Geochimica et Cosmochimica Acta, 1976, Vol. 40, pp. 103 to 115. Pergamon Press. Printed in Great Britain.

Chemical classification of iron meteorites—VIII. Groups IC, IIE, IIIF and 97 other irons

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(*Received* 30 *December* 1974; *accepted in revised form* 19 *June* 1975)

Abstract—Concentrations of Ni, Ga, Ge and Ir in 106 iron meteorites are reported. Three new groups are defined: IC, IIE and IIIF containing 10, 12 and 5 members, respectively, raising the number of independent groups to 12. Group IC is a cohenite-rich group distantly related to IA. Group IIE consists of those irons previously designated Weekeroo Station type and five others having similar compositions though diverse structures. The IIE irons are compositionally similar to the mesosiderites and pallasites, and the three groups probably formed at similar heliocentric distances. The mixing of the globular IIE silicates with the metal probably occurred during shock events. Group IIIF is a well-defined group of low-Ni and low-Ge irons. The compositions of these groups are summarized as follows:

Group	Ni (%)	Ga (ppm)	Ge (ppm)	Ir (ppm)
IC	6·1–6·8	42–54	85–250	0·07–10
IIE	7·5–9·7	21–28	62–75	0·5–8
IIIF	6·8–7·8	6·3–7·2	0·7–1·1	1·3–7·9

Data are reported on a number of anomalous irons including an interesting cluster of 5 plessitic octahedrites and ataxites with Ge/Ga atomic ratios between 10 and 16, among the highest values known in iron meteorites. Dermbach, at 42%, has the second highest Ni concentration known in an iron meteorite. The composition of metal and slicates in Mundrabilla indicate that it and its close relative, Waterville, are anomalous members of group IA. Several additional irons which appear to be mislabelled fragments of Canyon Diablo and Toluca are discussed.

INTRODUCTION

PREVIOUS papers in this series established the existence of 13 groups (WASSON, 1967; 1969; 1970a; WASSON and KIMBERLIN, 1967; WASSON and SCHAUDY, 1971; SCHAUDY *et al.*, 1972; SCOTT *et al.*, 1973), including 4 genetically related pairs (IAB, IIAB, IIIAB, IICD). The chief parameters used in the classification scheme are the concentrations of Ni, Ga and Ge in the metal, with additional evidence from the Ir content and the structure of the meteorite. Members of each group are genetically related to one another, and, in probably all cases, originated in a single parent body. The establishment of such a genetically significant classification scheme is an essential first step towards understanding the processes which formed the iron meteorites. SCOTT and WASSON (1975) have reviewed the classification and given a comparative survey of the groups. Unlike earlier papers in this series, this paper covers the entire span of Ge concentrations rather than a limited range.

EXPERIMENTAL AND RESULTS

The analytical techniques were described by WASSON and KIMBERLIN (1967) and KIMBERLIN *et al.* (1968). No significant changes have been made since then. Gallium, Ge and Ir are determined by neutron-activation analysis, and Ni by atomic absorption analysis on an aliquot of the dissolved sample. At least two and occasionally more replicates of each meteorite are analyzed in different irradiations. In Table 1 we list the means for the Ni, Ga, Ge and Ir determinations. The 95% confidence limits for the means are about ±2% for Ni, ±4% for Ga and Ge, and ±10% for Ir. Where scatter indicates lower precision, larger errors are listed. The Ge precision decreases below about 0·1 ppm and the 95% confidence limits increase to about ±15% at concentrations of 0·04 ppm.

With few exceptions, samples were sawed blocks with masses between 0·5 and 1·0 g. The smaller samples were generally taken from the more homogeneous irons, viz. hexahedrites and ataxites, while the larger samples came from medium and coarse octahedrites. Since Ni replicates seldom deviate from the confidence limits quoted above, we conclude that these samples contain representative amounts of kamacite and taenite. (One exception, however, was the analytical sample of St. Francois County discussed in the IC section.) Errors caused by segregation of Ga, Ge and Ir between these phases are then smaller than the values we list. In special cases, small but representative samples were obtained by cutting thin slices having large areas. Large inclusions were avoided and surface oxidation removed with a dental drill. Only sawings (the purity of which is less certain) were available for Murphy, Novorybinskoe and Repeev Khutor; for Abakan and Veliko-Nikolaevsky Priisk one of the two replicates was in the form of sawings. One replicate of Novorybinskoe showed a large increase in Ge content, equivalent for example to the addition of 0·04% of a IA iron, (this small amount did not produce detectable changes in Ni, Ga and Ir contents as

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Table 1. Ni, Ga, Ge and Ir concentrations in 106 iron meteorites

Meteorite	Chem. group	Struc. class	Band-width (mm)	Source*	Cat. No.	Ni (%) mean	Ga (ppm) mean	Ge (ppm) mean	Ir (ppm) mean
Abakan †	IIIA	Om		KMAN	---	7.97	20.3	42.3	4.6
Amates	IA	Og		BM	1959,942	8.09	66.2	237‡	1.8 ±3‖
Angra dos Reis (iron)	IIA	H		VC	---	5.48	57.2	188	33
Aprelsky[1]**	IIIB	Om	0.7§	KMAN	15020	10.07	19.4	37.0	0.054
Arltunga	IID-An	D	0.005	BM	1937,245	9.64	77	83	17 ±6
Avče	IIA	H		NMW	H10.028	5.49	58.1	182	58
Avoca (W. Aust.)	IIIA	Om		WAM	12793g	9.21	20.6	44.5	0.30 ±4
Bitburg	IB	Anom		FMNH	1258	12.43	34.8	140	0.46
Black Mountain	IA	Og	2.6	AmhC	1.3.33.4	6.73	98‡	460‡	2.2 ±4
Bridgewater	IID	Om	0.65	NMW	---	9.8 ±3	81	82	10
Brownfield (1966)[2]	IID	Om	0.75	MPIM	H44.3	10.32	78	85	11
California[3]	IA			SI	1681	7.7 ±3	66.7	253	2.0
Cedertown	IIA	H		SI	1511	5.36	63.2	181	8.2
Chesterville	IIA	H		YU	---	5.61	58.9	178	1.9
Chico Mountains	IIA	H		SI	---	5.50	59.3	176	6.2
Chulafinnee	IIIA	Om	1.10	NMW	---	7.47	17.8	33.7	5.6
Coolac	IA	Og	2.1	SI	1370	7.4 ±3	91	423	2.4 ±3
Corrizatillo	IA	Og	1.9	UMGM		6.4 ±5	81	337	1.0 ±3
Cratheús (1950)[4]	IIC	Opl	0.06	NMRJ	---	9.0 ±3	36.3	91	9.5
Cruz del Aire	Anom	Of	0.48	ASU	794	9.00	38.2	187	5.9
De Hoek[5]	Anom	Anom		GSP	---	9.95	0.236	0.079	0.27
Del Rio[6]	Anom	D	0.07	JSC	---	11.34	9.2‡	99	19
Dermbach[7]	Anom	Anom		HUB	---	42.1	4.66	0.144‡	0.029
Dorofeevka	Anom	Opl	0.09	KMAN	653	11.26	9.1	124	23
Elbogen	IID	Om	0.75	HarU	---	10.2 ±4	75	87	14
Ellicott[8]	IA	Om		FMNH	Me2732	8.01	57.1	252	3.3
Etosha[9]	IC			GSP		6.85	48.9	217	0.10
Forsyth County	IIA	H		SI	---	5.50	60.8	176	31
Fossil Springs[10]	IA	Og		ASU	34fs	6.98	78	308	1.7
Garhi Yasin	IIE	Om	1.0§	BM	1924,832	8.3 ±2	20.9	65‡	4.6
Haniet-el-Beguel	IA	Og	1.6	MHNP	---	8.3 ±7	67.4	271	2.4
Hayden Creek	IIIA	Om	1.00	BM	84438	7.58	18.4	36.6‡	8.1
Helt Township	IA	Og		SI	1323	7.05	79	347‡	2.0
Holland's Store	IIA	H		SI	127	5.35	60.9	182	20
Horse Creek	Anom	Anom		ASU	378.1x	5.75	47.6	110‡	2.5
Hraschina	IID	Om	0.7	NMW	J2694	10.6 ±7	75	89	13
Idaho[3]	IA			SI	1652	7.09	81	321	2.1
Iredell	IIB	Ogg	10	AMNH	117	6.0 ±2	58.1	163	0.07 ±3
Keen Mountain	IIA	H		SI	1513	5.38	62	183	12 ±3
Kendall County	Anom	Anom		FMNH	1022	5.45	75	355	1.7
Landes[11]	IA	Anom		AML	H91.47	6.3 ±2	89	414	2.9
Las Vegas	IA	Og		SI	1329	6.8 ±2	80	323	1.6 ±2
Lexington County	IA	Og	2.1	SI	3334	6.69	85	316‡	2.3
Livingston (Tennessee)	Anom	Om	0.8	SI	1420	6.64	45.3	250	0.73
Locust Grove	IIA	H		SI	---	5.55	60.6	180	7.5
Lonaconing	IIE	Og	2.0	MHNP	---	9.7 ±4	23.5	62.1	0.9 ±3
Lucky Hill¶	IIIA	Om		BM	56488	(7)	21‡	46‡	0.4 ±1
Magnesia	IIIC	Om	0.63	MHNP	2367	10.99	14.5	22.4	0.18
Maldyak	IIIA	Om	1.0	KMAN	1402	9.08	19.8	42.6	0.39
Mesa Verde Park	IB	Om	0.60	SI	1663	10.56	53.0	142	1.8
Michigan	IA	Og		SI	1446	8.16	69.7	251	2.2
Moab	IA	Og		SI	2067	6.98	83	330	1.6 ±3
Moctezuma	IA	Om	1.3	ASU	78a	7.98	67.2	244	2.3 ±3
Mooranoppin	IA	Og		{BM SI	82748 1609	7.75	79	328	1.3
Mount Egerton		Anom		SI	3272	6.2 ±2	35‡	99	1.8
Mount Ouray	IID	Om	0.80	HarU	---	10.13	71	84	16
Mount Stirling	IA	Og		{BM WAM	83613	7.4 ±4	85	346	1.5
Mundrabilla[12]	IA-An	Anom	0.55	MPIH	---	7.72	59.5	196‡	0.87
Murnpeowie	IC-An	Anom		AM	DR7886	6.42	41.8	85	1.8
Murphy	IIA	H		UCLA	275	5.42	60.5	186	5
Nagy-Vázsony	IA	Og	1.40	NMW	F5595	7.98	68.9	237	2.1
Navajo	IIB	Ogg	10	MPIH	---	5.50	55.0	180	0.49
Nazareth (iron)[13]	IIIA	Om	1.00	AML	H101.5	9.04	20.3	40.3	0.44
Neptune Mountains	IA	Og	1.9	SI	2614	7.13	74	269	2.0
New Leipzig	IA	Og	2.6	SI	1210	6.88	93	445	2.5
Nieder Finow	IA			HUB	---	8.27	72	257‡	2.7
Novorybinskoe	IVA	Of	0.3	KMAN	1100	9.1 ±3	2.45	0.20	0.90
Nuleri	IIIA	Om	1.0§	WAM	1/5025	7.44	18.0	36.7	9.3
Oakley (iron)	IIIF	Og	1.40	SI	780	7.32	7.2	1.13‡	5.5
Okahandja	IIA	H		MPIH	498	5.74	56.3	186	10

Table 1 *continued.*

Meteorite	Chem. group	Struc. class	Band-width (mm)	Source*	Cat. No.	Ni (%) mean	Ga (ppm) mean	Ge (ppm) mean	Ir (ppm) mean
Oscuro Mountains	IA	Og	1.75	FMNH	Me457	6.55	91	359	2.6
Pan de Azucar	IA	Og	2.2	SI	1558	6.89	82	308	2.2
Paneth's Iron[14]	IIIE	Og	1.5	BM	47192	8.90	17.0	34.1	0.37
Pima County	IIA	H		SI	---	5.56	60.3	181	8.9
Pittsburg	IA	Og	2.2	BM	35418	6.16	83‡	359	2.0
Quartz Mountain	IIIA	Om	1.10	ASU	310.2	7.85	18.6	36‡	4.2
Redfields[15]	Anom	Anom		WAM	13142	6.91	39.3	95	0.8 ±2
Rembang	IVA	Of		ANU	---	8.82	2.25	0.134	1.2
Repeev Khutor	Anom	Of	0.21	KMAN	216	14.3	11.6	193‡	3.0
Richa	IID	Om	0.55	BM	1966.55	10.0 ±4	78‡	91	16 ±3
Richland	IIA	H		SI	1735	5.40	60.6	182	8.2
Rosario	IA	Og	1.70	SI	626	7.10	89	401	1.5
St. Francois Co.	IC	Og	2.7	{AMNH USNM	65 130	6.77	49.2	247	0.11
Samelia	IIIA	Om	1.10	BM	1927,916	8.02	19.5	38.3	2.6
Sanchez Estate	IIA	H		ASU	293a	5.58	60.7	189	15
San Francisco del Mezquital	IIA	H		BM	43401	5.50	61.4	183‡	21
Sardis	IA	Og	2.5	SI	1381	6.58	94	400	1.3 ±2
Seymchan[16]	IIE	Og		KMAN	15012	9.15	24.6	68.3	0.55
Shirahagi	IVA	Of	0.3	ASU	685.1	7.87	2.19	0.120	2.4
Silver Crown	IA	Og	2.1	SI	3071	6.98	82	321	1.6 ±5
Smithsonian Iron[17]	IIB	Ogg	10	SI	1001	5.65	55.3	165	0.057
Ssyromolotovo	IIIA	Om	0.95	KMAN	65	7.85	19.6	40.9	3.3
Summit	IIB	Ogg	6	NMW	---	6.56	50.5	115	0.025±8
Tacubaya	IA	Og		FMNH	Me2149	8.13	66.9	249	1.9
Ternera	IVB	D		HUB	---	18.1	0.261	0.056	16
Tobychan[18]	IIE			KMAN	15071	7.82	27.6	75	5.7
Uegit	IIIA	Om	0.95	ANU	---	7.80	17.7	33.9	6.3
Union	IIA	H		SI	1299	5.79	60.5	187	3.2
Vaalbult	IA	Og	2.0	SAM	3308	6.84	84	323	1.7
Veliko-Nikolaevsky Priisk	IIIA	Om	1.15	KMAN	719	8.75	21.5	47.4	0.62
Verkhne Dnieprovsk[17]	IIE	Anom		BM	51183	8.78	22.8‡	70	6.1
Walker County	IIA	H		HarU	---	5.46	58.2	189	3.1
Wathena	IIA	H		SI	---	5.51	59.6	184	7.0
Yenberrie	IA	Og	2.1	SI	607	6.72	87	301	3.0
Youndegin	IA	Og	2.3	BM	1920,350	7.42	84	340	1.5 ±3
Zerhamra[19]	IIIA-An	Om	1.1	MHNP	---	8.00	18.2	33.5	10 ±3

* Source abbreviations are as follows: AM—Australian Museum; AmhC—Amherst College; AML—American Meteorite Laboratory; AMNH—American Museum of Natural History; ANU—Australian National University, Canberra; ASU—Arizona State University; BM—British Museum (Natural History); FMNH—Field Museum of Natural History, Chicago; GSP—Geological Survey, Pretoria; HarU—Harvard University; HUB—Humboldt Universität, Berlin; JSC—NASA Johnson Spacecraft Center, Houston; KMAN—Committee on Meteorites, Academy of Sciences, USSR; MHNP—Museum Histoire Naturelle, Paris; MPIH—Max-Planck-Institut, Heidelberg; MPIM—Max-Planck-Institut, Mainz; NMRJ—National Museum, Rio de Janeiro; NMW—Naturhistorisches Museum, Vienna; SAM—South African Museum; SI—U.S. National Museum of Natural History, Smithsonian Institution, Washington D.C.; UCLA—University of California, Los Angeles; UMGM—Universitetets Mineralogisk-Geologisk Museum, Oslo; VC—Vatican Collection; WAM—Western Australian Museum; YU—Yale University.

† Underlined meteorites are believed to be fragments of other meteorites which are identified in Table 6 and the text.

‡ Estimated error is about twice the usual value.

§ Bandwidths accurate to ±20% remainder from Buchwald (in press) are generally accurate to ±10%.

‖ To save space the listed errors are 95% confidence limits in the last digits of the mean values.

¶ Data corrected for severe oxidation, see text.

** References for size, discovery location, etc. of meteorites not listed by Hey (1966): 1. *Meteoritical Bull.* 48 (1969). Moscow. 2. *Meteoritical Bull.* 40 (1967). Moscow. 3. Exact locality unknown (R. S. Clarke private communication, 1971). 4. See Schaudy *et al.* (1972). 5. Frick and Viljoen (1973*a*). 6. King and Henderson (1969). 7. G. Hoppe (private communication, 1971). 8. Olsen *et al.* (1974). 9. Frick and Viljoen (1973*b*). 10. *Catalog of Meteorites*, Ariz. State Univ. (1970). 11. *Meteoritical Bull.* 51 (1972), *Meteoritics* **7**, 225. 12. Ramdohr and El Goresy (1971). 13. *Meteoritical Bull.* 51 (1972), *Meteoritics* **7**, 228. 14. Buchwald *et al.* (1974). 15. de Laeter *et al.* (1973). 16. *Meteoritical Bull.* 42 (1968) Moscow. 17. See text. 18. *Meteoritical Bull.* 51 (1972), *Meteoritics* **7**, 230. 19. Buchwald (1973).

expected). In addition, the Ge replicates on another powdered sample, Repeev Khutor, scatter more than normal. Both replicates of Lucky Hill and one replicate of Richa were severely oxidized, resulting in some scatter in their data. Our specimen of Sardis was also strongly oxidized. The cleaned samples except those in the form of sawings were etched before and after irradiation. Where possible meteorites were polished and etched for microscopy prior to sample cutting.

In Table 1 the meteorites are listed alphabetically along with the group assignment and compositional data. Names in italics have been paired with others which are identified in the text or Table 6. We also list structural class symbols and kamacite bandwidths where available; these are mostly from BUCHWALD (in press). Data for three of these meteorites appeared in earlier papers in this series. The analytical data listed in Table 1 supersede all earlier data including the compilation by WASSON (1974).

CLASSIFICATION

Group IC

Group IC is a new group of ten irons with 6·1–6·8% Ni (Table 2) which will be described in detail elsewhere (SCOTT, in preparation). Eight were analyzed by WASSON (1970a); Arispe, Bendegó, Chihuahua City, Mount Dooling, St. Francois County, Santa Rosa, Union County (all listed as I-An3) and Nocoleche (classed as anomalous). Data for two additional IC members, Etosha and Murnpeowie, plus new data for St. Francois County were obtained during this study. [This last iron was reanalyzed because its Ni content seemed too low for IC trends and the observed taenite content. Microscopic examination showed that WASSON'S (1970a) sample came from a single kamacite plate.] As can be seen in Fig. 1, the seven irons which are normal members of group IC occupy a very compact field beside the group IAB sequence on Ge–Ga and Ge–Ni plots. One anomalous member (Arispe, anomalous chiefly because of its high Ir content) also falls within these fields, whereas two others (Nocoleche and Murnpeowie, anomalous chiefly in terms of low Ge contents) fall well below these fields. Table 2 shows a much wider range of Ir values, but there is a negative Ir–Ni correlation, if data for Nocoleche and Arispe are ignored.

Table 2. Composition of group IC members arranged in order of increasing Ni content

Meteorite	Ni (%)	Ga (ppm)	Ge (ppm)	Ir (ppm)
Union County	6.12	54.8	245	2.1
Mount Dooling	6.26	52.0	234	1.2
Bendegó	6.39	54.0	234	0.20
Nocoleche*†	6.45	48.6	148	7.5
Murnpeowie†‡	6.42	41.8	85	1.8
Arispe†	6.54	50.3	243	9.7
Santa Rosa	6.63	50.6	222	0.068
Chihuahua City	6.68	52.7	212	0.11
St. Francois Co.‡	6.77	49.2	247	0.11
Etosha‡	6.85	48.9	217	0.10

* Data include replicates from WASSON'S (1970a) mislabelled Mt. Stirling specimen.

† Classed IC-Anomalous.

‡ Analyses from Table 1, remainder from WASSON (1970a).

Structurally group IC shows great diversity ranging from Arispe and Bendegó which are slowly cooled coarse octahedrites to Chihuahua City and Santa Rosa with more rapidly cooled polycrystalline structures with a very fine, faint octahedral structure. Nearly all IC members contain abundant cohenite (which in Nocoleche has decayed to graphite) and the morphology is somewhat different from that in group IA. Group IC is possibly distantly related to IA but can also be distinguished by lower contents of Au and As (SCOTT, in preparation). The three anomalous irons plotting close to IC (Fig. 1), Elton, Livingston (Tenn.) and Redfields, contain IA-like levels of Au and As and are not related to group IC. Figure 1 shows that IIAB plots close to IC but the scarcity of large phosphides in the latter and the distinct trends in both suggest they are not related.

Group IIE

The close relationship between Weekeroo Station, Colomera and Kodaikanal was recognized by BUNCH *et al.* (1970), chiefly on the basis of the mineralogy of their abundant silicates. WASSON (1970b) showed that their metallic portions were also very similar in composition, and that the Elga iron was also a member of the compositional cluster. He found a similar composition in the metal of Netschaëvo, despite the fact that its silicates are of chondritic composition whereas those of typical Weekeroo-type irons are more differentiated (OLSEN and JAROSEWICH, 1971).

SCOTT *et al.* (1973) showed that two irons that appear to be silicate free (Arlington and Barranca Blanca) are compositionally very similar to those discussed above, and designated them to be Weekeroo Station type also. Although the number of apparently related objects was large enough to allow designation as a group, compositional trends were poorly defined, and we chose to continue the practice of referring to these irons as Weekeroo Station type. Since preparation of that paper we have discovered no less than five additional irons which fall in this cluster. Trends are now somewhat better established, and we now believe that the cluster is worthy of group status. Members of this new group IIE are listed in Table 3. All five new members fall inside the Weekeroo-type Ge–Ga field, (SCOTT *et al.*, 1973, Fig. 5); they extend the upper Ni and lower Ir limits of the group from 8·6 to 9·7% and from 1·8 to 0·5 ppm, respectively.

Group IIE lacks many of the characteristic features of other meteorite groups. Interelement correlations are often weak, and mean kamacite bandwidths show a wide variation between 0·1 and 2 mm and are uncorrelated with Ni content (Table 3). The negative Ga–Ni and Ge–Ni correlations are significant at 80% level; the positive Ge–Ga correlation and negative Ir–Ni correlation are significant at the 95% and 90% level, respectively. Despite atypically weak correlations, the Ga and Ge concentration ranges (less than $\pm 15\%$ about the mean) are as small as those in other groups (Fig. 1).

Silicates, apart from those in Netschaëvo, are rounded and drop-like (Figs. 2 and 3). They are much more Fe-rich than those in group IAB, with orthopyroxene containing 14–25 mole % ferrosilite (Fs_{14-25}) and rare olivine grains Fa_{14-32}; they are not associated with graphite (BUNCH and OLSEN, 1968; BENCE and BURNETT, 1969; BUNCH *et al.*, 1970; WASSERBURG *et al.*, 1968). Netschaëvo is classed IIE-An because of the presence of chondrule-bearing angular silicates of chondritic bulk composition (ZAVARITSKII and KVASHA, 1952; BUCHWALD, 1967; OLSEN and JAROSEWICH, 1971). Silicates were not observed in any of the five new irons in this cluster but only small samples of each (<10 g) were available for study. Rutile, tridymite, silica-rich glass and whitlockite are common accessory minerals in the silicate-bearing members, and chromite is present in most members. Because of the small size of our samples and

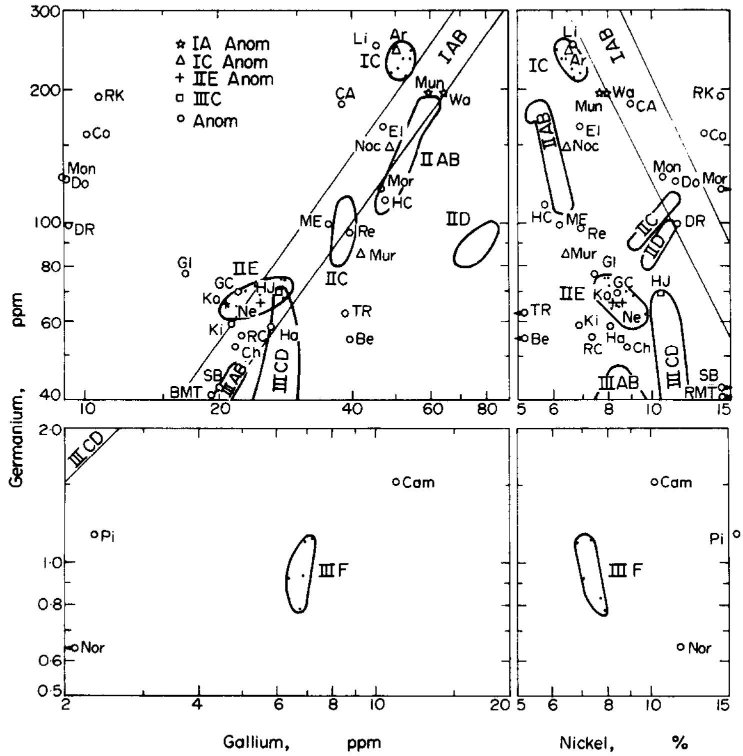


Fig. 1. Ge–Ga and Ge–Ni plots showing the locations of the new groups IC, IIE and IIIF relative to other groups and anomalous irons in the same general Ge concentration range. Members of IC, IIE and IIIF are shown as dots within the fields. A group of potentially related irons with exceptionally high Ge/Ga ratios is located on the left side of the upper left diagram. See text for further details. Abbreviations can be interpreted with the aid of Table 1 and the following list: Ar, Arispe; Be, Bellsbank; BMT, Babbs Mill (Troost's); Ch, Chebankol; Co, Corowa; El, Elton; GC, Gun Creek; Gl, Glenormiston; Ha, Hammond; HJ, Hassi Jekna; Ki, Kingston; Ko, Kodaikanal; Mon, Monahans; Mor, Morradal; Ne, Netschaevo; Noc, Nocoleche; RC, Reed City; SB, South Byron; TR, Tombigbee River; Wa, Waterville.

the structural diversity observed among members of this group (Fig. 4), we cannot further define the typical mineralogical characteristics for group IIE.

Very few analytical data on the metallic portion of IIE irons are available. Analyses of two by Smales *et al.* (1967) suggest that most trace-element concentrations are below IA levels.

Verkhne Dnieprovsk was listed as a IIIB member paired with Augustinovka by Scott *et al.* (1973), but it now appears that the analyzed sample from the Field Museum was not genuine Verkhne Dnieprovsk material. At the suggestion of A. A. Yavnel (private communication) we analyzed a piece of the 25 g sample in the British Museum (National History) and found it to be a IIE member. Our sample has a curious array of oriented kamacite platelets 0·1 mm wide, but these may represent a plessite field. Since the British Museum specimen of Verkhne Dnieprovsk was received in 1877, one year after its discovery, Yavnel (in preparation) believes that this represents the original material. It would seem that other material with this name but a IIIB composition should be relabelled Augustinovka.

Confession

We admit that in order to establish groups IIE and IC we have had to relax the requirement (Wasson and Kimberlin, 1967; Wasson, 1974) that group members have similar structure and mineralogy. Some members of these two groups could not have been identified from structural studies alone. Scott and Wasson (1975) discuss this problem and conclude that this procedure can be justified if additional parameters (As and Au in IC) or a larger membership (IIE) support the establishment of a proposed group. In these cases we note that the strength of a genetic link between any two members of a group must be considered weaker than in other groups, and more akin to that between normal and anomalous members of other groups (e.g. between Mundrabilla and other IA members, see below). Nevertheless, the advantages in identifying a cluster of related irons seem to outweigh the disadvantage that its members did not share entirely identical formation conditions. The diversity of silicate and refractory-element abundances in group IAB, for example, suggests that this group also should be considered a less cohesive group than the other major groups. The purpose in establishing a group is to assist the investigation of the origin and properties of its members and we believe these groupings satisfy this condition.

Group IIIF

Schaudy *et al.* (1972) described four irons (Clark County, Nelson County, Moonbi and St. Genevieve County) containing 6·8–7·8% Ni and narrow ranges of Ga, Ge and Ir contents. We now report data on an additional iron, Oakley, which lies in this narrow composition range, and raises the total to 5, the minimum number required for designation as a group.

As can be seen from the lower portion of Fig. 1, group IIIF forms compact fields on Ge–Ga and Ge–Ni plots. These fields are well removed from the loci of other analyzed irons. The data would be consistent with a positive correlation between Ge and Ga (as in all other groups) and a negative correlation between Ge and Ni. As in most other groups, a negative correlation (significant at the 95%

Table 3. Composition of metal in group IIE members arranged in order of increasing Ni content

Meteorite	Ni (%)	Ga (ppm)	Ge (ppm)	Ir (ppm)	Bandwidth (mm)	Cooling Rate (K My^{-1})
Weekeroo Station*	7.51	28.2	67.0	2.8	2.5	1.1
Tobychan	7.82	27.6	75	5.7	(1.5)§	-
Colomera*	7.86	28.4	75	7.9	-	-
Elga*	7.98	24.1	72	4	-	-
Barranca Blanca*	8.07	22.1	63.9	4.9	(2)§	-
Garhi Yasin	8.3	20.9	65	4.6	1.0§	3
Arlington*	8.42	21.8	64.9	5.8	0.8	4
Netschaëvo*†	8.6	24.8	66	1.8	1.25	1.4
Kodaikanal*†	8.71	21.9	68.7	5.5	0.1	400
Verkhne Dnieprovsk	8.78	22.8	70	6.1	(0.1)§	-
Seymchan	9.15	24.6	68.3	0.55	2§	0.3
Lonaconing	9.7	23.5	62.1	0.9	2.0	0.2

* Elemental data from SCOTT *et al.* (1973) with a correction for the silicate residue in Kodaikanal, others from Table 1.

† IIE-Anomalous.

‡ Bandwidth measurements from BUCHWALD (in press) and subject to errors of about $\pm 10\%$ except Kodaikanal, $\pm 40\%$.

§ Our estimated bandwidths for Barranca Blanca, Garhi Yasin, Verkhne Dnieprovsk and Seymchan (estimated from photo in KIROVA and DYAKANOVA, 1972); errors amount to about $\pm 30\%$ except for Barranca Blanca in which oriented kamacite is virtually absent, Verkhne Dnieprovsk and Tobychan for which only a rough estimate could be made from the small specimen available.

|| Kamacite plates visible in Colomera (Fig. 2) have not formed in the usual manner. They contain tiny oriented taenite blebs and may have formed when parallel platelets welded together.

confidence level) between Ni and Ir is observed. With the exception of Oakley, the IIIF members have been fairly well analyzed by other authors (references listed in SCOTT, 1972). Group characteristics include very low Co contents, fairly high Cr and low P. Our unpublished data indicate that interelement correlations within the group are similar to those in other major groups (excluding IAB).

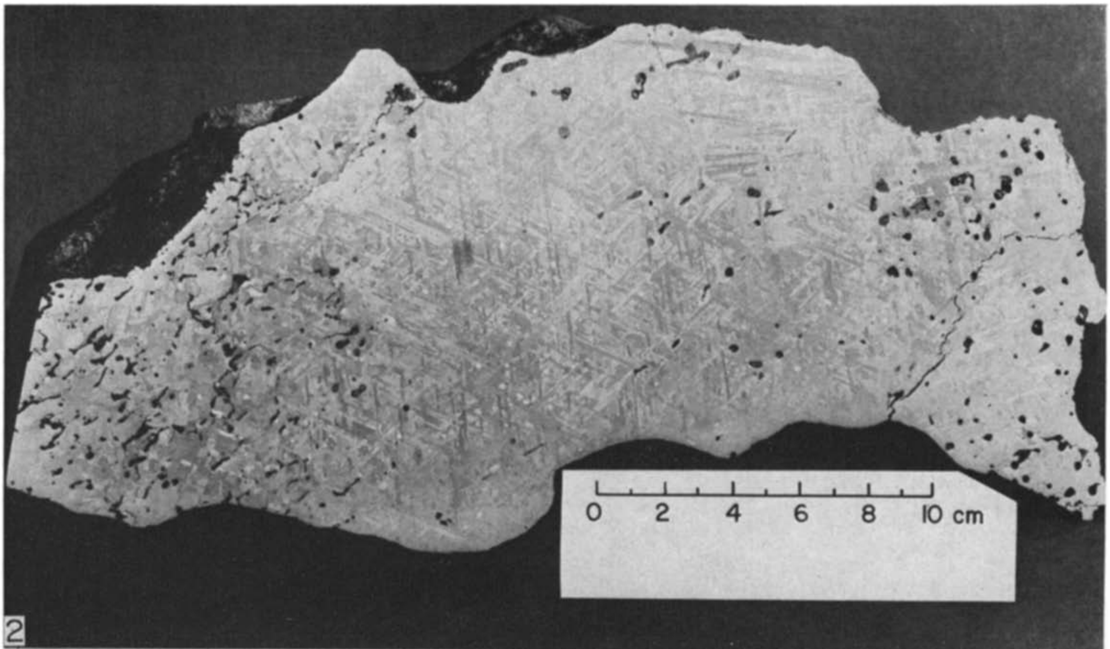
Large sections of IIIF members show few microscopic inclusions (Fig. 5); mm-sized troilite and schreibersite inclusions are rare. Microscopic daubréelite precipitates are usually abundant. Carbides, graphite and silicates have not been reported. As noted by SCHAUDY *et al.* (1972), Clark County (Fig. 5) and Nelson County show bandwidths varying from 1 to 10 mm while Moonbi and St. Genevieve County have bandwidths of about 0·5 mm. They suggested that bands greater than 1 mm in width formed by impingement, and could be neglected in cooling rate calculations; use of the smaller bands gave uniform cooling rates of about 20 K My^{-1} for these four members. GOLDSTEIN and SHORT (1967) recognized that kamacite plate impingement could be a problem at these low Ni contents and this may also account for the mean bandwidth of 1·4 mm in Oakley leading to a lower estimated cooling rate of about 5 K My^{-1}.

Members of other groups

In Table 1 we present analytical data for 32 irons in group IA and two in group IB. Nine of the former appear to be pieces of Canyon Diablo, Toluca or Youndegin and are discussed in the section on paired irons. A new analysis is presented for Youndegin as we believe that the value given by WASSON (1970a) was obtained from a mislabelled sample. Analyses of new specimens of Mount Stirling in Table 1 confirm earlier suspicions that the data reported by WASSON (1970a) were obtained from a mislabelled specimen of Nocoleche. HEY (1966) classed Bitburg as a pallasite, but RAMBALDI *et al.* (1974) found that the silicate compositions like that of the metal (Table 1) are entirely appropriate for a member of group IAB.

The sawing of the 6-ton Mundrabilla iron revealed an unusual structure with abundant troilite nodules and curious graphite morphologies (RAMDOHR and EL GORESY, 1971). Our data (Table 1) show that Waterville (WASSON, 1970a) has a very similar composition. The morphology of their graphite and troilite is also similar but troilite-free metal tends to be a few cm in diameter in Mundrabilla but only a few mm in Waterville. Figure 1 shows that the Ni, Ga and Ge of these two irons lie on the edge of the group IA sequence (but closer than some IA-An irons). We have classified both as anomalous group IA members because of the unusual troilite abundance and other uncharacteristic features: the Ir contents of Mundrabilla and Waterville (0·87 and 0·30 ppm, respectively) are lower than all but one other IA iron and their bandwidths of 0·55 and 1·1 mm are also especially low. Strong evidence that this pair of irons belongs to group IAB comes from electron-probe analyses of a silicate-rich section of Mundrabilla, kindly supplied by P. Ramdohr. R. W. Bild (private communication) found olivine (Fa_3), orthopyroxene (Fs_6), and albite ($Ab_{83}Ar_{13}Or_4$), a mineralogy typical of IAB irons (BUNCH *et al.*, 1970). Additional support for a IAB relationship, which was also favored by DE LAETER (1972), comes from other trace element data; contents of Au and As (SCOTT, 1975) match IA levels, while the Zn content of Mundrabilla (ROSMAN and DE LAETER, 1974) is at the low end of the characteristically high IA range.

In Table 1 we have listed Zerhamra as a IIIA-An meteorite because its composition shows minor deviations from the IIIAB sequence. Although its structure appears to be entirely appropriate for a low-Ni IIIA member



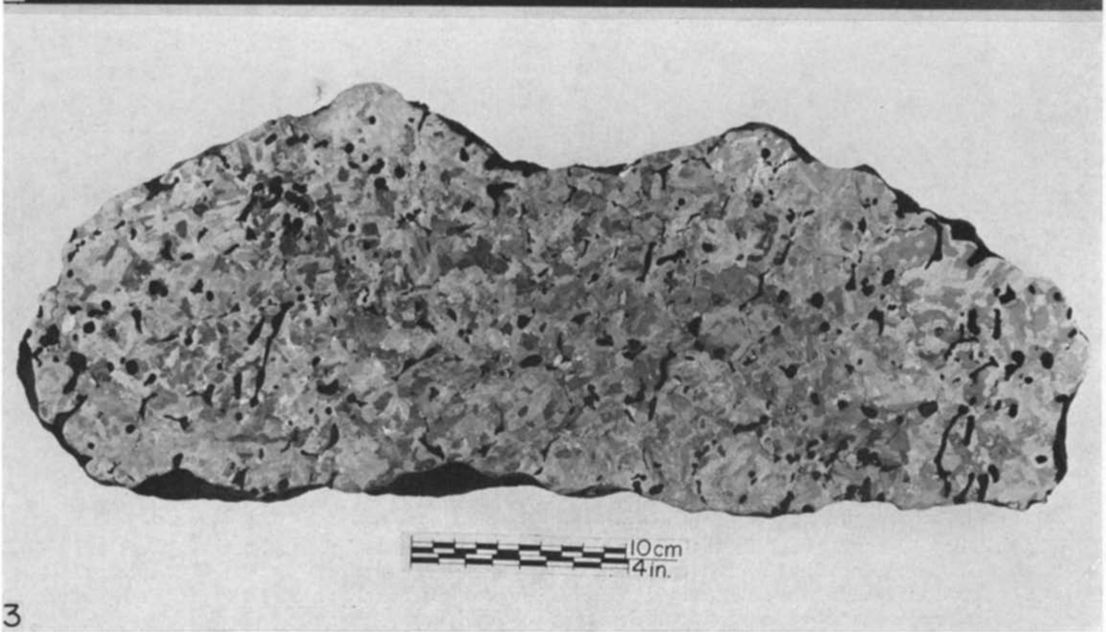
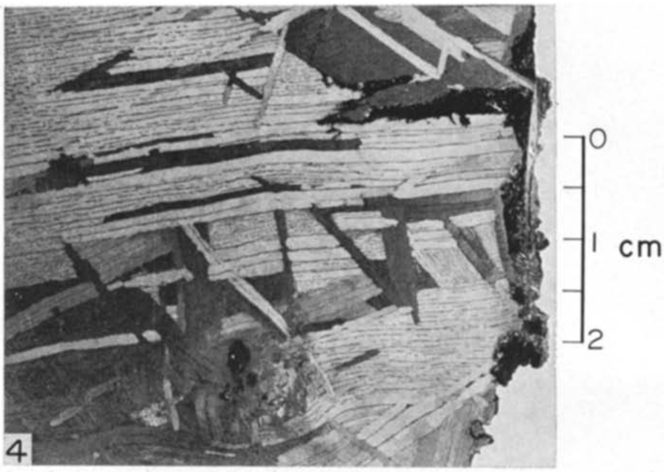


Fig. 2. Polished and etched section of the Colomera (IIE) iron meteorite. Rounded, dark silicate inclusions are abundant near the ends of the section, whereas most of the central portion is free of silicates (the light gray inclusions are mainly troilite). We believe that a shock event resulted in the melting and mixing of some metal and silicates. Perhaps the central silicate-free region was not melted. Photo supplied by D. S. Burnett.

Fig. 3. Polished and etched slice from another IIE member, Weekeroo Station. Rounded silicates (dark) are dispersed in a matrix of coarse kamacite grains which show an indistinct octahedral orientation. The shapes and preferential alignment of the silicates may have been preserved, or possibly even produced, by rapid solidification of the metal. Smithsonian Institution photo.



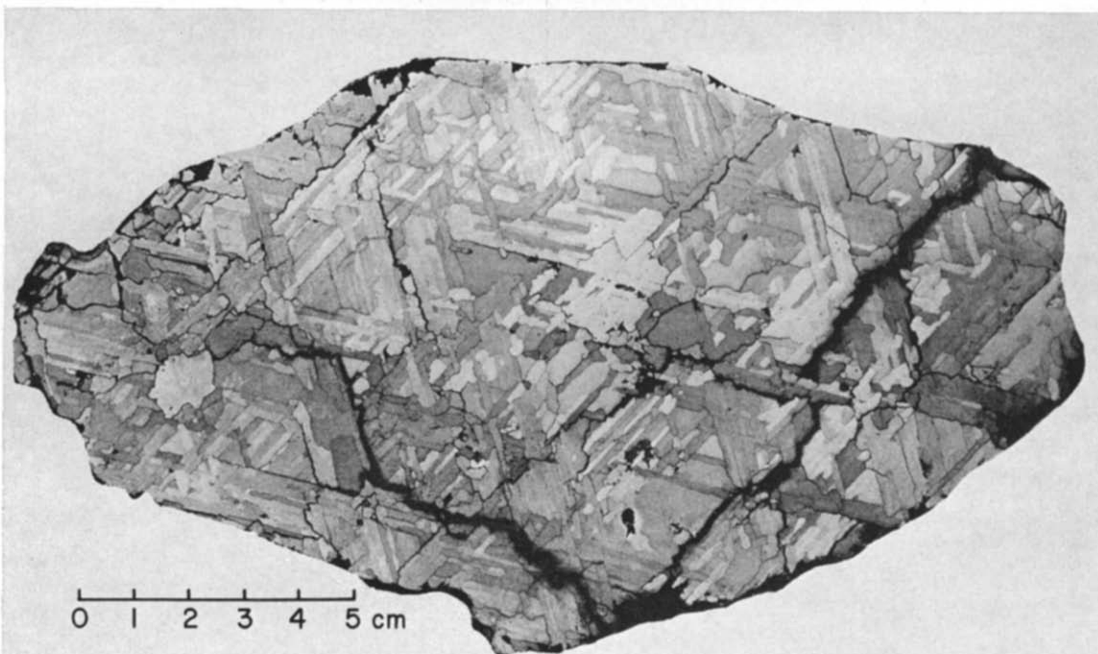


Fig. 4. Silicates are not visible in this IIE member, Arlington. The metal shows a curious plessitic Widmanstätten pattern with few well developed plates. Many areas show bent kamacite lamellae. Unlike most most other iron meteorite groups, group IIE (like IC) shows a great variety of structures (Figs. 2–4), and we have relied heavily on compositional data to establish this group. Smithsonian Institution photo.

Fig. 5. Polished and etched section of a IIIF meteorite, Clark County. Most of the surface is covered with normal kamacite bands about 1 mm across, but there are also some kamacite grains up to 10 mm in width which formed by plate impingement. The notable scarcity of macroscopic phosphide or sulfide inclusions is typical of IIIF members. Many fractures are visible, often filled with terrestrial oxidation products. Smithsonian Institution photo.

(BUCHWALD, 1973), its Ga and Ge contents are too low for the measured Ni content of 8·0% but would be more typical for a IIIA member with 7·5% Ni. Zerhamra plots close to the neighboring group IIIE, but the normal bandwidth and absence of haxonite suggest that Zerhamra is unrelated to IIIE.

The membership of group IID has shown a remarkable degree of growth since the six original members were defined by WASSON (1969). The compositions of the 13 members are listed in Table 4. These data show that in group IID there are positive Ge–Ni and negative Ir–Ni correlations significant at the 99 and 98% confidence levels, respectively, but a significant positive Ga–Ni correlation is not observed.

We include Arltunga in group IID despite its vastly different (ataxite) structure because its trace and minor element content are entirely appropriate for a low-Ni IID member. Its contents of Au, As, Co, Cr and Cu (LOVERING *et al.*, 1957; our unpublished data) in addition to its Ni, Ga, Ge and Ir concentrations (Table 4) are convincing evidence for overlooking the structural differences. We label it IID-An as a reminder of its structural idiosyncracy. Arltunga's bandwidth is about 0·005 mm, two orders of magnitude below the IID average and thus its cooling rate is about 10^4 times greater. The cooling rate of 500 K My^{-1} reported by GOLDSTEIN (1969) appears to be in error; WASSON'S (1971) equation derived from the Goldstein–Short curves for normal cooling rates yields a value of 40,000 K My^{-1} (or 0·04 K y^{-1}!).

This cooling rate seems to be faster than that recorded in the Widmanstätten pattern of any other iron. Clearly such a range of cooling rates cannot be produced in a single, highly conducting metal core. If, as seems likely, the trends within group IID were produced by fractional crystallization in a core, then Arltunga must have been subsequently removed and allowed to undergo independent cooling. It may be that the original structure of Arltunga was erased by a late heating event such as has affected Juromenha (IIIA) and Smithland (IVA). Nonetheless, the cooling rate recorded in Arltunga indicates that it was covered by a km-deep insulating layer following the reheating event.

Table 4. Composition of group IID members in order of increasing Ni content

Meteorite	Ni (%)	Ga (ppm)	Ge (ppm)	Ir (ppm)
Arltunga*	9.64	77	83	17
Bridgewater	9.8	81	82	10
N'Kandhla†	9.96	72	83	18
Richa	10.0	78	91	16
Carbo†	10.02	70	87	13
Puquios†	10.08	77	88	13
Mount Ouray	10.13	71	84	16
Elbogen	10.2	75	87	14
Rodeo†	10.2	82	93	8.0
Brownfield (1966)	10.32	78	85	11
Hraschina	10.6	75	89	13
Needles†‡	10.7	77	93	4.8
Wallapai†	11.3	83	98	3.5

* Classed as IID-Anom because of its ataxite structure.

† Data from WASSON (1969), remainder from Table 1.

‡ Nickel content increased slightly after an additional analysis.

Anomalous irons

Eleven anomalous (non-group) irons are listed in Table 1 and discussed below. Two, Del Rio and Dorofeevka, appear to be closely related to each other and to a third iron, Monahans (analyzed by WASSON, 1969; described by AXON and SMITH, 1972); their properties are summarized in Table 5. All three are ataxites or plessitic octahedrites with Ni contents 10·6–11·3%, very high Ge/Ga atomic ratios of 10–14 (Fig. 1), and appear to have low phosphide contents. KING and HENDERSON (1969) note similarities in the metallography of Del Rio and Monahans but observed some mineralogical differences.

Repeev Khutor also has a high Ge/Ga ratio of 16 and its data are also listed in Table 5. Relative to the other three irons it contains about 30% more Ni and Ga, 60% more Ge, and a factor of 4–6 less Ir. Such trends are typical of several iron meteorite groups (e.g. IIC, IVA), and it may be genetically related to the other irons. Another anomalous iron, Corowa, also has a similar Ge/Ga ratio (15) and Ge concentration. The bandwidths of Corowa and Repeev Khutor (BUCHWALD, in press, private communication) are about three times larger than those of Monahans, Del Rio and Dorofeevka (Table 5). The Ir concentration of Corowa, 0·75 ppm, is a factor of four lower than that of Repeev Khutor despite a lower Ni concentration. Apparent cooling rates for the 5 irons are listed in Table 5; a marked decrease in cooling rate with increasing Ni content is observed. Presently available evidence is not conclusive regarding a genetic link between Corowa and Repeev Khutor or between these and the triplet with lower Ni concentrations. These five irons warrant detailed chemical and petrographic comparison. The only other irons with Ge/Ga ratios above 10 are Butler (WASSON, 1970a), Emsland and Mbosi (SCOTT *et al.*, 1973) but the compositional relationships do not indicate that these are closely related to the irons in Table 5.

Dermbach has the second highest Ni content of any iron, 42%, ignoring the apparently extinct Lafayette iron (HEY, 1966). Like Oktibbeha County which has a bulk Ni content of about 60% (REED, 1972) it contains schreibersite and taenite but no kamacite. In Table 1 are data for Horse Creek and the metal from Mount Egerton. Although the enstatite abundant in the latter is apparently absent in Horse Creek, the presence in both of perryite and high Si concentrations in the metal (MCCALL, 1965; FREDRIKSSON and HENDERSON, 1965; and WASSON and WAI, 1970) suggested that these meteorites should have very similar contents of Ni, Ga, Ge and Ir in the metal, as is observed. Wasson and Wai proposed that both meteorites are closely related to the enstatite chondrites.

The structure of Kendall County is listed in Table 1 as anomalous because of the small dimensions (~ 2 mm) of its kamacite grains and the presence of abundant silicate and graphite. It contains highly reduced pyroxene ($Fs_{0\cdot 7}$) (MASON, 1967; BUNCH *et al.*, 1970), more reduced that that in differentiated metal-rich meteorites other than Tucson and Mt. Egerton. WAI and WASSON (1969) failed, however, to detect Si in the metal phase (<30 ppm). The high Ga and Ge contents in the metal might suggest a connection with group IA but the more reduced character of the silicates indicates it is a unique meteorite, perhaps produced from IA-like material by unknown processes (WASSON, 1970b).

De Hoek was described by FRICK and VILJOEN (1973a) as a plessitic octahedrite but the structure is in fact ataxitic; kamacite platelets are rare in the matrix of fine plessite. However, because of the abundant troilite inclusions on the relict taenite grain boundaries we prefer an anomalous structural classification. De Hoek's structure and composition resemble those of N'Goureyma. Its Ga and Ge con-

Table 5. Bandwidth and Ni, Ga, Ge and Ir contents of some anomalous irons with high Ge/Ga ratios

Meteorite	Ni (%)	Ga (ppm)	Ge (ppm)	Ir (ppm)	Bandwidth* (mm)	Cooling Rate (K My^{-1})
Monahans†	10.60	8.9	127	14	0.05	150
Dorofeevka	11.26	9.1	124	23	0.09	30
Del Rio	11.34	9.2	99	19	0.07	40
Corowa†	13.13	10.1	159	0.75	0.2	1.3
Repeev Khutor	14.3	11.6	193	3.0	0.21	0.57

* Measurements by V. F. Buchwald.
† Data from WASSON (1969), remainder from Table 1.

tents fall below 1 and 0·1 ppm, respectively, like those of N'Goureyma and a few other rapidly cooled irons, which, as noted by SCHAUDY *et al.* (1972), seem to form a rather ill-defined cluster of distantly related irons.

Livingston (Tenn.) and Redfields were briefly discussed under group IC as their Ni, Ga and Ge contents plot close to group IC fields on Fig. 1. However, the absence of cohenite and the high IA-like levels of Au and As in both irons argue against any such relationship. Redfields was described by DE LAETER *et al.* (1973) who also concluded it was a unique iron with its graphite and large, Ni-poor schreibersite inclusions. As can be best seen in the Ge–Ga plot in Fig. 1, Cruz del Aire shows no evidence of a close affinity to any other iron meteorite.

Paired meteorites

Twelve irons listed in italics in Table 1 are believed to be parts of other known meteorites. The evidence for these pairings is chiefly the chemical data presented in this paper but the structural, geographical and historical information were also considered. BUCHWALD (in press) also examined the evidence and reached similar conclusions. The pairings of four of these irons, Mooranoppin, Mount Stirling, Sanchez Estate and Tacubaya, were suggested earlier (see HEY, 1966) although only the Sanchez Estate pairing was accepted by Hey.

Four meteorites, Fossil Springs, Helt Township, Las Vegas and Moab, can be added to those listed by WASSON (1968) as belonging to the Canyon Diablo fall. Table 6 shows the chemical data on these irons and also on Idaho, which is chemically indistinguishable, but because of the absence of details about its discovery its pairing is uncertain. Also listed in Table 6 are data on three irons which we are confident are fragments of Toluca: Amates and Tacubaya [first paired with Toluca by NININGER and NININGER (1950) pp. 28 and 139] and Michigan. Subsequent analyses have reduced the small differences between the Toluca and Tacubaya analyses which caused WASSON (1970b) to question this pairing. Although BUNCH *et al.* (1970) found Toluca to contain Odessa-type silicates and Tacubaya Copiapo-type silicates we believe the minor mineralogical differences reflect the inhomogeneities in IAB irons.

In Table 6 we show the compositions of three other irons which are very similar to Toluca in composition: California, Moctezuma and Southern Arizona; the exact recovery locations are not known. If Moctezuma were found near the town of that name, the minimum separation from Southern Arizona would have been about 200 km, an order of magnitude greater than most strewn fields. However, both may have been transported from their original location. Further, the Toluca meteorites were surely used by the Indians, and it is quite plausible that despite the great distance (1500 km) between Toluca and northern Sonora, Toluca material may have been transported this far. Similar arguments regarding human transport also hold for California, and we consider it quite possible that all three of these irons are parts of the Toluca shower. Until stronger evidence is available, however, we choose not to consider the pairings definite. Our data clearly show that HEY'S (1966) pairing of Moctezuma with Cumpas (IIIA) was erroneous.

We confirm DE LAETER'S (1973) conclusion that Mount Stirling and Mooranoppin are part of the Youndegin fall. The composition of Sanchez Estate is the same as that of Coahuila to within the limits of experimental error; NININGERS' (1950, p. 92) contention that they are separate falls cannot be supported. Chemical data and mineralogy indicate that Abakan is part of the Toubil River fall (this pairing was independently suspected by A. A. Yavnel and V. F. Buchwald) and that Union is paired with Tocopilla.

HEY (1966) incorrectly lists the Smithsonian Iron as one of the Coahuila masses but our data show it to be a member of group IIB, not IIA. Its composition is close to that of two other IIB members, El Burro (WASSON, 1969) and Iredell (this paper) but in the absence of any information about its discovery location we tentatively consider it to be an independent meteorite. We originally thought a pairing with El Burro was likely in view of COHEN'S (1905) association of the Smithsonian Iron with Coahuila, but on rereading BREZINA'S (1886) paper referred to by Cohen, we found that he is clearly discussing Sanchez Estate (Coahuila) and not the Smithsonian Iron.

BUCHWALD *et al.* (1974) discovered a large, new IIIE member, Paneth's Iron, previously mislabelled 'Toluca'. Our Ga, Ge and Ir data indicate that it might be paired with Burlington. The diverse Ni contents (8·90 and 8·15%, respectively) require large sampling and analytical errors, but we have unpublished data on more strongly forged samples of Burlington which show Ni contents up to 11%. SILLIMAN (1844) reports that all but 5 kg of the original Burlington mass was forged; if Paneth's Iron is Burlington, it would have to be from a second, unreported mass.

FORMATION OF IIE IRONS

Relationship to other groups

There are several properties which appear to be related to the formation location of meteorites. BAEDECKER and WASSON (1975) emphasize that two properties of chondritic meteorites, the abundance of refractory elements and the degree of oxidation (measured as the Fe content of silicates), appear to have varied monotonically with distance from the Sun. They agree with ANDERS (1971) that the most reduced

Table 6. Chemical data for four irons that have been paired with Canyon Diablo and three that are part of the Toluca fall. Also shown below the dashed lines are four irons (not underlined) for which pairings are possible

Meteorite	Ni (%)	Ga (ppm)	Ge (ppm)	Ir (ppm)
Canyon Diablo*	6.98	82	324	1.9
Fossil Springs	6.98	78	308	1.7
Helt Township	7.05	79	347	2.0
Las Vegas	6.8±0.2	80	323	1.6±0.2
Moab	6.98	83	330	1.6±0.3
Idaho	7.09	81	321	2.1
Toluca	7.96	69.0	250	1.9
Amates	8.09	66.2	237	1.8
Michigan	8.16	69.7	251	2.2
Tacubaya	8.13	66.9	249	1.9
California	7.7	66.7	253	2.0
Moctezuma	7.98	67.2	244	2.3
Southern Arizona*	8.06	66.2	242	1.9

* Data from Wasson (1970a).

and refractory-poor chondrites (the enstatite chondrites) were formed nearest the Sun. Two other parameters which may fall within limited ranges at a given formation location are the isotopic composition of O and the Ge (or Ga) content of the metal. Evidence for the former is the narrow range observed in groups for which other evidence indicates close genetic relationships e.g. the three ordinary chondrite groups or the igneous achondrite clan of eucrites, howardites and diogenites (Reuter *et al.*, 1965; Taylor *et al.*, 1965). The association of Ge content of the metal with nebular location is more conjectural; as noted by Wai *et al.* (1968) and Scott (1972), the depletion of Ge relative to other strongly siderophilic elements in iron meteorite groups cannot easily have occurred in parent bodies, but must rather be attributed to nebular processes. If the material at each nebula location was reasonably well mixed, then the Ge variations represent differences between different nebular locations. There is insufficient evidence to decide whether or not these latter parameters varied monotonically with distance from the Sun.

The Ge and Ga concentrations of IIE and other groups having similar compositions can be compared on Fig. 6. In Ge–Ga space IIE lies along the upward extrapolation of each of the other groups, but is resolved from all members of these groups with the exception of the Brenham pallasite. On the Ge–Ni portion of the plot the IIE field is contiguous with the upper boundary of the mesosiderite and pallasite fields. Note that the exact locations of IIE members within the IIE fields are shown in Fig. 1.

The Fe/(Fe + Mg) atom ratios in the orthopyroxene of IIE irons are 16–22% (Bunch *et al.*, 1970), in mesosiderites 20–45% (Mason and Jarosewich, 1973). In pallasites, olivines (the only silicate) show Fe/(Fe + Mg) ratios ranging from 11 to 20% (Buseck and Goldstein, 1969); orthopyroxene in equilibrium with this olivine would have similar ratios. No silicates occur in IIIAB irons. During igneous fractionation high-temperature minerals such as olivine are formed with Fe/(Fe + Mg) ratios lower than those in the source materials, whereas ratios in basaltic magmas tend to be higher. Thus, the Fe/(Fe + Mg) ratios in the parent materials of the pallasites and the 'basaltic' mesosiderites could have been similar, any may have been in the general range found in the IIE silicates.

Values for $\delta^{18}O$ in Weekeroo Station are 4·9 and 4·2‰ for plagioclase and augite, respectively (data of R. N. Clayton and N. Onuma reported in Wasson *et al.*, 1974). These are to be compared with a $\delta^{18}O$ of 4·2‰ in the plagioclase from the Crab Orchard mesosiderite and 4·0–4·4‰ in the pyroxene of 3 mesosiderites (Taylor *et al.*, 1965). The $\delta^{18}O$ of olivine from two pallasites was found to be 3·6–4·0‰ (Reuter

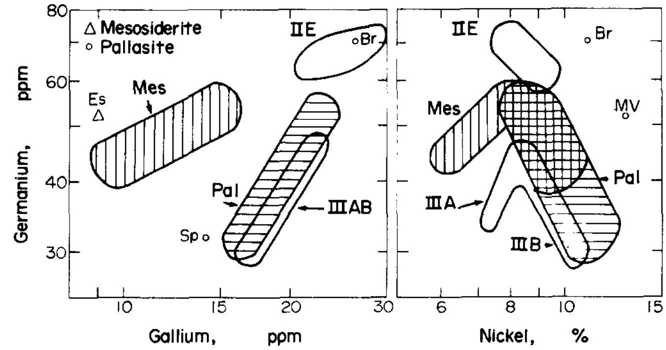


Fig. 6. Ge–Ga and Ge–Ni plots illustrating the close relationship between the compositions of the IIE irons, the metallic portions of mesosiderites and pallasites and, to a lesser degree, the IIIAB iron meteorites. The gross similarity in Ge and Ga concentrations, O-isotope data and Fe/(Fe + Mg) silicate ratios suggest that these groups formed at similar heliocentric distances. But their resolution on the Ge–Ga plot and their detailed silicate mineralogy indicate that different parent bodies were involved. Abbreviations: Br, Brenham; Es, Estherville; MV, Mount Vernon; Sp, Springwater.

et al., 1965). Taylor *et al.* (1965) note that terrestrial values in basalts are generally 1–2‰ higher than in ultramafic rocks. Thus the slightly elevated values in mesosiderites relative to pallasites are consistent with an origin in a single parent body or in two different parent bodies with similar bulk $\delta^{18}O$ values.

We conclude that the formation location of the IIE irons was near that of the mesosiderites and pallasites, and only a small distance from that of the IIIAB irons.

Additional evidence bearing on the origin

Although the Fe/(Fe + Mg) and O-isotope data link IIE silicates to those in the mesosiderites and pallasites, their bulk compositions are more nearly chondritic than either of these. In fact, the silicates of IIE-An Netschaëvo are chondritic and relict chondrules are preserved (Zavaritskii and Kvasha, 1952; Buchwald, 1967; Olsen and Jarosewich, 1971). Weekeroo Station is the other IIE iron for which we have a bulk silicate analysis; the composition is essentially that of chondritic material from which olivine has been removed (Olsen and Jarosewich, 1970).

One complication to the idea that the IIE silicates formed by removing the low-melting fraction from chondritic silicates is the great abundance of a K-feldspar, sanidine, on the exterior of Colomera (Wasserburg *et al.*, 1968). The Na/K ratios in chondrites lie in the range 6–17 (Goles, 1971) and the bulk of the K occurs as a minor constituent of albitic plagioclase. In fact, bulk Na/K ratios are 14 in Weekeroo Station and 6 in Netschaëvo (Olsen and Jarosewich, 1970, 1971), and K-rich feldspar is essentially absent in the silicates found in the interiors of IIE irons (Bunch and Olsen, 1968; Wasserburg *et al.*, 1968). It seems clear that the K-rich silicates were only deposited on the surface of Colomera after the formation of the interior silicates and their mixing with the metal. Since K is more volatile than Na, it may be that the great K enrichment in the Colomera phenocryst reflects vapor-phase transport as in a terrestrial pegmatite.

Radiogenic ages have been determined for Kodaikanal (3·8 ± 0·1 Gy; Burnett and Wasserburg, 1967), Weekeroo Station (4·4 ± 0·2 Gy; Wasserburg and Burnett, 1969) and Colomera (4·61 ± 0·04 Gy; Sanz *et al.*, 1970). The Kodaikanal age is similar to ages associated with a possible lunar cataclysmic bombardment (Tera *et al.*, 1974); if Kodaikanal was a closed system from 4·6 Gy until 3·8 Gy, Burnett and Wasserburg point out that a substantial increase in the Rb/Sr ratio must have occurred during the 3·8 Gy event, otherwise the initial $^{87}Sr/^{86}Sr$ ratio would be much higher. The age of Colomera (and probably also that of Weekeroo Station) is comparable to the age of the solar system. Sanz *et al.* (1970) note that the difference between initial $^{87}Sr/^{86}Sr$ ratio of Colomera and BABI indicates differentiation of Colomera about 39 My after the time of formation of the eucrites. The initial $^{87}Sr/^{86}Sr$ ratio in Colomera is low, and like that of Kodaikanal, indicates a chondritic Rb/Sr ratio prior to the 'event' which started the radiogenic clock 4·6 Gy ago. No ^{39}Ar-^{40}Ar ages or I- or Pu–Xe formation intervals have been reported for these meteorites. In summary, the age data indicate that silicates in most IIE irons were formed early in the solar system, but Kodaikanal was hot as recently as 3·8 Gy ago; in each case the heating event differentiated material having a roughly chondritic Rb/Sr ratio.

Bogard *et al.* (1971) reported the ^{132}Xe content of Weekeroo Station to be 9×10^{-11} cm^3 STP g^{-1}, similar to values found in type 6 ordinary chondrites (Marti *et al.*, 1969; Müller and Zähringer, 1969), about 3–4 times lower than the lowest values observed in IAB inclusions (Bogard *et al.*, 1971), and 2–20 times higher than those observed in the igneous meteorite classes, diogenites and eucrites (Zähringer, 1968; Müller and Zähringer, 1969). The ^{84}Kr concentration relationships in these meteorite groups are similar. The slightly higher concentrations in Weekeroo Station relative to the igneous classes suggest that the molten period was too brief to allow complete outgassing.

The most striking textural feature of the silicate-bearing IIE irons are the globular forms of the silicates (Figs. 2 and 3). As noted by Wasserburg *et al.* (1965, 1968), these can best be understood in terms of surface tension effects when both silicate and metal were molten. Olsen and Jarosewich (1970) also report textural evidence for two immiscible silicate melts in Weekeroo Station nodules.

In some regions (one is located just left of center in Fig. 2) an inclusion-rich area borders a region nearly free of silicates, suggesting that metal in the latter has not been molten. The alternative, that both the silicate-rich and silicate-free regions were molten but the latter remained liquid long enough (or solidified slow enough) to rid itself of silicates, seems less likely, since a monotonic increase in silicate abundance towards the edge is not observed.

The origin of the silicate-bearing IIE irons has been discussed in several papers. Wasserburg *et al.* (1968) stated that the large exterior phenocrysts (one with an 11 cm sanidine crystal) on the surface of Colomera indicated an origin as plums of iron in a pudding of silicates. Bunch *et al.* (1970) argued that these objects are mixtures of 'old' silicates in 'young' iron melts, and that the radiogenic clocks were not reset at the time the metal and silicate were mixed; they speculate that a 'zone-melting' process may have melted the metal. Wasserburg *et al.* (1968) and Wasson (1970b) argued that the rapid cooling needed to prevent unmixing of silicates and metal was only possible if a shock event produced the mixing. Wasson further proposed that Weekeroo-type silicates are a low-melting component removed from Netschaëvo-like chondritic silicates by this shock event. Olsen and Jarosewich (1970) proposed that Weekeroo-type silicates formed by removal of olivine from chondritic silicates, but they envisaged a slow igneous process rather than shock. They also suggested that the pallasites might be the complementary materials from this separation.

We believe that the evidence still favors an origin of IIE irons by shock of Netschaëvo-like parental material as described by WASSON (1970b). The size of the resulting metal masses may have been small (submeter) as proposed by WASSERBURG *et al.* (1968), although these authors failed to note how the phenocrysts were distributed on the surface of Colomera. If the occurrence were confined to one portion of the surface, then the original dimensions of the metallic mass cannot be inferred.

The metal cannot have been molten for more than a short period, else the metal and silicate would have unmixed. For example, ANDERS (1964) calculated that a grain of olivine with 0·2-cm radius can move a meter through molten Fe–Ni in 5 min if the metallic mass is located 1 km from the center of the parent body, and notes that the time required varies inversely with the distance of the region from the center of the parent body. The high abundance of Kr and Xe in Weekeroo silicates also indicates the molten period was brief. Thus a rapid deposition of heat followed by rapid cooling is required. Shock is the only process which can rapidly heat a small volume while leaving the surrounding volume relatively cool and able to conduct heat quickly from the initially heated area.

We have noted above that it seems unlikely that the 11 cm sanidine crystal on Colomera could have been present when the rapid mixing of metal and interior silicates occurred. Even had it been present, it seems unlikely that it could have survived the proposed shock event; it must have grown (or at least, recrystallized) following that event. On the other hand, the relatively low rate of cooling inferred from the structure of Colomera may be consistent (within the limits of our ignorance) with the growth of an 11 cm crystal during the period following the shock event. If the material is of pegmatitic origin, the large size of the crystal is more easily understood.

A scenario

The proposed origin of the IIE irons can be summarized as follows. Partial segregation of metal from silicate occurred by a non-igneous process, probably during the agglomeration process in the solar nebula. The process was presumably similar to that by which the IAB irons formed (WASSON, 1970a). The initial dimensions of silicate-free metal may have been a few cm, similar to those in Netschaëvo, or they may have been larger, perhaps a few tens of cm as found in largest silicate-free members of IIE. These metal inclusions were embedded in chondritic silicates. In contrast to the mesosiderite and pallasite parent bodies, which formed in the same general region, temperatures remained low, and igneous fractionation did not occur. As a result of shock heating, the low-melting fraction of the IIE silicates was mixed with some shock-liquified metal. In some cases rapid cooling prevented the gravitational separation of these phases; it is possible that some silicate-free IIE irons were also melted, but that temperatures remained high long enough to allow complete separation of metal from silicate. Of three documented cases, two shock events occurred early (4·4–4·6 Gy ago), and one somewhat later (3·8 Gy ago) in solar system history. Cooling rates (Table 3) following the shock events were vastly different (1 and 400 K My^{-1} in Weekeroo Station and Kodaikanal, respectively), indicating widely varying thickness of overburden. Meteorites bearing the complementary silicates (dominantly olivine, but undoubtedly 'contaminated' with lower melting materials because the shock process probably yields inefficient separations) are rare; Chassigny appears to be the best candidate (OLSEN and JAROSEWICH, 1970). Since we are proposing that these materials were separated from the IIE irons by at most a few m, they must also be in earth-crossing orbits. However, we note that (1) metal-rich meteorites are better able to survive atmospheric passage without fragmentation; and (2) no IIE irons are observed falls, and the recovery of iron meteorite finds is strongly favored both by their ability to survive extended weathering and (as noted by OLSEN and JAROSEWICH, 1970) the higher probability that they will have a distinctive appearance and thus be recognized by a potential finder. Thus, the rarity of these complementary meteorites is not strong evidence against this model.

Acknowledgements—We are most grateful to R. W. BILD, S. W. KASS, J. KIMBERLIN, G. PUSAVAT, K. L. ROBINSON and R. SCHAUDY for their invaluable experimental assistance. Samples were kindly provided by T. N. BARRY, R. BRETT, G. P. BROPHY, R. O. CHALMERS, R. S. CLARKE JR., W. S. CURVELLO, J. F. ENSLIN, O. F. FRIGSTAD, C. FRONDEL, G. HOPPE, G. I. HUSS, R. HUTCHISON, D. Y. JÉROME, E. L. KRINOV, G. KURAT, L. KVASHA, D. V. MANSON, D. MERRILEES, C. B. MOORE, E. J. OLSEN, C. PEARSON, P. PELLAS, P. RAMDOHR, S. J. B. REED, E. W. SALPETER, K. K. TUREKIAN, H. VOSHAGE, H. WÄNKE, G. WAPPLER and J. ZÄHRINGER. We thank V. F. BUCHWALD for his continuing advice and cooperation. Neutron irradiations were capably handled by J. BROWER and C. ASHBAUGH of UCLA and D. RUSLING of the Northrop Space Center and their associates. This research was mainly supported by NASA grant NGR-05-007-329.

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