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Chemical classification of iron meteorites—X. Multielement studies of 43 irons, resolution of group IIIE from IIIAB, and evaluation of Cu as a taxonomic parameter

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Abstract—We report structural and compositional data leading to the classification of 41 iron meteorites, increasing the number of classified independent iron meteorites to 576. We also obtained data on a new metal-rich mesosiderite and on two new iron masses that are paired with previously studied irons. For the first time in this series we also report concentrations of Cr, Co, Cu, As, Sb, W, Re and Au in each of these 44 meteorites. We determined 7 of these elements (all except Sb) in 30 previously studied ungrouped or unusual irons, and obtained Cu data on 104 irons, 21 pallasites, and 3 meteorite phases previously studied by E. Scott. We show that Cu possesses characteristics well suited to a taxonomic element: a siderophile nature, a large range among all irons, and a low range within magmatic groups. For the first time we report the partial resolution of the C-rich group IIIE from its populous twin group IIIAB on element-Ni diagrams other than Ir-Ni. Cachiyuyal previously classified ungrouped and Armanty (Xinjiang) previously classified IIIAB are reclassified IIIE. Despite the addition of 3 new irons and the reanalysis of 3 previously studied irons the members of the set of 15 ungrouped irons having very low Ga (<3 μg/g) and Ge (<0.7 μg/g) contents remain individualists. The same is generally true for irons having $100 \leq Ni \leq 180$ mg/g and compositional similarities to IIICD, but A80104 increases the Garden Head trio to a quartet. Algoma is reclassified from ungrouped to IIICD-an and Hassi-Jekna and Magnesia from IIICD to IIICD-an. The metal of Horse Creek and Mount Egerton is compositionally closely related to metal from EH chondrites. We suggest that the P-rich Bellsbank trio irons formed in the IIAB core in topographic lows filled with an immiscible, P-rich second liquid.

INTRODUCTION

CONCENTRATIONS of Ga and Ge, the most volatile siderophile elements, are the best parameters for classifying iron meteorites. Such data are not sufficient, however, and data on Ni, Ir, and structure are essential for detailed classification. In the 9 previous papers in this series (see list in KRACHER *et al.*, 1980) we defined the properties of 13 independent iron meteorite groups. Each of these groups appears to have originated in a separate parent body.

In the present paper we report Ni, Ga, Ge and Ir data on 2 paired irons, a metal-rich mesosiderite, and 41 independent irons, bringing our classified total to 576 independent falls. Thirty-two of the new irons are grouped and 9 are ungrouped. In order to add precision to the classification we now report instrumental-neutron-activation-analysis (INAA) data on 8 additional elements in each of the classified irons. These offer additional tests of possible genetic links between ungrouped irons and groups and among each other. In part to investigate such links we also report INAA data for 30 irons previously studied by radiochemical-neutron-activation analysis (RNAA).

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EXPERIMENTAL

The procedures are essentially those described by KRACHER *et al.* (1980), based upon the INAA technique of WILLIS and WASSON (1981) and the RNAA schemes of WASSON and KIMBERLIN (1967) and KIMBERLIN *et al.* (1968). Radiochemical separation of Sb (WILLIS, 1981) has been added to the procedure, and the determination of Ge recovered from RNAA is now accomplished by inductively-coupled plasma emission spectroscopy (ICP), supplanting the colorimetric method at a substantial savings in time and effort.

Gallium and Ir are determined both by INAA and RNAA. For meteorites containing greater than 0.2 μg/g Ir, the INAA value is used exclusively. For Ir contents between 0.2 and 0.02 μg/g the average of INAA and RNAA values is used, each weighted on the basis of the analytical precision. For lower Ir contents the RNAA value is used. The INAA value for Ga is averaged arithmetically with the RNAA value for concentrations above 0.5 μg/g. Atomic absorption analysis Ni data are used except where laboratory problems were encountered, in which case INAA Ni values are also included in the reported mean.

Samples were sawn into blocks roughly $3 \times 5 \times 5$ mm in size, having masses between 0.4 and 0.7 g. For meteorites with coarse structures slightly larger samples were used. Two replicates were run for each meteorite except in cases of limited sample mass or of established pairing with a previously analyzed meteorite. Only turnings of Huangling and highly-weathered samples of Dorrigo and Yongning were available.

In Table 1 the meteorites are listed alphabetically along with group assignment and compositional data for Ni, Ga, Ge, and Ir. The 95% confidence limits for the means listed in Table 1 are about ±2% for Ni, ±4% for Ga and Ge, and ±9% for Ir. Where poor reproducibility indicated lower precision larger uncertainties are listed. Also listed in Table 1

Table 1. Mean concentrations of Ni, Ga, Ge and Ir, group assignments and structural information for 41 independent iron meteorites and a mesosiderite.

Meteorite	Group	Struc. class	Width mm	Source*	Cat. No.	Ni mg/g	Ga µg/g	Ge µg/g	Ir µg/g
Alikatnima	ungr	D	-	SAuM	G5683C	138.7	0.28	0.14$^+$	4.2
Allan Hills A77255	ungr	D	-	MWG	6	124.2	0.083$^+$	0.058	10
Allan Hills A77283	IA	Og	1.8	MWG	5	74.7	77.2	320	2.0
Allan Hills A78100	IIA	H	-	MWG	2	54.4$^+$	59.0	181$^+$	27
Allan Hills A78252	IVA	Of	0.4	MWG	5	96±3	2.44	0.138	0.37
Allan Hills A80104	ungr	D	-	MWG	1	162.7	6.03	10.2	0.083
Bocaiuva	ungr	anom	0.2	MNB	-	84.9	19.5	178	2.9
Brainard	IIIB	Om	1.0	AML	H357.4	90.9	22.5	45.2	0.059
Cosmo Newbery	IIA	H	-	WAM	-	56.1	63.2	180	19
Derrick Peak A78009	IIB	Ogg	5	MWG	4	65.4	55.1	135	0.014
Dorrigo	ungr	Opl	0.15§	AM	DR6632	163$^+$	17$^+$	1.9$^+$	11$^+$
Floydada	IIIB	Om	0.9	AML	H387.2	90.9	21.1	41.4	0.013
Fuzzy Creek	IVA	anom	-	AML	H377.3	118±3	2.28	0.138	0.18
Glen Rose	ungr	Off	0.1	AML	H375.2	93.7	0.74	0.305	3.9
Gnowangerup	IIIA	Om	1.0	WAM	-	87.5$^+$	22.8	48$^-$	0.32
Guanghua	IVA	Of	0.3	HuBG	-	77.3	1.71	0.091	2.8
Guixi	IIIA	Om	1.2	BP	-	81±2	20.0	39.7	2.4
Hasparos	IA	Og	2.4	UCLA	1099	64±2	94.7$^-$	486$^-$	5.6
Hebei	IIIA	Om	1.1	HeBG	-	76.9	20.1	36.9	5.4
Huangling	IVA	-	-	IGG	-	78$^+$	1.8$^+$	<0.18#	2.8$^+$
Jianshi	IIIA	Om	1.0	IGB	-	86±5	21.3	44.5	0.39
Leshan	ungr	Of	0.5	IGB	-	95±4	21.3$^-$	68.9	4.1
Liangcheng	IIIA	Om	1.3	IGG	-	78.8	21.6	45.7	0.54
Longchang	IVA-an	anom	-	GIC	-	86$^-$	2.10$^-$	<0.4#	3.7
Muzaffarpur	ungr	Opl	0.10§	GSI		142.7	14.9	28.6	0.55
Ningbo	IVA	Of	0.3	IGG	-	82±3	2.21	0.134	2.0
Nova-Petropolis	IIIA	Om	1.3	MNB	-	78.3	19.9	36.5	9.4
Paloduro	IIIE	Og	1.6	AML	H376.2	91.0	19.7	37.7	0.104
Purgatory Peak A77006	IA	Og	1.8	MWG	4	74.0	77.2	284	2.1
Quarat al Hanish	IIICD-an	Of	0.4	UCLA	1086	128.5	17.2	29.7	0.85
Reckling Peak A79015	MES-an	anom	-	MWG	11	100	12.9	42.9	0.51$^-$
Reckling Peak A80226	IA	anom	1.2	MWG	1	84.0	68.4	255	2.1
Red Rock	IIIA	Om	1.1	UCLA	1071D	77.1	21.6	41.8	2.1
Siratik	IIA	anom	-	NMW	A294	55.5	59.2	188	11
Sombrerete	ungr	anom	-	AMNH	4493	100±3	19.1	11.3	0.073
Squaw Creek	IIA	anom	-	AML	-	54.5	59.0	182	9.7
Techado	IIE	Om	0.6	UNM	-	88.8	23.2	70.2	4.9
Tepla	IIIB	Om	0.9§	NMP	-	100	21.1	39.9	0.014
Tonganoxie	IIIA	Om	1.1§	ASU	120a	75.4	19.9	38$^-$	3.8
Wimberley	IIIB	Om	1.0	UCLA	1064	92.0	21.0	41.3	0.15
Yingde	IVA	Of	0.3	IGB	-	77.2	1.85	0.115	2.9
Yongning	IA	Ogg	3	IGG	-	64$^-$	98$^-$	490$^-$	3.8$^-$

§ Bandwidth measurements from Buchwald (1975).

* Source abbreviations are as follows: AM--Australian Museum, Sydney; AML--American Meteorite Laboratory, Denver; AMNH--American Museum of Natural History, New York; ASU--Arizona State Institute, Chengdu; HeBG--Hebei Bureau of Geology, Shijiazhuang; HuBG--Hubei Bureau of Geology, Wuhan; IGB--Academia Sinica, Institute of Geology, Beijing; IGG--Academia Sinica, Institute of Geochemistry, Guiyang; MNB--Museu Nacional Brazil, Rio de Janeiro; MWG--Meteorite Working Group, Johnson Space Center, Houston; NMP--National Museum, Prague; NMW--Naturhistorisches Museum, Vienna; UCLA--University of California, Los Angeles; UNM-- University of New Mexico, Albuquerque; SAuM--South Australian Museum, Adelaide; WAM-Western Australian Museum, Perth.

$^+$ Uncertainty about 1.1-1.4X normal.

$^-$ Uncertainty about 1.4-2.8X normal.

\# Sample contaminated in this element; datum for information only and should not be used.

are the structural class, kamacite bandwidth and the source of the samples. The mean kamacite bandwidths determined on our small analytical samples have high relative uncertainties of about ±20%.

CLASSIFICATION

Of the 42 meteorites in Tables 1 and 2, 33 are new members of established compositional groups, and 9 are ungrouped although possibly distantly related to one group or another.

Group members

The 33 meteorites assigned to groups consist of 5 new members of IAB, 5 of IIAB, 1 of IIE, 12 of IIIAB, 1 of IIICD, 1 of IIIE, 7 of IVA and 1 mesosiderite. We will discuss these in that order.

The 5 new members of group IAB are all in the low-Ni, high-Ge portion of this group; their Ge contents range only from 255 to 490 µg/g. Allan Hills A77283 is remarkable because it contains diamonds and lonsdaleite of shock origin (CLARKE *et al.*, 1981). Curiously, it has a chemical composition indistinguishable from Canyon Diablo, a point also recognized on the basis of less complete data by CLARKE *et al.* (1981), who noted that its structure is also identical to that of Canyon Diablo. This raises three possibilities listed in order of increasing degree of scientific interest: (1) A77283 is actually a mislabelled specimen of Canyon Diablo; (2) Canyon Diablo may have contained diamonds be-

Table 2. Instrumental-neutron-activation concentrations of 8 elements in 41 independent irons and a mesosiderite.

	Group	Cr µg/g	Co mg/g	Cu µg/g	As µg/g	Sb§ ng/g	W µg/g	Re ng/g	Au µg/g
Alikatnima	ungr	470	5.23	16*	1.23	4=	0.79	1060	0.511
Allan Hills A77255	ungr	363	5.66	10	0.29	2=	1.23	1010	.070
Allan Hills A77283	IA	21	4.81	146	15.4	400*	1.08	245	1.72
Allan Hills A78100	IIA	37	4.38	136	4.08	52*	4.03	2680	0.544
Allan Hills A78252	IVA	100	4.04	154	13.3	6*	0.46	<100	2.54
Allan Hills A80104	ungr	8	6.81	299	26.1	570	0.41	<30	2.66
Bocaiuva	ungr	150=	4.17	305	9.85	130	1.28	312	0.917
Brainard	IIIB	22	5.79	158	12.4	91	0.46	<60	1.52
Cosmo Newbery	IIA	56+	4.53	146	4.27	57*	3.88	2130	0.612
Derrick Peak A78009	IIB	29	4.62	117	9.55	100*	0.66	<60	1.20
Dorrigo	ungr	84	4.13	332	11.4	59=	8.0	1270	2.90
Floydada	IIIB	10=	5.22	149	12.4	105*	0.44	<70	1.52
Fuzzy Creek	IVA	17*	4.22	178	14.2	4=	0.25	<100	2.85
Glen Rose	ungr	163	4.94	57	1.37	6*	0.65	258	0.272
Gnowangerup	IIIA	<25	5.25	135	9.57	100	0.59	<70	1.28
Guanghua	IVA	306	3.79	150	2.20	2=	0.65	390	0.695
Guixi	IIIA	82	4.82	178	4.94	95=	1.51	239	0.718
Hasparos	IA	27	4.66	155	12.4	310	1.73	506	1.55
Hebei	IIIA	<40	4.92	162	4.21	48*	1.21	559	0.63
Huangling	IVA	337	3.61	150	2.26	7+	0.85	372	0.653
Jianshi	IIIA	53	5.06	171	11.1	150+	0.69	<70	1.14
Leshan	ungr	14=	4.41	325	18.0	700=	1.49	463	1.79
Liangcheng	IIIA	53	4.97	157	6.81	59=	0.84	<70	0.928
Longchang	IVA-an	350=	4.12	162	4.75	4200#	1.32	530	0.620
Muzaffarpur	ungr	16=	6.06	213	32.2	430	0.38	78	3.37
Ningbo	IVA	89	3.80	138	5.21	6=	0.56	265	1.15
Nova-Petropolis	IIIA	60=	4.99	176	4.20	42	1.30	1200	0.618
Paloduro	IIIE	130=	4.82	139	5.92	51=	0.88	<100	0.900
Purgatory Peak A77006	IA	28+	4.68	142	14.2	430	1.00	263	1.65
Quarat al Hanish	IIICD-an	30*	5.40	212	26.7	320=	0.27=	100*	2.78
Reckling Peak A79015	MES-an	150=	4.73	201	12.3	500=	0.79	<90	1.48
Reckling Peak A80226	IA	23*	4.88	173	17.1	450=	0.90	222	1.74
Red Rock	IIIA	23+	4.96	165	7.25	67	1.05	202	0.915
Siratik	IIA	55	4.52	137	4.24	51	3.32	929	0.581
Sombrerete	ungr	40	5.07	247	21.2	180=	2.04	<100	2.27
Squaw Creek	IIA	61	4.35	134	4.41	47*	3.54	940	0.599
Techado	IIE	<20	4.43	287	15.5	380	1.13	576	1.72
Tepla	IIIB	10	5.44	167	15.3	120	0.30	<30	1.82
Tonganoxie	IIIA	62	4.85	167	4.42	170+	1.11	385	0.636
Wimberley	IIIB	20=	5.30	130	13.2	160	0.49	<100	1.63
Yingde	IVA	342	3.69	152	2.43	2=	0.67	339	0.705
Yongning	IA	33=	4.2=	156=	11=	350=	2.3=	380=	1.5=
95% confidence limit on mean		12%	6%	8%	7%	8%	8%	15%	8%

+ only one analysis; * uncertainty is 1.1–1.4x normal value; = uncertainty is 1.4–2.8X normal value; # sample contaminated in this element; § Sb values <300 µg/g determined by RNAA.

fore it fell (CLARKE *et al.*, 1981); (3) A77283 is ejecta from the Arizona Meteor Crater. R. S. CLARKE JR. (private commun.) states that the recovery and curatorial documentation of A77283 are extensive and complete, and that there is no doubt the analyzed meteorite was recovered in Antarctica. This conclusion is reinforced by the presence of a heat altered zone (CLARKE *et al.*, 1981).

It is a remarkable coincidence that the compositions of A77283 and Canyon Diablo are so similar, since there is strong geographic evidence that the Canyon Diablo diamonds were produced by terrestrial impact. NININGER (1956) and HEYMANN *et al.* (1966) report that diamond-bearing Canyon Diablo specimens are almost exclusively found in the highly-shocked debris collected near the crater rim. In a study by HEYMANN *et al.*, only 1 of 15 diamond-bearing specimens was from the surrounding plains.

If the Canyon Diablo diamonds were produced by impact with the Earth, is it possible that A77283 is ejecta from that impact? The ballistic velocity required to throw a fragment to Antarctica is about 7 km s^{-1}, the orbital velocity. It seems possible that a small fragment (10.5 kg) could have been spalled off the rear of the projectile and accelerated out the top of the atmosphere by the shock release and by the expanding debris cloud. The heat-altered zone would have developed on reentry into the atmosphere. OTT *et al.* (1982) state that noble-gas data indicate a burial depth < 15 cm, which is not necessarily inconsistent with such a picture. An argument against this picture is that other similar fragments should have been recovered from locations around the globe.

The Ge content of Purgatory Peak A77006 is about 12% lower than that of A77283, in support of the conclusion of CLARKE *et al.* (1980) that these are distinct falls. The Hasparos meteorite has the highest Ir content found in a group IA iron, slightly higher than but similar to that of Osseo (WASSON, 1970). Yongning is a low-Ni, high-Ge member of group IA. The only available sample was severely weathered and the structure could not be adequately determined. Several troilite bodies up to 1 cm across were discovered by accident during sampling. Our concentration data were increased by about 3% to allow for dilution by O as a result of oxidation.

Two new group IIA meteorites, Allan Hills A78100 and Cosmo Newbery, are normal hexahedrites with abundant rhabdite inclusions. The IIA irons Siratik and Squaw Creek (previously tentatively named Glen Rose (b)) have each had their primary textures erased by reheating; note that this appears to be a genuine Siratik specimen in contrast to the numerous pseudometeorites that carry this name. Derrick Peak A78009, a coarsest octahedrite of group IIB, is one of 16 paired masses (CLARKE, 1982a).

Figure 1 shows 8 log-log element-Ni diagrams for group IIE members; also shown are locations of the newly analyzed irons Techado and Leshan. The IIE element-Ni diagrams show more scatter than those of the large magmatic groups such as IIIAB. Techado falls in or near the loosely defined IIE cluster on all these diagrams, and is especially similar to Arlington and to the IIIE-an Netschaevo iron-with-chondritic-inclusions. We designate Techado IIE, but Leshan we leave ungrouped. Group IIE deserves thorough compositional reexamination.

The eight IIIA and four IIIB meteorites in Tables 1 and 2 are medium octahedrites having structures typical for IIIAB irons of their compositions. Four are from China and are independent meteorites based on their compositions, especially their Ir contents. Tepla is an extremely corroded iron in which only small amounts of native metal persist. The data on Tepla are typical of a high-Ni member of group IIIB, and we conclude that our metal samples were representative despite the weathering effects.

Quarat al Hanish, a new iron from Egypt (UNDERWOOD *et al.*, 1982) lies along the IIICD element-Ni trends for Ga, Co and Cu but differs by a factor of 1.2–1.5 for Ge, Ir and Au. We tentatively designate it an anomalous member of IIICD, but it may be ungrouped. In a later section we discuss the confusing compositional relationships among IIICD and related irons.

Paloduro contains abundant schreibersite and, in plessite fields, haxonite precipitates and graphite lamellae (from haxonite decomposition). Its high C content and its high band width of 1.6 mm are all consistent with its assignment as the tenth member of the small group IIIE. Two additional irons are reclassified into IIIE in a later section.

Group IVA is expanded by the incorporation of six new members. Five are from China and three of these have compositions too similar to be clearly resolved by our data: Guanghua, Huangling, and Yingde. The structures of Guanghua and Yingde are similar, but we only have drillings of Huangling and were unable to examine its metallographic structure. The composition of Huangling is not consistent with BIAN'S (1981) tentative listing as a mesosiderite. If it contains silicates, it may be similar to Steinbach and/or São João Nepomuceno. Both Guanghua and Huangling were discovered in Hubei province and we suspect that they may be paired. We tentatively list them as independent pending structural examination of Huangling. The large (300 kg) Yingde IVA iron was found 1000 km to the south in Guangdong province and seems unlikely to be related to the other two.

Longchang is designated IVA-an, anomalous because the structure and composition of the pieces available to us have been too strongly altered by humans to permit confirmation that it is a normal IVA member. The texture of Longchang (WANG *et al.*, 1983) indicates that it has been strongly reheated and partly melted and oxidized, probably in an attempt to use it as a source for steel. Its Ge content is 3× higher than expected in group IVA, and the Sb content is ≳8 μg/g, far higher than in any iron other than Oktibbeha County. Most other elements (Co, Cu, Ga, As, Ir, Au), however, are consistent with Longchang being a IVA iron at the low-Ni end of the group. We conclude that the elevated Ge and Sb contents reflect contamination during this processing; we earlier observed elevated Ge contents in a forged sample of IIIE Burlington (SCOTT *et al.*, 1973), perhaps as a result of contamination by coal.

The Fuzzy Creek iron (earlier temporarily designated Ballinger (b)) is classified IVA based on composition. It is structurally an ataxite; the expected IVA fine octahedral structure is not resolvable, perhaps erased by reheating. Its Ni content is the highest of group IVA, 10 mg/g higher than Duel Hill (1854). The latter was classified by SCHAUDY *et al.* (1972) as an anomalous member of group IVA, anomalous because of an Ir content 2× higher than the trend extrapolated to higher Ni contents. We reanalyzed Duel Hill (1854) by INAA; data are compared with those of Fuzzy Creek in Table 3. We found 0.34 μg/g Ir in concordance with an extrapolation of the IVA trend. *Nostra culpa*; examination of our RNAA Ir records showed the concentration of 0.64 μg/g reported by SCHAUDY *et al.* (1972) and quoted in BUCHWALD (1975) to be a copying error.

Figure 2 shows Ga-, Ge-, Cu-, Ir-, As-, and Au-Ni log/log diagrams for group IVA; the positions of Duel Hill (1854) and Fuzzy Creek are indicated. Group IVA seems likely to have formed by fractional crystallization of a single core (SCOTT, 1972; WILLIS and WASSON, 1981) although evidence of cooling-rate variations have suggested multiple cores to some researchers (MOREN and GOLDSTEIN, 1979; RASMUSSEN, 1982).

The generally positive trend on the Au-Ni and As-Ni plots at Ni contents ≤ 96 mg/g reflects the fact that these three elements have solid/liquid partition coefficients < 1 and so become enriched in successive increments of crystallization. Recent experimental de-

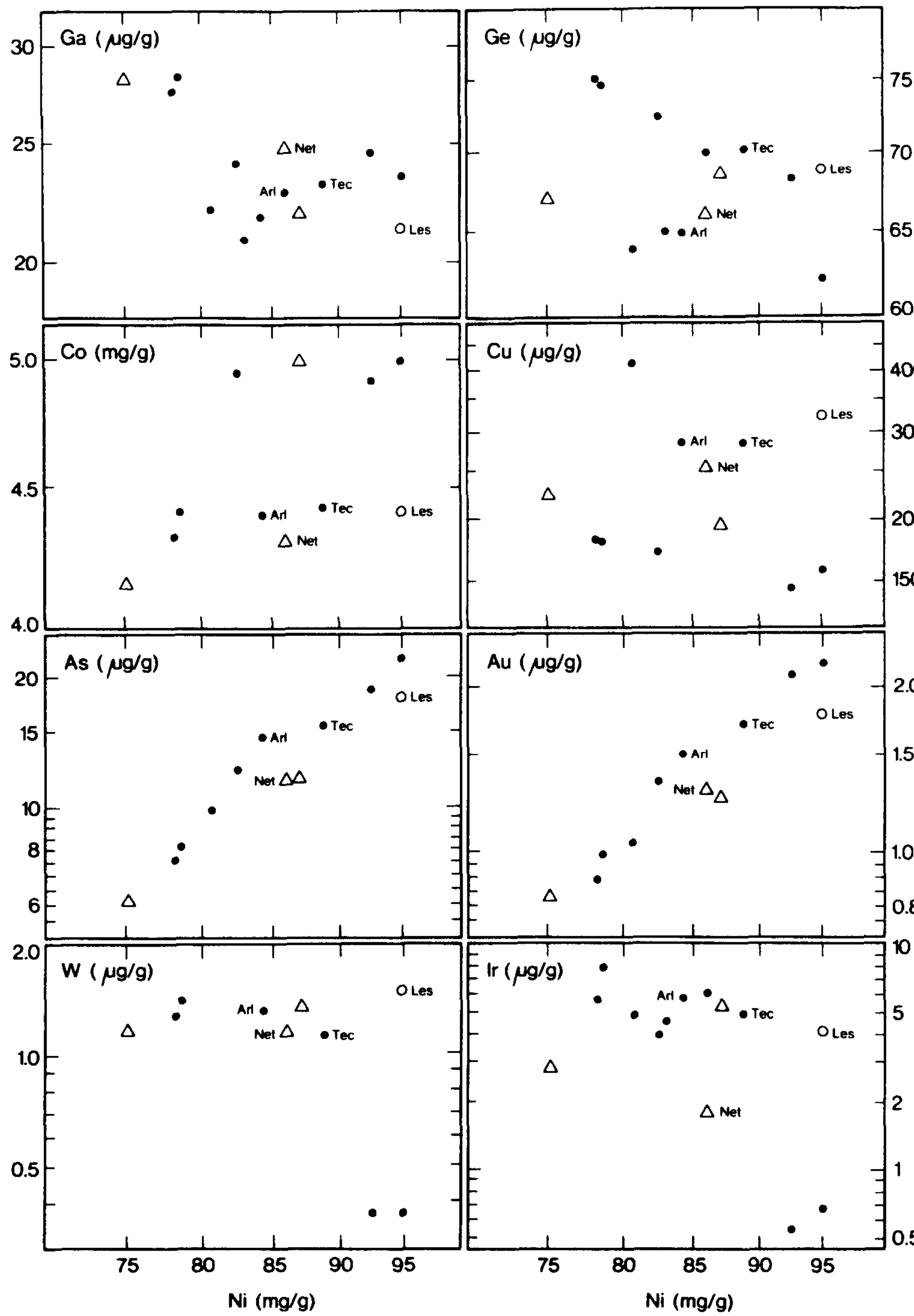

FIG. 1. Two new medium octahedrites Techado (Tec) and Leshan (Les) are related to the group IIE irons. We tentatively list Leshan as ungrouped because of its slightly deviant position on the Co-, Cu- and Ir-Ni diagrams. Techado is compositionally closely related to Arlington (Arl) and to Netschaevo (Net) and is classified IIE. The IIE irons do not show the typical patterns of magmatic groups, and require additional detailed study.

terminations (JONES and DRAKE, 1983; WILLIS and GOLDSTEIN, 1982) of solid/liquid distribution coefficients in Fe-Ni alloys demonstrate that *D*(Au) increases as the amount of S, P or C in the liquid increases, as would obtain during fractional crystallization. At very low S contents *D*(Au) is ~0.4. The apparent leveling of the Au *vs.* Ni trend at high Ni content may be an indication that *D*(Au) had increased to ~1 by the time the fraction of the IVA core represented by Duel Hill (1854) and Fuzzy Creek solidified. Although there are no experimental results for As partition coefficients, As and Au display like trends in all of the iron meteorite

Table 3. Compositions of the two IVA meteorites having the highest Ni concentrations. The classification of Duel Hill (1854) is changed from IVA-an to IVA; see text.

	Cr μg/g	Co mg/g	Ni mg/g	Cu μg/g	Ga ng/g	Ge ng/g	As μg/g	W ng/g	Ir ng/g	Au μg/g
Duel Hill (1854)	32	4.28	105	220	1.98	111	14.6	286	339	2.71
Fuzzy Creek	17	4.22	118	177	2.28	138	14.1	250	178	2.85

groups, and their solid-liquid distribution coefficients appear to be very similar at most liquid compositions.

The Cu contents of these two meteorites are about 2× higher than the value of ~100 μg/g extrapolated from the trend at Ni ≤ 96 mg/g (Fig. 2). Possible explanations of the aberrently high Cu values in Fuzzy Creek and Duel Hill are discussed in the section on Cu later in this paper. Because the other trends seem so consistent with IVA membership, we are confident that Duel Hill and Fuzzy Creek are normal (as opposed to anomalous) IVA members.

Reckling Peak A79015 was classified a metal-rich mesosiderite by PRINZ *et al.* (1982a) and CLARKE and MASON (1982). The metal has Ni, Ga and Ge values that are higher than but broadly consistent with the range exhibited by the mesosiderites (WASSON *et al.*, 1974). The Ir content of A79015, however, is 5–10× lower than that previously encountered in mesosiderites.

The elements listed in Table 2 provide a means for comparison with group IIIAB irons, which have been postulated by several researchers as the source of the metal phase in mesosiderites. Comparable trace element analyses of mesosiderite metal are not yet available. A79015 would fall within the IIIAB compositional fields for As, Au, Ir, W and Co *vs.* Ni were the Ni content of the metal ~ 1% lower, but the Cu value is far higher than the IIIAB range. We tentatively designate A79015 an anomalous mesosiderite pending the better definition of elemental trends in mesosiderite metal.

Ungrouped meteorites

Sombrerete is a unique iron with Na- and P-rich silicate inclusions (PRINZ *et al.*, 1982a). Prior to determination of Ge we tentatively designated Sombrerete IIE-an (WANG *et al.*, 1982) because the data were adequately fit by extrapolations of the interelement trends of group IIE. However, the Ge content is 6× lower than normally found in group IIE and Sombrerete is now designated ungrouped. The O-isotopic composition of Sombrerete is $\delta^{17}O$ = 0.32‰, $\delta^{18}O$ = 3.33‰ (MAYEDA and CLAYTON, 1980), far away from the combined IIE-H-chondrite field, and not particularly near any other meteorite, the nearest being the ungrouped Acapulco chondrite.

Bocaiuva contains silicate inclusions of roughly chondritic mineralogy (CURVELLO *et al.*, 1983). The metal composition is unique in its combination of Ni, Ga, and Ge, dissimilar to both groups IAB and IIE, the two main silicate-bearing iron meteorite groups. It has a high Ge/Ga ratio similar to the minor group IIF (KRACHER *et al.*, 1980) and the Eagle-Station trio of high-Ni pallasites. On element-Ni diagrams Bocaiuva metal fits the interelement trends of group IIE (except for Ge); and the olivine-rich mineralogy is roughly complementary to the differentiated silicate inclusions found in IIE. However, the olivine is much too magnesian (Fa8) to have been been in equilibrium with the *ca.* Fa20 values in IIE olivine, and this together with the divergent Ge value seems to preclude a close relationship to IIE.

Leshan is closely related to Techado and other high-Ni group-IIE irons. However, as shown in Fig. 1, it diverges from IIE trends on Co-Ni, Cu-Ni and Ir-Ni diagrams. We currently designate Leshan ungrouped, but it may be as closely related to some IIE members as are other meteorites currently assigned to this inadequately defined group. Note, for example, the separation of IIE into two subgroups based on Co (Fig. 1).

The new Allan Hills ataxite A80104 is a virtual twin of Gay Gulch, and thus becomes the fourth member of a quartet that also includes Garden Head and Kofa. Linville (KRACHER *et al.*, 1980) and Muzaffarpur show some compositional resemblance to members of the Garden Head quartet and also, like them, some suggestion of a relationship to group IIICD. The possible relationship of these irons to group IIICD is discussed in a later section.

As discussed by BUCHWALD (1975), Dorrigo is a highly weathered plessitic octahedrite. From F. L. Sutherland of the Australian Museum we received a generous sample of the best preserved material he could recognize. The material could be crumbled by squeezing. An opaque mineral with dimensions ~ 5 mm we initially mistook for metal turned out to be a nickel sulfide, apparently a terrestrial oxidation product. The small piece of metal we finally winnowed out of the oxidation products was large enough for only one sample; the composition is reported in Tables 1 and 2. There is little doubt that some kamacite had been oxidized in this plessitic sample; if the oxidation products were lost, the concentrations of elements that have taenite/kamacite ratios < 1 (Fe, Co) would be depressed, those with ratios > 1 (all other elements in our set) would be elevated. If the oxidized kamacite constituents were not lost, then the concentrations of all elements would be depressed because of dilution with oxygen. The latter effect seems to have been minor since the measured Ni content of 160 mg/g is higher than the value of 110 ± 20 predicted by BUCHWALD

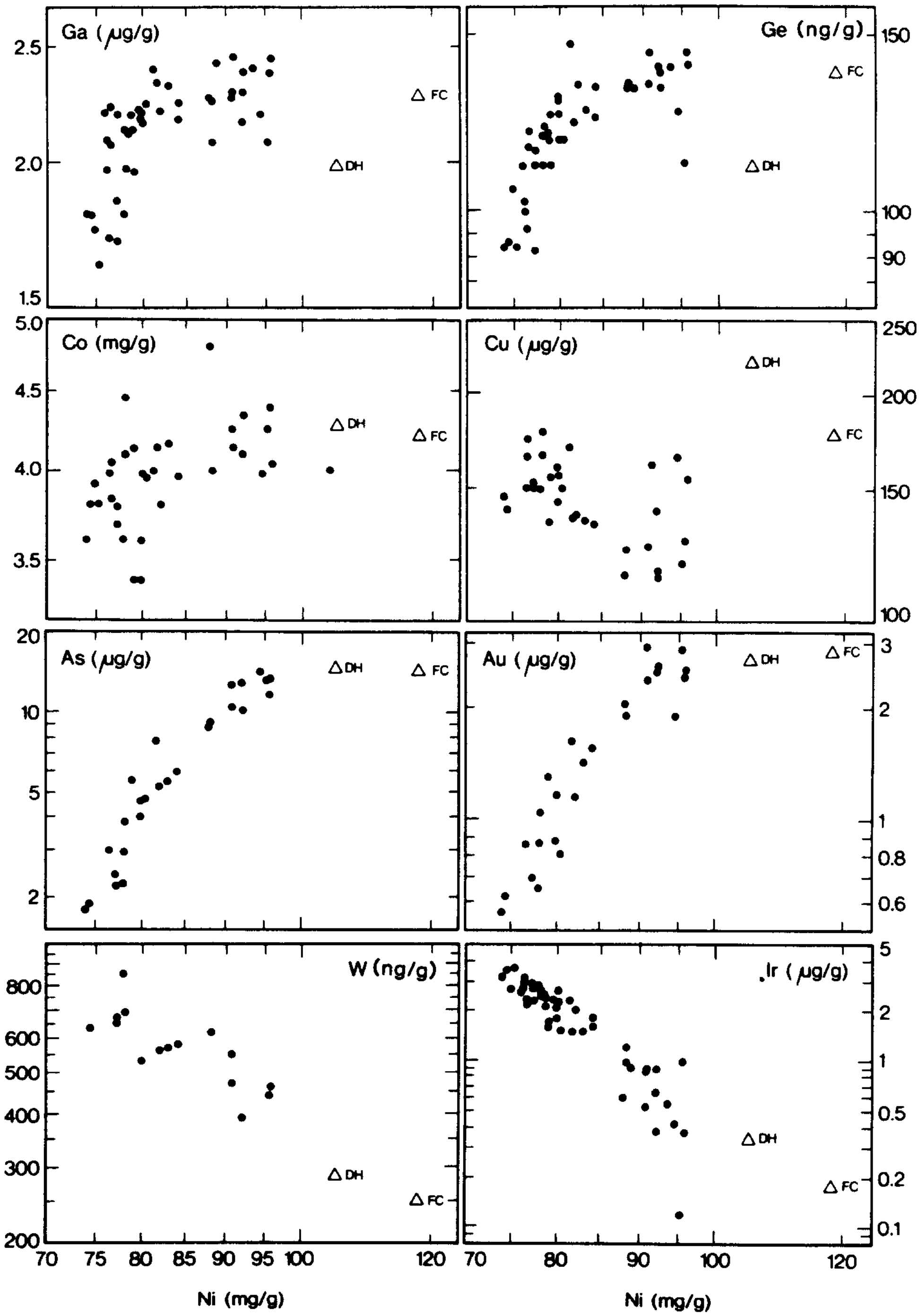

FIG. 2. The positions of high-Ni IVA members Duel Hill (1854) and Fuzzy Creek (symbols DH and FC) form plausible extensions of group-IVA trends on Ga-, Ge-, Ir-, As- and Au-Ni diagrams, and can surely be considered normal IVA members. On the Cu-Ni diagram they are about 1.5× higher than expected, perhaps the result of late-stage influx of an FeS-rich liquid.

(1975) on the basis of its residual plessitic structure, and our uncorrected INAA Fe and Ni concentrations total 950 mg/g. Our experience with other highly oxidized irons whose compositions are predictable based on their position within a magmatic group shows that elemental concentrations are generally within about ±30% of those expected.

If the Dorrigo values are reasonable approximations of its original composition, its closest relatives are to be sought among irons with 100 < Ni < 180 mg/g, 10 < Ga < 30 μg/g and Ga/Ge ~ 10. The 3 candidates are then Soroti, Cambria and Barbacena. We find that As and Au are much higher than in the former two but similar to those in Barbacena. Allowing for Nielevation and Co depression, the match is adequate, and we conclude that Dorrigo's closest relative is Barbacena.

Alikatnima is a unique ataxite that is related compositionally to Allan Hills A77255, Babb's Mill (Blake's) and Nordheim, and to a slightly smaller de-

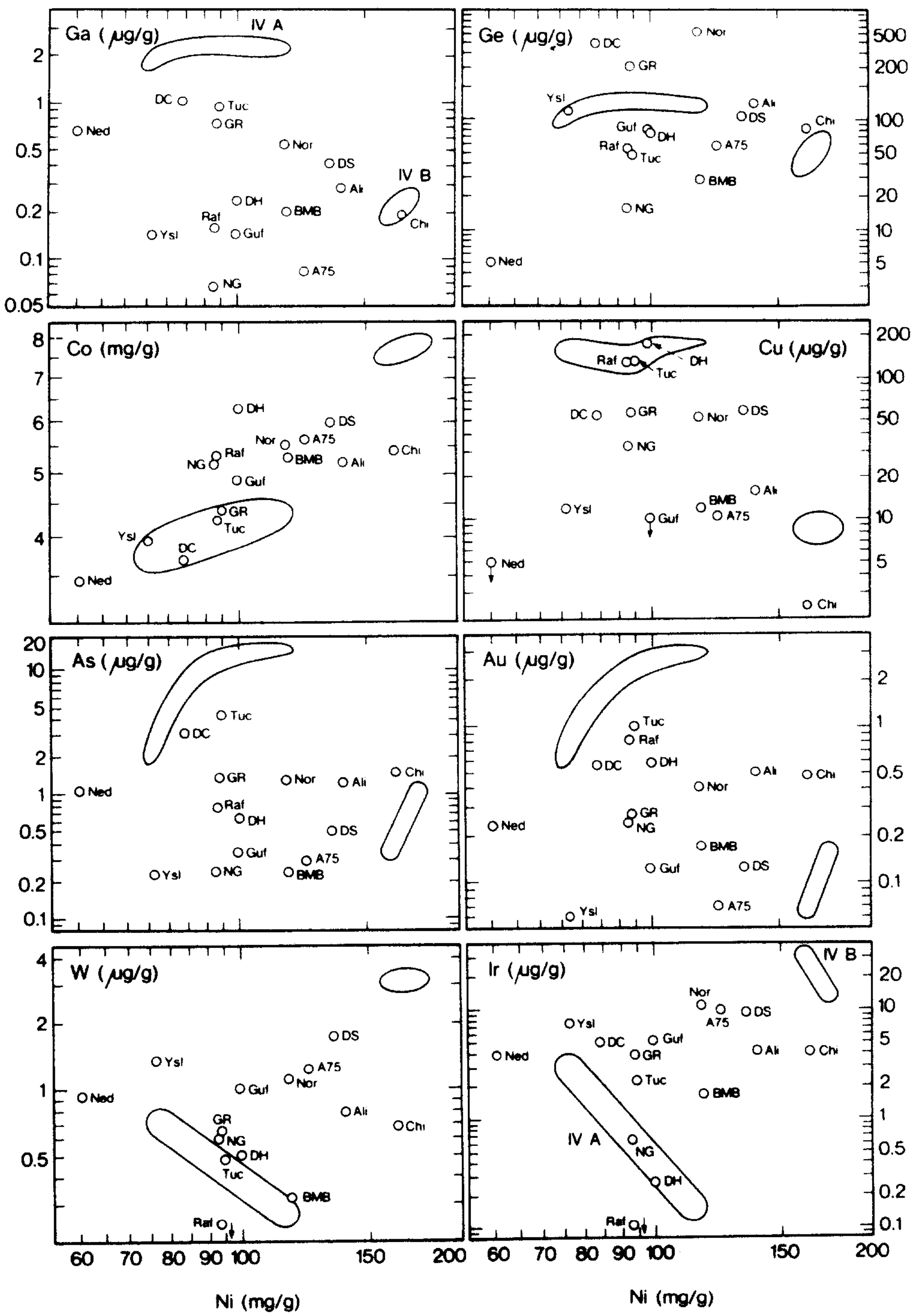

FIG. 3. Compositional space near groups IVA and IVB is populated by a number of ungrouped irons. Three are newly analyzed: Glen Rose (GR), Alikatnima (Ali) and Allan Hills A77255 (A75). Glen Rose is closely related to Denver City (DC), another iron from Texas. Alikatnima and A77255 are both related to Babb's Mill (Blake's) (BMB), and to a lesser degree, to Nordheim (Nor), Guffey (Guf) and Deep Springs (DS). The two irons of this ungrouped set having the lowest Ni contents Nedagolla (Ned) and Ysleta (Ysl) are not closely related to each other nor to any other irons. Other ungrouped irons in the set are Rafruti (Raf), N'Goureyma (NG), Tucson (Tuc), DeHoek (DH) and Chinga (Chi).

gree, Deep Springs and Guffey (Fig. 3). The Alikatnima fine matrix of duplex kamacite and taenite contains several parallel zones of shear deformation in which the fabric is warped and schreibersite bodies are fractured.

Allan Hills A77255 is an ataxite that is similar in structure to Nordheim (CLARKE, 1982a). The detailed composition of A77255 (Fig. 3) is similar to but distinct from Nordheim and is more closely related to the ungrouped ataxite Babb's Mill (Blake's) iron. As previously noted A77255 also shows affinities to Alikatnima and to a lesser degree, Deep Springs and Guffey. An intriguing feature of A77255 is a 5-mm round silicate inclusion (mineralogy not yet described) near the surface of the meteorite (CLARKE, 1982a).

Glen Rose is a finest octahedrite with a Ga concentration 3× lower and a Ge concentration 2× higher than those in IVA. It is closely related in composition to another iron from Texas, the Denver City meteorite (SCOTT *et al.*, 1977), but compositional differences are too great to indicate a paired fall. On several of the Fig. 3 diagrams these irons also plot near Guffey.

Paired meteorites

In Table 4 we list data on 3 sets of paired meteorites.

The Antarctic field surveys have recovered two sets of paired iron meteorites: the IA Allan Hills A76002 set (CLARKE *et al.*, 1980) and the IIAB Derrick Peak A78001-16 set (CLARKE, 1982a,b). Our analyses of all five of the Allan Hills set show only minor variability attributed entirely to uncertainty in analytical and sampling precision, consistent with a paired designation for these 5 irons. We have only analyzed one of the Derrick Peak set, D78009; data are listed in Tables 1 and 2.

The INAA data on the IIICD Dongling iron from the border beteween Guizhou and Guangxi Provinces, China, (Table 4) are virtually identical to those of Nantan (KRACHER *et al.*, 1980). Since Dongling was found only ~50 km from the location of the Nantan, Guangxi, shower it seems likely that these are paired and that Dongling was transported to the area where it was recovered.

The Lamesa, Texas, iron is very similar in composition to the IIICD Carlton meteorite. We are informed by the donor, J. DUPONT (private commun., 1983), that Lamesa has large troilite inclusions whereas Carlton does not. However, BUCHWALD (1975) reports that Carlton displays substantial mineralogical and textural variability and in one area resembles Pitts in being rich in troilite. There are no other known irons closely similar in composition to these two members of group IIICD. Even though their reported discovery locations are roughly 300 km apart, their similarity in composition and metallographic structure is so great that we recommend that they be paired.

REEXAMINATION OF UNGROUPED AND OTHER UNUSUAL IRONS

Of the 577 independent iron meteorites analyzed to date, roughly 14% do not belong to the chemical groups. It seems *a priori* likely that the ungrouped irons formed by the same processes that fractionated the grouped irons—processes occurring during the primary condensation of metal in the solar nebula and the secondary igneous processes of melting and crystallization which occurred on parent bodies (SCOTT, 1979). It seems likely that in most cases the small populations of the grouplets (1–4 closely related irons) simply reflect the fact that such materials are not currently in Earth-crossing orbits. The magnitude of their original populations in the early solar system cannot be inferred from the fraction among irons in our collections.

We analyzed numerous ungrouped irons by INAA in order to investigate the detailed compositional relationships among ungrouped irons and between these irons and the established chemical groups. The new trace element data are listed in Tables 5–9 along with the Ni, Ga, Ge, Ir and structural class from the original reports.

The anomalous hexahedrite Horse Creek and the anomalous stony-iron Mount Egerton are closely associated with the enstatite meteorites (WAI and WASSON, 1970; SCOTT and WASSON, 1976), chiefly on the basis of the similar Si and P contents of the metal and the presence of the silicide mineral perryite. As can be seen in Table 5, the composition of the metal phase of these two meteorites is similar to that of metal separated from EH and EL chondrites, and to bulk EH siderophiles (concentrations increased by a factor of 4 to facilitate comparison). The similarity to the EH metal is particularly striking for Co, Ni, As, W, Re, Ir (except for the anomalously low Ir in the Abee SKW metal nodule) and Au. The somewhat lower Cu, Ga and Ge contents either reflect volatilization loss (these are the three most volatile siderophiles) or distribution into phases that were not analyzed with the metal. The EL metal has a much lower Si content than Horse Creek and Mount Egerton. Its Cu is 2× lower, As and Au 1.1–1.2× lower and Ir about 2× higher. Although EL Ga and Ge contents are closer than those in EH to the Horse Creek and Mount Egerton compositions, on balance the relationship of the latter to the EH chondrites seems much stronger, in support of the conclusions of WAI and WASSON (1970).

Kendall County contains inclusions consisting of graphite and a highly reduced silicate assemblage (BUNCH *et al.*, 1970; PRINZ *et al.*, 1982b). Its Ga and Ge contents (Table 6) are in the IA range but its Ni content of 55 mg/g is about 10

Table 4. Data on several new irons that appeared to be paired with the IAB iron A76002 and the IIICD irons Nantan and Carlton.

	Cr µg/g	Co mg/g	Ni mg/g	Cu µg/g	Ga µg/g	Ge µg/g	As µg/g	Sb ng/g	W µg/g	Re ng/g	Ir µg/g	Au µg/g
A76002	--	4.57	70.0	144	92.4	423	11.0	249	1.37	300	2.40	1.50
A77250	28	4.46	69.0	158	88.0	410	11.2	308	1.83	290	2.50	1.45
A77263	29	4.47	67.0	143	98.0	--	11.9	--	1.51	320	2.53	1.57
A77289	37	4.49	67.0	141	101.0	--	12.5	--	1.66	280	2.65	1.58
A77290	--	4.40	69.0	164	92.0	--	11.3	--	1.55	300	2.48	1.46
Nantan	--	4.85	69.0	137	79.0	293	12.8	309	1.10	210	1.72	1.64
Dongling	48	4.60	71.7	156	82.6	--	12.7	400	1.30	--	1.56	1.62
Carlton	<15	5.62	135	271	11.4	8.6	24.0	770	<0.20	<90	0.055	1.87
Lamesa	10*	5.62	129	330	13.3	11.4	23.6	680	<0.20	<30	0.041	1.85

*Uncertainty ±2 mg/g

Table 5. Comparison of Horse Creek and Mount Egerton metal with metallic portions of EH and EL chondrites. Bulk EH data from Baedecker and Wasson (1974); SKW Abee data from Sears et al. (1982); RC data from Rambaldi and Cendales (1980).

	Co mg/g	Ni mg/g	Cu µg/g	Ga µg/g	Ge µg/g	As µg/g	W ng/g	Re ng/g	Ir µg/g	Au µg/g
Horse Creek	3.38	57.5	170	47.2	110	12.0	530	190	2.40	1.29
Mount Egerton	3.33	67.0	172	38.0	99	12.7	490	280	2.30	1.48
Bulk EH (X4)	3.44	68	770	78	168	15.2	550	208	2.12	1.36
Abee (SKW)	3.08	68.8	450	64.6	--	12.7	450	<380	0.95	1.40
Abee (RC)	3.66	71.0	244	71.0	198	14.5	664	187	2.43	1.35
Hvittis (RC)	3.77	65.0	97	57.0	125	11.1	612	273	2.97	1.10

mg/g lower than that at the edge of the IAB field. The additional elemental concentrations (Table 6) are in the range found in low-Ni, high-Ge IA members except that Cu (445 μg/g), is 2-3× higher than in IA. Three IA-related irons of higher Ni content that contain similarly high Cu abundances are Mertzon, Annaheim, and Harlowton. According to CLAYTON *et al.* (1983), a deviant O-isotope composition indicates that Kendall County is "probably not in the IAB group", in support of our interpretation of the compositional and structural data. A measure of the difference in O-isotope composition is $\Delta^{17}O = \delta^{17}O - 0.52 \cdot \delta^{18}O$. The mean $\Delta^{17}O$ for IAB is -0.46 ± 0.10‰ where the uncertainty is one sample standard deviation; $\Delta^{17}O$ for Kendall County is -0.30‰, only 1.6 standard deviations from the IAB mean.

Two meteorites were classified as anomalous members of group IIIAB because they plotted to the right of the Ir-Ni trend (WASSON, 1974). The INAA analyses for Delegate and Treysa (Table 6) show contents of W and Re higher than the IIIAB trend, similar to Ir. The Au and As contents plot near the element-Ni trends. The compositional data can be understood in terms of mixing models. If an early, high-Ir solid became detached from the roof and settled to the floor to accumulate with solids just crystallizing from the melt, a deviation qualitatively similar to those observed could be produced. But we are skeptical that early metal could have been dislodged and mixed together with later metal having a degree of crystallization 0.10–0.20 higher.

Picacho is the iron that fixes the low-Ni extreme of group IIIAB. According to SCOTT *et al.* (1973) it contains 70.8 mg/g Ni and 19 μg/g Ir. Because the low-Ni extreme of a magmatic group holds the key to the bulk composition of the group it appeared well to also determine our full suite of INAA elements in Picacho. These are listed in Table 6. All are consistent with Picacho lying at the low Ni extreme, but it has moved slightly closer to the remainder of IIIAB; we have revised Ni up to 72.5 mg/g and Ir down to 18 μg/g. This still levaes Picacho's Ir much higher than the second highest values of 14 μg/g reported in Davis Mountain, Kenton County, Costilla Peak and Verissimo.

COPPER AS A TAXONOMIC PARAMETER

Copper shares certain properties with Ga and Ge that make them excellent taxonomic parameters. Because the solid/liquid partition coefficient k_{Cu} is near unity, Cu displays a small range within most groups (less than a factor of 2) and, because of its high volatility, variations between groups can be large.

Because of the importance of Cu we reevaluated gamma-ray spectra from INAA runs by E. R. D. Scott during 1974 and 1975, and extracted Cu data from most of these. The experimental details and results are given in the Appendix. Figure 4 shows the Cu-Ni trends in 8 magmatic groups of iron meteorites based on these and literature data. The three largest magmatic groups IIAB, IIIAB and IVA are outlined, whereas individual points are shown for the small groups IC, IIC, IID, IIF and IIIF. The IIE, IIIE and IVB distributions are shown in Figs. 1, 5, and 3, respectively, and the nonmagmatic groups IAB and IIICD were illustrated in KRACHER *et al.* (1980). The range of Cu maximum values among magmatic groups extends from ~8 μg/g in IVB to 330 μg/g in IID and IIF. The total range in the highly populated group IIIAB is from 180 to 115 μg/g, a factor of 1.6; the range of Ge in IIIAB is comparable. The low slopes are consistent with the solid/liquid metal distribution coefficient near the value of 1.05 reported by WILLIS and GOLDSTEIN (1982).

Copper is a moderately volatile siderophile element, predicted to condense from a cooling solar nebula at a temperature intermediate to those of As and Ga

Table 6. Composition and structural data for IA-related Kendall County, 3 IIIAB and 3 low-Ge ungrouped irons.

	class	struc.	Cr µg/g	Co mg/g	Ni mg/g	Cu µg/g	Ga µg/g	Ge µg/g	As µg/g	W µg/g	Re ng/g	Ir µg/g	Au µg/g
Kendall County	ungr	anom	230*	3.96	54.5	445	73.1	355	11.0	1.09	296	1.9	1.44
Picacho	IIIAB	Om	136	4.88	72.5	183	18.9	33.9	3.04	1.63	2280	18	0.49
Delegate	IIIAB-an	Om	<50	5.38	95.0	120	20.3	41.7	16.8	0.68	190	1.6	1.76
Treysa	IIIAB-an	Om	<40	5.39	93±3	114	20.4	43.1	16.6	1.05	100	1.0	1.81
Nedagolla	ungr	anom	2200	3.44	60.2	<5*	0.66+	0.005+	1.06	0.94	510	4.6	0.235
Ysleta	ungr	anom	505	4.02	76.2	12*	0.14+	0.12*	0.23	1.40	700	7.6	0.063
Nordheim	ungr	D	230	5.54	116.4	53	0.55	0.64	1.30	1.12	1420	11	0.41

+uncertainty 1.1-1.5X normal.
*uncertainty 1.6-2.8X normal.

Table 7. Concentrations of 11 elements in 4 IIIE irons and in Murfreesboro.

	Struc.	Cr µg/g	Co mg/g	Ni mg/g	Cu µg/g	Ga µg/g	Ge µg/g	As µg/g	W µg/g	Re ng/g	Ir µg/g	Au µg/g
Armanty	Om	30	5.10	96±3	123	16.9	31.3	15.4	0.42	<150	0.22	1.90
Burlington	Om	410	4.84	82.4	140	16.9	34.9	5.40	1.11	≤50	0.43	0.80
Paneth's Iron	Om	391	4.87	83.9	150	17.0	34.1	5.87	1.19	≤50	0.34	0.89
Cachiyuyal	Om	167	4.64	81.5	152	17.0	30.3	4.24	1.55	234	2.55	0.57
Murfreesboro	Om	159	4.72	78.1	151	17.3	30.2	3.11	1.59	152	1.75	0.53

(WAI and WASSON, 1977). The Cu/Ni ratio in the metal of iron meteorites is always lower than that in CI chondrites, even for groups such as IIAB and the low-Ni extreme of IAB that have roughly CI Ga/Ni and Ge/Ni ratios. WILLIS (1980) reports CI-normalized Cu/Ni ratios near 0.18 in groups IAB and IIAB. Curiously, the abundance ratio is also near 0.18 in IIIAB and IVA even though these groups have CI-normalized Ga/Ni ratios of 0.2 and 0.04, respectively. This coincidence among the 4 largest groups limits the usefulness of Cu as a taxonomic element for these groups.

In the magmatic groups the similar Cu/Ni ratios may have resulted from the fortuitous combination of two factors that have opposite effects: (1) the higher the volatile content of the parent body, the higher the Cu abundance in the entire core; and (2) the higher the volatile content of the parent body, the larger the fraction of Cu that was extracted into a hypothetical, early formed FeS-rich liquid that was not in equilibrium with the metal-rich liquid during the crystallization of the latter (KRACHER and WASSON, 1982). The very low Cu content of group IVB may reflect the isolation of the metal from the nebula prior to condensation of Cu (KELLY and LARIMER, 1977) or to severe planetary outgassing (RASMUSSEN *et al.*, 1984). As discussed later, ungrouped irons having Ga and Ge contents comparable to groups IVA and IVB show a wide range of Cu concentrations.

In iron meteorites Cu has high contents in troilite (Table 10; NICHIPORUK and CHODOS, 1959) and small schreibersite crystals (JOCHUM *et al.*, 1980); it (rarely) occurs as native copper in association with troilite (KRACHER *et al.*, 1977). In most meteorites these inclusions contain only a small fraction of the bulk Cu, and their avoidance during sampling cannot account in full for the depletion of Cu in iron meteorites. CLARKE and JAROSEWICH (1978) note that the Cu content of taenite is higher than that of kamacite, though they don't quote actual ratios.

The trends on Fig. 4 are negative with similar slopes with the exception of IIIF. As noted above, these negative slopes imply k_{Cu} values slightly greater than 1. The high positive slope in IIIF clearly implies processes other than a simple fractional crystallization. The contents of nonmetals such as C, P and S in IIIF are low, quite similar to those in IVA, thus there is no reason to expect k_{Cu} to be as low as 0.5, as implied by the slope. The nonmagmatic groups have positive Cu-Ni slopes, and we therefore examined the possibility that IIIF might be nonmagmatic by comparing its element-Ni trends with those in IAB and IIICD (WASSON *et al.*, 1980). In fact, the IIIF trends tend to be magmatic to an extreme degree. Whereas the element-Ni slopes for P, As and Au in IAB and IIICD are much lower than those in magmatic groups, those in IIIF are higher than in any other magmatic group.

An alternate if somewhat complex possibility is based on the above-mentioned suggestion of KRACHER and WASSON (1982) that several iron-meteorite parent bodies had layered liquid cores as a result of episodic melting. If a S-rich upper layer gradually mixed into the metal-rich lower layer, late-crystallizing irons could have high contents of those elements such as Cu that were preferentially extracted into the early S-rich melt.

Table 8. Elemental concentration data and structural class for re-analysed meteorites related to group IIICD. Meteorites arranged in order of increasing Ni.

	struc.	Co mg/g	Ni mg/g	Cu µg/g	Ga µg/g	Ge µg/g	As µg/g	W µg/g	Re ng/g	Ir ng/g	Au µg/g
Washington County	anom	5.15	99.5	139	17.0	20.5	7.3	0.37	<50	58	1.29
Ventura	Of	6.10	102	155	13.9	25.0	20.9	0.93	<100	152	2.16
Algoma	Om	5.52	106	264	20.3	38.3	25.4	<0.25	<150	360	2.40
Victoria West	Of	5.68	121	158	16.3	31.4	30.3	0.26	<70	22	3.00
Soroti	anom	6.22	130	327	12.0	5.23	22.6	<0.09	<29	<8	1.72
El Qoseir	D	6.49	138	326	6.50	11.7	6.5	1.41	615	5000	0.255
Mount Magnet	Opl	6.30	148	196	7.80	5.00	25.0	<0.05	<60	18	2.72
Gay Gulch+	Opl	6.90	151	235	6.68	10.7	21.1	0.34	<17	95	2.68
Linville*	anom	5.90	158	278	7.50	16.1	29.1	<0.12	<20	12	2.90
Garden Head+	Opl	6.27	170	426	10.7	16.6	23.8	0.18	<26	120	2.61
Kofa+	Opl	7.22	183	450	4.79	8.61	28.4	0.34	<16	98	2.96

* Analytical data from Kracher et al. (1980).
+ Means based on duplicate analyses; data for first sample reported by Kracher et al. (1980).

The elevated Cu contents of the high-Ni IVA irons Duel Hill (1854) and Fuzzy Creek (Fig. 2) could be explained in terms of the following models: (1) during the last stages of solidification of the IVA core D(Cu) drastically increased or decreased in value; or (2) Fuzzy Creek and Duel Hill were not fragments of the IVA core; or (3) Cu-rich materials were added to the liquid core during its last stages of crystallization. Because of the generally low concentrations of C, S and P, it seems doubtful that the metal/liquid distribution coefficient changed appreciably even during late stage crystallization. The only possible change would be a change in the mean k value resulting from the onset of crystallization of a second phase. Such a second phase was surely minor, thus it could only change the mean k if its k was very large, if the phase was included in analyzed sample, and then only for the first period immediately after the phase because stable, since subsequent melts would be highly depleted in Cu. The observation that Fuzzy Creek and Duel Hill (1854) are close to other IVA element-Ni trends leads us to reject the second model.

The most plausible model is the third. If the IVA core was layered, the low volatile abundance indicates that initial volume of the FeS-rich layer was small compared to the metal-rich layer, and thus its potential for contamination only became important at a late stage in the crystallization history. At that point incorporation of such an FeS- and Cu-rich liquid could have caused the observed 2-fold increase in Cu above the extrapolated values, and the enhanced S could have caused the enhanced k_{As} and k_{Au} values mentioned earlier.

The IIE Cu-Ni diagram (Fig. 1) is quite disorderly. If IIE is a magmatic group we would expect the orderly decreasing trends found in the larger groups (Fig. 4), and ranges by factors of $\sim$1.6 rather than $\sim$2.6 as observed here. Particularly strange is the high (416 g/g) Cu value in Barranca Blanca (Ni = 81 mg/g), but even if it is neglected, the trend is only a caricature of the downward sloping trends in other groups. It does not seem to be worthwhile to speculate on the reasons for this scatter until a thorough investigation of IIE has been completed, but the Cu and Co diagrams in Fig. 1 give reason to doubt that IIE as currently defined is entirely of magmatic origin.

COMPOSITIONAL COMPARISON OF GROUPS IIIE AND IIIAB

Group IIIE irons were distinguished from IIIAB by SCOTT *et al.* (1973) on the basis of their lower Ga/Ni and Ge/Ni ratios, their wider, swollen kamacite bands and the ubiquitous presence of haxonite, $(Fe, Ni)_{23}C$. In WILLIS' (1980) review of iron meteorite compositions he reported no evidence of compositional distinctions on element-Ni diagrams other than those based on Ga and Ge.

This research group has analyzed by INAA all the IIIE irons and numerous IIIAB irons during the past 9 years. In the present study we report in Tables 1 and 2 data on a new IIIE iron Paloduro, in Table 7

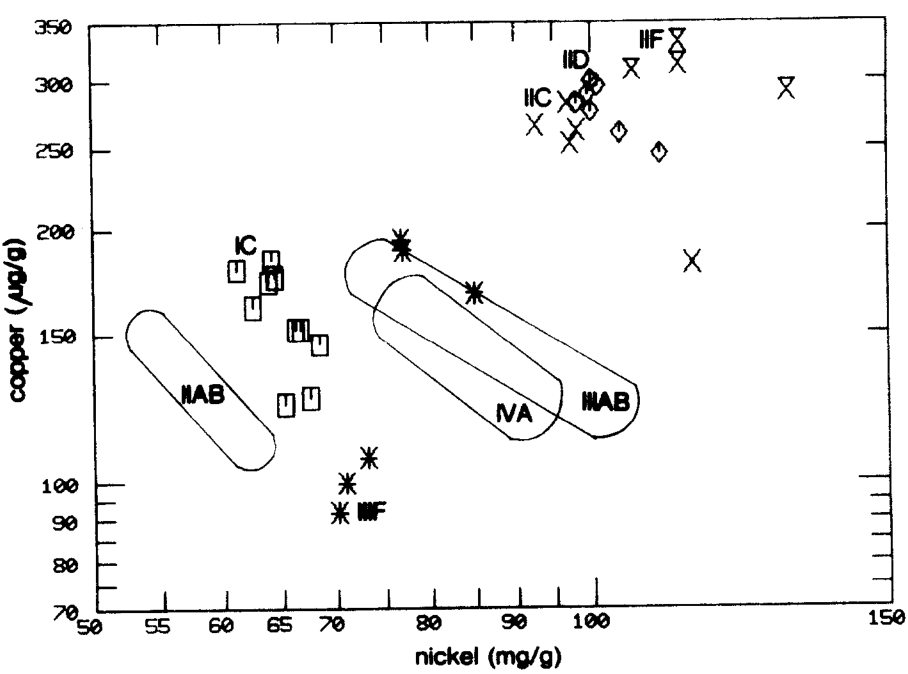

FIG. 4. Copper concentrations decrease with increasing Ni in most magmatic groups. The total range within groups is small (factor of $\sim$1.6) and the range between the maximum in group IIF (330 μg/g) and that in group IVB ($\sim$10 μg/g, not shown) is large, thus Cu possesses the characteristic desired of a taxonomic parameter. The trend in IIIF is positive, perhaps because there was a gradual influx of a Cu-rich and FeS-rich liquid into the IIIF magma.

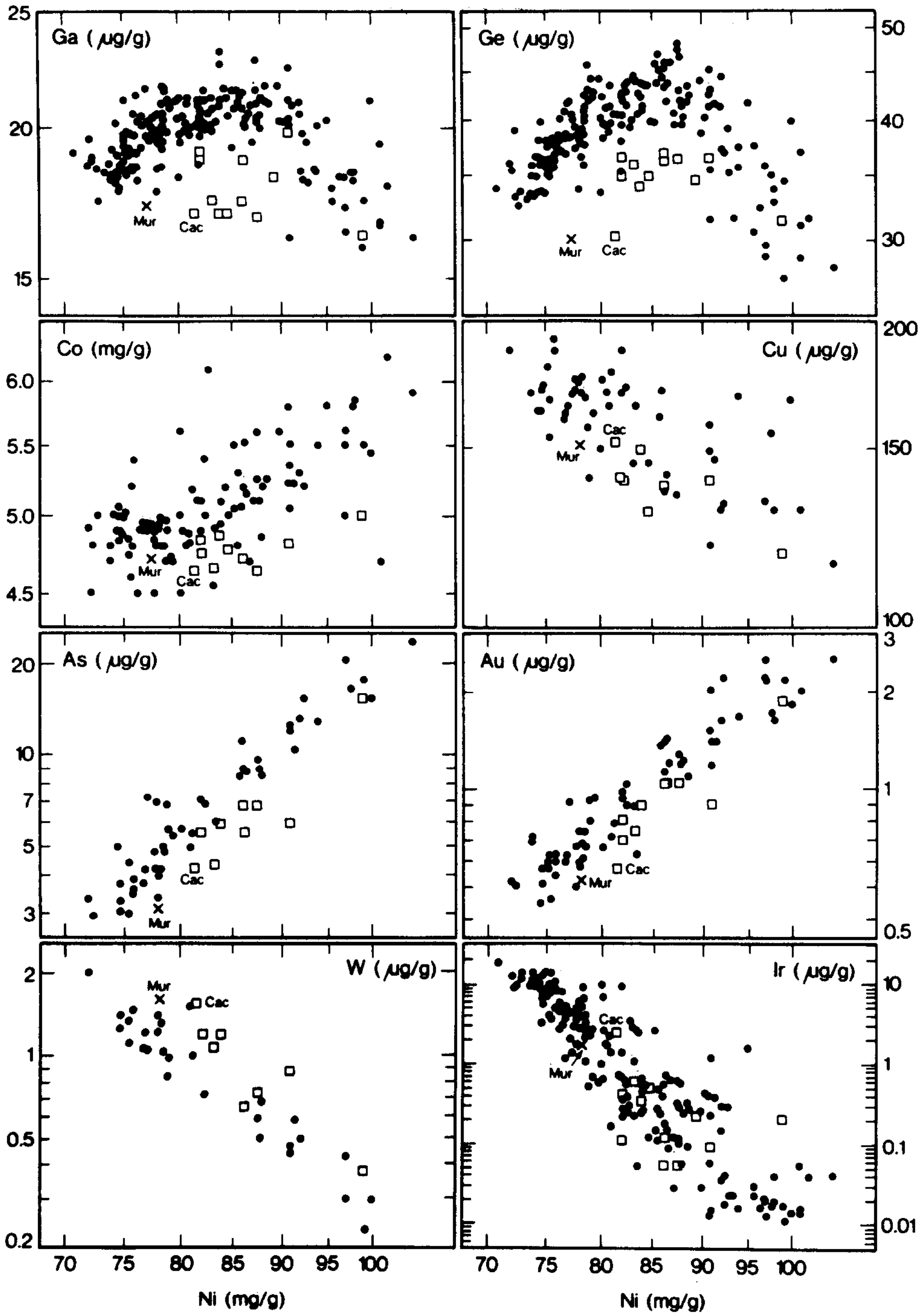

FIG. 5. The original compositional bases for resolving the minor group IIIE (filled circles) from the large group IIIAB (symbol %) were the lower Ga/Ni and Ge/Ni ratios in IIIE. These Co-, Cu-, As-, Au- and W-Ni diagrams show substantial resolution also in terms of these element pairs; only on the Ir-Ni diagram do IIE and IIIAB superpose. In this study we report the reclassification of two irons into IIIE; Cachiyuyal (Cac) is now the IIIE iron with lowest Ni content, Xinjiang (Xin) that with highest-Ni content. Murfreesboro (Mur) falls in the IIIE fields but is left ungrouped because it does not contain carbides.

additional data on Armanty (= Xinjiang), and Cachiyuyal, two irons recently reclassified into IIIE (bringing the total to 12), and new data on Paneth's iron and Burlington, two potentially paired IIIE irons. Also in Table 7 are data on Murfreesboro, which is compositionally closely related to IIIE but not included in the group.

When we constructed our usual 8 element-Ni diagrams (Fig. 5) we discovered that IIIE was clearly displaced to one side of the main IIIAB field for all ele-

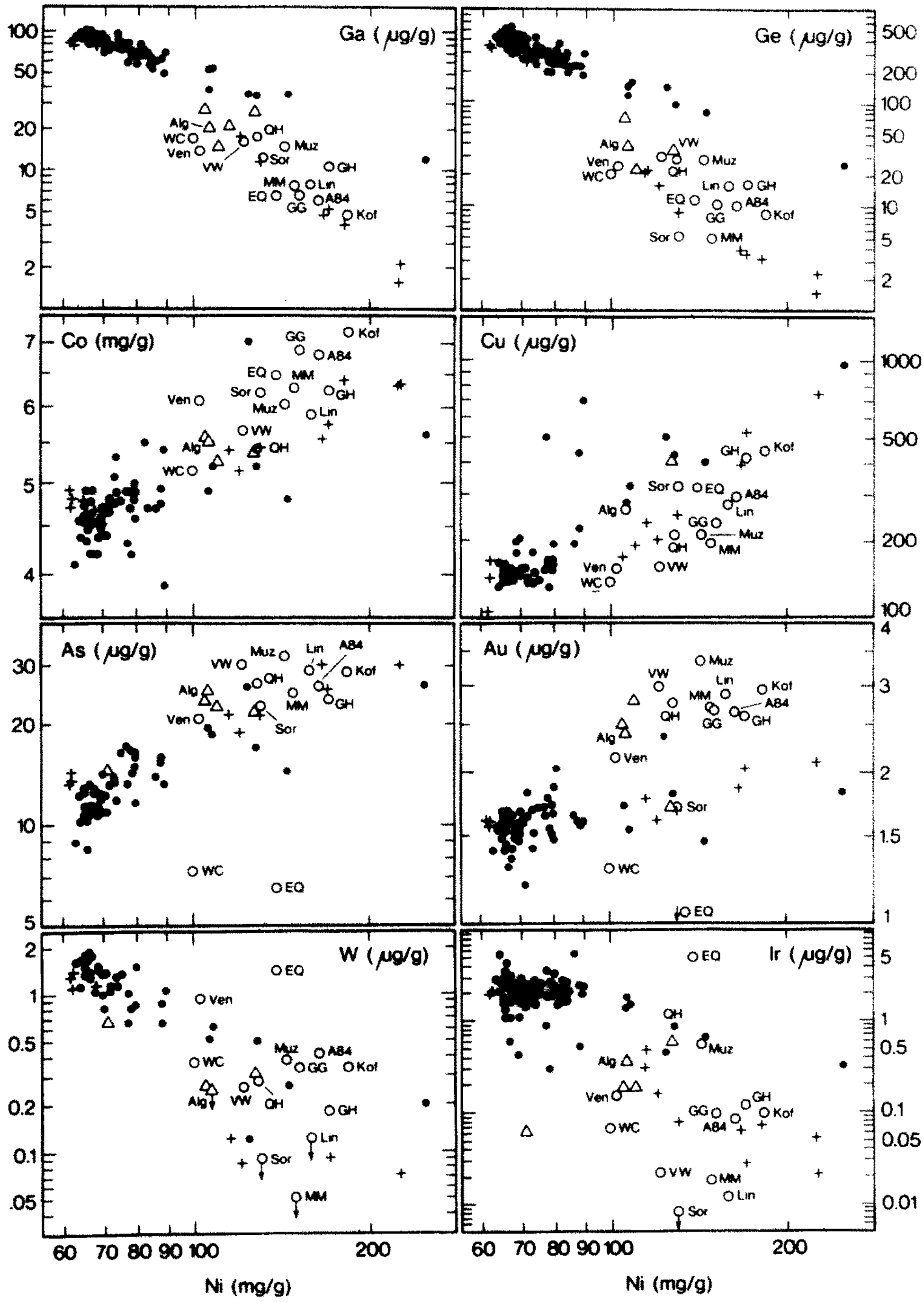

FIG. 6. Three newly classified irons fall in or near IIICD fields in the range 100 ≤ Ni ≤ 180 mg/g: Quarat al Hanish (QH), Muzaffarpur (Muz) and Allan Hills A80104 (A84). We also show the positions of Washington County (WC), Ventura (Ven), Algoma (Alg), Victoria West (VW), Soroti (Sor), El Qoseir (EQ) and Mount Magnet (MM), and analyzed IAB and IIICD irons. Quarat al Hanish is in IIICD fields of all diagrams except Au- and Ir-Ni, and is designated IIICD-an. A80104 is very similar to Gay Gulch (GG), and these two together with Garden Head (GH) and Kofa (Kof) form a compact grouplet. Muzaffarpur is never far from this quartet, but not close enough to make the quartet a group. On all diagrams Algoma falls near IIICD Hassi-Jekna (105 mg/g Ni). These two and Magnesia (110 mg/g Ni) have Au contents about 1.5 times higher than expected of IIICD irons, and we (re)designate them IIICD-an. The other ungrouped irons are not closely related to IAB, IIICD or each other.

ments except Ir. On four of these diagrams (Co, As, Au and W) the IIIE field lies to the high-Ni side of IIIAB, suggesting a mechanism involving dilution of IIIAB-like material by Ni, but on the Cu diagram the IIIE points fall on the low-Ni side of IIIAB, thus the differences seem best explained the conventional way—differences in initial magma composition combined with small differences in distribution coefficients. A simple description of the differences between IIIE and IIIAB is that if one fits lines or curves to the IIIAB fields, all Fig. 6 diagrams except that involving Ir would show IIIE irons plotting to one side of the curve. The data in Fig. 5 still include some scatter resulting from controllable factors such as slightly miscalibrated standards, and we are confident that these groups can be still better resolved with greater analytical effort.

The giant Armanty iron (= Xinjiang), at 30 t the third largest meteorite in the world, has been reanalyzed and is reclassified as a member of group IIIE. Turnings of Xinjiang analysed by KRACHER *et al.* (1980) led to a classification of IIIAB. Our current study is based on a large sample suitable for microscopic examination and more precise chemical analysis. The bandwidth is 1.2–1.3 mm, compared to ~1.0 mm in IIIB irons having similar Ni contents. Both haxonite and graphite are observed in plessite. The Ni content of 96 mg/g is the highest known in IIIE. The Ir content of 0.22 μg/g is about 20× higher than expected, but this deviation is not greater than that observed in the IIIAB irons Delegate and Treysa (see above).

Until this study all known IIIE irons had Ir contents lower than 0.7 μg/g. For a fractionally crystallized core with near-chondritic bulk siderophile abundances one expects to find low-Ni material with Ir contents of 4 μg/g (the concentration in low-Ni IVA irons) to 60 μg/g (the value at the IIAB extreme). It follows that the low Ni, high Ir members of IIIE had not been identified, and we reanalysed two meteorites as potential candidates. Cachiyuyal and Murfreesboro have Ga and Ge contents intermediate to IIIE and IIIAB. BUCHWALD (1975) considered these two irons possibly related. Cachiyuyal contains inclusions of graphite from the decomposition of haxonite and its bandwidth of 1.3 mm is greater than those of typical IIIAB irons having similar Ni contents (BUCHWALD, 1975); both properties suggest a relation to group IIIE. Murfreesboro has a bandwidth of only 0.95 mm and carbides have not been reported, yet it is nearly identical in composition to Cachiyuyal (Table 8). Both irons fit all IIIE trends; their positions are indicated in Fig. 6. We reclassify Cachiyuyal from ungrouped to IIIE. Because it lacks C and swollen kamacite, we continue to designate Murfreesboro ungrouped.

Paneth's Iron and Burlington are two members of IIIE for which little is known about the history and distribution of material (BUCHWALD, 1975); SCOTT and WASSON (1976) suggested these two irons might be paired. We gathered INAA data to examine this possibility (Table 8). The two are indeed very similar in composition, more similar than any other pair of IIIE irons, especially since the new Ni values are much nearer than the atomic absorption results published earlier. However, there appears to be a systematic difference between them consistent with Paneth's Iron forming later than Burlington in the crystallization sequence: Ir and Cr are lower, Ni, As and Au are higher in Paneth's Iron. The chief exceptions are Cu and W, which are higher in Paneth's Iron despite k_X values > 1. We now consider it unlikely that the two are paired, but the differences are too small to rule out this possibility.

IRONS COMPOSITIONALLY RELATED TO IIICD

Three of our newly analyzed high-Ni irons, Allan Hills A80104, Muzaffarpur and Quarat al Hanish fell in or near IIICD fields on many element-Ni diagrams. This stimulated us to gather INAA data on several previously classified irons having 100 ≤ Ni ≤ 180 mg/g and Ga and Ge contents in the general IIICD ranges. Data for 11 such irons are listed in Table 8. The data are means of duplicate analyses except Soroti for which only one analysis has been completed. These data supplant values based on the first analysis of Garden Head, Gay Gulch and Kofa reported by KRACHER *et al.* (1980); the Linville data are repeated from that paper.

The locations of the 3 new and 11 previously studied irons are plotted on 8 log-log element-Ni diagrams in Fig. 6 together with the available data for members of groups IAB and IIICD. As noted by KRACHER *et al.* (1980) and WASSON *et al.* (1980), at the low-Ni extremes these two groups converge on all diagrams with the possible exception of As, but in the Ni range here discussed they are well resolved on the Ga-, Ge-, W- and Ir-Ni diagrams and partially resolved on most of the other diagrams.

Based on the Ga- and Ge-Ni diagrams all 14 irons show more affinity to IIICD than IAB; on the Ir-Ni diagrams only El Qoseir, and Quarat al Hanish are above the IIICD field; El Qoseir is far above the IAB field as well. On the Co-Ni diagram the IIICD field is slightly higher than the IAB field, and the 14 irons in this set are all in or slightly above the IIICD field. On the Cu-Ni diagram the IIICD field is slightly below the IAB field, and the 14 irons plot in or below the IIICD field. The IIICD field is above that of IAB in the As-Ni diagram and 12 irons fall in or above the IIICD field; Washington County and El Qoseir are low by a large factor of 3–5.

The most interesting Fig. 6 diagram is Au-Ni, which fails to resolve IIICD and IAB. On this diagram 11 of the 14 irons form a new field about 1.5× higher than most IIICD irons; they are joined by two irons previously classified IIICD, Hassi-Jekna and Magnesia, the points at 105 and 110 mg/g Ni. Washington County and El Qosier fall well below the IAB–IIICD field; Soroti is in the midst of the field. On the W-Ni diagram the IIICD field is lower than the IAB field but only Ventura and El Qoseir plot above IAB and Muzaffarpur, Gay Gulch, A80104, Garden Head and Kofa fall in the IAB field. Unfortunately, only W upper limits are available for 4 of the irons.

We draw the following classificational conclusions based on these observations. Based on the extreme Au, As, W and Ir values El Qoseir and Washington County,[1] a unique, solar-

[1] Washington County has a structure indicating strong reheating and metamorphism; some P-rich striations may indicate shear and deformation (BUCHWALD, 1975). BECKER and PEPIN (1984) suggest that the high trapped rare-gas contents were incorporated during accretion. We are skeptical about this process, since there is no independent evidence that accretion could produce such large masses of silicate-free metal. We find it much more likely that the Washington County precursor material was originally produced by melting and separation of metal from silicates. It later incorporated solar-wind while exposed in a (metallic) parent-body regolith, and the bulk rare gas distribution was established by an impact that produced the shear, deformation and incipient melting followed by rapid cooling.

rare-gas-rich (FISHER and SCHAEFFER, 1960; BECKER and PEPIN, 1984) iron, are not closely related to IAB, IIICD or any of the other irons included in this set. At the other extreme, the Garden Head quartet (GH, Gay Gulch, A80104 and Kofa) sticks together on all diagrams; given one more closely related iron we would distinguish them as a new group. They show no evidence of an inverse relationship between Au and Ir, thus we tentatively infer that they did not form by fractional crystallization. We suggest that the locus of related irons on these diagrams might be near lines connecting the quartet with the low-Ni extremes of IAB or IIICD, similar to the trends in these groups. The iron that is most consistently near such loci is Muzaffarpur, but its separation on the Au and As plots seems too great to allow it to be chosen as a fifth member to define the group.

In an earlier section we classified Quarat al Hanish IIICD-an, anomalous because of its high Au and slightly elevated As and Ir contents. The one iron that falls directly in the IIICD Au-Ni field is Soroti, but it is slightly outside the IIICD field on the Ge- and Co-Ni diagrams, and with its Ir concentration now revised down >8×, it is now well outside the IIICD Ir-Ni trend.

Algoma is remarkably similar to Hassi-Jekna; their only appreciable difference is for Cu which is 1.5× higher in Hassi-Jekna. Because of the anomalous Au contents of these irons and Magnesia we hold it best designate all of them IIICD-an.

The remaining four irons are excluded from IIICD on the following bases: Linville, Ge high, Au high, Ir low; Mount Magnet, Co high, Cu low, Au high, W low, Ir low; Ventura, Ga low, Co high, Au high, W high; Victoria West, Cu low, As high, Au high, Ir low.

POSSIBLE RELATIONSHIP BETWEEN IIAB AND THE BELLSBANK TRIO

The trio of meteorites Bellsbank, La Primitiva, and Tombigbee River are similar meteorites which form a grouplet of Ni-poor and P-rich irons (WASSON and KIMBERLIN, 1967; SCOTT *et al.*, 1973). Their structural classes and compositions are listed in Table 9. The bulk Ni contents of these irons approach 60 mg/g when the amount of Ni in schreibersite (100–150 mg/g) is added to the kamacite content. The concentrations of most elements listed in Table 6 are probably reasonably representative of the bulk. Although JOCHUM *et al.* (1980) found large enrichments of Cu and other trace elements in phosphides separated from several iron meteorites, data on La Primitiva schreibersite (E.R.D. SCOTT, unpub.) shows schreibersite/metal weight ratios ≤ 0.75 for Co, Cu, Ga, As, Ir and Au. From the low Ir, and high Au and As contents of these irons we infer that they resulted from a large degree of solid/liquid fractionation, and that the degree of crystallization increases through the sequence Bellsbank-Tombigbee-La Primitiva.

Concentrations of several elements in the Bellsbank trio (all listed elements except Co, Ni and Ir) are in the general range expected if IIB trends are extrapolated to a higher degree of crystallization, as can be seen by comparison of the data listed in Table 9 for Jerslev, Derrick Peak A78009 and São Julião. On the other hand, the Co, Ni and Ir data are sufficient to rule out a simple model involving formation by a higher degree of fractional crystallization even if expected minor-element effects on distribution coefficients are included (WILLIS and GOLDSTEIN, 1982; JONES and DRAKE, 1983).

The very high bulk P contents suggest an alternative link to IIB. It is improbable that so much P could have dissolved in Fe-Ni during equilibrium crystallization since k_P values are ≤0.28 at S contents in the mother liquor up to 185 mg/g; the only higher value was 0.67 at 214 mg/g S (JONES and DRAKE, 1983). If we assume that k_P was ≤0.3, incorporation of 20 mg/g P by equilibrium crystallization would require ≳65 mg/g P in the liquid, a remarkably high though not necessarily impossible P content. Sulfur is 50× more abundant than P in chrondritic matter, and even after extraction of an early S-rich liquid from the IIAB mantle (KRACHER and WASSON, 1982), the S content of the residual core liquid should have been much higher than that of P. According to SCHURMANN and NEUBERT (1980) and JONES and DRAKE (1982), P contents ≥ 30 mg/g should lead to the formation of immiscible P-rich and S-rich liquids. According to BUCHWALD (1966), the morphology of the large hieroglyphic schreibersites indicates crystallization directly from the liquid phase. CLARKE and GOLDSTEIN (1978) argue for an origin by solid-state precipitation, but we discuss below our reasons for doubting this interpretation.

JONES and DRAKE (1983) measured the composition of one pair of immiscible liquids, and found that the combined Fe and Ni content of the S-rich liquid was 698 mg/g, that of the P-rich liquid 885 mg/g; it follows

Table 9. Concentrations of 10 elements in the Bellsbank trio, and in three IIB irons that might be from the same core.

	Struct.	P* mg/g	Co mg/g	Ni mg/g	Ni blk* mg/g	Cu µg/g	Ga µg/g	Ge µg/g	As µg/g	Ir ng/g	Au µg/g
Jerslev+	Ogg	7	4.80	56.6	59	125	58.0	168	6.9	190	0.83
Der Peak A78009	Ogg	-	4.62	65.4	-	117	55.1	135	9.6	14	1.20
São Julião+	Ogg	9	5.50	61.0	64	102	46.2	107	12.3	12	1.37
Bellsbank	H-Ogg	20	5.15	41.3	53	92	39.2	54.6	17.6	100	1.47
Tombigbee	H-Ogg	18	5.20	43.0	51	74	38.0	63.0	17.4	<20	1.42
La Primitiva#	H-Ogg	17	5.42	50.0	58	102	35.0	39.0	18.1	44	1.69

+ Unpublished data of J. Willis. # Unpublished data of E.R.D. Scott.

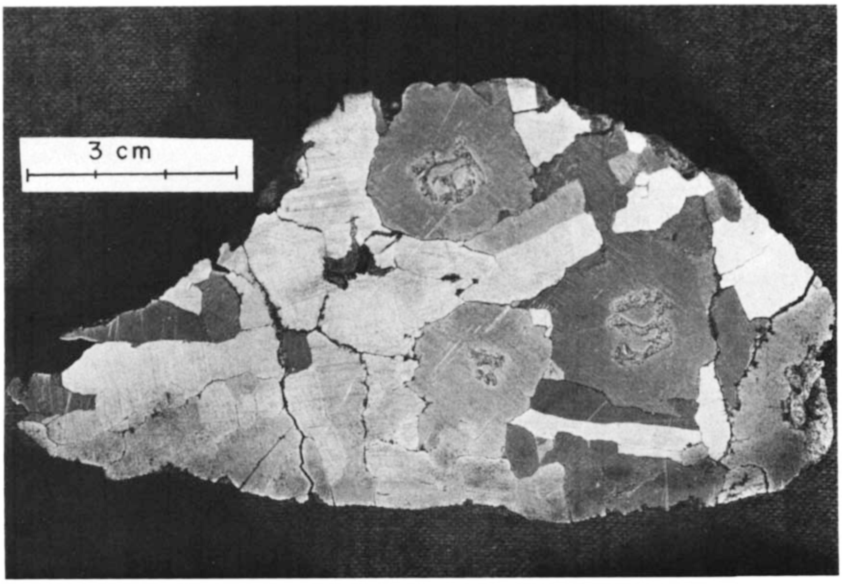

FIG. 7. Polished and etched section of the Santa Luzia IIB iron. We suggest that the 3½ round nodules consisting of exterior swathing kamacite and interior hieroglyphic schreibersite were produced by the crystallization of a trapped, P-rich, second immiscible liquid. (Smithsonian Institution photo).

that the P-rich melt was substantially denser, perhaps by about 1 g cm^{-3}. Because the concentration of S in cores were surely much higher than those of P, it seems probable that meteoritic S-rich melts were almost always less dense than P-rich melts and that, at the onset of immiscibility, the volume of any P-rich melt was much less than that of the coexisting S-rich melt.

What degree of crystallization yields a P content $\gtrsim$ 30 mg/g? The IIAB parent body had high volatile abundances and (based on the low initial Ni contents) was highly reduced. If we assume a CI-chondrite P/Ni mass ratio of 0.095, the inferred initial Ni concentration of 61.5 mg/g (WILLIS, 1980) yields an initial P content of only 5.84 mg/g. On the basis of the observed P contents in IIAB irons WILLIS (1980) independently inferred a P content of 6.0 mg/g. Thus if k_P were $\geq$0.1 at least 80% of the IIAB core crystallized before the P content was high enough to produce immiscibility. As we discussed elsewhere (*e.g.*, ESBENSEN *et al.*, 1982) most metal was probably deposited in the interior of crystallizing core, and the radius of this solid core was thus about 93% that of the entire core when immiscibility occurred. The surface of this inner core was probably quite irregular, and the dense P-rich liquid would have settled into the gravitational lows as it formed.

This leads to the intriguing hypothesis that the Bellsbank trio irons formed in these P-rich-liquid-filled lows during late stages in the solidification history of the IIAB parent body. We can imagine two ways in which these meteorites were produced: (1) schreibersite was already a liquidus phase, and schreibersite and metal crystallized simultaneously while the P-rich liquid remained in equilibrium with the S-rich liquid; or (2) P-rich liquid became isolated in interstices and crystallized as a closed system.

These lead to somewhat different predictions. In the first model, the P-rich liquid pockets were too small to evolve out of equilibrium with the main magma, thus the metal crystallizing was also in equilibrium with the S-rich liquid. The differences in Table 9 are not explained. In contrast, trapping of P-rich liquid followed by closed-system crystallization would lead to high P contents and, if the As and Au contents of the P-rich liquid were similar to or greater than those in the S-rich liquid, to higher As and Au contents as well. JONES and DRAKE (1983) reported that Au/Ni ratios were 2.5× greater in their P-rich liquid than in the S-rich liquid. If the Cu content of the P-rich liquid was lower than that in simultaneously crystallizing IIAB metal, this would account for the lower Cu values in the Bellsbank trio relative to IIAB.

CLARKE and GOLDSTEIN (1978) noted a structural similarity between Bellsbank and certain portions of the IIB iron Santa Luzia (Fig. 7) in which rounded areas of swathing kamacite 2–4 cm across enclose hieroglyphic schreibersite and minor troilite (we are indebted to R. S. Clarke for calling this to our attention). Clarke and Goldstein prefer the interpretation that the schreibersite formed by subsolidus precipitation, and state that "no need was found to invoke eutectic liquids to account for-the-massive schreibersite morphologies." We also agree that eutectic liquids were not involved, but find that the petrological evidence favors an origin as trapped liquid pockets. The regions are always round (Fig. 7), consistent with minimization of interfacial tension. The kamacite seems to have crystallized first, followed by the massive schreibersite and finally by the troilite. This is the expected sequence for a P-rich liquid having the composition observed by JONES and DRAKE (1983).

We thus suggest that these nodules in Santa Luzia formed by precisely the same process by which the Bellsbank trio formed. CLARKE and GOLDSTEIN (1978) report extensive phase composition data on the Santa Luzia nodules. The kamacite has consistently low Ni contents ranging from 23 to 53 mg/g and averaging about 45 mg/g, similar to the Ni contents in the kamacite of the Bellsbank trio; the Ni content of the kamacite in the surrounding coarsest octahedrite region averages about 70 mg/g. Obviously diffusional transport has not been sufficient to equilibrate these different kinds of kamacite. The Ni contents of massive schreibersites in two Santa Luzia nodules is 160–179 mg/g, whereas that of the one massive schreibersite studied in Bellsbank is only 124 mg/g. This difference does not fit the simple picture, but may only indicate some minor diffusional mixing of Ni into the small Santa Luzia nodules, less into the hypothetical Bellsbank trio regions having linear dimension > 10× greater.

An obvious test of our model is to determine key elements like Cu, As and Au in Santa Luzia nodules and in the surrounding coarsest octahedrite regions and compare the trends to those observed in the data tabulated in Table 9.

A possible test of this hypothesis might be based on cosmic-ray ages, which should be generally similar in the Bellsbank trio and in IIB irons. Unfortunately we find ages only for the IIB irons Sikhote-Alin (355 Ma) and the Ainsworth-Ponca-Creek pair (~1000 Ma) (VOSHAGE, 1967).

The experiment of JONES and DRAKE (1983) yielded a Ni/Fe ratio in the P-rich liquid 1.6× higher than that in the S-rich liquid, suggesting 90–100 mg/g Ni in the bulk P-rich liquid. There is probably no way to rationalize such a high Ni content in the Bellsbank parental liquid, but these could be higher than the Table 5 values if there was incomplete preservation of associated schreibersite during fragmentation in space and during atmospheric passage. If the schreibersite content were about 50% larger than estimated by BUCHWALD (1975) the Ni concentrations would be in the 62–68 mg/g range characteristic of the high-Ni portion of IIB.

We tentatively leave the Bellsbank trio irons ungrouped. If future research confirms the link to IIAB we will redesignate them IIB-an.

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APPENDIX: EXTRACTION OF INAA COPPER DATA

During 1974 and 1975 E. R. D. Scott initiated the application of INAA to iron meteorites in our laboratory. During these two years he analyzed two or more replicate samples of about 150 irons and pallasites. Copper was not determined, and no Cu flux monitor was included in the reactor runs. A run typically included about 16 samples.

We have reexamined Scott's gamma-ray spectra and discovered peaks for the ^{64}Cu 1346-keV gamma line and the 511-keV line produced by positron annihilation. We now claim treasure hunter's rights on these data. The counting rate of the annihilation line was typically about 160× greater than that of the gamma line. Although the annihilation line has the same energy for positrons from all sources (including pair creation by high energy gammas), in these iron-meteorite spectra comparison with the 1346-keV line showed that the fraction of the 511-keV counts resulting from ^{64}Cu decay was $\gtrsim$95% for Cu contents $\geq$ 50 μg/g. Because of its higher intensity, the 511-keV line yielded more precise data for most samples. In those cases where the Cu content based on the 511-keV line was appreciably ($\gtrsim$10%) higher than that based on the 1346 gamma line, the reported value is based on the latter. If the 1346-keV line could not be resolved data are reported as upper limits.

Since flux monitors were not available, we used meteorites for which reasonably precise Cu analytical data were available as flux monitors. Especially important was Canyon Diablo, which Scott analyzed in 12 separate runs. WILLIS (1980) reviewed published sources of iron meteorite data, and concluded that the data of MOORE *et al.* (1969), SMALES *et al.* (1967), COBB (1967), EASTON *et al.* (1978) and his own unpublished INAA data were all of good quality, though he recommended increasing the Smales *et al.* data by a factor of 1.15. Several of these well-analyzed irons were among the 150 irons, and could be used as primary standards. More important, data from previous studies demonstrated that the trends in the large groups IIAB, IIIAB and IVA and in the IA portion of IAB showed little scatter about Cu-Ni and Cu-Ir trend lines, lending confidence in our ability to estimate the Cu contents of members of these groups from their Ni and Ir contents. Such estimated Cu contents were used as secondary standards.

One or more of these primary or secondary standards was present in each INAA run. If more than one was present, one was chosen as the flux monitor for the initial calculation for that run, and the other standards were used as controls. We then adjusted the entire run independently for each of the two photon energies to roughly maximize the agreement of the calculated Cu contents with those expected in all the standards.

The replicates were determined in a series of interlocking runs, which offered an additional control. After the initial tabulation, additional 5-10% upward or downward adjustments on individual runs were made to maximize agreement of replicates within the limits allowed by statistical uncertainties and anticipated sampling scatter of the reference samples.

Copper data for 128 iron meteorites, pallasites and separated phases are listed in Table 10. After adjustments most duplicates agreed to within 14%, implying relative 70% confidence limits on the mean of ~6%. In 27 samples (data entries marked by asterisks) the duplicate differed by ~15-29%, implying relative 70% confidence limits of ~10%. A similar uncertainty applies to 11 samples analyzed only one time. We do not report data for two meteorites (Elton and Admire) that showed still larger differences between replicates. Based on good agreement with data from other reliable sources any systematic error in these data appears to be ≤5% relative.

As can be seen for the numerous upper limits reported for irons with low volatile contents, the minimum Cu content determinable from these data is about 10 μg/g. With the improved detectors now available and with improved counting strategy the current limit is 5-7 μg/g.

We were surprised that the Cu replicates agreed so well. This indicates that none of the minor phases occasionally analyzed together with the metal contain extremely high Cu phase/metal ratios. This is verified by our data on separated phases. The Cu content of Mundrabilla troilite is 2.4× that of the metal, small enough to cause negligible enhancements in most of our metal samples. The Cu content of La Primitiva schreibersite is only 0.75 that of the metal. This value will yield no appreciable enhancements or depressions. The higher schreibersite/metal ratios of 2-4 found in most small (rhabditic) schreibersites by JOCHUM *et al.* (1980) would lead to positive errors ≤5% in most of our samples.

Table 10. Concentration of Cu (in μg/g) in 104 irons, 21 pallasites and 3 separated phases analyzed by Scott. Long meteorite names are abbreviated or truncated after 15 spaces.

Anoka	202	La Primitiva	102+
Arispe	124	La P. (schreib)	75*
Arltunga	282	Livingston	242
Babbs's M. (B1)	12*	Lonaconing	158
Ballinger	142	Marjalahti	126
Bear Lodge	156	Matatiele	151
Bendego	173	Mount Dooling	162
Benedict	162	Mount Stirling	136
Bennett County	141	Mount Vernon	305
Bitburg	504	Mundrabilla	153
Bluewater	151	Mundrab. (troi)	372+
Brahin	155	Mungindi	236*
Brenham	185	Murnpeowie	184
Brenham (oliv)	<18+	Needles	238
Buenaventura	130	Nelson County	92
Butler	153	Newport	256
Cabin Creek	216*	Netschaevo	255
Campo del Cielo	138	N'Goureyma	48
Canyon Diablo	154	N'Kandhla	290
Cape of Good Ho	<8	Nocoleche	176
Carbo	301	Oakley	107
Carver	142	Osseo	164*
Chihuahua City	152*	Paneth's Iron	151
Chinga	14*	Pavlodar	117
Chupaderos	148	Persimmon Creek	402
Cincinnati	162*	Phillips County	207+
Clark County	100*	Pitts	431*
Coahuila	160	Pittsburg	102
Cold Bay	311*	Port Orford	295+
Colomera	181	Rafruti	130
Colonia Obrerra	130*	Rawlinna	298+
Corrizatillo	166*	Redfields	112
Cranbourne	141	Rembang	124
Dayton	524*	St. Francois Co.	126*
De Hoek	268	St. Genevieve Co	195
Deep Springs	<5	San Cristobal	968
Denver City	55*	Santa Rosa	152
Dora	253	Santa Rosalia	224+
Duel Hill (1873)	160	Santiago Papasq	126
Eagle Station	442*	Sao Joan Nepomu	156
Elga	173	Seneca Township	134
Ellicott (b)	158*	Seymchan	145
El Mirage	141	Shingle Springs	<13
El Sampal	135*	Sikhote-Alin	113
Esquel	113	Skookum	<9
Etosha	146*	South Bend	157
Finmarken	196	Springwater	210*
Fort Pierre	163	Steinbach	200
Freda	740*	Tacoma	138
Glorieta Mt.	256	Tlacotepec	<8
Guffey	<10	Tobychan	183
Hayden Creek	194*	Tocapilla	134
Hassi-Jekna	172	Tucson	132
Henbury	181	Uegit	180*
Hill City	125	Union County	179
Huckitta	91	Wallapai	246
Imilac	158	Waterville	166
Iron Creek	162	Weaver Mountain	<8
Kallijarv	178	Weekeroo Statio	224
Kifkakhsyagan	175+	Wiley	182
Kinsella	140	Willow Creek	141
Klamath Falls	168	Woodbine	280*
Kodaikanal	195*	York (iron)	163+
Krasnojarsk	75	Zacatecas (1792)	128

* High relative uncertainty (about ±10 %) on these samples. + Single analysis only.