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The Chemical Classification of Iron Meteorites

IV. Irons with Ge Concentrations Greater than 190 ppm and other Meteorites Associated with Group I

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Concentrations of Ni, Ga, Ge, and Ir are reported for 87 iron meteorites with high Ge concentrations. Chemical group I is defined as those iron meteorites with 190–520 ppm Ge which fall within "main-sequence" fields on Ge vs. Ga and Ge vs. Ni plots. The Ni, Ga, and Ir ranges are 6.4–8.6%, 56–100 ppm, and 0.6–5.5 ppm, respectively. The Ge–Ga correlation is positive, Ge–Ni and Ga–Ni correlations negative, and Ir is not correlated with the other three elements. Members of group I have similar structures with kamacite bandwidths generally falling in the coarse-octahedrite range, and with numerous, often large inclusions which frequently contain silicates. Three additional categories of anomalous irons which show evidence of a relationship to group I are also defined. Category I-An1 includes irons which fall off the main sequence in Ge–Ga or Ge–Ni plots, but have structures which are very similar to those in group I. Category I-An2 includes main-sequence irons with Ge concentrations between 78 and 190 ppm, and other irons with Copiapo-type silicate inclusions. Category I-An3 irons are similar to the group I members in Ga and Ge contents, and insofar as they are rich in inclusions, but are anomalous in structure, and are not as likely to be genetically related to group I as are the former two categories. A consideration of available evidence indicates that group I is one of the most primitive groups of iron meteorites. The present relationship between metal and silicates appears to have formed nonigneously, perhaps as a result of metal–silicate fractionation in the solar nebula.

INTRODUCTION

This is the fourth of a series of papers reporting the results of a study of the concentrations of Ni, Ga, Ge, and Ir in the iron meteorites. These data together with structural observations have proven of value for defining groups of related irons. The previous reports dealt with irons having low Ge concentrations (Wasson, 1967), irons having Ge concentrations in the 8–100 ppm range (Wasson and Kimberlin, 1967), and irons with Ge concentrations between 80 and 200 ppm (Wasson, 1969). In this paper I discuss composition evidence obtained from a study of iron meteorites with high Ge concentrations. These meteorites include the members of chemical group I, which is one of the two largest groups of iron meteorites, and which, together with the closely related Copiapo-type irons, includes the majority of the irons-with-silicate-inclusions.

EXPERIMENTAL

The procedure for Ni, Ga, and Ge has been reported by Wasson and Kimberlin (1967). No important changes have been made since that time. Nickel is determined on an aliquot of the dissolved sample by atomic absorption spectrometry. The precision (at 95% confidence of the method is about 2% of the mean of two determinations. Gallium and germanium are determined by radiochemical neutron activation The 95% confidence limits of the means of determinations are about ±4%. Iridium is determined by the neutron-activation procedure described by Kimberlin *et al.* (1968).

The 95% confidence limits on the means of two determinations extend about $\pm 10\%$ about the mean.

Our results agree quite well with previously reported values. A detailed comparison if Ni, Ga, and Ge values was given by Wasson and Kimberlin (1967), and a comparison of Ir values by Kimberlin *et al.* (1968).

Samples

The meteorites are listed alphabetically in Table II. With four exceptions, each specimen was polished and etched, and the structure observed under a microscope. Kamacite bandwidths and other appropriate structural details were recorded, and provided the basis for assigning the irons into the structural classification of V. Buchwald (private communication, 1969), which is listed in Table I. [I prefer this classification, which has equal logarithmic bandwidth intervals, to that of Goldstein (1969), which has variable bandwidth ranges.] In columns 3 and 4 of Table II are listed structural-class symbols and kamacite widths of irons showing octahedral orientations of the kamacite. The structural classes have been confirmed by Buchwald, and about half of the bandwidths represent his determinations from studies of large sections of the irons in major museums. In columns 5 and 6 are listed the source and catalog number of the analyzed samples.

The typical size of the irradiated samples was about 1 gm. Sampling variations were generally found to be small, although these were the major contribution to the errors. All samples were relatively unoxidized, with the exception of Cookeville, Cranbourne, Pine River, Shrewsbury, and Zenda. Houck was available to us only as sawings. The only sample listed in Table II which may have been mislabeled is Mount Stirling. I have listed all investigated samples which are accorded separate entries in the Hey (1966) catalog, even though, as discussed later, it is clear that a number of them belong to paired falls.

In columns 7 through 12 of Table II are listed mean Ni, mean Ga, replicate and mean Ge, and replicate and mean Ir concentrations in 87 iron meteorites, including five which are repeated from the third paper

TABLE I

Structural Classification According to Buchwald[a,b]

Class	Symbol	Kamacite bandwidth (mm)	Remarks
Hexahedrites	H	—	No octahedral orientation even in large sections
Coarsest octahedrites	Ogg	>3.3	Taenite may or may not be present
Coarse octahedrites	Og	1.3–3.3	—
Medium octahedrites	Om	0.5–1.3	—
Fine octahedrites	Of	0.2–0.5	—
Finest octahedrites	Off	<0.2	Distinct bands of kamacite
Plessitic octahedrites	Opl	<0.2	Kamacite sparks and spindles
Ataxites	D	—	Well-developed, slowly annealed plessite, kamacite spindles very rare
Anomalous	Anom	—	Wastebasket class which includes all irons which demand individual descriptions, such as Four Corners, Zacatecas, Rafrüti, N'Goureyma, and Nedagolla

[a] Private communication.

[b] Each octahedrite class corresponds to a range of a factor of 2.5 in kamacite bandwidth. The boundaries are chosen in such a fashion that most meteorites belonging to a particular chemical group fall within a single structural class, and such that the differences between these classes and Tschermak-Prior classes were minimized.

TABLE II

Mean Concentrations of Ni and Ga and Mean and Replicate Concentrations of Ge and Ir in 87 Iron Meteorites Which are Members of Group I, are Related to Group I, or Contain More than 190 ppm Ge[a]

Meteorite	Chem. group	Struc. class	Band width[a] (mm)	Source[b]	Catalog no.	Ni (%) mean	Ga (ppm) mean	Ge (ppm) Replicates	Ge (ppm) mean	Ir (ppm) Replicates	Ir (ppm) mean
Annaheim	I-An1	Og	*1.5*	GSC	0116302	7.74	79.8	300, 303	302	3.4, 3.5	3.5
Arispe	I-An3	Og	3.0	UCLA	14	6.54	50.3	250, 238, 242	243	10.5, 8.9	9.7
Aroos	I	Og	*2.6*	MPIM	9011	6.71	88.2	454, 387, 387	387	1.6, 1.6	1.6
Ashfork	I	Og	2.4	AMNH	2619	6.97	83.2	333, 330, 327	330	2.3	2.3 ± 0.3
Bahjoi	I-An1	Og	1.5	SI	1807	7.95	62.7	274, 270	272	1.8, 2.1	1.9
Balfour Downs	I	Om-Og	1.3	AMNH	4187	8.39	56.4	193, 194	194	2.2, 1.9	2.0
Ballinger	I-An1	Og	2.9	AMNH	2613	6.19	84.5	332, 319	326	2.2, 2.1	2.1
Bendego	I-An3	Og	1.8	FMNH	Me5	6.39	54.0	222, 246	234	0.18, 0.22	0.20
Bischtübe	I	Og	1.8	FMNH	Me932	7.88	68.4	242, 235	238	1.8, 2.1	1.9
Bloody Basin	I	Og	2.0	ASU	723	6.79	81.6	324, 321, 314	320	2.0	2.0 ± 0.3
Bogou	I	Og	1.9	SI	2245	7.15	77.4	293, 308	301	1.4	1.4 ± 0.4
Bohumilitz	I	Og	1.9	FMNH	Me898	7.37	75.3	260, 269	264	1.6, 2.1	1.8
Bolivia	I	Og	2.8	SI	793	6.6 ± 0.2	85.4	444, 386, 349	393[c]	1.6, 1.3	1.5
Burgavli	I	Og	2.6	KMAN	2260	6.71	95.8	508, 530	519	1.1, 1.2	1.1
Burkett	I	Og	2.0	AMNH	860	6.87	87.2	364, 372	368	2.3, 1.9	2.1
Butler	Anom	Opl	0.15	HarU	3541	15.2 ± 0.3	87.1	2000, 2050, 1890, 1920, 1990	1970	1.2, 1.2	1.2
Campo del Cielo	I	Og	3.0	UPit	393	6.62	90.0	390, 393	392	3.0, 3.3	3.2
Camp Verde	I	Og	2.0	ASU	440.1	7.06	78.2	311, 333	322	2.1, 1.9	2.0
Canyon Diablo	I	Og	2.0	UCLA	77	6.98	81.8	313, 328, 328	324	1.7, 2.1	1.9
Canyon Diablo (1936)	I-An1	Om	1.1	ASU	371.2	7.9 ± 0.3	79.3	313, 321	317	2.0[c], 1.8[c]	2.0 ± 0.4
Canyon Diablo (1949)	I-An1	Om	1.1	ASU	586.1	8.2 ± 0.3	80.1	336[c], 340[c], 327	332[c, d]	1.8[c], 2.1[c]	2.0 ± 0.4
Casey County	I	Og	2.2	HarU	373	6.96	81.7	310, 324	317	1.1, 1.1	1.1
Chihuahua City	I-An3	Anom	Anom	ASU	27a	6.68	52.7	215, 209	212	0.10, 0.13	0.11 ± 0.02
Colfax	I-An2	Om	0.60	FMNH	Me1961	10.84	52.8	157, 149	153	1.4, 1.6	1.5
Comanche	I	Og	1.8	SI	2246	8.1 ± 0.2	73.9	266, 272	269	2.2, 2.2	2.2
Cookeville	I	Og	2.4	SI	2731	6.4 ± 0.5	91.4	397, 392	395	2.1, 2.1, 2.1	2.1
Copiapo	I-An2	Anom	2.5	MHNP	615	7.01	69.8	250, 255	252	2.5, 2.4	2.5
Cosby's Creek	I	Og	2.2	HarU	143	6.57	91.5	431, 431	431	3.2, 2.6	2.9
Cranbourne	I	Og	1.8	FMNH	Me499	6.80	85.4	349, 368	358	1.7, 1.8	1.8
Deelfontein	I	Og	1.3	GSSA	—	7.11	83.1	304, 307	306	1.3, 1.5	1.4
Deport	I	Og	2.0	UCLA	139	8.11	69.9	264, 246	255	2.0, 2.3	2.2

TABLE II (*contd.*)

Meteorite	Chem. group	Struc. class	Band width[a] (mm)	Source[b]	Catalog no.	Ni (%) mean	Ga (ppm) mean	Ge (ppm) Replicates	Ge (ppm) Mean	Ir (ppm) Replicates	Ir (ppm) Mean
Dungannon	I	Og	*1.9*	FMNH	2090	6.9 ± 0.2	78.5	333, 327	330	2.0, 2.1	2.1
Ehrenberg	I	Og	*2.0*	HarU	273	6.98	79.9	318, 310	314	1.7, 1.8	1.8
Elton	Anom	Anom	*0.55*	MSC	—	6.97	46.3	166, 163	165	0.044, 0.062	0.053 ± 0.009
Fair Oaks	I	Og	*1.6*	ASU	722	7.08	81.8	317, 320	318	1.9, 1.9	1.9
Four Corners	I-An2	Anom	0.85	ASU	166a	8.90	48.7	178, 180	179	1.9, 2.0	2.0
Gladstone	I	Og	2.8	GSQ	—	6.53	93.7	409, 428	418	2.8, 3.2	3.0
Goose Lake	I-An1	Om	1.2	SI	1332	8.00	67.2	317, 307, 292	305	2.3, 2.3	2.3
Hope	I	Og	2.1	SI	3477	6.77	85.7	410, 387	398	0.66, 0.52	0.59
Houck	I	Og	—	FMNH	Me2108	7.1 ± 0.2	80.5	329, 331	330	1.7, 2.0	1.8
Jenkins	I	Og	*2.0*	LawU	—	6.85	86.2	362, 344	353	2.0, 1.5	1.8
Jenny's Creek	I	Og	2.4	FMNH	Me114	7.0 ± 0.2	84.6	329, 310	320	1.8, 2.8	2.3 ± 0.5
Karee Kloof	I-An1	Og	1.6	PEM	—	8.1 ± 0.3	79.5	353, 356	355	1.5, 1.5	1.5
Leeds	I	Og	*1.4*	ASU	69a	7.99	67.1	242, 239	241	2.3, 2.0	2.1
Linwood	I	Og	*3.1*	HarU	632	6.4 ± 0.2	90.4	379, 370	374	2.7, 2.6	2.7
Magura	I	Og	*2.8*	UCLA	423	6.67	94.6	475, 491	483	3.0, 3.4	3.2
Mayerthorpe	I	Og	*2.0*	UAlb	—	7.19	75.5	276, 289	283	2.4, 2.4	2.4
Mazapil	I	Om	*0.8*	AMNH	136	8.64	60.2	221, 221	221	5.4, 5.6	5.5
McCamey	I	Og	*1.5*	HarU	675	7.07	74.1	268, 282, 292	281	2.0, 2.0, 2.2	2.0
Mertzon	I-An3	Om	*0.6*	SI	1435	8.98	68.0	295, 290	293	2.5, 2.3	2.4
Misteca	I	Og	1.4	BM	35173	8.27	67.8	231, 235	233	1.0[e], 1.8, 1.4	1.6 ± 0.3
Monument Rock	I	Og	*1.9*	ASU	587.1	6.84	80.9	308, 332	320	1.8, 2.0	1.9
Morrill	I-An3	Om	*0.9*	ASU	195.1	8.38	58.0	305, 286	296	1.7, 1.6	1.7
Mt. Ayliff	I	Og	—	AMNH	2228	7.76	70.0[c]	273, 218	250[c, d]	1.6, 2.4, 1.5	1.8 ± 0.3
Mt. Dooling	I-An3	Anom	Anom	WAM	—	6.26	51.5	237, 230	234	1.0, 1.3	1.2
Mt. Sterling	Anom	Og	*2.5*	AM	—	6.48	48.0	137, 148	142	6.3, 7.2	6.7
Nocoleche	Anom	Og	*2.4*	AMNH	164	6.4 ± 0.3	49.3	149, 146	148	8.2, 8.2	8.2
Odessa	I	Og	*1.6*	UCLA	420	7.20	74.7	271, 295, 292	285	2.3, 2.2, 2.2	2.2
Ogallala	I	Og	*1.7*	ASU	90.1	7.85	66.7	280, 252	266	2.7, 2.5	2.6
Osseo	I	Og	*2.5*	UCLA	302	6.44	91.7	433, 468	450	6.3, 4.5	5.4 ± 0.9
Persimmon Creek	I-An2	Anom	*0.05*	SI	318	14.45	34.1	74.4, 82.2	78.3	0.65, 0.66	0.65
Pine River	I-An2	Anom	—	LawU	—	7.40	76.9	236, 232	234	2.5, 2.8	2.6
Pitts	I-An2	Anom	*0.16*	SI	1378	12.80	33.0	93.1, 95.4	94.2	0.78, 0.94	0.86

Queensland	I	Og	—	AMNH	165	6.78	86.9	385, 375	380	2.6, 2.6	2.6
Rifle	I	Og	*1.7*	ASU	528.3	7.20	77.2	276, 280, 286	281	2.0, 1.4	1.7
St. Francois County	I-An3	Ogg	*4.0*	AMNH	65	6.12	48.1	254, 238	246	0.12, 0.10	0.11 ± 0.02
Santa Rosa	I-An3	Anom	Anom	IGB	—	6.63	50.6	227, 220, 228, 215	222	0.062, 0.068, 0.078 0.062	0.068
Sarepta	I	Og	*3.1*	HarU	216	6.55	99.9	453, 460	457	3.8, 2.8	3.4 ± 0.5[d]
Seeläsgen	I	Og	*7.0*	MIUT	g46.2185	6.47	96.8	488, 497	493	1.1, 1.1	1.1
Seligman	I	Og	*1.8*	ASU	583.3	6.69	91.3	431, 416	423	2.9, 2.8, 2.6	2.8
Seymour	I	Og	*2.1*	HarU	669	6.54	89.0	381, 382	382	1.8, 1.7	1.7
Shrewsbury	I	Om	1.2	HarU	463	8.42	61.4	203, 205	204	2.5, 2.6	2.6
Smithville	I	Og	*1.8*	FMNH	Me50	6.78	86.9	357, 370	363	2.0, 1.9	2.0
Southern Arizona	I	Og	*1.8*	SI	1445	8.06	66.2	241, 243	242	1.7, 2.1	1.9
Surprise Springs	I	Og	*1.4*	FMNH	Me854	8.12	69.6	259, 271	265	2.0, 1.9	2.0
Thoreau	I	Og	*1.8*	UNM	16.1	7.4 ± 0.2	73.8[c]	271	271[c]	1.9	1.9 ± 0.3
Toluca	I	Og	*1.4*	AML	128.415	8.07	70.6	246, 247	246	2.0, 1.7	1.8
Udei Station	I-An2	Anom	Anom	AMNH	3946	8.83	60.4	203, 205	204	0.56, 0.47	0.51
Union County	I-An3	Anom	Anom	ASU	326.1	6.12	54.8	240, 251	245	2.2, 2.0	2.1
Waldron Ridge	I	Og	*1.5*	AMNH	111	7.55	74.6	286, 277	282	1.6, 2.4	2.0 ± 0.4
Waterville	Anom	Anom	*1.1*	SI	1512	7.81	64.8	200, 193	196	0.30, 0.30	0.30
Wichita County	I	Og	*1.6*	SI	1181	6.78	86.9	353, 330	341	2.1, 2.0	2.1
Wickenburg	I	Og	*2.0*	ASU	455.1	7.07	82.6	309, 332	321	1.6, 1.9	1.8
Woodbine	I-An2	Anom	*0.4*	SI	2169	10.6 ± 0.5	36.7	113, 115	114	1.4, 1.4	1.4
Youndegin	I	Og	*2.0*	UCLA	402	6.38	90.8	375, 391	383	2.0, 2.0	2.0
Zacatecas	I-An3	Anom	Anom	UCLA	403	5.88	83.8	314, 299	307	2.1, 2.2	2.2
Zenda	I-An1	Om	*0.9*	LawU	—	8.50 ± 0.3	54.7	212, 217	214	2.1, 2.2, 1.8	2.1

[a] Bandwidth values in normal type determined on large sections by V. Buchwald, and are averages of ranges which extend about ±20% about the means. Values in italics by the author, and are subject to errors of about ±10% in addition to the 20% natural ranges.

[b] The source abbreviations are to be deciphered as follows: AM, Australian Museum; AML, American Meteorite Laboratory; AMNH, American Museum of Natural History; ASU, Arizona State University; BM, British Museum; FMNH, Field Museum of Natural History; GSC, Geological Survey of Canada; GSQ, Geological Survey of Queensland; GSSA, Geological Survey of South Africa; HarU, Harvard University; IGB, Instituto Geophysico, Bogota; KMAN, Committee on Meteorites, Academy of Sciences, USSR; LawU, Lawrence University; MHNP, Museum Histoire Naturelle, Paris; MIUT, Mineralogisches Institut, Universität Tübingen; MPIM, Max-Planck Institut, Mainz; MSC, Manned Spacecraft Center, PEM; Port Elizabeth Museum; SI, National Museum of Natural History, Smithsonian Institution; UAlb, University of Alberta,; UCLA University of California, Los Angeles; UNM, University of New Mexico; UPit, University of Pittsburgh; WAM, Western Australian Museum.

[c] Value believed to be of lower than usual accuracy.

[d] Weighted mean.

[e] Value not included in the mean.

in this series (Wasson, 1969). Column 2 lists the chemical group to which the objects have been assigned. Ninety-five per cent confidence error limits are listed for mean Ni and Ir concentrations when these limits exceed 2% and 10% of the mean values, respectively. Except as noted, all mean Ga and Ge concentrations are believed precise to within 4%. Some of the results are slightly different from those previously published.

Classification

Previous Work

Goldberg *et al.* (1951) defined Group I as those iron meteorites with 45–100 ppm Ga. Lovering *et al.* (1957) divided this group in two, and redefined group I to be those irons with 80–100 ppm Ga, and 300–420 ppm Ge. Smales *et al.* (1967) determined Ga and Ge (and nine other trace elements) with greater accuracy in a number of irons, but did not attempt to redefine the limits set by the former authors. Cobb (1967) determined Ga, Ir, and four other elements in a number of irons, and defined a group of coarse octahedrites which are all normal or related anomalous members of what I define to be group I. Nichiporuk and Brown (1965) determined Ru, Rh, Pd, Ir, and Pt in 24 irons, including three normal group I members and two anomalous members. Thirteen of the irons listed in Table II were included in my previous study of Arizona octahedrites (Wasson, 1968).

Wasson and Kimberlin (1967) noted that

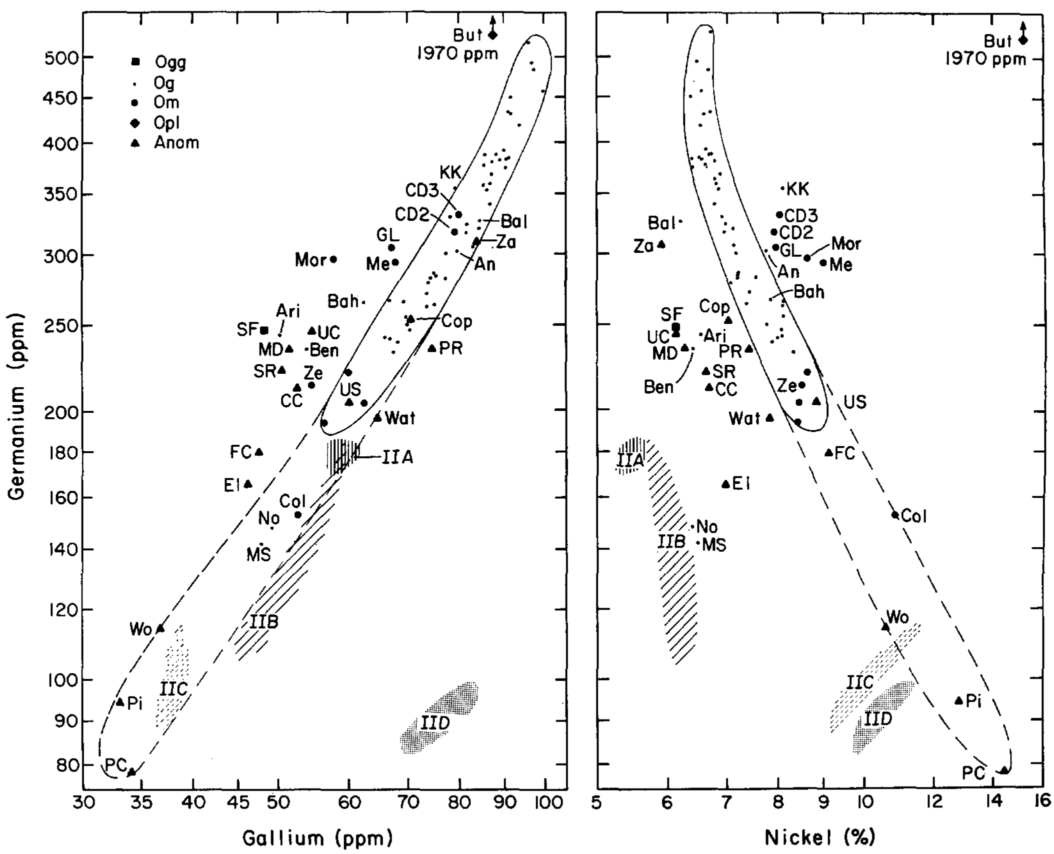

FIG. 1. Plots of Ge vs. Ga and Ge vs. Ni for iron meteorites with Ge concentrations above about 190 ppm, and other related objects with Ge concentrations down to 78 ppm. Group I is defined as those meteorites which fall within the fields defined by closed curves *on both plots*. There is evidence that these fields actually extend down to 78 ppm Ge, as shown by the broken lines. The positions of the previously defined groups IIA, IIB, IIC, and IID are indicated by shading.

genetic groups of iron meteorites are characterized by (1) limited concentration ranges of all elements compared to the range found in the iron meteorites as a whole; (2) smooth variations in the concentration of one element plotted against that of another; (3) similar structures. These rules have been applied in the discussion which follows to define a relatively compact group I, and additional types of irons which appear related to these normal group I members to a greater or lesser extent.

Group 1: Main-Sequence Irons with Ge Concentrations Greater than 190 ppm

In Fig. 1 are plotted Ge versus Ga and Ge versus Ni for the meteorites listed in Table II. The majority of the points fall in rather compact fields on both plots. These meteorites are designated "chemical group I," and are listed in Table III in order of decreasing Ge concentration. Fifty-three of these irons (including nine believed to be fragments of Canyon Diablo) are coarse octahedrites and three are medium octahydrites. All are similar in both gross and detailed structure. All meteorites which Lovering *et al.* (1967) included in their group I and which we have analyzed are members of chemical group I, as are also several other irons which they designated as anomalous or as members of their group II.

As seen in Fig. 1, Ge is positively correlated with Ga, and negatively correlated with Ni in group I, although there is no Ge–Ni correlation at Ge concentrations above 350 ppm. In Fig. 2 Ir is plotted versus Ni. There is no correlation between these two elements for group I members nor is there between Ir and Ge or Ga. However, the total range of Ir concentrations in group I is less than an order of magnitude, considerably smaller than that encountered in other large groups such as IIIA, IIA, or IIB. If the data on Hope, Mazapil, and Osseo are not included, the Ir range is about a factor of 3.

The area subtended by the group I fields on the Ge–Ga–Ni plots is considerably larger than those of the eight groups defined in our earlier papers. The Ge range is a factor of 3, which is to be compared with a

TABLE III. COMPOSITION OF GROUP I MEMBERS IN ORDER OF DECREASING Ge CONTENT

Meteorite	Ni (%)	Ga (ppm)	Ge (ppm)	Ir (ppm)
Burgavli	6.71	95.8	519	1.1
Seeläsgen	6.47	96.8	493	1.1
Magura	6.67	94.6	483	3.2
Sarepta	6.55	99.9	457	3.4
Osseo	6.44	91.7	450	5.4
Cosby's Creek	6.57	91.5	431	2.9
Seligman	6.69	91.3	423	2.8
Gladstone	6.53	93.7	418	3.0
Hope	6.77	85.7	398	0.59
Cookeville	6.4	91.4	395	2.1
Bolivia	6.6	85.4	393	1.5
Campo del Cielo	6.62	90.0	392	3.2
Aroos	6.71	88.2	387	1.6
Youndegin	6.38	90.8	383	2.0
Seymour	6.54	89.0	382	1.7
Queensland	6.78	86.9	380	2.6
Linwood	6.4	90.4	374	2.7
Burkett	6.87	87.2	368	2.1
Smithville	6.78	86.9	363	2.0
Cranbourne	6.80	85.4	358	1.8
Jenkins	6.85	86.2	353	1.8
Wichita County	6.78	86.9	341	2.1
Dungannon	6.9	78.5	330	2.1
Canyon Diablo[a]	6.98	81.8	324	1.9
Jenny's Creek	7.0	84.6	320	2.3
Casey County	6.96	81.7	317	1.1
Deelfontein	7.11	83.1	306	1.4
Bogou	7.15	77.4	301	1.4
Odessa	7.20	74.7	285	2.2
Mayerthorpe	7.19	75.5	283	2.4
Waldron Ridge	7.55	74.6	282	2.0
Rifle	7.20	77.2	281	1.7
McCamey	7.07	74.1	281	2.0
Thoreau	7.4	73.8	271	1.9
Comanche	8.1	73.9	269	2.2
Ogallala	7.85	66.7	266	2.6
Surprise Springs	8.12	69.6	265	2.0
Bohumilitz	7.37	75.3	264	1.8
Deport	8.11	69.9	255	2.2
Mount Ayliff	7.76	70.0	250	1.8
Toluca	8.07	70.6	246	1.8
Southern Arizona	8.06	66.2	242	1.9
Leeds	7.99	67.1	241	2.1
Bischtübe	7.88	68.4	238	1.9
Misteca	8.27	67.8	233	1.6
Mazapil	8.64	60.2	221	5.5
Shrewsbury	8.42	61.4	204	2.6
Balfour Downs	8.39	56.4	194	2.0

[a] The following meteorites are also members of group I, but are believed to be fragments of the Canyon Diablo fall: Ashfork, Bloody Basin, Camp Verde, Ehrenberg, Fair Oaks, Houck, Monument Rock, and Wickenburg.

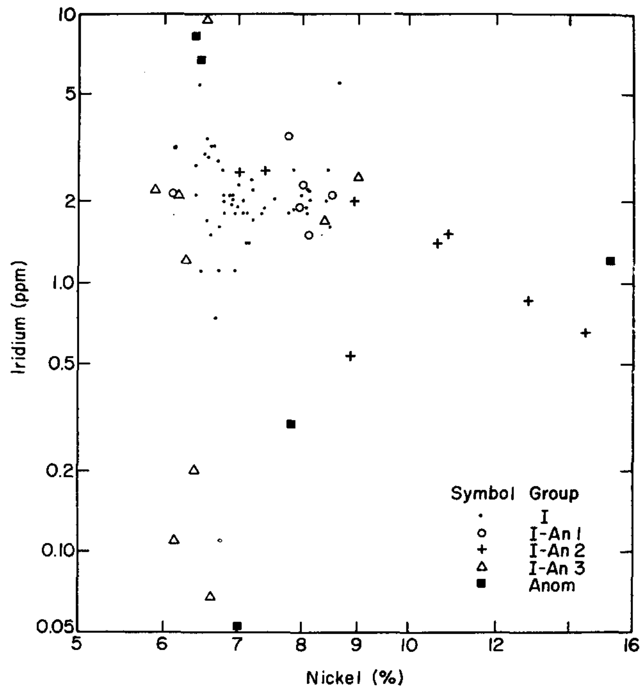

FIG. 2. Plot of Ir vs. Ni for group I iron meteorites, and other irons having similar compositions. There is no Ir–Ni correlation in group I, in contrast to the negative correlations found in most of the chemical groups.

factor of 1.7 in group IIB, the group with the second largest range. These ranges are nonetheless considerably smaller than the factor of 4×10^5 variation in Ge found in the iron meteorites as a whole.

Structurally, group I members are characterized by their richness in inclusions. Figure 3 illustrates a large polished and etched section of the Rifle coarse octahedrite, which is a typical member of the group. The interiors of the round inclusions consist mainly of troilite and graphite, and are surrounded by a shell of schreibersite. These inclusions range in size from a fraction of a centimeter up to 4 cm in this section, and even larger in some irons. Silicates and other accessory minerals are often found in this type of inclusion. The irons with Odessa-type silicate inclusions (Toluca, Odessa, Linwood, and Campo del Cielo) studied by Bunch *et al.* (1969) are members of group I. Also visible in the Rifle section are schreibersite inclusions in both lamellar and irregular form. A feature unique to members of this group is the presence of areas 10 cm or more across in which nearly every kamacite lamella has a cohenite center. The right half of the Rifle section is such a cohenite-rich area, whereas the kamacite in the left half of the section is relatively cohenite-free. The author knows of no instance where an iron meteorite showing a cohenite distribution similar to that in the right half of Fig. 3 is not a member of group I.

Figure 4 shows polished and etched sections of the low-Ni group I member, Hope[1], and the high-Ni member, Balfour Downs. The higher Ni content of Balfour Downs is reflected in its larger content of plessite and the in narrower widths of its kamacite bands. The mean bandwidths of 2.1 and 1.3 mm for Hope and Balfour Downs, respectively, are both consistent with a cooling rate of about 2×10^{-6} °C year^{-1}, according to the graphs of Short and Goldstein (1967).

[1] The discovery location of the Hope, Arkansas, iron is incorrectly listed in Hey (1966) as Boaz, Alabama.

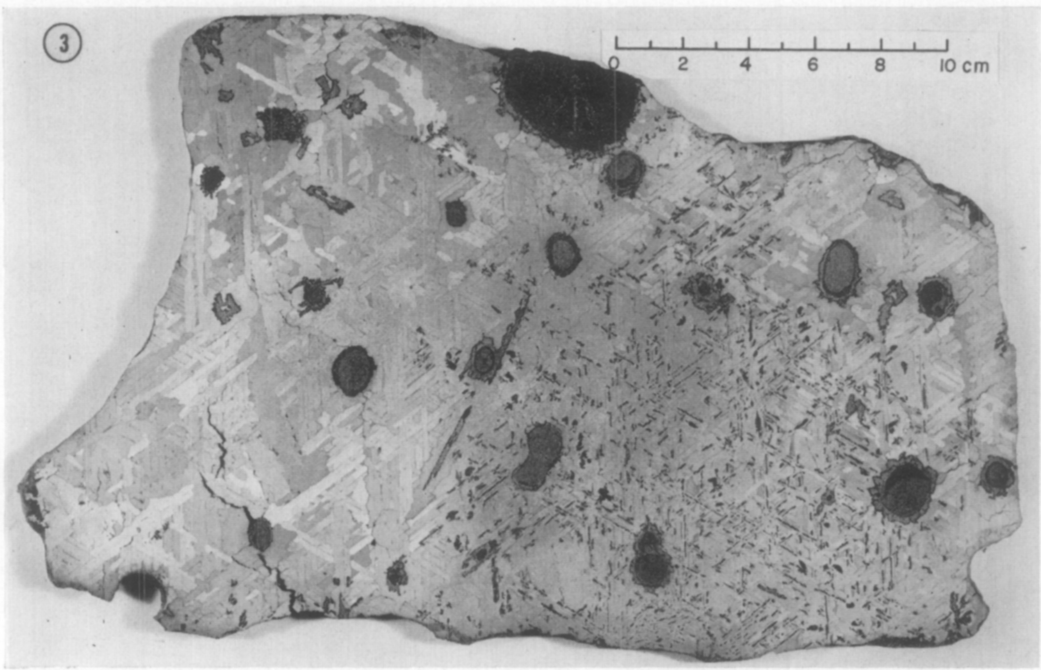

FIG. 3. A polished and etched section of the Rifle iron meteorite showing the high content of inclusions which is characteristic of group I irons. The large, rounded inclusions consist mainly of troilite and graphite surrounded by a shell of schreibersite. The latter mineral also occurs by itself in lamellar and irregular forms. The right half of this section is rich in cohenite, occurring in the centers of kamacite lamella. Photograph courtesy of Smithsonian Institution.

Group I: Irons with Anomalous Composition but Normal Structure

Six meteorites with Ge concentrations between 200 and 360 ppm fall slightly outside the group I fields on the Ge–Ga and Ge–Ni plots, but have structures which V. Buchwald (private communication) finds indistinguishable from those of normal group I members. These are listed in Table IV along with two additional irons (Annaheim and Zenda), which the author believes to fall in the same category, but which Buchwald has not yet studied. I designate these irons by the symbol I-An1.

Two of these objects, Canyon Diablo (1936) and Canyon Diablo (1949) were found near the Canyon Diablo crater, and almost certainly represent local inhomogeneities in the original, 50-m mass. As pointed out in Wasson (1968), other fragments from this source fall into the group I fields. It is interesting to note that although the Ni content of Canyon Diablo fragments varies by more than 1% absolute, the Ga,

TABLE IV

NI, GA, GE, AND IR IN METEORITES DESIGNATED I-AN1 WHICH ARE OUTSIDE THE "MAIN SEQUENCE" IN COMPOSITION BUT HAVE STRUCTURES VERY SIMILAR TO THOSE OF GROUP I MEMBERS

Meteorite	Ni (%)	Ga (ppm)	Ge (ppm)	Ir (ppm)
Karee Kloof	8.1	79.5	355	1.5
Canyon Diablo (1949)[a]	8.2	80.1	332	2.0
Ballinger	6.19	84.5	326	2.1
Canyon Diablo (1936)[a]	7.9	79.3	317	2.0
Goose Lake	8.00	67.2	305	2.3
Annaheim	7.74	79.8	302	3.5
Bahjoi	7.95	62.7	272	1.9
Zenda	8.5	54.7	214	2.1

[a] Although the high Ni contents of these two Canyon Diablo fragments causes them to fall outside the main sequence on the Ge–Ni plot, in all likelihood they represent local variations in the 50-m crater-producing mass.

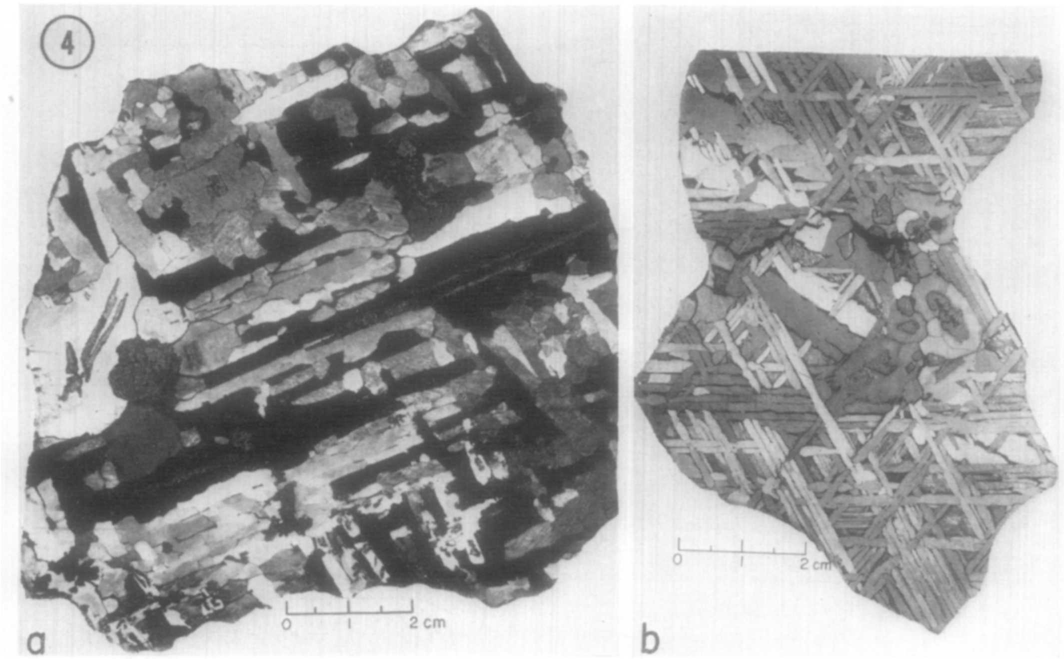

FIG. 4. (a) Hope, a Ni-poor group I member, and (b) Balfour Downs, a Ni-rich group I member. The bandwidths are smaller and there is much more plessite (mainly present as finely banded areas) in Balfour Downs. The inclusions in Balfour Downs are mainly schreibersite, whereas schreibersite, troilite, and cohenite are clearly visible in this section of Hope. Photographs courtesy of Smithsonian Institution.

Ge, and Ir contents never fall more than two standard deviations away from the grand mean. This is interpreted to indicate that the latter are less strongly fractionated between kamacite and taenite than is Ni. Goldstein's (1966) microprobe study of Ge and Ni in Butler confirms that this is the case for Ge.

That two irons in this category are variant fragments of a large group I iron suggests that all members of this group may have originated together with the group I irons, and may be nothing more than extreme variations in an initially somewhat inhomogeneous population. If so, this indicates that this group will be similar to group I members in other properties, such as cooling rates, concentrations of other trace elements, and in cosmic-ray or solidification ages. The few data that are available, such as the Smales *et al.* (1967) and Fouché and Smales (1966) studies of 11 additional trace elements in Goose Lake and several normal group I members, indicate that this is indeed correct. Additional evidence is found in the Ir data shown in Fig. 2, which show a slightly smaller range among the I-An1 irons than found among the normal group I members.

Group I: Main-Sequence Irons with Ge Concentrations Below 190 ppm and Other Irons with Copiapo-Type Silicate Inclusions

In their comprehensive study of nonmetallic minerals in irons-with-silicate inclusions, Bunch *et al.* (1969) found that eight of the 18 irons investigated contained similar inclusions, which were designated Copiapo-style inclusions. We have studied seven of these objects (all except Tacubaya) and find that their metal compositions plot in or near the main-sequence group I fields, or extrapolations of these fields down to 78 ppm Ge. The extensions of the fields are enclosed by broken lines in Fig. 1. An additional object, Colfax, also falls in the extended field. These eight irons are listed in Table V and are designated by the symbol I-An2. Figure 2 shows that there is a pronounced negative correlation of Ir and Ni in this group. Udei Station is an exception to this correlation, and is also exceptional in that it falls in the group I fields on both the Ge–Ni and Ge–Ga plots.

The structure of a high-Ni iron, Persimmon Creek, is illustrated in Fig. 5. The cooling rate indicated by the 0.05 mm bandwidth and 14.45% Ni concentration is about 5×10^{-6}°C year^{-1}. This is slightly higher than the value of about 2×10^{-6}°C year^{-1} found for most group I members, but can be considered to be the same within the errors inherent in the Short and Goldstein (1967) method for the estimation of cooling rates, particularly when applied to irons differing so much in Ni concentration.

TABLE V

IRONS (DESIGNATED I-An2) LYING ON THE GROUP I MAIN SEQUENCE BUT WITH LESS THAN 190 PPM Ge, AND OTHER IRONS WITH COPIAPO-TYPE SILICATE INCLUSIONS

Meteorite	Ni (%)	Ga (ppm)	Ge (ppm)	Ir (ppm)
Copiapo	7.01	69.8	252	2.5
Pine River	7.40	76.9	234	2.6
Udei Station	8.83	60.4	204	0.51
Four Corners	8.90	48.7	179	2.0
Colfax	10.84	52.8	153	1.5
Woodbine	10.6	36.7	114	1.4
Pitts	12.80	33.0	94.2	0.86
Persimmon Creek	14.45	34.1	78.3	0.65

It appears that the I-An2 irons are as closely related to group I as are the I-An1 meteorites, and that they can be expected

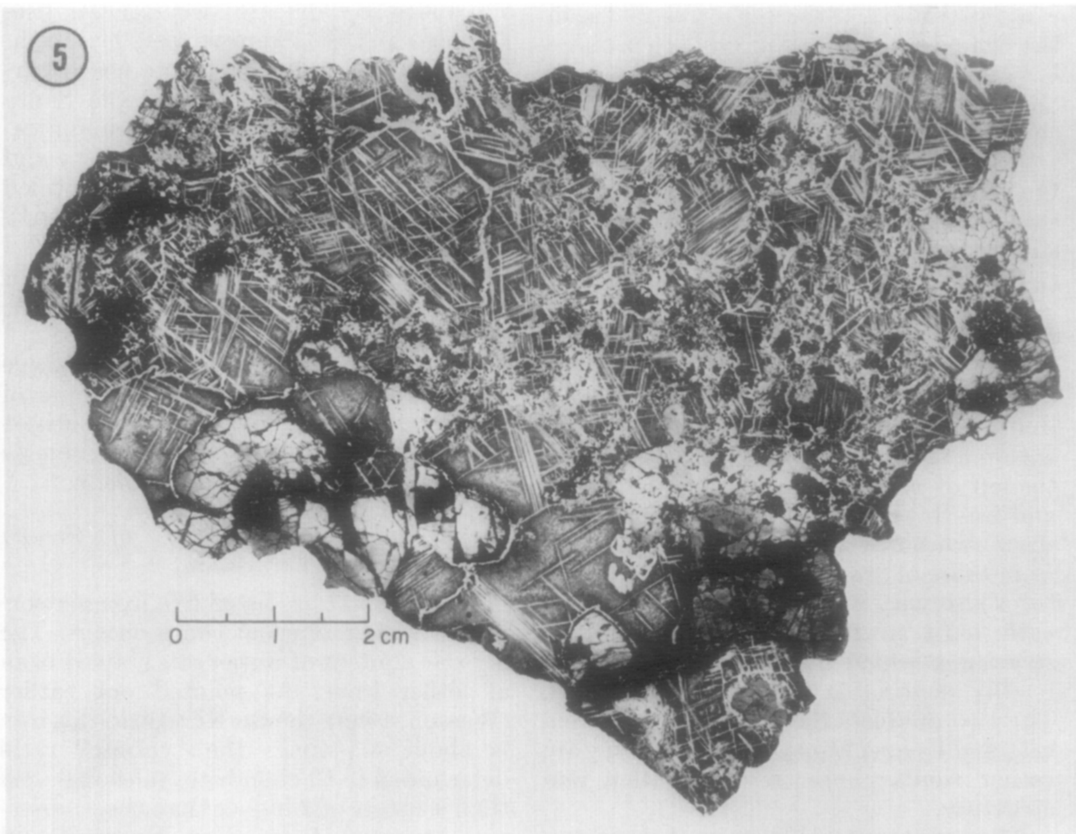

FIG. 5. Polished and etched section of the most Ni-rich I-An2 iron, Persimmon Creek. The larger silicate inclusions are rounded and surrounded by swathing kamacite. The smaller silicate inclusions are present as irregular patches. Most of the metal is fine plessite, which is crossed by kamacite bands about 0.05 mm thick. Photograph courtesy of Smithsonian Institution.

to display similarities in most other properties which may be investigated. The most extensive data now available are those on nonmetallic mineral composition reported by Bunch *et al.* (1969). These authors point out that Odessa-type inclusions (group I members) are very similar to Copiapo-type inclusions, and are chiefly to be distinguished on the basis of differences in mineral abundances and the texture of the nodules. The only phase which is distinctly different between the two types is troilite; Copiapo-type troilite is much lower in its Mn, Zn, and Ti contents than is Odessa-type troilite. It would be necessary to survey the troilite in group I irons more thoroughly, however, before one could be confident that the true troilite compositional range is adequately defined by the four objects which Bunch and coworkers studied. If there is a true hiatus in the composition of this or any other phase between the two types, my previous conclusion that there is a very close relationship between them will have to be modified.

A somewhat more detailed discussion of the metal compositions of and the relationship between these and other irons-with-silicate-inclusions will be given in Wasson (1970).

Irons with Anomalous Composition and Structure Which May Be Related to Group I

In Table VI are listed a group of ten irons (designated I-An3), most of which fall within a rather limited region distinctly to the left of the group I fields on the Ge–Ga and Ge–Ni plots (Fig. 1). These irons also show structures which are distinguishable from those of group I members. The structures also vary within this loose grouping, with most of the irons having unique structures which make polished sections readily identifiable to the experienced eye. The two doublets Santa Rosa–Chihuahua City and Union County–Mount Dooling are rather similar both in composition and structure.

These meteorites, like group I members, are relatively rich in inclusions. In particular, most, and perhaps all, are rich in bulk carbon content, as evidenced by the identification of cohenite or graphite in most of them. Brett (1967), in his summary of confirmed cohenite occurrences, lists Bendego and St. Francois County. Buchwald and Wasson (1968) note the occurrence of cohenite and graphite in Santa Rosa, and Buchwald (private communication) has identified cohenite in Arispe and Chihuahua City. [He has also identified cohenite in Colfax (I-An2), Zenda (I-An1), and Nocoleche (anom.).]

TABLE VI

IRONS (DESIGNATED I-An3) WHICH ARE ANOMALOUS IN BOTH COMPOSITION AND STRUCTURE, BUT WHICH SHOW EVIDENCE OF BEING RELATED TO THE MEMBERS OF GROUP I

Meteorite	Ni (%)	Ga (ppm)	Ge (ppm)	Ir (ppm)
Zacatecas	5.88	83.8	307	2.2
Morrill	8.38	58.0	296	1.7
Mertzon	8.98	68.0	293	2.4
St. Francois County	6.12	48.1	246	0.11
Union County	6.12	54.8	245	2.1
Arispe	6.54	50.3	243	9.7
Bendego	6.39	54.0	234	0.20
Mount Dooling	6.26	51.5	234	1.2
Santa Rosa	6.63	50.6	222	0.068
Chihuahua City	6.68	52.7	212	0.11

There is little further evidence either for or against a relationship between these eight irons and the main-sequence group I members. I feel confident that a positive link will eventually emerge for some of them, but at this time it appears wisest to treat each of them as anomalous objects (or in two cases, as similar doublets).

Irons for Which Evidence of Genetic Relationships is Very Weak

In Table VII are listed five iron meteorites of rather unusual compositions. The high Ge content of Butler sets it apart from all other irons. As pointed out earlier (Wasson, 1966), the Ge/Ni ratio in this iron is about 3.5 times the "cosmic" ratio determined in Cl chondrites (although less than a factor of 2 higher than those observed in group I members Burgavli and Seeläsgen). Waterville is unusually rich in troilite, and when dissolved left a nonmagnetic, black residue presumed to be graphite. It is the most likely of these five

TABLE VII

ANOMALOUS IRONS WHICH ARE NOT BELIEVED TO BE RELATED TO ANY CHEMICAL GROUP

Meteorite	Ni (%)	Ga (ppm)	Ge (ppm)	Ir (ppm)
Butler	15.2	87.1	1970	1.2
Waterville	7.81	64.8	196	0.30
Elton	6.9	46.3	165	0.053
Nocoleche	6.4	49.3	148	8.2
Mount Sterling	6.48	48.0	142	6.7

irons to be related to group I. Elton is a very unusual iron which has kamacite bands only 0.55 mm wide in some areas, and in others massive kamacite of centimeter dimensions associated with large skeletal schreibersite inclusions. Areas of the latter type are common in the low-Ge end of Group IIB, but Elton falls far outside the IIB fields on the basis of our analyses. If the Ge content of Elton were 100 ppm instead of 165 ppm, I would probably assign it to group IIB. Nocoleche and the (possibly mislabeled) sample of Mount Stirling were discussed in the previous paper of this series (Wasson, 1969). Although they plot relatively close to the IIB fields, they are more likely to be related to the I-An3 irons (particularly Arispe) on the basis of their structure and Ir contents.

Paired Falls

It is important for purposes of weighting experimental data to be aware of those irons which are fragments of the same fall but masquerading under different names in the Hey (1966) catalog. It is equally important to know which meteorites thought to be "paired" are, in fact, from separate falls.

The most flagrant case of name proliferation associated with a single fall is provided by the Arizona octahedrites. In an earlier publication (Wasson, 1968), I pointed out that 9 coarse and 2 medium octahedrites from Arizona [Ashfork, Bloody Basin, Camp Verde, Canyon Diablo Canyon Diablo (1936), Canyon Diablo (1949), Ehrenberg, Fair Oaks, Houck, Monument Rock, and Wickenburg (iron)] have Ga, Ge, and Ir contents which are identical within experimental error, and should all be attributed to the Canyon Diablo fall. Two of these objects are enriched in Ni, and fall in the category I-An1, but such Ni-rich fragments are, in fact, quite common near the Arizona crater (Moore *et al.*, 1967; see also Axon, 1969 for a photograph of a Ni-poor area in Canyon Diablo), and there is no justification for either considering these objects to be separate falls, or "satellites" of the larger, crater-producing mass.

It has occasionally been suggested that Canyon Diablo, Odessa, and Wichita County might form parts of a pair or triangle. The data in Table II indicate that these objects have resulted from three separate falls. There is a good possibility that some of the other irons are transported fragments of Odessa, however. McCamey is almost certainly such a mass, and Thoreau is also a likely candidate for such an assignment. Mayerthorpe, Waldron Ridge, and Rifle have compositions which are the same as that of Odessa within experimental errors, but are not believed to be paired because of either large mass (Rifle) or the large geographical separation between the discovery locations of these objects and that of Odessa.

The Hey (1966) catalog lists Cosby's Creek paired with Waldron Ridge and Greenbrier County. My unpublished data show that Greenbrier County is a member of group IIIA, and the data in Table II rule out the possibility that Cosby's Creek and Waldron Ridge are paired. Gladstone and Queensland have been paired and unpaired in various reports (see Wiik and Mason, 1965). I interpret the data in Table II to indicate that it is unlikely that these two objects are paired. However, the differences are not outside the maximum errors which could accumulate from sampling and irradiation in separate runs.

DISCUSSION

This section will be limited to a discussion of group I irons, with occasional reference to data obtained from the other categories which I believe to be related to group I.

Cooling Rates

Goldstein and Short (1967) have estimated cooling rates of iron meteorites on the basis of their kamacite bandwidths and bulk Ni contents. No member of group I or the categories I-An1 or I-An2 falls outside the range $1–3.5 \times 10^{-6}$°C year^{-1} except the high-Ni iron, Persimmon Creek for which Goldstein and Short estimate a cooling rate of 10×10^{-6}°C year^{-1}, a factor of 2 higher than my estimate based on their curves (their high value is the result of their use of a Ni concentration of 13.6%, whereas we determined a value of 14.45%). I interpret the cooling-rate data to indicate that the group I irons were stored in regions having a similar thermal history, and probably within a single parent body.

Cosmic-Ray Ages

The most accurate and abundant cosmic-ray age data are those based on the ^{40}K–^{41}K method reported by Voshage (1967). His study included seven members of group I as well as the I-An3 irons Arispe and Bendego. The latter two fall together with four group I members in a cluster at about 900 My (megayears). The other three group I irons cluster at about 570 My. These data indicate that the group I irons are associated with two parent bodies or one parent body which experienced two major breakup events. The coincidence of the Arispe and Bendego ages with those of group I irons suggests that they may have originated in the same body. Many more data are needed, however, before the applicability of these conclusions to the whole spectrum of group I and group I-associated irons can be judged.

Rb–Sr Age Determinations

The availability of silicate inclusions in the group I and I-An2 irons have made them prime targets for Rb–Sr age determinations, which is the only technique believed to be wholly accurate for age measurements on iron meteorites, although K–Ar ages of silicate inclusions are also rather reliable. Such data are summarized by Wasserburg and Burnett (1969). The Rb–Sr ages of Toluca and Four Corners are given as 4.7 ± 0.5 Gy (gigayears). K–Ar ages of these two irons fall in the range of 4.5–4.7 Gy. Pine River, Linwood, Toluca, Odessa, and Copiapo are plotted together and shown to be consistent with an isochron of 4.55 Gy. Although no error is stated, the data are also clearly consistent with an age as high as 4.7 Gy. An isochron is shown for Campo del Cielo which gives an age of 4.7 Gy, with an error which is probably less than 0.2 Gy. The oldest stony meteorites appear to be about 4.7 Gy. Thus, the group I irons seem to have been formed very early in the history of the solar system, with a *maximum* of about 0.2 Gy involved in differentiation and cooling to a point where isotopic exchange no longer occurred between minerals, and with evidence that the period involved was much smaller than this. This places severe limits on the temperatures which the interior of a sizeable group I parent body could have reached and still cooled to a point where Rb and Sr ceased to exchange, and makes a high-temperature, igneous stage in the history of the parent body rather unlikely.

Chemical Evidence Relating to the Origin of the Group I Irons

Smales *et al.* (1967) and Fouché and Smales (1966) have published data on the concentration of thirteen elements in 67 and 70 iron meteorites, respectively, only two of which (Ga and Ge) were included in the present study. Ten of their meteorites are members of group I, and are listed in Tables 19 and 20 of the former paper. In order to compare the data for different groups of irons, and those with data from other classes of meteorites, it is convenient to normalize the data to Ni or Fe. With the exception of the Ni-rich group IVB, the choice has a relatively small effect on the results. I have chosen to normalize to Ni, and represent the data by plotting it versus Cameron's (1968) "cosmic" abundances, which are mainly derived from analyses of Cl chondrites. Figure 6 shows a plot of group I atomic abundances versus the cosmic abundances for the 13 elements studied by Smales and co-workers, and for our Ir values. Eight of the elements fall very near to the line which corresponds to

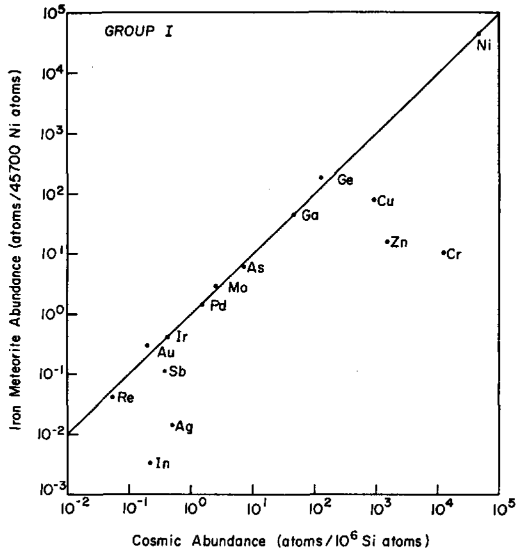

FIG. 6. Elemental abundances in group I iron meteorites plotted against cosmic (mainly C-1 chondrite) abundances, and normalized at Ni. Cosmic abundances from Cameron (1968). All elements which concentrate in the metal lie near the line which corresponds to equal abundances in the two types of meteorites, whereas the sulfide-forming elements are depleted in the iron-meteorite metal.

a 1:1 ratio of group I cosmic abundances, and Sb is only about a factor of 3 below the line. The other five elements (Cr, Cu, Zn, Ag, and Sb) tend to concentrate in sulfide phases, and their depletion may mainly reflect the fact that Smales and co-workers avoided inclusions in their sampling. Similar plots for the other large groups (IIA, IIIA, and IVA) show depletions of As, Sb, and some other elements relative to group I, and occasional enrichment of Re and Ir. I conclude that the evidence indicates that the group I irons are more nearly like a carbonaceous chondrite, initial-solar-system starting material than are the members of other large, resolved iron-meteorite groups. Anders (1964) made a similar suggestion based on the Lovering *et al.* (1957) Ga and Ge data.

An average of three unpublished analyses by E. Jarosewich of large silicate inclusions from Campo del Cielo is given by Bunch *et al.* (1969). The composition of these inclusions is remarkably similar to the silicate portion of H-group chondrites, except that FeO is about 2.5 times lower in Campo del Cielo. This indicates that the silicate material is "primitive" and has never experienced severe differentiation.

Nonigneous Origin and Primitive Nature of the Group I Irons

It has long been believed that the iron meteorites represent the core (or cores) of one or more meteorite parent bodies. Although this belief is related to the wide acceptance that the Earth has a metallic core, it is also based on the seemingly obvious fact that iron meteorites are highly differentiated objects, and the logical conclusion that formation of large masses of metal by igneous differentiation in a planetary body would lead to core formation.

Wasson and Wetherill (1970) have discussed various processes involved in the formation of iron meteorites. One of the firmest conclusions that they and others (e.g., Fish *et al.*, 1960) reach is that there is no simple way to suspend small silicate grains in molten metal even in the smallest imaginable gravitational field. The silicate would rise to the top of the metal in a time well under a year, which is extremely short by cosmic standards. One can devise a model whereby gravitational separation of phases occurs as a result of the melting of silicate material. This would allow the formation of metallic cores (or of metallic nodules, depending on the circumstances) which were never molten, and these might have silicate fragments included. However, this type of model demands that the included silicates be relatively high-melting (e.g., olivine) and not the chondritic-type material which is found in Campo del Cielo. *It seems inescapable that the group I irons have not been molten since the silicates and metal attained their presently observed locations.* Bunch *et al.* (1969) propose that the silicates were engulfed by an iron melt, but do not provide details as to how such a melt could be generated or small particles caused to remain suspended in some cases, nor do they discuss the question of fractionation of the silicates in such a high-temperature process.

An alternative possibility is that the

metal has never been molten since accretion. In this case the large dimensions of the γ-iron crystals, which were precursors to the Widmanstätten pattern, have formed by solid-state diffusion from accreted particles of unknown, but quite possibly small (e.g., millimeter-sized) dimensions. The metal–silicate fractionation which brought about the great enrichment in metal in these meteorites occurred in the solar nebula, and was probably the same process which brought about the metal-silicate fractionations observed in the ordinary chondrites and in the enstatite chondrites and achondrites (see Wasson and Wai, 1970). In both the ordinary and enstatite chondrites increasing degree of metal enrichment is correlated with increasingly reducing conditions (as represented by the Fe content of ferromagnesian minerals in the former and the Si content of the metal in the latter). It is interesting to speculate that the group I irons are at one end of a fractionation sequence which may include objects similar to the ordinary or carbonaceous chondrites as its more oxidized members.

Acknowledgments

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