows the determination of the four elements Ni, Ga, Ge and Ir in a single sample. More details of some aspects of the procedure for Ga and Ge can be found in WASSON and KIMBERLIN (1966). The separation sequence is as follows. Meteorite samples weighing about 0·8–1·4 g are irradiated with thermal neutrons at a flux of 10^{12} neutrons /cm^2 per sec in the core of the UCLA reactor. After the irradiation, the samples are etched lightly and dissolved in a refluxing mixture of about 25 ml total volume which is 3 N in HNO_3 and 1·5 N in HCl, and which contains known amounts of Ga, Ge, As, Ir and sometimes other carriers. After dissolution, the volume of the solution is adjusted to exactly 50 ml, and an aliquot is taken for Ni determination. The amount of this aliquot is chosen such that subsequent redilution to 50 ml gives a solution containing approximately 40 ppm Ni. A typical aliquot size is 1 ml.

The remaining solution from the dissolution is reduced in volume by evaporation to approximately 30 ml, and sufficient HCl is added to make the solution 8 M in HCl. Germanium is extracted from this mixture into CCl_4. The residual aqueous layer is cooled, and Ga is extracted with isopropyl ether. The residual aqueous mixture is taken to dryness with 2 ml H_2SO_4, taken up in H_2O, oxidized with Cl_2 and HNO_3, and the Ir is removed by passing this mixture through an anion-exchange column.

Nickel determination

The Ni is determined by atomic absorption spectrometry. A single-slot laminar-flow burner is used, with the acetylene–air flame adjusted to be as hot as possible while remaining steady. If a cooler flame is used, the Ni absorbance is reduced by interference from PO_4^{3-}. Samples and standards are kept at the same temperature, since there is a substantial temperature effect on the aspiration rate, and thus on the absorbance. A full set of standards are run with each batch of samples. The 3414 Å line of Ni is employed, and about 45 % absorption is normally found for a 40 ppm Ni solution. No interference from any of the carriers or known components of iron meteorites are found under these conditions.

In order to test the precision of the method, Ni was determined in eight samples each of the meteorites Negrillos and Grant. These should be representative of the best and worst samples which one will normally encounter in meteorite studies. Negrillos is a hexahedrite consisting almost entirely of kamacite, with a few very small rhabditic schreibersite inclusions. Grant is a fine-to-medium octahedrite with large Brezina lamellae inclusions of schreibersite, each of which is surrounded by large bands of swathing kamacite (Grant is similar to Mt. Edith, which is illustrated in Fig. 6). Samples of this object would be expected to show high Ni concentrations if a large amount of schreibersite were present, and low Ni concentrations if an unusually large amount of kamacite were present. The results of determinations are shown in Table 1. The relative standard deviation of the determinations on Negrillos is 0·9%, whereas that for the Grant determinations is 1·6%. The standard deviations would have been somewhat larger had

Table 1. Replicate determinations of the Ni content of the Negrillos and Grant meteorites

	Ni concentration (%)									
Sample	1	2	3	4	5	6	7	8	Mean	σ
Negrillos	5·40	5·42	5·47	5·41	5·39	5·38	5·47	5·32	5·41	0·05
Grant	9·22	9·17	9·10	9·33	9·29	9·27	9·33	9·60	9·29	0·15

each of the samples been run on separate days. On the basis of these data the 95% confidence limits of the mean for duplicate determinations is estimated to be about 2% of the mean for most of our samples. Any systematic bias should be of this magnitude or less.

Determination of Ga *and* Ge

The procedure used for the determination of Ga and Ge is very similar to that previously published (Wasson and Kimberlin, 1966; Wasson, 1967a, b). Most of the Ge determinations were made using the 11-hr Ge^{77} isotope [which accounts for the relatively high upper limits given for the Ge concentrations of Chinga and Babb's Mill (Blake's)]. All counting is performed on liquid samples. A 3 × 3 in. well-type scintillation detector is used for counting the 0·84-MeV gamma of Ga^{72}, whereas a 1¾ × 2 in. detector is used for the 0·20–0·25 MeV peaks of Ge^{75-77}. About 6 ml of solution is counted in standard wells. As noted by Wasson (1967b), the recovery of Ga carrier is now determined by atomic absorption spectrometry.

The precision of the procedure in this concentration range is considerably better than that estimated earlier (Wasson, 1967a) for very low concentrations. We believe that the 95% confidence limits on the mean of duplicate determinations of Ga and Ge is of the order of ±4% of the means. Any bias due to systematic errors is expected to be of this magnitude or less.

Determination of Ir

The procedure for the neutron-activation determination of iridium is given in detail elsewhere (Kimberlin *et al.*, 1967). It is based on the 74-day Ir^{192} isotope. A brief outline of the procedure follows: The Ir forms a dark band on the top of the anion-exchange column. The top portion of the column is removed, and Ir is batch extracted by heating in 30 ml H_2O containing about 0·5 g hydrazine. Additional purification is obtained by precipitating hydrous IrO_2 with $NaBrO_3$. The precipitate is dissolved in a known amount of H_2O containing a few drops of HCl and H_2O_2. If the gamma-spectrum is not clean, the sample is purified further by passage through a cation-exchange column and/or additional IrO_2 precipitations. In order to measure the recovery of Ir carrier, an aliquot of the diluted sample solution is evaporated onto high-purity Al foil, and the Ir content is determined by nondestructive neutron-activation analysis.

The relative standard deviation for eight replicate samples of Negrillos was found to be 2·6%, whereas that found for eight samples of Grant was 10·5%. Thus, 95% confidence limits for the means of duplicate analyses will vary from about 5% for inclusion-free irons with high Ir contents such as Negrillos (64 ppm Ir) to about 20% for inclusion-rich irons with low Ir contents such as Grant (0·049 ppm Ir). Systematic errors may have been quite serious. Baedecker (1967) has shown that a great deal of care is necessary to insure exchange between

Table 2. A comparison of our Ge, Ga, Ni and Ir results with those of other investigators

Meteorite	Ni concentrations (%)			Ga concentrations (ppm)				Ge concentrations (ppm)				Ir concentrations (ppm)	
	Henderson*	Goldberg	This work	Goldberg	Lovering	Smales	This work	Lovering	Smales	Shima	This work	Nichiporuk	This work
Bear Creek	—	10·02	9·99	17·5	15	—	18·8	25	—	—	32·8	<0·4	—
Canyon Diablo	—	7·11	7·19	76·3	74	79·7	81·8	283	322	307	328	1·8	1·9
Coahuila	5·59	5·65	5·54	64·5	54	51	57·6	152	175	—	178	14·8	—
Drum Mountains	8·59	—	8·35	21·0	—	—	20·4	—	—	—	41·8	—	—
Glorieta Mountain	11·79	—	12·04	—	12	14·2	13·4	18	10·9	—	11·1	—	—
Goose Lake	8·39	8·48	7·92	75·1	57	—	65·7	221	290†	—	307	2·2	1·7
Grant	9·35	—	9·29	—	—	—	20·5	—	—	64·2	37·5	—	0·049
Henbury	—	7·59	7·47	17·2	60‡	15	17·4	209‡	36	—	34·2	2·3‡	12
Negrillos	5·32	—	5·41	—	55	—	59·5	136	—	89	176	—	45
Odessa	—	7·55	7·55	69·3	—	—	74·7	—	—	405	298	1·8	—
Sandia Mountains	5·92	5·94	4·85	56·5	53	—	59·0	143	184†	—	174	<0·4	0·25
Spearman	—	8·78	8·65	21·4	19	—	20·2	53	44†	—	46·0	0·3	—

* The references to the Ni determinations by Henderson are as follows: Coahuila, Glorieta Mountain, Grant, Sandia Mountains, *Amer. J. Sci.* **239**, 407 (1941); Drum Mountains, *Smithsonian Misc. Coll.* **110**, No. 12 (1948); Goose Lake, *Proc. U.S. Natl. Museum* **107**, 339 (1958); Negrillos, *Amer. Miner.* **26**, 546 (1941).

† These results are taken from Smales *et al.* (1958); the other values in this column are from Smales *et al.* (1967).

‡ The "Henbury" sample studied by Lovering *et al.* (1957) and Nichiporuk and Brown (1965) is not a genuine Henbury; on the basis of their results we think it may be Toluca.

the different chemical species in which Ir can exist in solution. We have confirmed his findings, and some of our results may be low because of incomplete exchange between sample and carrier Ir. We do not believe that such errors exceed the 20% precision limits (at 95% confidence) which we assign to the reported data, however.

Comparison with the results of other investigators

Table 2 compares some of our results (including data of several irons not discussed in this paper) with those reported by other investigators. In general, there is quite good agreement between the various research groups involved. Our Ni results are compared with those of HENDERSON and GOLDBERG *et al.* (1951). The only serious discrepancy is for Goose Lake, for which our Ni result is about 6% lower relative to the other values.

Our Ga results are compared with those of GOLDBERG *et al.* (1951), LOVERING *et al.* (1957) and SMALES *et al.* (1967). Differences amounting to more than 10% are rare except that the values of LOVERING *et al.* are systematically 10–15% lower than those of the other research groups. COBB and MORGAN (1965) have reported Ga concentrations which are systematically about 20% higher than ours. More recent results by COBB (1967) agree quite well with our data.

Comparisons for Ge are made with the data reported by LOVERING *et al.* (1957), SMALES *et al.* (1958, 1967) and SHIMA (1964). Consistent agreement is found with the values of SMALES. The values of LOVERING *et al.* seem to be somewhat less accurate, and SHIMA's errors amount to as much as a factor of 2 of the reported value.

Table 2 compares our Ir results with those reported by NICHIPORUK and BROWN (1965). The agreement is quite good, except for the midlabelled Henbury specimen. COBB (1957) reports Ir concentration data for thirty-three irons, a few of which have also been studied in our group. The agreement is quite good, considering the large errors in our data.

RESULTS

The concentrations of Ni, Ga and Ge in sixty-nine iron meteorites and six pallasites are listed in Table 3. Concentrations of Ir are listed in those cases where our data was judged to have an accuracy of at least $\pm 30\%$. These same samples were used for determinations of all four elements starting in September 1966. Earlier, Ir and Ni values were determined on separate samples.

The meteorites are listed in alphabetical order. Mean values are listed along with error estimates which are meant to be 95% confidence limits of the means. These are based on the errors described in the previous section, though the limits have been increased in those cases where substantial differences were observed between replicate analyses.

Descriptions of all samples are found in the appendix. Two irons were found to be mislabelled, and are called *pseudo*Apoala and *pseudo*Misteca. They are probably specimens of the Misteca and Yanhuitlan irons.

CLASSIFICATION

Groups of genetically-related iron meteorites

In a recent paper, WASSON (1967c) has attempted to define the characteristics of resolved, genetically related groups of iron meteorites. These are as follows:

1. The extreme range of concentration of an element within the group will be considerably smaller than that observed in the meteorites as a whole.

2. Concentrations of particular elements will vary coherently within a group. A plot of the concentrations of two different siderophilic elements against each other will, within sampling and experimental error, give a line or a smooth curve on a log–log plot.

Table 3. Mean concentration of Ni, Ga and Ge in seventy-five iron meteorites and pallasites, and of Ir in thirty-two irons and two pallasites. Individual determinations are also listed for Ga and Ge. Errors are 95% uncertainty limits, and are listed only where these limits exceed 2, 4, 4 and 20% of the means for Ni, Ga, Ge and Ir, respectively.

Meteorite	Ni (%) mean	Ga (ppm) replicates	Ga (ppm) mean	Ge (ppm) replicates	Ge (ppm) mean	Ir (ppm) mean
Admire	9·7 ± 0·6	*22·4, 19·3*	20·9	*51·6, 45·3*	48·4	—
Aggie Creek	8·44	*20·6, 20·4*	20·5	*41·2, 38·6*	39·9	0·70 ± 0·20
Anoka	12·04	*18·1, 17·4*	17.8	*16·2, 16·1*	16·2	—
Apoala, *authentico-*	9·69	*18·8, 17·8*	18·3	*35·9, 34·6*	35·2	—
Apoala, *pseudo-*	8·23	*21·9, 22·6*	22.2	*42·4, 42·7*	42.6	1.3
Babb's Mill (Blake's)	11·9 ± 0·3*	*0·203*	0·203	*<0·28*	<0·28	2·1 < 0·5*
Barranca Blanca	7·96	*20·4, 23·9*	22·1	*61·6, 66·2*	63·9	5·0
Bear Creek	9·99	*18·6, 19·0*	18·8	*33·9, 31·7*	32·8	—
Bella Roca	10·16	*17·1, 16·3*	16·7	*31·3, 31·0*	31·1	—
Bellsbank	4·0 ± 0·3	*38·3, 40·2*	39·2	*55·0, 54·2*	54·6	0·15
Boxhole	7·68	*18·9, 17·3*	18·1	*37·6, 36·9*	37·2	—
Breece	9·6 ± 0·04	*19·6, 19·2*	19·4	*37·9, 37·9*	37·9	—
Brenham	11·1 ± 0·5	*25·6, 26·7*	26·2	*68·0· 75·4*	71·7	—
Cambria	10·40	*10·9, 11·0*	10·9	*1·54, 1·58*	1·56	0·84 ± 0·20
Canyon City	7·78	*18·3, 19·5, 19·2*	19·5	*36·2, 35·5, 36·2*	36·0	10
Cape York	7·47	*19·0, 19·4*	19·2	*36·6, 35·4*	36·0	4·9
Carbo	9·98	*65·9, 65·8, 74·1*	68·6	*89·1, 82·6, 90·0*	87·2	13
Carlton	13·20	*11·9, 10·9*	11·4	*8·82, 8·64*	8·73	—
Carthage	8·35	*21·0, 21·9*	21·5	*44·2, 43·3*	43·7	—
Chinga	16·7 ± 0·5*	*0·188*	0·188	*<0·18*	<0·18	—
Chupaderos	10·40	*17·0, 16·7*	16·9	*30·0, 30·8*	31·1	—
Costilla Peak	7·55	*18·9, 18·5*	18·7	*33·6, 33·6*	33·6	13
Cuernavaca	10·4 ± 0·5	*16·9, 15·6, 16·8*	16·4	*32·1, 30·6, 31·9*	31·6	—
Delegate	9·69	*20·5, 20·1*	20·3	*41·9, 41·6*	41·7	—
Descubridora	7·70	*20·4, 20·6*	20·5	*40·0, 39·5*	39·7	2·1
Drum Mountains	8·35	*20·5, 20·3*	20·4	*42·9, 40·6*	41·8	—
Edmonton, Ky.	12·65	*25·4, 25·4*	25·4	*34·8, 34·4*	34·6	—
Franceville	8·32	*19·2, 21·4*	20·3	*40·9, 43·9*	42·4	0·37
Glenormiston	7·36	*15·7, 18·0*	16·9	*78·7, 74·9*	76·8	3·0
Glorieta Mountain	12·04	*14·8, 11·9*	13·4	*11·2, 11·0*	11·1	—
Grand Rapids	9·41	*17·0, 17·0*	17·0	*14·2, 13·7*	14·0	—
Grant	9·29	*21·4, 19·6*	20·5	*37·9, 37·0*	37·5	0·049
Gun Creek	8·45	*22·4, 22·3*	22·4	*67·3, 72·1*	69·7	—
Hammond	8·18	*27·1, 25·2*	26·2	*56·6, 60·1*	58·4	—
Henbury	7·47	*16·6, 18·1*	17·4	*34·3, 34·1*	34·2	12
Imilac	9·8 ± 0·8	*21·4, 21·0*	21·2	*44·9, 46·1*	45·5	0·10 ± 0·03
Knowles	9·4 ± 0·4	*19·0, 18·0*	18·5	*33·7, 27·7*	30·7	0·026
Krasnojarsk	8·8 ± 0·5	*22·4, 22·8*	22·6	*57·7, 54·6*	55·1	0·25 ± 0·10
Maria Elena	7·75	*1·80, 1·65*	1·73	*0·096, 0·097*	0·096	2·7 ± 0·8

Table 3. (continued)

Meteorite	Ni (%) mean	Ga (ppm) replicates	Ga (ppm) mean	Ge (ppm) replicates	Ge (ppm) mean	Ir (ppm) mean
Mbosi	8·88	*2·38, 2·70*	2·54	*26·3, 27·6*	26·9	7·0
Merceditas	7·93	*18·5, 19·0*	18·8	*38·2, 41·1*	39·7	—
Misteca, *pseudo-*	—	*1·60*	1·60	*0·10*	0·10	—
Mount Edith	9·6 ± 0·5	*20·5, 19·6*	20·1	*38·6, 38·2*	38·4	—
Mungindi	11·74	*19·6*, 19·*8*	19·7	*21·6, 22·5*	22·1	—
Nelson County	6·93	*6·72, 5·82, 6·45*	6·33	†*1·80, 0·876, 0·804*	0·840	8·5 ± 2·0
New Baltimore	6·48	*21·0, 19·5*	20·3	*35·5, 39·1*	37·3	—
Norfolk	7·49	*20·8, 19·6*	20·2	*38·9, 37·4*	38·1	—
Norfork	7·88	*20·8, 19·9*	20·4	*41·4, 40·9*	41·2	—
Providence	8·28	*20·4, 19·9*	20·2	*40·8, 42·2*	41·5	0·41
Rodeo	9·74	*82·8, 84·5*	83·6	*91·0, 99·8*	95·4	—
Roper River	9·81	*18·4, 17·8*	18·1	*34·3, 33·6*	33·9	—
Ruff's Mountain	8·65	*19·7, 22·9, 22·0*	21·5	*48·6, 46·1, 45·9*	46·5	0·56
Sacramento Mountains	7·75	*19·9, 18·5*	19·2	*36·3, 36·9*	36·6	—
Sams Valley	9·91	*18·6, 18·2*	18·4	*36·3, 33·9*	35·1	—
San Angelo	7·68	*18·5, 20·0, 19·0*	19·2	*40·6, 38·1*	39·3	9·0
Sanderson	9·87	*19·0, 17·3*	18·2	*36·6, 35·1*	35·8	—
Seneca Township	8·52	*2·19, 2·07, 2·25*	2·17	*0·47,*† *0·14,*† *0·124*	0·124	1·9
Social Circle	7·78	*1·64, 1·62*	1·63	*0·093, 0·091*	0·092	2·8
South Byron	18·20	*20·1, 19·1*	19·6	*45·9, 44·2*	45·0	27
Spearman	8·65	*20·3, 20·0*	20·2	*45·1, 46·9*	46·0	—
Springwater	12·3 ± 0·5	*14·8, 13·3*	14·1	*29·2, 34·5*	31·9	—
Tamarugal	8·44	*21·8, 21·4*	21·6	*46·9, 42·5, 42·1*	43·8	0·56
Tambo Quemado	10·12	*17·9, 17·3, 17·5*	17·6	*29·5, 32·4*	31·0	—
Thule	8·48	*19·0, 19·6*	19·3	*40·9, 38·8*	39·8	2·5
Thurlow	9·92 ± 0·40	*15·5, 16·3*	15·9	*27·8, 28·3*	28·0	—
Tieraco Creek	10·72	*16·5, 15·9*	16·2	*27·8, 28·1*	28·0	—
Tombigbee River	4·3 ± 0·5	*37·5, 38·4, 39·6*	38·5	*62·6, 62·3, 62·7*	62·5	—
Trenton	8·34	*22·9, 18·7*	20·8	*43·8, 45·1*	44·5	2·7
Treysa	9·1 ± 0·4	*18·2, 22·5*	20·4	*43·0, 43·2*	43·1	1·3
Verkhne Dnieprovsk	9·86	*17·7, 18·5*	18·9	*32·0, 34·2*	33·1	—
Victoria West	11·98	*14·5, 16·1*	15·3	*30·3, 32·4*	31·4	—
Wallapai	11·61	*82·6, 83·6*	83·1	*106·7, 97·7*	102·2	—
Weekeroo Station	7·25	*27·6, 28·9*	28·2	*66·8, 67·1*	67·0	4·2 ± 1·8
Willamette	7·62	*18·2, 18·4*	18·3	*37·6, 35·7*	36·7	4·7
Williamstown	7·53	*18·6, 17·8*	18·2	*33·3, 32·5*	32·9	12

* The mean Ni and Ir value listed for Babb's Mill (Blake's) and Chinga represent single determinations only.

† Datum not used in calculation of mean.

3. All members of the group will show similar textures. They will have similar types and amounts of inclusions, and similar morphological relationships between the kamacite, taenite and minor phases, insofar as later reheatings have not altered these features.

Figure 1 shows the behavior of Ge, Ga and Ni in 140 iron meteorites measured in our group. On the basis of these data, five groups can be defined quite clearly. These five groups have been designated by roman numerals and capital letters as I, IIIA,

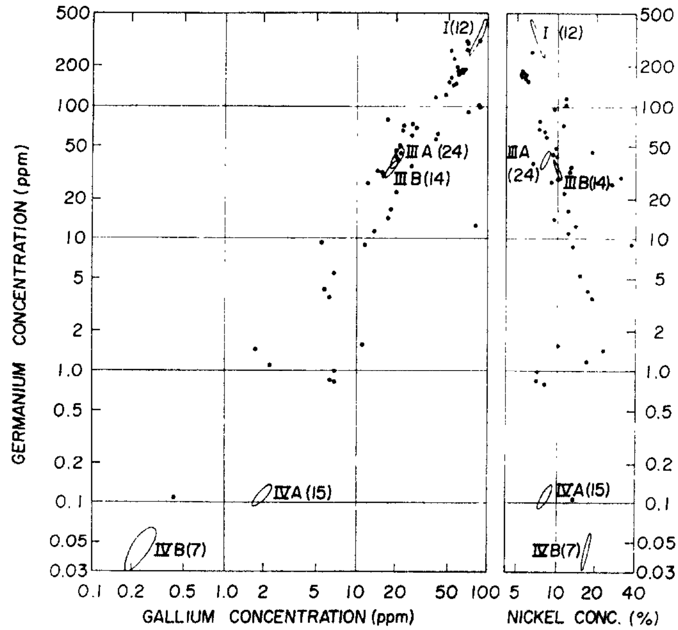

Fig. 1. Plots of germanium concentration vs. gallium concentration for ca. 150 iron meteorites, and of germanium concentration vs. nickel concentration for ca. 100 meteorites. The resolved chemical groups are encircled and labelled, with the population of the group given in parentheses.

IIIB, IVA and IVB. The numeral part of the designation is retained from the original Ga–Ge classification of LOVERING *et al.* (1957).

It should be understood that similarity in Ga and Ge content is not sufficient justification to establish a genetic relationship between irons. In fact, plots of Ge vs. Ni have much more utility than Ge–Ga plots in searching for such relationships. Data of these two elements are sufficient to distinguish and define each of the five groups shown on Fig. 1.

A priori, each group should be assumed independent, and not a subdivision (subgroup) of a larger grouping. As we will see shortly, IIIA and IIIB are exceptions to this rule.

The present paper is concerned chiefly with iron meteorites having Ge concentrations in the 8–100 ppm range. Figure 2 shows a plot of Ge vs. Ga for these irons. Figure 3 shows a similar plot of Ge vs. Ni for the same meteorites. These plots are

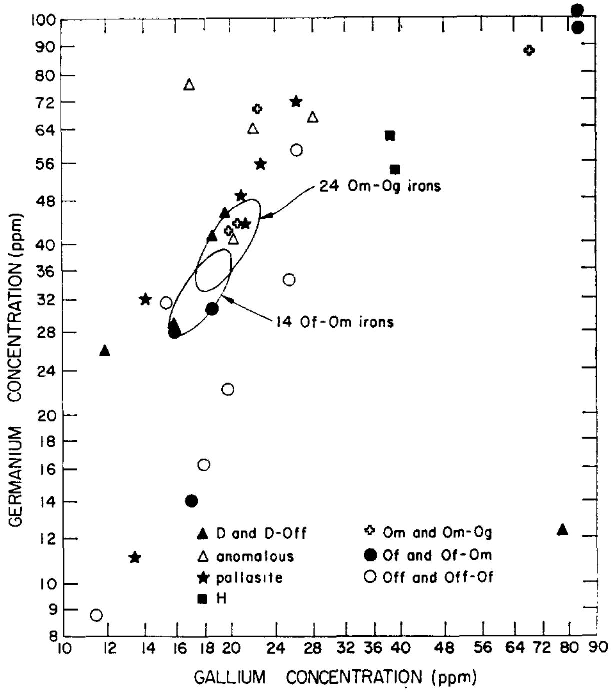

Fig. 2. Relationship between germanium concentration and gallium concentration in meteorites containing 8–100 ppm germanium. The two outlined fields show the location of chemical group IIIA (twenty-four Om–Og irons) and group IIIB (fourteen Of–Om irons).

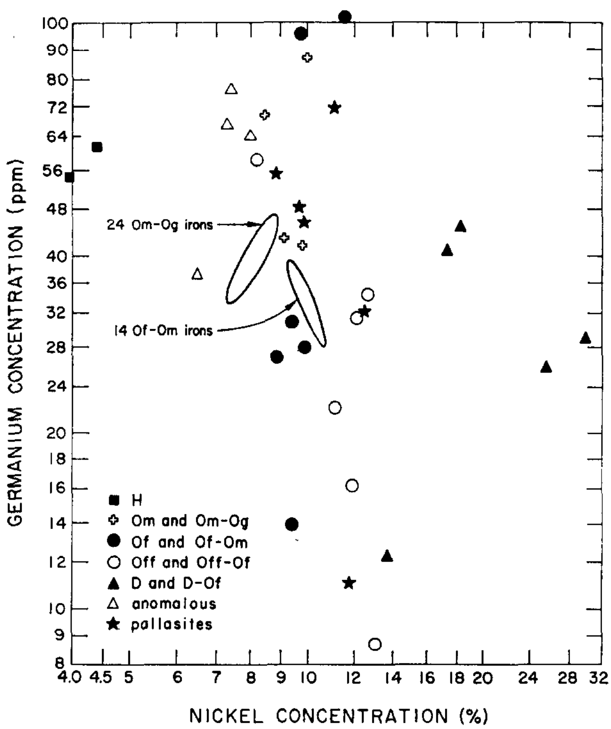

Fig. 3. Relationship between germanium concentration and nickel concentration in meteorites containing 8–100 ppm germanium. Note the complete resolution of the IIIA field (twenty-four Om–Og irons) from the IIIB field (fourteen Of–Om irons).

discussed in detail below. Information regarding the structures, conditions, and sources of our samples is found in the appendix.

Groups IIIA *and* IIIB

LOVERING and co-workers (1957) defined their Ga–Ge group III as those meteorites having 15–80 ppm Ge and 8–24 ppm Ga. This was the most populated group which they found, and included 33% of the eighty-eight irons which they studied. It also covered the widest concentration ranges, the ratio of the upper-to-lower concentration limits being 5·3 and 3·0 for Ge and Ga, respectively. They classified most of the irons in the group as medium octahedrites, which they defined as having kamacite band widths between 0·5 and 2·0 mm.

We have studied a large number of the "medium octahedrites" investigated by LOVERING *et al.* With our improved techniques the concentration range populated by these irons has shrunken considerably. In addition, we have found that there are two distinct structural groups present. In the belief that more resolution kamacite bandwidth was needed than offered by the LOVERING *et al.* limits, we have adopted the limits proposed by BUCHWALD and MUNCK (1965). These, along with the symbols for the different structures, are summarized as follows: coarsest octahedrites (Ogg), 2–4 mm; coarse octahedrites (Og), 1–2 mm; medium octahedrites (Om), 0·5–1·0 mm; fine octahedrites (Of), 0·25–0·50 mm; finest octahedrites (Off), <0·25 mm; ataxites (D); hexahedrites (H); pallasites (P). Short descriptions of the structure of the present selection of irons are given in the appendix. The "medium octahedrites" of Lovering's group III are found to consist of a Of–Om group having kamacite bandwidths of roughly 0·5 mm, and a Om–Og group with bandwidths of roughly 1·0 mm. Although most members of these two groups can be distinguished on the basis of structure and Ge concentration, a few irons have been found which are intermediate in structure and composition. As discussed below, we now believe that the two groups are genetically related, and more properly to be considered subgroups of a larger group.

In Table 4 are listed the data for twenty-four members of group IIIA in order of decreasing Ge content, and in Table 5 the data for fourteen members of group IIIB. The distinguishing characteristics of these groups are as follows. The mean contents of Ga and Ge are higher in group IIIA than in IIIB, the range in Ge being 33–46 and 28–38 ppm in IIIA and IIIB, respectively. There is no overlap in the Ni concentrations; group IIIA has Ni contents ranging from 7·4 to 8·7% whereas Ni in group IIIB ranges from 9·2 to 10·7%. There is a positive correlation between Ge and Ga in both groups, as seen in Fig. 2. This is similar to the situation found earlier for groups IVA and IVB (WASSON, 1967a). The concentrations of Ge and Ni show a positive correlation in group IIIA, but a negative correlation in group IIIB. Groups IVA and IVB showed positive correlations between Ge and Ni, but preliminary data (WASSON, 1967c, see also Fig. 1) show that group I is also like IIIB in showing a negative correlation.

Preliminary results on Ir indicate that all members of groups IIIB have Ir contents between 0·02 and 0·09 ppm. The Ir concentrations in group IIIA are somewhat better determined, and show a range of 0·3–13 ppm. Plots of Ir vs. Ni

Table 4. Mean Ni, Ga, Ge and Ir concentrations in group IIIA meteorites, listed in order of decreasing Ge content

Meteorite	Ni (%)	Ga (ppm)	Ge (ppm)	Ir (ppm)
Ruff's Mountain	8·65	21·5	46·5	0·56
Spearman	8·65	20·2	46·0	—
Trenton	8·34	20·8	44·5	2·7
Tamarugal	8·44	21·6	43·8	0·56
Carthage	8·35	21·5	43·7	—
*pseudo*Apoala	8·23	22·2	42·6	1·3
Franceville	8·32	20·3	42·4	0·37
Drum Mountains	8·35	20·4	41·8	—
Providence	8·28	20·2	41·5	0·41
Norfork	7·88	20·4	41·2	—
Aggie Creek	8·44	20·5	39·9	0·70
Thule	8·48	19·3	39·8	2·5
Merceditas	7·93	18·8	39·7	—
Descubridora	7·70	20·5	39·7	2·1
San Angelo	7·68	19·2	39·3	9·0
Norfolk	7·49	20·2	38·1	—
Boxhole	7·68	18·1	37·2	—
Willamette	7·62	18·3	37·6	4·7
Sacramento Mountains	7·75	19·2	36·6	—
Canyon City	7·78	19·5	33·0	10
Cape York	7·47	19·2	36·0	4·9
Henbury	7·47	17·4	34·2	12
Costilla Peak	7·55	18·7	33·6	13
Williamstown	7·53	18·2	32·9	12

Table 5. Mean Ni, Ga, Ge and Ir concentrations in group IIIB meteorites, listed in order of decreasing Ge content

Meteorite	Ni (%)	Ga (ppm)	Ge (ppm)	Ir (ppm)
Mount Edith	9·6	20·1	38·4	—
Breece	9·6	19·4	37·9	—
Grant	9·29	20·5	37·5	0·049
Sanderson	9·87	18·2	35·8	—
*authentico*Apoala	9·69	18·3	35·2	—
Sams Valley	9·91	18·4	35·1	—
Roper River	9·81	18·1	33·9	—
Verkhne Dnieprovsk	9·86	18·9	33·1	—
Bear Creek	9·99	18·8	32·8	—
Cuernavaca	10·4	16·3	31·6	—
Chupaderos	10·40	16·9	31·1	—
Bella Roca	10·16	16·7	31·1	—
Tambo Quemado	10·12	17·6	31·0	—
Tieraco Creek	10·72	16·2	28·0	—

and vs. Ge are shown for group IIIA irons in Fig. 4. There is an apparent anti-correlation of Ir and Ni or Ge. The range of Ir values is much larger than those found for Ni, Ge or Ga.

There are relatively few IIIA irons having intermediate Ir or Ni contents, and this is suggestive that IIIA may be further resolvable into smaller groups. This idea received some reinforcement from the observations of GOLDSTEIN and SHORT that the kamacite bands have about the same widths in extreme members of IIIA,

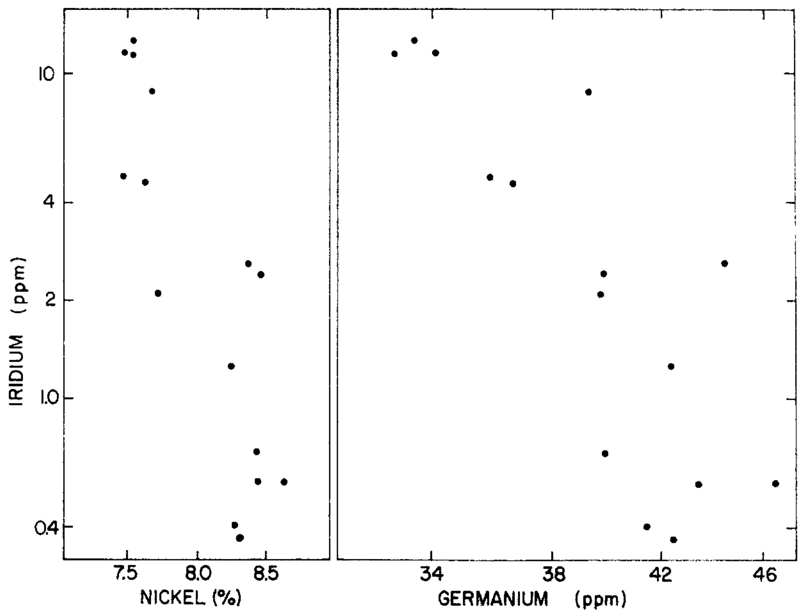

Fig. 4. Plots of iridium concentration vs. nickel concentration, and of iridium concentration vs. germanium concentration in group IIIA iron meteorites. The axes are logarithmic, with the vertical (Ir) scale compressed by a factor of 8 compared to the horizontal scale.

despite 15% differences in Ni concentration. These observations indicate increasing cooling rates with decreasing Ni concentration. Another indication of complexity in IIIA is the observation of SMALES *et al.* (1967) that whereas As concentrations are about 4 ppm for Henbury and six other irons of similar Ga and Ge content, they are about 8 ppm for three irons (including Spearman) having somewhat higher Ga and Ge contents. COBB (1967) subdivides these (IIIA) irons chiefly on the basis of their Ir contents.

After surveying all the evidence, we conclude that it is insufficient to be used for subdividing group IIIA at the present time. If we plot any two elements against each other (see, e.g. Fig. 4), in no case can the distribution be conclusively divided into two populations. We conclude that IIIA is fully resolved.

Several of the IIIB irons were called to our attention by Dr. E. OLSEN. In a joint study of OLSEN and FREDRIKSSON (1966), phosphate minerals had been found in the irons Bella Roca, Chupaderos, Sams Valley and Verkhne Dnieprovsk and OLSEN later

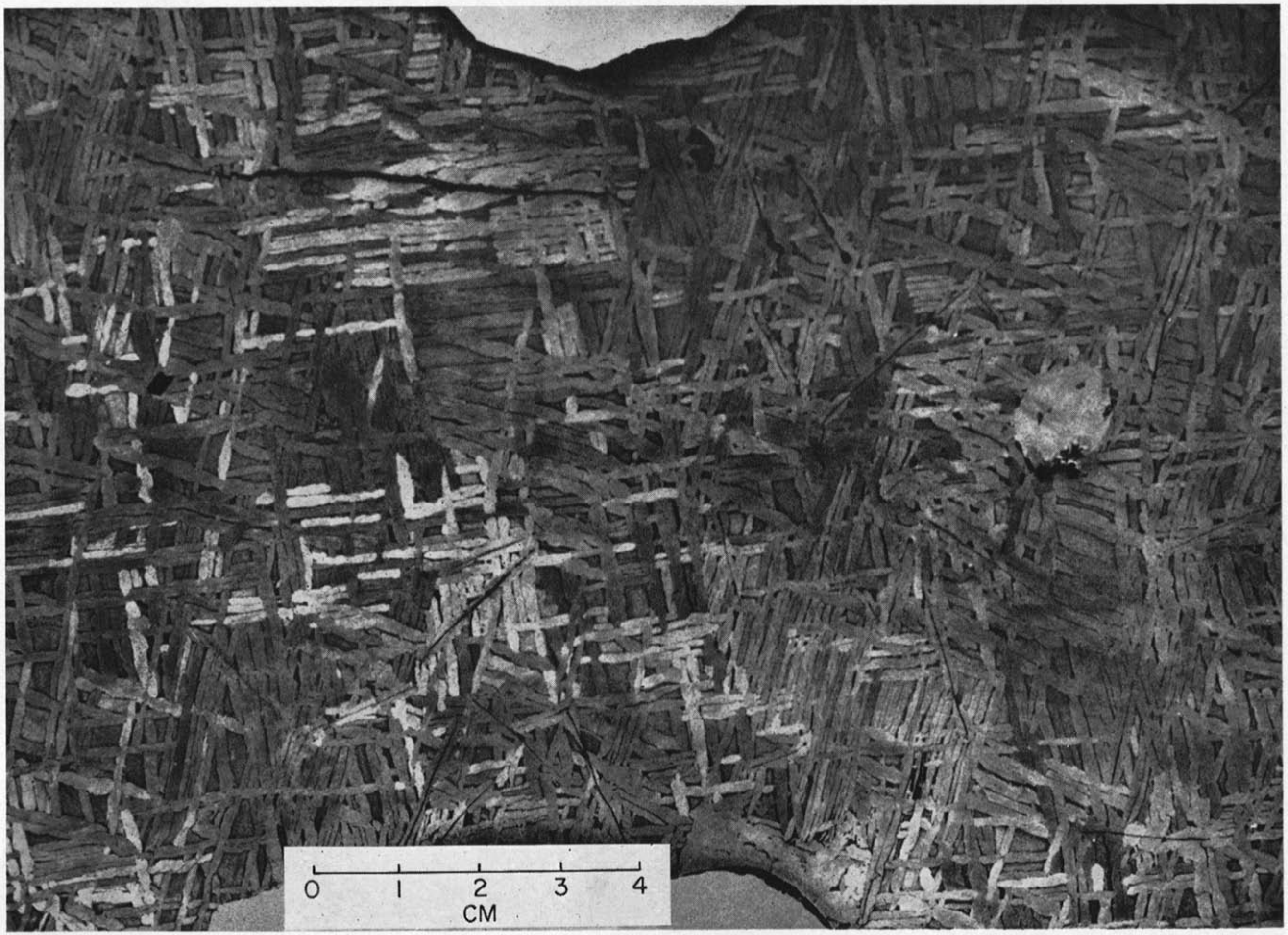

Fig. 5. Polished and etched surface of the Drum Mountains octahedrite, a typical high-Ni member of group IIIA (photograph courtesy of the Division of Meteorites, U.S. National Museum).

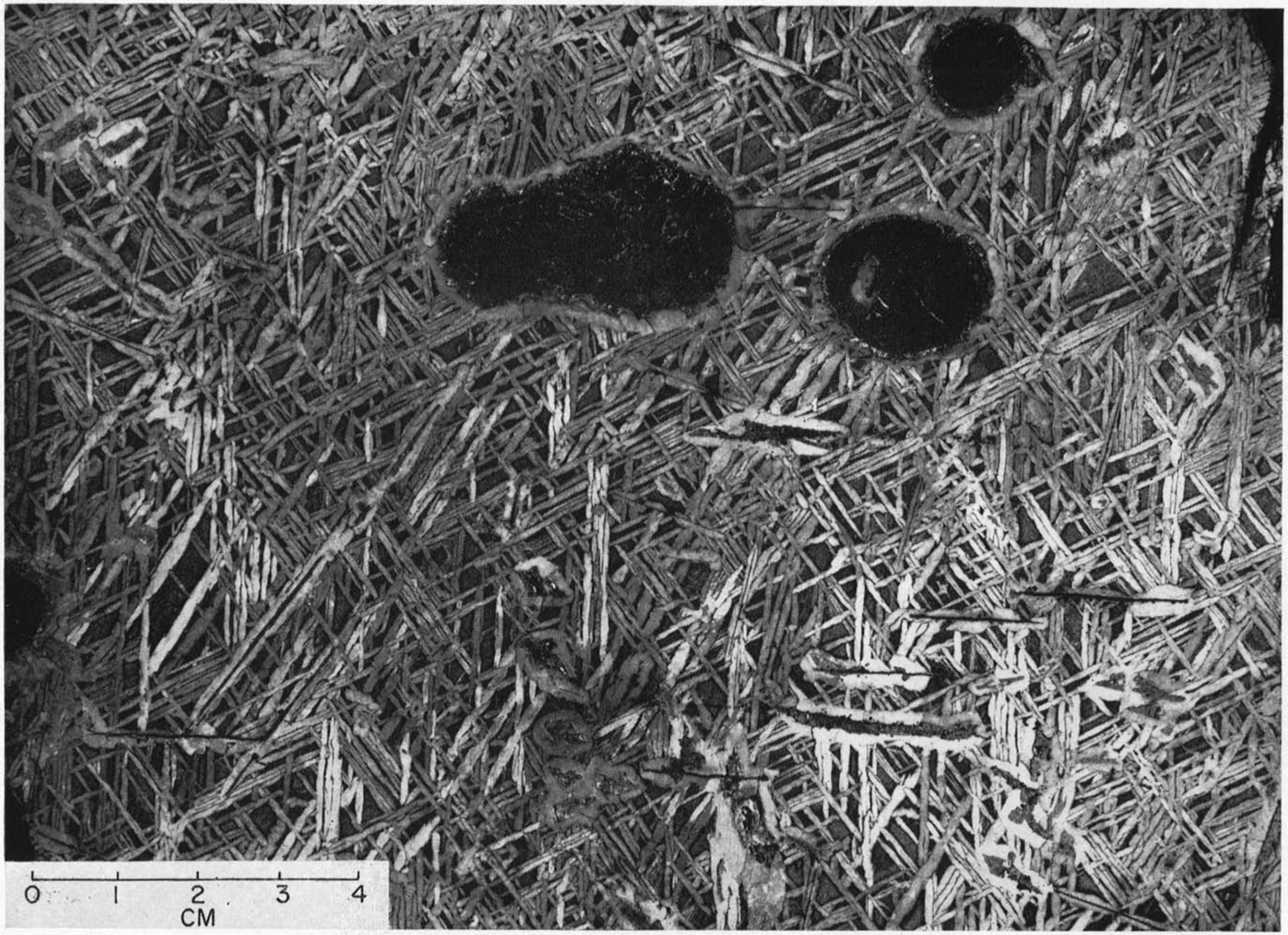

Fig. 6. Polished and etched section of the Mount Edith octahedrite, a typical low-Ni member of group IIIB (photograph courtesy of the Division of Meteorites, U.S. National Museum).

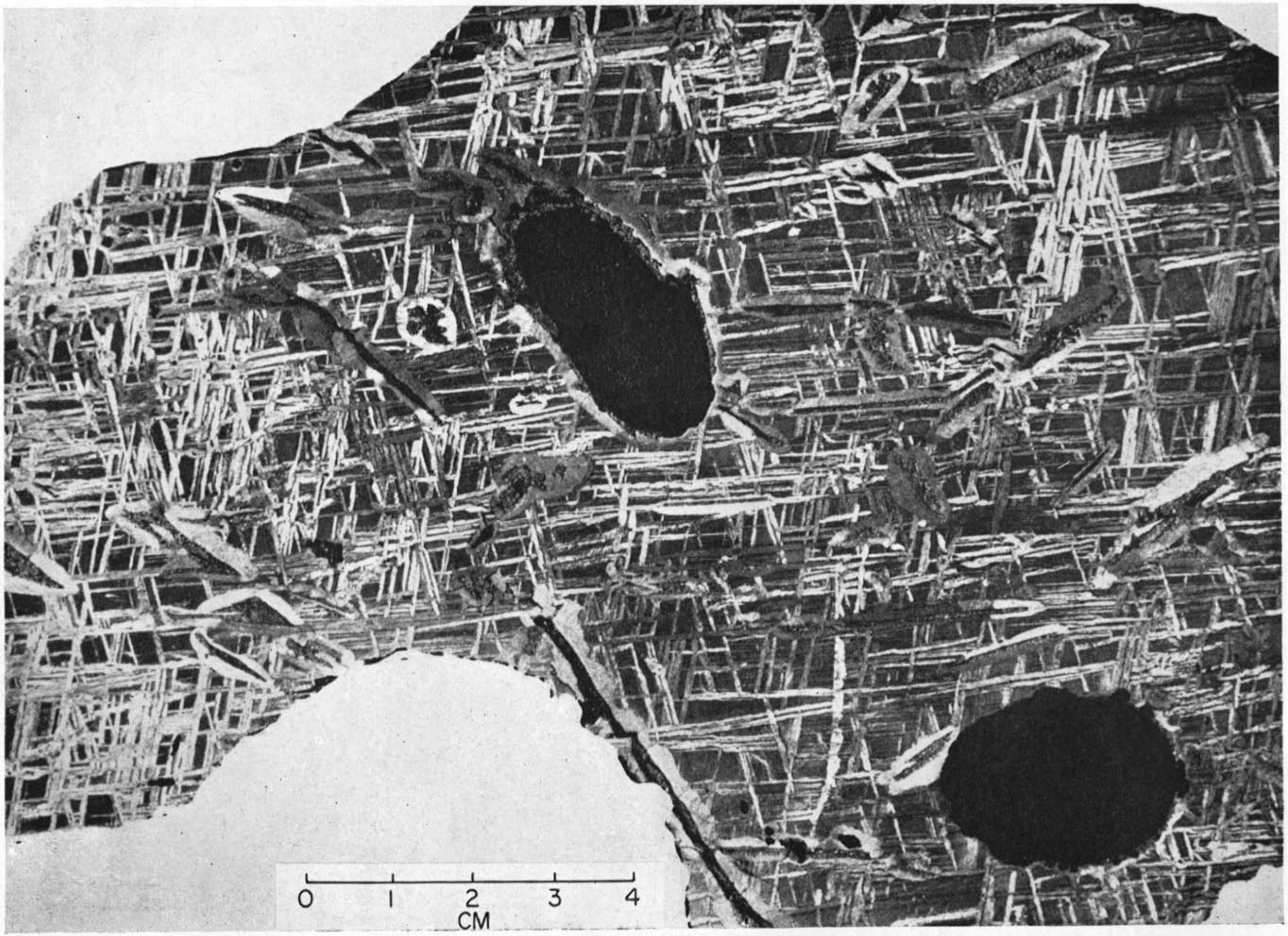

Fig. 7. Polished and etched section of the Tieraco Creek octahedrite, a typical high-Ni member of group IIIB (photograph courtesy of the Division of Meteorites, U.S. National Museum).

found such minerals in Cuernavaca and Breece. These irons are all IIIB irons, and include representatives of the extreme compositions to be found within the group.

As mentioned above, groups IIIA and IIIB are characterized by quite different structures. The IIIA irons have regular kamacite bands which average about 1 mm in thickness.* The amount of inclusions is small, and the type of inclusion varies from primarily troilite in low-Ni members to primarily schreibersite in high-Ni members. Figure 5 is a photograph of a typical high-Ni IIIA iron, Drum Mountains. Numerous "needles" of schreibersite are observed, but the total amount of such inclusions is less than 1% of the area of the section. Compare this structure with that of the low-Ni member of group IIIB, Mt. Edith, shown in Fig. 6, and that of a high-Ni member of IIIB, Tieraco Creek, shown in Fig. 7. Here we see that the kamacite bands are often "swollen", and that large nodules of troilite are present. Schreibersite is in the form of large laths, which are known as Brezina lamellae. The difference between Mt. Edith and Tieraco Creek is subtle; the latter has smaller kamacite lamellae and larger areas of fine plessite. The difference between Drum Mountains and the latter irons is unmistakable.

Nonetheless, GOLDSTEIN (private communication) informs us that he has found some irons (such as Owens Valley) which are intermediate in structure between the two groups, and we have recently obtained tentative data on an iron which is intermediate in composition and structure (Cleveland). Furthermore, if one examines all available compositional evidence, such as the data presented by SMALES *et al.* (1967) and FOUCHÉ and SMALES (1967), one finds that in most cases, the trace element content of the IIIB irons is in the direction of any trend in concentrations which is found in group IIIA, and in no case is there a major quantum jump in going from the high-Ni IIIA irons to the low-Ni IIIB members. The difference in concentration of a given element between Spearman or Caperr (high-Ni (IIIA) to Breece or Mt. Edith (low-Ni IIIB) is generally no greater than that between the former irons and Henbury low-Ni IIIA).

Thus, there seems to be no chemical criterion which would rule out the possibility that groups IIIA and IIIB are co-genetic. On the contrary, the evidence seems more in favor of an origin in the same parent body. The opposite correlations between Ge and Ni concentrations within the two groups then becomes even more puzzling and fascinating. Not only does one have to explain how the formation of the irons could produce such different trends, but one must devise a mechanism for such processes within the same parent body. Since, with rare exceptions, members of IIIA and IIIB can be clearly distinguished, it would seem prudent to retain these designations. Whether they should be designated as groups or subgroups seems of little importance, but one must bear in mind their probable co-genetic origins.

Pallasites

Six pallasites have been included in the present study. They are represented by filled stars on Figs. 2 and 3. Our data on them are summarized in Table 6, which also lists olivine composition data from MASON (1963). The Ge concentrations vary

* Some of the IIIA irons seem to have had their structures altered by a cosmic reheating; in particular Willamette and Ruff's Mountain show this effect (BUCHWALD, 1966).

by a factor of six among these objects. Whereas our investigations in other cases have led to a compaction of Lovering *et al.* groups, in this case the Ge contents of the end members, Brenham and Glorieta Mountain, have moved farther apart. There is a definite tendency for Ga to increase with increasing Ge concentration, but there is no apparent correlation between these elements and Ni. Ir is low in all the pallasites, and seems to range from 0·05 to 0·25 ppm. Our Ni result on Admire is considerably lower than the value of 12·45% reported by Lovering *et al.* (1957), but otherwise our data agree within the respective experimental errors. Mason points out that the

Table 6. Mean Ni, Ga, Ge concentrations in the metallic fractions of six pallasites, and the mole per cent fayalite reported by Mason (1963) in the olivine fractions of the same objects

Pallasite	Ni (%)	Ga (ppm)	Ge (ppm)	Ir (ppm)	Olivine composition (%fa)
Brenham	11·1	26·2	71·7	—	12
Krasnojarsk	8·8	22·6	55·1	0·25	13
Admire	9·7	20·9	48·4	—	11
Imilac	9·8	21·2	45·5	0·10	12
Springwater	12·3	14·1	31·9	—	18
Glorieta Mountain	12·04	13·4	11·1	—	13

fayalite content of the pallasitic olivine tends to increase with increasing Ni content of the metal, and our data are marginally consistent with this interpretation. Our measurements include substantial sampling errors because of the great variation in dimensions of the metallic matrix material, and in the schreibersite content of the samples.

General observations of the Widmanstätten structure of the pallasites are difficult to make except for the two which have large areas of clear metal, Brenham and Glorieta Mountain. Although these irons are clearly to be classified as fine or medium octahedrites, their detailed structure differs from that of any other irons examined by the authors. The kamacite bands show a continuous range in width up to about 1 mm, and the entire mass could be described as banded plessite. The edges of the kamacite bands are very irregular.

We believe that the pallasites are all members of a single genetic group. The similarity in bulk chemical composition, Ir content, and structure are the main arguments in favor of this premise. The main argument against it is the large range of Ge content observed, and the lack of a pronounced correlation between concentrations of different elements. It is curious that the two members showing the extreme Ge concentrations are the same two which show large metallic regions. The pallasites have numerous curious properties, however, not least of which is the very existence of matter composed of almost equal amounts of olivine and metal.

A possible group IIIC

It seems fairly likely that some or all members of the quartet, Anoka, Carlton, Edmonton and Mungindi, are related. The data on them are summarized in Table 7.

Plots of Ge vs. Ga and Ni (Figs. 2 and 3) show that these irons fall along smooth curves, though not necessarily along straight lines. The structures are quite similar, and are distinguished by long regular kamacite bands. Unfortunately, our Ir data are of low accuracy, and we can only state that they have Ir contents less than 1 ppm. Further study is in order.

Table 7. Mean Ni, Ga and Ge concentrations in four irons which may be genetically related

Meteorite	Ni (%)	Ga (ppm)	Ge (ppm)
Edmonton, Ky.	12·65	25·4	34·6
Mungindi	11·74	19·7	22·1
Anoka	12·04	17·8	16·2
Carlton	13·20	11·4	8·73

Doublets

There are five doublets each composed of more-or-less similar meteorites. The data on them are summarized in Table 8. The doublets are arranged in order of decreasing Ni content. The first is Rodeo-Wallapai. These irons have very similar structures, and show a strong resemblance to the IIIB irons, though the mean dimensions of the schreibersite inclusions and kamacite inclusions may be somewhat smaller.

Table 8. Mean Ni, Ga, Ge and Ir concentrations in five pairs of similar irons, listed in order of decreasing Ge content

Meteorite	Ni (%)	Ga (ppm)	Ge (ppm)	Ir (ppm)
Wallapai	11·61	83·1	102·2	—
Rodeo	9·74	83·6	95·4	—
Tombigbee River	4·3	38·5	62·5	—
Bellsbank	4·0	39·2	54·6	0·15
South Byron	18·2	19·6	45·0	27
Babb's Mill (Troost's)*	17·3	18·6	41·5	—
Knowles	9·4	18·5	30·7	0·026
Thurlow	9·92	15·9	28·0	—
Lime Creek*	30·0	15·8	29·0	—
San Cristobal*	25·6	11·9	25·8	—

* The results of these meteorites are taken from WASSON (1967a).

The second doublet consists of Tombigbee River and Bellsbank, the only two hexahedrites in this study. The objects are distinguished by large amounts of schreibersite, mainly in the form of irregular inclusions, and by their low Ni contents, which are among the lowest which have ever been found in iron meteroties. The only other iron which is definitely known to have less than 5·0% Ni is La Primitiva (HENDERSON and PERRY, 1958). SMALES *et al.* (1967) have found Ga and Ge contents in La Primitiva which are very similar to those in Bellsbank and Tombigbee. Thus, these three irons seem to represent the nucleus of a minor group. We will postpone giving it a designation, however, until our studies of other hexahedrites have progressed further.

The third doublet consists of South Byron and Babb's Mill (Troost's). These irons are very similar in their contents of Ni, Ga and Ge, but no Ir value has been determined for Babb's Mill (Troost's). The structures are extremely similar, consisting of fine dark plessite virtually free of inclusions. It is perhaps well to note here that: (1) Babb's Mill (Troost's iron) and Babb's Mill (Blake's iron) show very different compositions, and are definitely different falls; and (2) the literature Ni content of 13·5% for South Byron (Prior and Hey, 1953) is almost 5% lower than our value of 18·2%.

The fourth doublet consists of Lime Creek and San Cristobal, two irons with very high Ni contents of 30 and 26%, respectively. We have not carried out any measurements on these irons in addition to those reported in Wasson (1967a).

The fifth doublet consists of Knowles and Thurlow. These irons have very similar contents of Ni, Ga and Ge, and appear to have similar Ir contents. They have quite similar and very attractive Widmanstätten structures, with the plessitic fields between the primary kamacite bands filled with very fine, octahedrally oriented bands. These irons have Ga and Ge contents similar to those of the lowest member of group IIIB, Tieraco Creek. They differ, however, in Ni content and structure.

Additions to groups IVA *and* IVB

Table 9 lists data on three new irons belonging to group IVA and one new member of group IVB. For completeness, we have also listed the results obtained on *pseudo*-Misteca, which is really Yanhuitlan, a fine octahedrite studied in the first paper of this series. The new members of IVA are Seneca Township, Maria Elena and Social Circle. The latter two have the lowest Ga and Ge contents found in that group. Note that the structure (Off–Of) and Ni content (8·52%) which we report for Seneca Township are quite different from those listed in Hey (1966) (Om, 10·41%). The addition of these irons increases the known population of group IVA to fifteen.

Table 9. Mean Ni, Ga, Ge and Ir concentrations in four meteorites belonging to group IVA and one belonging to group IVB

Meteorite	Ni (%)	Ga (ppm)	Ge (ppm)	Ir (ppm)
IVA irons:				
Seneca Township	8·52	2·17	0·124	1·9
*pseudo*Misteca	—	1·60	0·10	—
Maria Elena	7·75	1·73	0·096	2·7
Social Circle	7·78	1·63	0·092	2·8
IVB iron:				
Chinga	16·7	0·188	$<0{\cdot}18$	—

Our limited data on the iron, Chinga, which may have been crater-forming (Krinov, reported in Prior and Hey, 1953), indicate that it is a member of group IVB. This brings to seven the number of members of IVB.

Apparently unique irons

Data for those irons from Table 3 which have not been discussed are summarized in Table 10, again in order of decreasing Ge content. These will each be discussed very briefly. Carbo is similar in Ga, Ge anl Ni content to Wallapai and Rodeo, but its average kamacite band width is about 50% greater. Thus it would appear to have originated in a region having a lower cooling rate than that present at the origin of the latter two irons. Carbo has one of the highest cosmic-ray ages determined by VOSHAGE (1967).

Table 10. Mean Ni, Ga, Ge and Ir in sixteen irons having more-or-less unique compositions

Meteorite	Ni (%)	Ga (ppm)	Ge (ppm)	Ir (ppm)
Carbo	9·98 %	68·6	87·2	13
Glenormiston	7·36	16·9	76·8	3·0
Weekeroo Station	7·25	28·2	67·0	4·2
Barranca Blanca	7·96	22·1	63·9	5·0
Gun Creek	8·45	22·4	69·7	—
Hammond	8·18	26·2	58·4	—
Treysa	9·1	20·4	43·1	1·3
Delegate	9·69	20·3	41·7	—
New Baltimore	6·48	20·3	37·3	—
Victoria West	11·98	15·3	31·4	—
Mbosi	8·88	2·54	26·9	7·0
Grand Rapids	9·41	17·0	14·0	—
Cowra*	13·7	78	12·3	—
Cambria	10·40	10·9	1·56	0·84
Nelson County	6·93	6·33	0·840	8·5
Babb's Mill (Blake's)	11·94	0·203	<0·28	2·1

* The results on Cowra are taken from WASSON (1967a).

The next three meteorites to be discussed are somewhat similar in structure and chemical composition, but the differences are such that they do not form an obvious group according to the criteria listed at the start of this section. These three are Glenormiston, Weekeroo Station and Barranca Blanca. These have normally been called brecciated octahedrites (PRIOR and HEY, 1953). A better classification would probably be the "polycrystalline iron" category of BUCHWALD and MUNCK (1965), but we simply list them as "anomalous". The objects contain kamacite and taenite the former as irregular grains and the latter together with plessite at irregular interstitial positions. The grains in Barranca Blanca and Glenormiston are in the 0·5–1·0 cm range and show no orientation in our small sections, whereas in Weekeroo Station (where our section is larger) they seem to be typically 2 mm × 1 cm in dimensions and may possibly be oriented. Weekeroo Station has silicate inclusions, which have been used by WASSERBURG *et al.* (1965) to determine a Rb–Sr age of about 4·7 × 10^9 yr for this object (it should probably be pointed out that this first seemingly accurate solidification age to be measured in an iron meteorite was determined on one with "anomalous" chemical composition). Barranca Blanca contains chromite and what appears to be silicate (FLETCHER, 1889), and Glenormiston seems likely to have such minerals in its inclusions. The jumps in chemical composition in going from one to another of these irons are well outside of analytical error. If they are genetically related, then they (like the pallasites) have not been subject to the stringent "equilibrium" or "steady state" processes which have determined the features of the other resolved groups.

Gun Creek is similar in composition to Hammond, but has a coarser structure. Hammond is the only known exception to the rule that all irons with band widths smaller than 0·4 mm and Ni contents less than 9·5% are members of group IVA. Our sample of Treysa was consumed before adequate structural and Ni data were obtained. It needs further work, and could possibly be a member of group IIIA. Delegate seems clearly anomalous in structure and composition though similar in its properties to features of either IIIA or IIIB. It may be intermediate in composition between the two groups, but seems to have too high an Ni concentration. New Baltimore has a very odd structure and a much lower Ni content that the IIIA irons, which it resembles in Ga and Ge content. Victoria West has a striking and unique appearance. It was studied because BUCHWALD and MUNCH classified it into the same structural class (plessitic octahedrites) as the high-Ge iron, Butler. Its composition and appearance are found to be quite different from Butler's. The next iron, Mbosi, at ~26 tons, is one of the largest meteorites known. It has a uniquely high Ge:Ga ratio for irons in this range of Ge concentrations. Grand Rapids resembles the irons which may form a group IIIC except for a lower Ni content and slightly coarser structure. Cowra has a very low Ge:Ga ratio for irons in this range of Ge concentrations. Cambria has a very low Ge:Ga ratio, but concentrations of each element a factor of 8 lower than found in Cowra. Cambria has a unique structure, containing roughly 15% troilite by volume.

Nelson County is similar in Ga, Ge and Ni contents to Clark County or the Moonbi-St. Genevieve County pair (WASSON, 1967a) but has a much coarser structure than any of these irons, and would not seem to be related to them.

Babb's Mill (Blake's) is quite different from Babb's Mill (Troost's), and should certainly be cataloged separately. COHEN (1905) showed that they were quite different and listed Babb's Mill (Blake's iron) under the name Green County. The exact name is probably not too important, but catalogs should clearly distinguish between these two irons. Babb's Mill (Blake's) has a unique composition insofar as our limited results go. Our sample was only sufficient for two runs, and the second will only be made when a higher flux of thermal neutrons is available.

INTERPRETATION

Fractionation processes

Significant variations in the concentrations of all elements are observed among the members of groups IIIA and IIIB, which are well outside the experimental uncertainty. These variations do not occur in a random fashion, but rather they are related to the changes in concentration of the other elements which are present. This can readily be seen in the plots of Ge vs. Ga and vs. Ni which are shown in

Figs. 2 and 3, and to a lesser extent in the Ir vs. Ni and Ge plots in Fig. 4. These coherent variations in chemical composition are probably the result of fractionation processes which have occurred within one extended region in the meteorite parent body. It is also possible that evidence of fractional condensation processes such as those proposed by LARIMER and ANDERS (1967) have been preserved in the iron meteorites. The coherent variations within a group are not likely to be due to this process unless the irons have originated as single entities, as proposed by UREY (1959). We will not consider this possibility further at this time.

One can distinguish two "events" in the evolution of the meteorite parent body which could result in major fractionation effects in the metallic fraction: (1) the initial separation of the metal from a primordial matrix which probably was similar in composition to the chondrites, and (2) major fractionation within the separated metallic masses. It is difficult to see how the first type of event could give the coherent variation in composition observed for groups IIIA and IIIB. Fractionation within the separated mass could very well result in such variations, however, and it is of interest to consider possible processes. According to WASSON and WETHERILL (1967), the two most likely fractionation processes are: (1) fractional crystallization; and (2) equilibrium separation of elements in a single phase within a gravitational field. The former process will occur in those bodies where conditions are such that convective mixing of the residual liquid can occur during the solidification process. The latter process demands a relatively strong gravitational field, such as would be found near the edge of a core having a radius of at least 100 km. Both of these processes would tend to give a radial variation in composition of the irons. This is obvious for the latter process, and would also result in the former process if the metallic mass is a core which solidifies from edge to center or vice versa.

It should, in principle, be possible to distinguish between these two processes on the basis of the variations within the groups. For example, gravitational separation should show the greatest effects in elements having high atomic weights and low partial molal volumes (BREWER, 1951). Thus, the large Ir fractionation within IIIA (or IIIAB) might reflect such an effect. Fractional crystallization is somewhat less amenable to theoretical prediction, but better suited to experimental attack. Experimental data for "meteoritic" systems are not available, but the authors plan to initiate a study of the distribution of elements between solid and liquid metal of composition similar to the iron meteorites.

As mentioned in the previous section, groups IIIA and IIIB seem to be co-genetic, and we must search for mechanisms that can cause Ge and Ni to fractionate in parallel and in opposition within the same parent body. It is probably important that groups I and IIIB, the two groups which show a negative correlation between Ge and Ni, are both very rich in non-metallic minor elements. Group IIIB members have a high content of P and S, and group I members contain large amounts of C, S and P. There may be relatively strong chemical interactions between Ga and Ge and some of these elements.

Evidence for paired falls

It is of interest to point out which of the irons in our study meet the following (necessary but not sufficient) qualifications of paired falls: (1) chemical composition and structure which are identical within the limits of our resolution; and (2) discovery points within 100 km of each other. The only pair which meets these qualifications is one suggested to us by E. P. HENDERSON (private communication), Breece and Grant.

On the number of parent bodies

The chemical groupings of iron meteorites have been used as an argument for a multiplicity of parent bodies since the pioneering study of GOLDBERG *et al.* (1951). The further resolution of the iron meteorite spectrum which we have achieved has certainly strengthened this argument, and the simplest hypothesis seems to be one-to-one relationship between groups and parent bodies. It is by no means impossible that any two groups are related, but is difficult to believe that they have come from contiguous regions. The differing Ge–Ni correlations between groups IIIA and IIIB were used formerly by us as an argument for believing that these groups originated in different parent bodies. We now believe that they are exceptions to the above statement, and have arisen in contiguous or nearly contiguous regions of the same parent body. We do not believe that any of the groups I, IIIAB, IVA, or IVB are closely related.

An interesting point is whether a different parent body should be associated with each of the pairs and unique irons mentioned in the previous section. Should this be the case, it would require perhaps 30–50 parent bodies to account for the whole spectrum of iron meteorites. There are two things which tend to reduce this number, however. Some of the anomalous irons may be end members of some of the large groups, with intermediate members missing from our terrestrial sample. Other irons may be "raisins" from a raisin-bread structure in an inhomogenous silicate matrix, and thus be quite different in composition from other irons from the same parent body. Analytical data on a large number of irons from the same planet would then be necessary to establish some sort of statistical matrix showing a genetic relationship.

The pallasites

The data on the pallasites are summarized in Table 6 in the previous section. These curious objects are quite similar in structure and in overall chemical composition, and would seem to have originated in a limited region of a single planet. They show a larger range of Ge and Ga concentrations than that encountered in any of the other groups, however. Our data on the Ir contents of these objects are incomplete, but they seem to all lie in the 0·02–0·2 ppm range, and probably occupy only a small fraction of this range. One might propose that the large range of Ga and Ge concentration in the metal phases of these objects is the result of a distribution of these elements between the metal and olivine phases. This is not the case, however, for the Ge and Ga concentrations of the olivine are very low—about 1 ppm each (S.N. TANDON and C. WAI, private communication). The Ge and Ga are clearly concentrated in the metal.

The cooling rates determined by GOLDSTEIN and SHORT (1967) for the pallasites are quite low, indicating that they have originated in a relatively large body. This is also consistent with the fact that the high temperatures which were necessary to produce such pure olivine would likely have demanded a larger than average body.

This suggests in turn that this parent body should have had a relatively large core. There is no single group of irons which can be definitely associated with the pallasites however. The best candidates would be the members of the very tentative "Edmonton, Ky. group." These objects have quite different detailed metallic structures but this may not be sufficient grounds to rule out a genetic relationship. These irons are rarer than the pallasites. It would appear that if the pallasites were associated with a "core," the fragments of said core are under-represented in the sample of irons available for study.

Cosmic-ray ages

VOSHAGE (1967) has recently reported cosmic-ray ages for a number of the irons included in this study. Table 11 lists his cosmic-ray age data along with our Ge

Table 11. Cosmic-ray age data of VOSHAGE (1967) for ions belonging to groups IIIA and IIIB

Meteorite	Ge (ppm)	Ni (%)	Age (10^6 yr)
Group IIIA:			
Trenton	44·5	8·34	575
Tamarugal	43·8	8·44	585
Norfork	41·2	7·88	700
Merceditas	39·7	7·93	600
Descubridora	39·7	7·70	510
San Angelo	39·3	7·68	580
Norfolk	38·1	7·49	685
Sacramento Mountains	36·6	7·75	285
Williamstown	32·9	7·53	660
Group IIIB:			
Mount Edith	38·4	9·6	710
Grant	37·5	9·29	695
Sanderson	35·8	9·87	590

and Ni values for members of groups IIIA and IIIB. Within each group, the meteorites are listed in order of decreasing Ge content.

Cosmic-ray ages are a measure of the length of time that a meteoritic fragment has existed in interplanetary space since it was reduced to its preatmospheric dimensions. The fact that the members of resolved groups show such limited ranges of cosmic-ray ages indicates that most of these objects were formed in one major collision, and thus tends to reinforce the idea that members of these groups are genetically related. There seems to be no reason why all members of such groups should show identical ages, however. Secondary collisions, for example, would be expected to produce some irons showing lower ages.

If more than one major event were responsible for the observed ages, the interesting possibility would arise that this might be correlated with the chemical composition of the meteorite. If the compositions are indications of a radial distribution, a typical separation distance of the extreme members of group IIIA (or IIIAB) might be of the order of tens of kilometers. Under such circumstances it is likely that each major collisional event would produce debris with appreciable differences in mean chemical composition. No evidence for such a dependence is found in Table 11, however.

The apparent coincidence in cosmic-ray ages between members of groups IIIA and IIIB deserves comment. The probability that this could be due to chance is not especially low, when one considers that 60–67 irons which Voshage studied show ages in the range 200–925 10^6 yr. Nonetheless, it tends to confirm the view that these two groups have arisen within a single parent body.

Cooling rates

WOOD (1964) and GOLDSTEIN and SHORT (1967) report cooling rates for iron meteorites based on electron microprobe measurements of diffusion gradients between gamma- and alpha-phases of meteoritic nickel–iron. Unfortunately, only very few data have been published. The IIIA irons which have been studied are Trenton and Santa Apolonia, for which WOOD determined cooling rates of $10°/10^6$ yr, and Spearman, for which GOLDSTEIN and SHORT report a cooling rate of $4°/10^6$ yr. One IIIB meteorite, Grant, was studied by both groups, and found to have a cooling rate of $5°/10^6$ yr. Recently, WOOD (1967) has stated that his earlier cooling rate determinations are to be increased by a factor of 4, which leads to differences between his values and those of GOLDSTEIN and SHORT of at least this factor. Thus, the accuracy with which cooling rates are known at present is not high. The precision of the results of a single research group are thought to be as good as $+25\%$ for meteorites of similar composition and structure. GOLDSTEIN and SHORT (private communication) have rough data which show a tendency for the cooling rate to decrease with increasing Ni content in group IIIA. Group IIIB is found to have a "constant" cooling rate about equal to that found in high-Ni IIIA irons.

It is important to point out that a mass of metallic iron which is cooling by the conduction of heat through a surrounding silicate shell will have a constant cooling rate throughout, as a result of the fact that the metal has a much higher thermal conductivity than the silicate. The tentative data of GOLDSTEIN and SHORT reporting appreciable differences in cooling rates within group IIIA is of great importance for our understanding of the origin of the iron meteorites. We are concerned that this effect may have resulted from changes in chemical and physical parameters which are associated with the overall variations in chemical composition, however. For example, the amount of schreibersite (and thus the amount of P in the total sample) increases with increasing Ni content throughout IIIA. Pains must be taken to investigate the effect of this extra P on the stability fields of the Fe–Ni phase diagram, the degree of undercooling before nucleation of the kamacite, and on the diffusion coefficients.

SUMMARY

This study is second of a series reporting the investigation of the composition of a large number of iron meteorites in an effort to define the properties of resolved, genetic groups of these objects. The characterization of such groups is a prerequisite for the proper interpretation of other data which can be determined on the iron meteorites, such as that obtained in metallurgical or isotopic investigations. The first paper in this series reported on thirty-four irons. The present report has raised

the total number of irons to 102 and also added six pallasites. We estimate that our statistical coverage of the spectrum of chemical compositions is now 60% complete. A random selection of irons would have 40% with Ge contents higher than 100 ppm. In the future papers which will conclude the survey, we expect to bring the total number of investigated irons up to 200 (including several in the composition range covered in these first two reports), which will represent about 33% of all known iron meteorites.

Our studies to date have resulted in the delineation of four major chemical groups, including one, IIIAB, which shows two distinct branches. These are designated IVA, IVB (WASSON, 1967a), IIIAB (this paper), and I (WASSON, 1967c). The simplest explanation of these groups seems to be an origin in four different parent bodies. It is very difficult to imagine origins in *contiguous* regions of the same parent body.

Variations in composition occur within each of the groups. These do not occur stepwise, however, but are such that the concentration of each element varies smoothly from member to member between the extreme limits of the groups. We think that it is very likely that these differences represent different distances from the center of mass of the parent body. This possibility can be checked by gathering accurate data on the variations of other elements within the different groups.

A considerable body of evidence now exists which can be used to test appropriate models for the origin of the iron meteorites. This will be the subject of a forthcoming report (WASSON and WETHERILL, 1967).

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Appendix

Table 12. Descriptions and sources of iron–meteorite specimens

Meteorite	Source*	Catalog number†	Kam. band width (mm)	Structural class‡	Remarks
Admire	Krantz	—	—	P	Specimen strongly weathered, but interior of metal unoxidized.
Aggie Creek	USNM	1448	0·8–1·3	Om–Og	Regular kam. bands; sparse, small schr. inclusions.
*authentico*Apoala	CNHM	Me1008	0·3–0·7	Of–Om	Brezina lamellae; some weathering near crust and cracks.
*pseudo*Apoala	UCLA	1	0·7–1·1	Om–Og	Possibly a specimen of Misteca; kam. is polycrystalline.
Babb's Mill (Blake's)	NHMW	D2192	—	(D)	Composition distinctly different from Babb's Mill (Troost's)
Barranca Blanca	BM	41187	—	anom.	Unoriented, ca. 1 cm kam. grains, interstitial taenite.
Bear Creek	UCLA	1	0·4–0·7	Of–Om	Brezina lamellae, abundant fine plessite; see pl. 6, NININGER (1952).
Bella Roca	CNHM	Me985	0·3–0·6	Of–Om	Brezina lamellae; see Fig. 26, p. 66, MASON (1962).
Bellsbank	GSP	—	—	H	Large skeletal schr. inclusions; see pl. 2, HENDERSON (1965).
Boxhole	UCLA	1	—	(Om)	Deformed and reheated specimen, with no observable structure.
Breece	UCLA	1	0·4–0·7	Of–Om	Brezina lamellae; very similar to Mount Edith, see Fig. 6.
Brenham	UCLA	3	0·1–0·4	Off–Of	UCLA specimen shows large metallic area free of olivine; Ward's specimen shows normal pallasite structure; abundant schr.
	WNSE	—	—	P	
Cambria	Amherst	—	0·15–0·3	Off–Of	Large inclusiosn of schr. and troilite in Amherst section.
Canyon City	UCLA	1	0·8–1·1	Om–Og	Regular kam. bands; specimen etches very slowly.
Cape York	MMUC	—	1·1–1·5	Og	From Savik I; kam. bands coarser than in typical IIIA iron.
Carbo	MPIM	25/1	0·6–1·1	Om	Numerous inclusions, mainly schr. wider kam. than Rodeo.
Carlton	UCLA	1	0·13–0·3	Off	Long, regular kam. bands; large, irregular schr. inclusions.
Carthage	MPIH	301	0·8–1·2	Om–Og	Indistinct structure; few inclusions; plessite relatively rare.

Table 12. (continued)

Meteorite	Source*	Catalog number†	Kam. band width (mm)	Structural class‡	Remarks
Chinga	ANSSSR	856–2	—	D	No structure, no inclusions; shows what appear to be flow striae.
Chupaderos	CNHM	Me1045	0·3–0·8	Of–Om	Brezina lamellae; lightly weathered.
Costilla Peak	CNHM	Me856	0·7–1·1	Om–Og	Regular kam. bands; etches slowly; some 0·4 cm troilite inclusions.
Cuernavaca	CNHM	Me1024	0·3–0·6	Of–Om	Some oxidation along Brezina lamellae.
Delegate	AM	DR7888	ca. 1·0	(Om)	Widely varying band widths; smallish Brezina lamellae.
Descubridora	UCLA	1	ca. 1·0	Om–Og	Very small surface available for study.
Drum Mountains	USNM	1417	0·8–1·3	Om–Og	Shown in Fig. 5; a few thin, long schr. inclusions.
Edmonton, Ky.	USNM	1413	0·15–0·3	Off	Long, regular kam. bands; much fine plessite; shown p. 139 Mason (1962).
Franceville	UCLA	1	0·8–1·1	Om–Og	Regular kam. bands; few inclusions; slight oxidation near crack.
Glenormiston	QM	—	—	anom.	Less than 1 cm^2 observed; resembles Barranca Blanca.
Glorieta Mountain	UCLA	1	0·1–0·4	Off–Of	Our sample showed no pallasitic parts; metal similar to Brenham.
Grand Rapids	UCLA	1417	0·3–0·5	Of	Long, regular kam. bands; numerous 0·4 mm schr. inclusions.
Grant	USNM	836	0·3–0·8	Of–Om	Brezina lamellae; very similar to Mount Edith, Fig. 6.
Gun Creek	Harvard	—	0·6–0·9	Om	Etches slowly; regular kam. bands; fine schr. lamellae.
Hammond	Yale	P96	0·15–0·4	Off–Of	Brezina lamellae; kam. bands deformed in our specimen.
Henbury	UCLA	1	0·7–1·1	Om–Og	Regular kam. bands; no inclusions seen in 3 cm^2 area.
Imilac	UCLA	1	—	P	Roughly equal amounts of metal and olivine, dimensions ca. 1 cm.
Knowles	AMNH	772	0·5–0·6	Of–Om	Plessite abundant, shows striking octahedral pattern; much schr.
Krasnojarsk	UCLA	1	—	P	Roughly equal amounts of metal, olivine; schr. at interfaces.

Maria Elena	USNM	1221	0·12–0·25	Off	Regular kam. bands; etches slowly; no inclusions in 6 cm^2 area.
Mbosi	MPIH	539	0·4–0·7	Of–Om	Regular kam. bands; etches slowly; strongly oxidized near crust.
Merceditas	AMNH	741	0·8–1·1	Om–Og	Regular kam. bands; few inclusions; shown on p. 138, MASON (1962).
*pseudo*Misteca	ASU	162a	0·15–0·5	Off–Of	Yanhuitlan; genuine Misteca is Om–Og; see HEY (1966), MOORE and LEWIS (1964).
Mount Edith	CNHM	Me1959a	0·4–0·7	Of–Om	Illustrated in Fig. 6; Brezina lamellae and large troilite nodules.
Mungindi	AM	3669	0·15–0·25	Off	Long, regular kam. bands, often containing schreibersite inclusions.
Nelson County	Harvard	—	ca. 4	(Ogg)	Coarse structure not accurately observable; few inclusions
New Baltimore	Harvard	—	1–4	anom.	Curious structure; some 4 mm bands, some 1 mm bands; taenite rare.
Norfolk	UCLA	1	0·8–1·1	Om–Og	Regular kam. bands having many minute cracks; few inclusions.
Norfork	UCLA	1	0·7–1·1	Om–Og	Very small specimen; regular kam. bands; few inclusions.
Providence	USNM	1340	0·7–1·1	Om–Og	Regular, very indistinct kam. bands; some mm-sized inclusions.
Rodeo	CNHM	Me1128	0·3–0·5	Of	Structure similar to IIIB irons; abundant schr.; somewhat oxidized.
Roper River	NMV§	9346	0·5–0·7	Om	Small specimen; apparently similar to Mount Edith, Fig. 6.
Ruff's Mountain	UCLA	1	0·7–1·2	Om–Og	Strong evidence of reheating, see Buchwald (1966); few inclusions.
Sacramento Mountains	USNM	1495	0·8–1·1	Om–Og	Regular kam. bands; abundant banded plessite fields; some oxidation.
Sams Valley	CNHM	Me1976	0·4–0·8	Of–Om	Brezina lamellae; similar to Mount Edith, Fig. 6.
San Angelo	UCLA	1	0·6–1·1	Om–Og	Regular kam. bands; etches faster than most IIIA irons; few inclusions.
Sanderson	ASU	441.3x	0·3–0·6	Of–Om	Brezina lamellae.
Seneca Township	USNM	1325	0·15–0·3	Off–Of	Regular kam. bands; abundant banded plessite fields; some oxidation.
Social Circle	USNM	1675	0·15–0·3	Off–Of	Etches very slowly; polycrystalline kam.; few troilite inclusions.
South Byron	CNHM	Me2554	—	D	Sample consists entirely of fine dark plessite.
Spearman	UCLA	1	0·9–1·3	Om–Og	Regular kam. bands, containing 0·1 mm schr. inclusions.

Table 12. (continued)

Meteorite	Source*	Catalog number†	Kam band width (mm)	Structural class‡	Remarks
Springwater	UCLA	1	—	P	Metal and olivine about equally abundant; schr. at interfaces.
Tamarugal	UCLA	1	0·8–1·2	Om–Og	Regular kam. bands; 13 mm^2 schr. inclusion each 5 cm^2 area.
Tambo Quemado	UCLA	1	0·8–1·2	Om–Og	Brezina lamellae; similar to Tieraco Creek, Fig. 7.
Thule	MMUC	—	0·8–1·3	Om–Og	Regular bands, containing numerous small schr. inclusions.
Thurlow	CNHM	Me870	0·3–0·5	Of	Very attractive structure; much schr.; octahedral plessite.
Tieraco Creek	AM	DR1980	0·3–0·6	Of–Om	Brezina lamellae. Shown in Fig. 7.
Tombigbee River	UCLA	1	—	H	Large, skeletal schr. inclusions; some oxidation.
Trenton	UCLA	1	0·7–1·1	Om–Og	Regular kam. bands; a few small schr. inclusions.
Treysa	MPIM	—	ca. 1	(Om)	Not observed in detail before consumption.
Verkhne Dnieprovsk	CNHM	Me862	0·2–0·7	Of–Om	Brezina lamellae; some oxidation.
Victoria West	SAM	1	0·13–0·3	Off–Of	Large plessite fields with striking octahedral structure; oxidation.
Wallapai	UCLA	1	0·3–0·5	Of	Similar to Rodeo; numerous 0·1 × 0·4 mm schr. inclusions.
Weekeroo Station	Harvard	—	—	anom.	No octahedral pattern distinguishable; samples F and H of WASSERBURG *et al.*
Willamette	UCLA	1	ca. 1	(Om)	Consists of 1–4 mm grains, but appears to be reheated IIIA structure.
Williamstown	AMNH	791	0·6–1·0	Om	Regular kam. bands; no schr.; some 1 mm^2 troilite droplets.

* The meanings of the source abbreviations are as follows: AM, Australian Museum; Amherst, Amherst College; AMNH, American Museum of Natural History; ANSSSR, Academy of Sciences, U.S.S.R.; ASU, Arizona State University; BM, British Museum; CNHM, Field Museum of Natural History; GSP, Geological Survey, Pretoria; Krantz, Fa. F. Krantz, Bonn; Harvard, Mineralogical Museum, Harvard University; MMUC, Mineralogical Museum of the University, Copenhagen; MPIH, Max-Planck Institut für Kernphysik, Heidelberg; MPIM, Max-Planck Institut für Chemie, Mainz; NHMW, Naturhistorisches Museum, Vienna; NMV, National Museum of Victoria; QM, Queensland Museum; SAM, South African Museum; UCLA, Leonard Collection of Meteorites, UCLA; USNM, U.S National Museum; WNSE, Ward's Natural Science Establishment; Yale, Yale University.

† The numbers listed for the UCLA collection are specimen numbers. The complete catalog number is the Leonard co-ordinate number (LEONARD, 1956) followed by this specimen number.

‡ We have used the structural class definitions given by BUCHWALD and MUNCK (1965). If 20% of the primary kam. bands fell into a second class, we have listed both symbols.

§ Via J. F. LOVERING.

Appendix—Description of Meteorite Samples

The sources of the meteorite specimens which were investigated are shown in Table 12 Also listed are structural data, and notes regarding the textures and conditions of the specimens Each specimen was polished and etched in nital, and observed at low power (15×) under a microscope. The structural classification scheme of Buchwald and Munck (1965) is followed. This is summarized as follows: Ogg, 2·0–4·0 mm; Og, 1·0–2·0 mm; Om, 0·5–1·0 mm; Of, 0·25–0·50 mm; Off, 0·25 mm; H, hexahedrite; D, ataxite; P, pallasite. Photographs of the different structures are helpful in understanding the progression of structures which are observed within the groups. A few references are cited to this end, and frequent reference is made to Figs. 5, 6 and 7 of the *Classification* section of this report. Kamacite and schreibersite are abbreviated kam. and schr. throughout Table 12.