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Relationship between iron-meteorite composition and size: Compositional distribution of irons from North Africa

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Abstract

During the past three decades many iron meteorites have been collected from the deserts of North Africa. Almost all are now characterized, and the distribution among classes is found to be very different from those that were in museums prior to the collection of meteorites from hot and cold (Antarctica) deserts. Similar to the iron meteorites from Antarctica, the irons from Northwest Africa include a high fraction of ungrouped irons and of minor subgroups of group IAB. The different distribution is attributed to the small median size of the desert meteorites (~1.3 kg in North African irons, ~30 kg in non-desert irons). It appears that a sizable fraction of these small (several centimeter) masses constitute melt pockets produced by impacts in chondritic regoliths; they were never part of a large (meter-to-kilometer) magma bodies. As a result, a meter-size fragment ejected from the regolith of the asteroid may contain several of these small metallic masses. It may be that such stochastic sampling effects enhanced the fraction of IAB-sHL irons among the irons from Northwest Africa.

The variety observed in small meteoroids is also enhanced because (relative to large) small fragments are more efficiently ejected from asteroids and because the orbital parameters of small meteoroids are more strongly affected by collisions and drag effects, they evolve to have Earth-crossing perihelia more rapidly than large meteoroids; as a result, the set of small meteoroids tends to sample a larger number of parent asteroids than does the set of larger meteoroids.

1. INTRODUCTION

Since 1970 a large number of meteorites have been collected from desert locales, the cold deserts of Antarctica and hot deserts on several continents. Most of the meteorites now in museums and other meteorite collections were found in deserts.

Wasson (1990) pointed out that, whereas 85% of the set of ~600 iron meteorites collected prior to ~1980 were members of groups with the remaining 15% ungrouped, 39% of the then-known 31 Antarctic irons are ungrouped. He noted that the only physical property that distinguishes the two sets is size (represented by mass); the median mass of Antarctic irons is 300–400 g, about 80–100 times smaller than the mean mass of non-Antarctic irons. He proposed that, because of their higher ejection velocities from craters, small meteoroids are transferred from asteroids to Earth more efficiently than large meteoroids, and, as a result, that smaller meteorites represent a larger number of asteroids than larger meteorites.

Now, two decades later, a similar set of new irons has been recovered from hot desert regions (mainly the Sahara) of North Africa. These irons are also small, but somewhat larger than the Antarctic irons; the median mass is about 1300 g.

The classification of ungrouped irons has changed since the 1990 paper. A number of the meteorites that were designated ungrouped in 1990 are now recognized to be members of the IAB complex, a set of largely metallic (but frequently silicate-bearing) meteorites that seems to largely represent small to miniscule magma bodies produced by impacts on carbonaceous-chondrite parent asteroids (Wasson and Kallemeyn, 2002).

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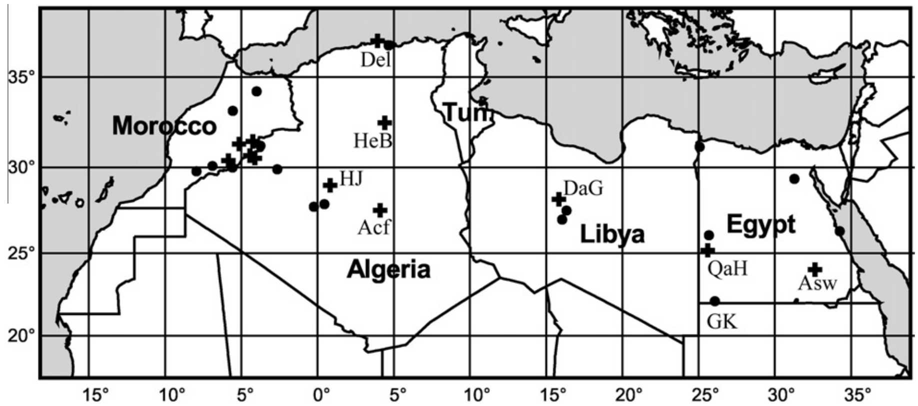

Fig. 1. Map of North Africa showing recovery locations of iron meteorites. No irons are known to have been recovered between 15 and 22° N latitude. Crosses show the location of irons that belong to the IAB complex; dots represent irons not part of this complex. The dense cluster of irons on the border between Morocco and Algeria shows the main recovery locations of NWA irons. Locality abbreviations: Acf. Acfer; Asw, Aswan; DaG, Dar al Gani; Del, Dellys; HeB, Haniet el Beguel; HJ, Hassi Jekna; GK, Gebel Kamil; QaH, Quarat al Hanish.

It therefore seemed worthwhile to carefully classify the irons from North Africa using traditional information sources (elemental composition, metallographic structure and, where available, isotopic composition) and to compare their statistical distribution with that of irons from Antarctica.

2. THE SAMPLE SET: THE IRON METEORITE GEOGRAPHY OF NORTH AFRICA

Fig. 1 is a map of North Africa prepared by J. N. Grossman; symbols show the locations where meteorites

Table 1
Name, classification, structure, mass and probable pairing of 63 classified North African iron meteorites (50 well-classified + 12 paired with these + one IIIAB lacking detailed data).

Meteorite	Group	strctr	ma (g)	Paired with	Meteorite	Group	strctr	ma (g)	Paired with
Acfer 234	IAB-ungr	Off	621		NWA 3201	IIAB	Ogg	1896	Foum Zguid
Aswan	IAB-ungr	Om	12000		NWA 3202	IIAB	H	395	
Dar al Gani 406	IAB-sLL	Og	5100		NWA 3204	IAB-sHL	Opl	762	
Dar al Gani 413	IIAB	H	156		NWA 3205	IAB-ungr	Off	1374	
Dellys	IAB-sLM	Om	76		NWA 3206	IAB-sLH	D	174	
Djebel In-Azzene	IIIAB	Om	12500		NWA 3208	IIIAB	Om	159	
Dor el Gani	IIIAB	Om	2580	Ni data only	NWA 4233	IAB-sLM	Of	444	
El Qoseir	ungr	D	2505		NWA 4700	IAB-sLL	Om	3080	Zagora
Foum Zguid	IIAB	Ogg	6000	(Primary)	NWA 4701	IAB-sHH	D	1276	
Hassi-Jekna	IAB-sHL	Of	1250	(Primary)	NWA 4702	ungr	D	123	
Gebel Kamil	ungr	D	>1 t		NWA 4703	IAB-sLL	Om	114	Zagora
Haniet-el-Beguel	IAB-MG	Og	2000		NWA 4704	IIIAB	Om	277	
Kharga	IVA	Of	1040		NWA 4705	ungr	Opl	195	
NEA 0002	IID	Of	5480		NWA 4706	IAB-sHL	Of	227	Hassi Jekna
NWA 0176	ungr	anom	2000	Primary	NWA 4707	IIIAB	Om	585	
NWA 0468	IAB-ungr	anom	6100		NWA 4708	IIIAB	Om	9625	NWA 1430
NWA 0854	IAB-MG	Og	45000	(Primary)	NWA 4709	IAB-MG	Og	82	NWA 0854
NWA 0859	ungr	Opl	75300		NWA 4710	IAB-sHL	Of	2340	Hassi Jekna
NWA 0860	IIIAB	Om	32000		NWA 4711	IAB-sHL	Om	394	NWA 2151
NWA 0959	IVA	Of	415		NWA 4713	IAB-sLM	D	154	
NWA 0968	IAB-sLM	Off	20	NWA 2680	NWA 5289	IVA	Of	296	
NWA 1430	IIIAB	Om	113000	(Primary)	NWA 5549	IAB-MG	Og	>12000	
NWA 1611	IAB-MG	Og	6000		NWA 5608	IIE	anom	41	
NWA 2151	IAB-sHL	Om	417	(Primary)	NWA 6259	ungr	D	1805	
NWA 2311	IAB-sLL	Om	1435		NWA 6279	IIAB	Ogg	11445	Foum Zguid
NWA 2428	IAB-sHL	Opl	1650		Quarat al Hanish	1AB-sHL	Of	593	
NWA 2677	IAB-sLM	Of	100		Sahara 03505	ungr	IIE	65	
NWA 2678	IIAB	D	381		Tagounite	IIIAB	Om	3300	
NWA 2679	IAB-sHL	Off	412		Tamentit	IIIAB	Om	510000	
NWA 2680	IAB-sLM	Off	12050	(Primary)	Zagora	IAB-sLL	Om	50000	(Primary)
NWA 2743	IC	Og	5463		Zerhamra	IIIAB	Om	630000	
NWA 3200	IAB-sHL	Of	512	Hassi Jekna					

have been recovered (or, in some cases, the city where the irons were purchased by dealers or collectors). The map extends down the 18° N latitude; no iron meteorites are known for the latitude band between 22° and 15° N latitude.

During the past three decades a remarkably large number of meteorites has been recovered in Morocco and Algeria and a handful from Libya and Egypt. Most of these changed hands several times before they became available for scientific study, with the result that detailed provenance information is not available. During 1980s several of them were given place names based on available information but, with the exception of a few recovered by search parties, there is much uncertainty regarding the actual recovery localities.

Because of these provenance uncertainties the Nomenclature Committee of the Meteoritical Society has chosen to designate nearly all the currently recovered meteorites with the name Northwest Africa xxxx where the numbers currently being assigned comprise four-digits starting with 6. Many of the recovered meteorites are paired, i.e., they are fragments from the same shower as another NWA meteorite with a lower number. Most recovered meteorites are chondrites with the fraction of differentiated meteorites around 10% and only a minor fraction of these are irons.

Five African countries border the Mediterranean Sea. Iron meteorites are known in four (all except Tunisia). The cluster of points on the border between Morocco and Algeria consists of NWA irons; it appears that a large fraction of these came into the possession of dealers and collectors through transactions completed in the city of Erfoud, Morocco, which is located within this cluster.

My UCLA associates and I have now analyzed most of the irons from North Africa. In this paper I discuss 63 North African irons of which 56 were analyzed in the UCLA lab and 7 in other labs. From this set of 63, 12 irons appear to be paired, i.e., to be parts of the same shower as one of the independent irons. I also studied the metal of one North African mesosiderite.

Table 1 lists the names, classifications and masses of the samples in alphabetical order. The paired irons discussed in the Appendix are listed in the fourth and the rightmost column of Table 1. The longest known (lowest numbered) member of the paired set is, with one exception, listed as the primary and the name of that iron is listed for the other irons with which it is paired. The exception is the tiny (20-g) NWA 0968; because it is so small, the much larger (12 kg) NWA 2680 was chosen as the primary.

3. NEUTRON ACTIVATION TECHNIQUES

The UCLA team currently determines up to 15 elements (14 plus Fe) in metal by instrumental neutron-activation analysis (INAA) in replicate analyses; data for Fe are used for internal normalization (Wasson et al., 2007; Wasson and Choe, 2009). With INAA our team can measure Cr, Fe, Co, Ni, Cu, Ga, As, Ir and Au in all iron meteorites. As discussed in Wasson and Choe (2009), our team achieves very high precision for Co, Fe, Ga and Au (95% relative confidence limits on means (of duplicate analyses) of 1.5–3%) and high precision (4–6% confidence limits) on Ni, As and Ir. The analytical precision for Cr is high (~5%) but sampling errors can be large and there is a minor interference from the $^{54}Fe(n,\alpha)^{51}Cr$ reaction that adds about 6 μg/g apparent Cr to our values (which are not corrected). For the remaining elements (Ge, Ru, Sb, W, Re, Os and Pt) concentrations in a minor fraction of the irons are below our detection limits. We achieve confidence limits of 7–10% for concentrations higher than the following values (in μg/g): Ge, 150; Ru, 5, Sb, 0.20, W, 0.3, Re, 0.10, Os, 1.0 and Pt, 2.

A key aspect of our present techniques is that the samples and standards are of uniform size and shape to the degree that this is practical, thus minimizing geometric effects on the gamma-ray spectra. Because our goal is to obtain metal compositions, we avoid non-metallic inclusions and multiply all values by a factor required to force the contents of Fe and Ni to total 990 mg/g. In rare cases a secondary correction is required to account for Fe present in sulfide, silicates or phosphides. Most meteorites are analyzed twice to improve the precision. More details are given in Wasson et al. (2007) and Wasson et al. (1989).

The fact that many of the IAB irons have large sulfide or phosphide inclusions or are silicate-rich (with silicate clasts occupying from 15% to 45% of their volumes) introduces sampling errors into metal analyses. There is frequently a thick layer of swathing kamacite next to inclusions or silicates thus the kamacite/taenite ratio can show considerable variation in our 500-mg samples. Because Ni is 6–9 times more abundant in taenite than kamacite, such variations reduce the precision of our Ni analyses. An example is Ni in Zagora where the analysis of two additional samples led to a reduction in our mean Ni concentration from 98 to 93 mg/g.

Table 2 gives mean compositions for the North African irons; irons are ordered by classification (group) and, within groups, based on increasing Au. Data are also listed for the metal fraction of a mesosiderite. Listed in italics at the bottom of Table 2 are data for 7 North African irons extracted from various issues of the Meteoritical Bulletin Database, (2010) (henceforth abbreviated MBDB, 2010) and RNAA data for Haniet-el-Beguel from Scott and Wasson (1976). For the three irons DaG (Dar al Gani) 406, DaG 413 and Djebel in-Azzene I requested and received some supplementary data from the analyst, Bernhard Spettel.

To reduce the length of the text in the remainder of this paper I will generally drop the NWA from the names of NWA xxxx irons. (The reader should recognize that, for the numbers 0999 and below the official name does not include the first zero; 0468 is NWA 468.)

4. CLASSIFICATION AND PAIRINGS OF IRON METEORITES IN THE IAB COMPLEX

4.1. Review of IAB taxonomy

Wasson and Kallemeyn (2002) reexamined and improved the available neutron-activation data for non-magmatic group IAB and closely related groups and grouplets and made a major revision of the classification scheme. They suggested that meteorites that belong to the

Table 2
Data for 14 elements in 53 iron meteorites and metal from one mesosiderite from North Africa analyzed in the UCLA neutron activation laboratory. Meteorites are listed in order of class and in order of Au content within classes. Listed in italics at the bottom of the table are incomplete data for 8 additional iron meteorites. Data for 7 analyzed in other laboratories were extracted from the MBDB (2010); those for Haniet-el-Beguel are RNAA data from our lab.

Meteorite	Cr μg/g	Co mg/g	Ni mg/g	Cu μg/g	Ga μg/g	Ge μg/g	As μg/g	Ru μg/g	Sb ng/g	W μg/g	Re ng/g	Ir μg/g	Pt μg/g	Au μg/g	Class
NWA 0854	30	4.54	67.5	140	89.1	400	10.7		180	1.20	210	2.07	6.9	1.461	IAB-MG
NWA 1611	23	4.68	67.4	140	84.9	303	13.5		254	1.09	168	1.81	5.4	1.547	IAB-MG
NWA 4709	27	4.65	69.1	162	90.1	475	11.2	8.2	346	1.25	191	2.13	7.1	1.517	IAB-MG
NWA 5549	191	4.55	68.8	129	81.6	370	11.9	7.3	268	0.96	399	4.08	7.1	1.488	IAB-MG
NWA 3206	12	5.97	195.2	589	3.50	<80	28.5	3.2	711	0.05	<30	0.049	0.9	1.804	IAB-sLH
NWA 2311	17	4.87	97.8	421	61.8	206	15.9	4.7	672	0.68	163	1.64	4.2	1.778	IAB-sLL
NWA 4700	16	5.00	80.0	155	75.4	300	17.0	0.8	449	0.87	230	2.75	6.1	1.839	IAB-sLL
NWA 4703	16	4.79	85.2	187	76.9	269	16.6	5.5	404	0.86	255	2.78	5.3	1.815	IAB-sLL
Zagora	64	4.83	92.6	267	70.1	226	15.6		350	0.88	267	2.88	6.3	1.768	IAB-sLL
NWA 0968	63	5.45	132.5	481	26.8	<200	21.9		872	0.15	156	1.96	4.4	1.719	IAB-sLMa
NWA 2677	15	5.66	141.9	244	11.4	<50	22.3		570		<20	0.061		1.606	IAB-sLMa
NWA 2680	92	5.36	136.6	548	24.3	<140	19.4	2.8	908	0.33	176	2.04	5.1	1.728	IAB-sLMa
NWA 4713	24	5.30	144.5	593	33.6	<80	19.2	1.7	900	0.22	56	0.909	2.2	1.629	IAB-sLMa
NWA 4701	14	6.07	169.3	337	8.80	<80	34.1	0.9	514	<0.06	<50	0.019	<2.0	3.201	IAB-sHH
Hassi-Jekna	17	5.53	106.4	177	24.1	70	26.6		322	0.21	<20	0.229	1.5	2.400	IAB-sHL
NWA 2151	15	5.46	104.2	178	18.1	<70	21.3	3.1	216	0.51	55	0.598	4.8	2.441	IAB-sHL
NWA 2428	22	5.58	117.7	200	16.8		28.3	1.6	180	0.17	109	1.09	2.5	2.646	IAB-sHL
NWA 2679	20	5.59	111.8	82	12.9	<60	32.3	<1.5	<200	0.22	<20	0.174	1.9	3.276	IAB-sHL
NWA 3200	15	5.53	106.7	168	21.8	<80	24.7	1.3	222	0.29	<50	0.193	1.9	2.350	IAB-sHL
NWA 4706[*]	15	5.49	107.8	192	22.0	67	23.5	1.1	242	0.26	<30	0.194	2.4	2.344	IAB-sHL
Quarat al Hanish	34	5.51	127.5	212	16.7	30	26.7		316	0.27	100	0.856		2.780	IAB-sHL
NWA 3204	13	5.85	114.8	178	34.7	170	25.6	2.7	360	0.25	<20	0.147	3.7	2.762	IAB-sHLa
Acfer 234	78	4.48	87.3	345	21.2	~100	12.7	7.9	220	1.01	540	5.01	9.6	1.280	IAB-ungr
Aswan	18	5.92	82.0	122	20.8	42	16.6			1.66	<50	0.249	12.1	1.670	IAB-ungr
Dellys	11	5.37	90.7	125	21.1	<50	14.2	3.4	630	0.46	33	0.406	5.9	1.612	IAB-ungr
NWA 0468	1200	7.19	118.5	263	31.0	117	22.8		431	0.65	281	2.75	4.0	2.214	IAB-ungr
NWA 3205	19	8.09	117.1	197	33.3	52	16.9	17.4	<150	1.41	1260	14.8	21.9	1.794	IAB-ungr
NWA 2743	53	4.76	67.5	137	52.6	195	8.28		<150	0.88	20	0.127	5.4	0.971	IC
Foum Zguid	22	4.97	58.1	113	55.5	153	9.91		<200	0.72	<40	0.021	5.3	1.078	IIAB
NWA 2678	106	4.47	54.5	134	58.0	~160	3.83	27.0	<150	3.17	2369	25.7	30.6	0.527	IIAB
NWA 3201	14	5.11	52.1	118	51.6		11.1	2.4	<150	0.54	<30	0.017	3.7	1.089	IIAB
NWA 3202	138	4.51	56.1	131	58.9	162	4.14	24.3	<150	2.82	853	11.4	28.4	0.570	IIAB
NWA 6279	22	4.86	64.7	117	54.9	163	9.67	3.9	<150	0.56	<20	0.016	3.7	1.095	IIAB
NEA 0002	132	6.58	102.2	259	70.6	~100	4.25	20.3	<150	3.01	2150	22.6	22.4	0.556	IID
NWA 5608	315	4.75	85.4	248	28.3	92	13.1	8.2	114	1.04	415	3.77	9.0	1.322	IIE
NWA 0860	37	5.22	83.6	151	20.5	<50	7.88		<100	0.63	<60	0.404	6.3	1.064	IIIAB
NWA 1430	38	5.06	77.4	187	19.2	<60	4.55		<150	1.14	312	3.89	13.0	0.675	IIIAB
NWA 3208	203	4.95	75.8	164	17.7	<50	3.25	17.7	<150	1.34	2174	18.9	16.5	0.478	IIIAB
NWA 4707	35	5.18	81.8	163	22.1	<70	6.71	7.9	<150	0.71	47	0.748	7.6	0.874	IIIAB
NWA 4708	56	5.07	78.9	210	20.0	<80	4.88		<120	1.08	285	3.86	12.6	0.679	IIIAB
Tagounite	74	4.97	80.1	177	20.7	42	4.37		34	1.22	421	5.28	12.2	0.623	IIIAB
Tamentit	31	5.18	85.2	144	20.8	43	8.29		<120	0.75	203	2.50	8.0	1.039	IIIAB

Zerhamra	65	4.95	78.8	175	19.2	34	4.47			1.22	900	8.87	13.4	0.622	IIIAB
NWA 4704	39	4.89	89.0	154	17.5	<60	4.73	4.9	<150	0.79	<50	0.149	5.7	0.863	IIIE
Kharga	21	4.37	117.7	200	1.63	<50	15.1	1.6	<150	0.25	<20	0.222	2.8	2.708	IVA
NWA 0959	49	4.27	94.8	128	1.81	<50	14.8		<100	0.22	43	0.346	3.4	2.628	IVA
NWA 2676	412	4.67	83.9	176	12.4	<100	9.71	9.6	<150	0.97	474	4.34	15.6	1.036	Mes
El Qoseir	24	6.56	135.0	873	6.19	12	6.59			1.40	550	4.71		0.271	ungr
Gebel Kamil	32	7.43	207.7	486	49.3	123	13.6	3.1	280	0.43	34	1.45	4.1	1.536	ungr
NWA 0176	430	4.14	86.0	300	18.7	137	9.42		100	1.16	355	3.62	8.5	0.862	ungr
NWA 0859	12	12.93	163.4	291	87.2	2290	53.7		369	6.72	305	2.42	38.0	6.480	ungr
NWA 4702	208	4.37	54.3	115	44.6	110	6.00	5.4	<150	0.92	<50	0.093	6.4	0.704	ungr
NWA 4705	34	13.19	200.1	339	15.0	1300	32.8	75.6	<230	3.35	5073	58.9	83.0	3.246	ungr
NWA 6259	9	6.12	426	3400	5.80		37.9	4730				0.024	1.7	3.239	ungr
Dar al Gani 406		*4.39*	*67.1*		*91.2*	*305*						*2.68*		*1.760*	*IAB-sLL*
Dar al Gani 413		*4.17*	*54.7*		*61.7*							*4.74*		*0.555*	*IIAB*
Djebel In-Azzene		*5.00*	*103.0*		*18.0*	*33*						*0.018*		*2.290*	*IIIAB*
Dor el Gani			*70.5*												*IIIAB*
Haniet-el-Beguel			*83.0*		*67.4*	*271*						*2.40*			*IAB-MG*
NWA 4233		*4.82*	*123.0*		*26.8*	*45.0*	*13.5*					*1.38*		*1.74*	*IAB-sLM*
NWA 5289		*4.04*	*90.2*	*111*	*2.0*	*<1*	*12.0*			*0.36*	*0*	*0.80*	*3.8*	*2.33*	*IVA*
Sahara 03505		*4.14*	*90.2*	*341*	*21.2*	*32.5*						*3.55*	*0.78*	*1.00*	*IIE*

* NWA 4706 data are the mean of one analysis each of NWA 4706 and NWA 4710.

IAB complex can generally be distinguished by high concentrations of Au (>1.3 μg/g), As (>10 μg/g), Co (>3.9 μg/g) and Sb (>180 ng/g). They also required that the Ge/Ga mass ratio be in the range from 0.4 to 7. If massive silicates are present, these are generally roughly chondritic (=subchondritic). If the O-isotopic composition is determined from silicates or other oxides, $\Delta^{17}O$ is $<-0.35‰$ (and generally $\sim-0.5‰$).

Wasson and Kallemeyn (2002) noted that the compositional core of the original group IAB was quite compact on Ni–Au and several other element-Au diagrams and suggested that the compositional clusterings in this set of irons (called the main group of IAB and abbreviated IAB-MG) could be used as examples to assess whether other similarly compact compositional clusters were also groups or grouplets. The full set of closely related meteorites was designated the IAB complex. Based on O-isotopic and other data it is now widely accepted that these irons formed by melting carbonaceous chondritic materials, possibly with associated fractionation by processes such as volatile transport and/or crystal fractionation. The melting events must have been brief because chondritic inclusions did not appreciably differentiate (though some minor migration of low-melting liquids has occurred); impacts are the probable heat source. Internal heating (e.g., by ^{26}Al decay) would result in slow heating and ample time for phase separation.

Wasson and Kallemeyn (2002) found that the closely related group originally designated IIICD separated into two distinct fields on several diagrams (e.g., Ni–Au, As–Au, Co–Au) and showed that there was also relatively strong evidence for three additional compositional clusters of irons having compositional ranges similar to those in the main group, especially on Ni–Au diagrams.

These five additional sets of irons were designated IAB subgroups and given names based on their positions on Ni–Au diagrams. The three subgroups with mean Au contents similar to that of the main group were designated low-Au subgroups and these were then divided into high-Ni, medium-Ni and low-Ni subgroups. Capital letters L, M and H were incorporated into the abbreviations of the names of the subgroups. Thus the IAB subgroup containing the high-Ni part of the former IIICD set was now called the low-Au, high-Ni subgroup and abbreviated IAB-sLH. The subgroup formed from low-Ni members of the former IIICD are designated IAB-sLM. The positions of the fields for the main group and the five subgroups are shown on Ni–Au and Ga–Au diagrams in Fig. 2.

The sLM and sLH subgroups largely correspond to the old group IIICD and I cannot fully rule out the possibility that the small hiatus between these subgroups on compositional diagrams such as Ni–Au and Ga–Au reflect stochastic sampling and that they will be filled in as additional meteorites are analyzed. The relationship between the MG and sLL is even more intimate; there is no hiatus on most diagrams, just an offset in slope on the Ni–Au diagram that is reinforced on some other diagrams. The subgroups sHL and sHH are not yet well defined, a proper petrographic, metallographic and isotopic study remains for the future. There is no doubt that most are members of the IAB complex but the group fields overlap on several element-Au diagrams.

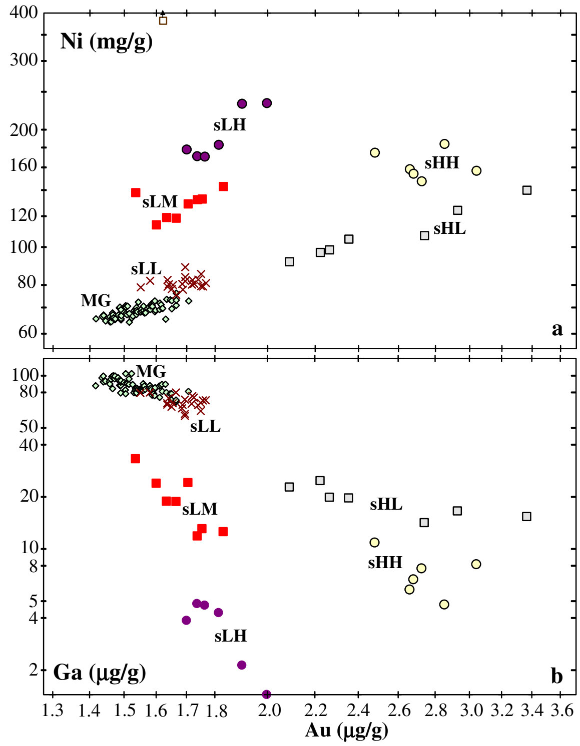

Fig. 2. Log element-log Au diagram for Ni and Ga showing locations of the IAB main group (MG) and for the five subgroups. Subgroups are named based on their Au and Ni contents; the subgroup with low Au and high Ni is designated IAB-sLH and here abbreviated to sLH. It is possible that pairs of the groups and subgroups are related: sLH with sLM, sLL with MG, and sHH with sHL.

When dealing with the compositional classification of iron meteorites it is a truism that, the more element concentrations you have and the greater the precision with which they are determined, the more accurate the classificational assignment. This is particularly true for the irons of the IAB complex. Because the elements behave differently in the magmatic groups compared to the IAB main group and subgroups, some elements are more valuable in the one than in the other category.

For example, Ir–Au diagrams can be used to infer degrees of crystallization or melt trapping (e.g., Wasson, 1999) in magmatic groups whereas the degree of systematic Ir variation among most members of the groups of the IAB complex is about the same as the degree of random (sampling) scatter. Arsenic, which correlates almost perfectly with Au across the various magmatic groups, can help resolve closely related IAB subgroups such as sLH and sLM. More details are given in the following discussion.

4.2. Classification of North African irons in the IAB complex

In Figs. 3 and 4 I illustrate element-Au trends in Northwest African irons belonging to the IAB complex. The data for independent North African irons are shown as small black-filled circles; seven (secondary) paired North African irons are shown as small circles with light interior shading near the filled circle for the primary. All other points are members of the IAB complex from the remainder of the world (almost all are taken from Wasson and Kallemeyn, 2002).

With a few exceptions, the irons are listed in Table 2 in order of discussion; within groups they are listed in order of increasing Au content. I will focus mainly on the six best taxonomic elements in our data set: Ni, Au, Co, Ga, As and Ir and thus on the element-Au diagrams in Figs. 3 and 4a. Of the remaining three elements plotted in Fig. 4, two (Ge and Sb) have low precisions because they are near our detection limits and a third, Cu, scatters because of sampling errors, probably reflecting the heterogeneous distribution of impact induced metallic Cu. These latter three elements will mainly be used to help decide ambiguous cases of pairing or group assignment.

Data are listed for four MG irons, two of which are paired (4709 with 0854, also know as Ziz). All four fall within the MG field on the Fig. 3 diagrams. Listed in the bottom section of Table 2 is Haniet-el-Beguel that has Ni, Ga, Ge and Ir contents (Scott and Wasson, 1976) suggesting that it is a member of the main group. The only sLH iron, NWA 3206, is in the center of all five sLH fields in Figs. 3 and 4a; it is compositionally very closely related to the sLH iron that has a slightly higher Au content, LEW 86540 (labeled on Fig. 3a).

NWA 2677 was analyzed first by A. Campbell (see MBDB, 2010) and reanalyzed at UCLA; the UCLA data (which differ to a minor degree from those of Campbell) plot on or near the preexisting sLM field on the five taxonomic diagrams. The structure (Fig. 5a) is typical of sLM irons.

There are four North African irons that plot with the sLM irons on some but not all of the Fig. 3 diagrams. The least deviant one is 4713, which is marginally outside the previously defined cluster on the Ni and Ir diagrams; it is however, an ataxite, whereas the other sLM irons are fine octahedrites. I designate it an anomalous member of sLM (IAB-sLM-an).

Data for the paired set 0968 with 2680 plot in or near the sLM fields on three diagrams, but because Ir contents of these irons are high by a factor of two compared to the highest sLM (Persimmon Creek, with 0.85 µg/g Ir) and because they have a peculiar structure (Fig. 5b) with abundant silicates and centimeter-size metal domains, each with a different orientation of the Widmanstätten pattern, it seems best to also call 2680 an anomalous member of sLM.

One iron not analyzed at UCLA is probably a member of sLM; NWA 4233 was analyzed by B. Spettel (MBDB, 2010). The structure of 4233 (Fig. 5c) is typical of irons in sLM.

Dellys falls in the sLM fields on the Co, Ga and Ir diagrams but not on Ni and As; I designate it IAB-ungr and list it with the other IAB-ungr in Table 2.

There are four sLL irons, three of which are paired (4700 and 4703 with Zagora). The fourth, 2311, is similar in composition with the exception of its low (factor of 2) Ir, a difference that allows membership in sLL but is too great to be consistent with pairing with Zagora.

There is one sHH iron (4701); in contrast, there are 10 members of sHL including four that are paired (3200,

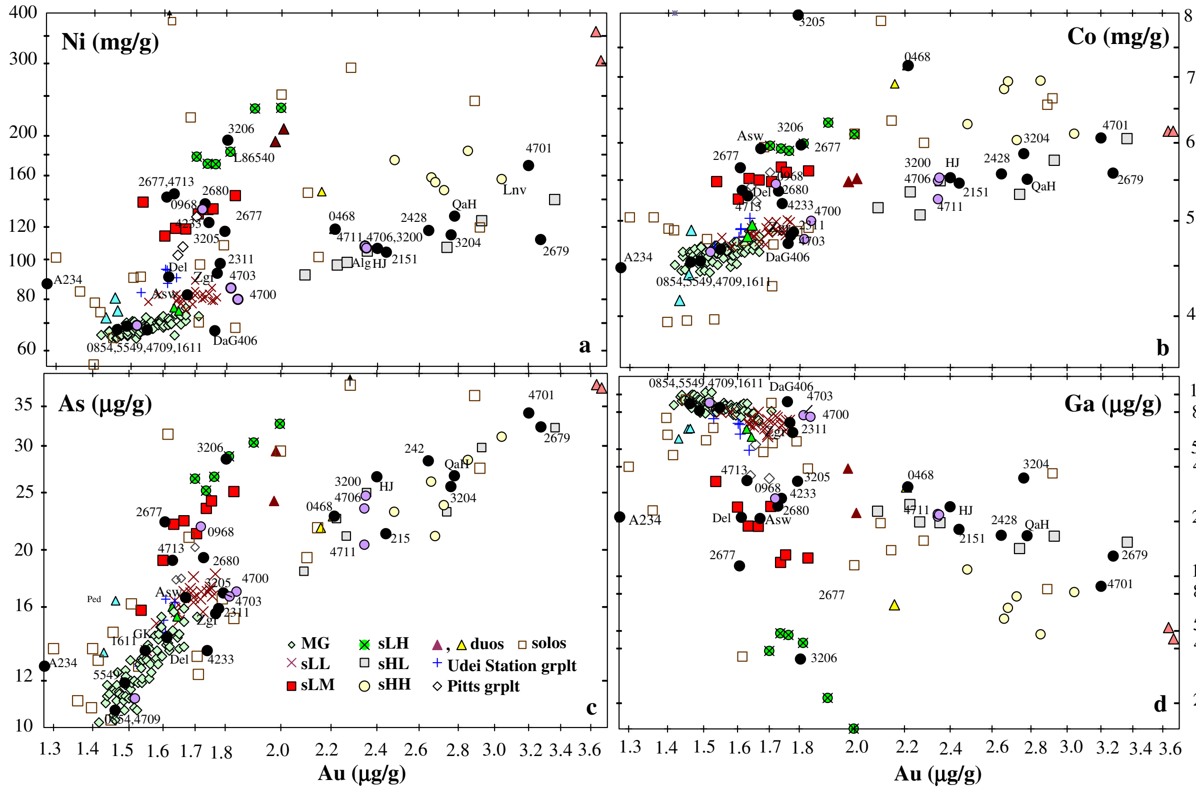

Fig. 3. Log element-log Au diagram for Ni, Co, As and Ga showing the positions of irons in the IAB complex. The first three are positively correlated with Au in the six groups whereas Ga is negatively correlated. Centroids of the groups reverse positions on the Ga–Au diagram compared to the other three diagrams. A moderate fraction of these irons are not members of groups, but are either members of related pairs (duos) or are not closely related to any other known iron. The North African members of the IAB complex are shown as black-filled circles with labels giving abbreviations of their names; secondary paired irons are the lightly shaded circles plotting near the point for the primary.

4706 and 4710 with Hassi Jekna, 4711 with 2151); two sHL irons (Hassi Jekna and Quarat al Hanish) were included in the study of Wasson and Kallemeyn (2002). Because both sHH and sHL are not well defined I will discuss these seven independent falls together.

The sHH and sHL fields overlap on the element-Au plots for As and Ir but the centroid for Ir is substantially different, ~0.2 µg/g for sHL and ~0.1 µg/g for sHH. The one North African sHH (4701) plots near the border between sHH and sHL on the Ni, Co and Ga diagrams (Fig. 3a, b and d) but slightly closer to sHH. It is within the common field on the As diagram and its low Ir value (0.02 µg/g) implies sHH membership.

The Hassi-Jekna four-member set plots in the heart of the sHL fields on the Ni, Co and Ga diagrams (Fig. 3a, b and d); its Ir content of 0.2 µg/g is consistent with sHL and its As is within the (unresolved) SHH and sHL fields. The 2151 pair plots near the HJ set on all these diagrams, but its two times higher Ir implies that it is independent and not part of this set.

The sHL 2428, 3204 and Qarat al Hanish (QaH) plot near one another on the Ni, As and Co diagrams. However, QaH was found in Egypt, thousands of km away from the other two, and 2428 and 3204 differ by large amounts on the Ga and Ir diagrams (Figs. 3d and 4a). In fact, the Ga content of 3204 plots outside the sHL field (by a factor of ~2), enough to make it sHL-an. The structure of 2428 is quite attractive (Fig. 5d); it has been shock damaged and reannealed to create en-echelon steps in the swathing kamacite.

The remaining sHL is 2679 which is within the As, Ga and Ir fields but low enough to require a slight expansion of the Ni and Co fields. It has a striking Off-Opl structure (Fig. 5e) that is much finer than other sHL irons having similar Ni contents. Additional studies are needed to determine how closely related it is to the other sHL irons.

The IAB-ungr each require separate discussion. In general, I assume that there is no error in Au and assess possible relationships to the groups in terms of the remaining five taxonomic elements. Acfer 234 is, however, an exception in that its Au is much lower than that of the nearest group, the MG, enough to already declare it to be IAB-ungr. The open square that is relatively near it on all diagrams is EET 84300; these irons may be similar enough to allow classification as a duo but I have tentatively chosen to leave them separate. As discussed above, Dellys is near the sLM fields on all diagrams but is designated ungrouped because its As and Ni values are too deviant.

The Aswan IAB-ungr iron plots in the sLL field on the Ni and As diagrams but much higher (in the sLH field) on the Co diagram and lower (in the sLM fields) on the Ga and Ir diagrams. IAB-ungr NWA 3205 plots in the sLL field or

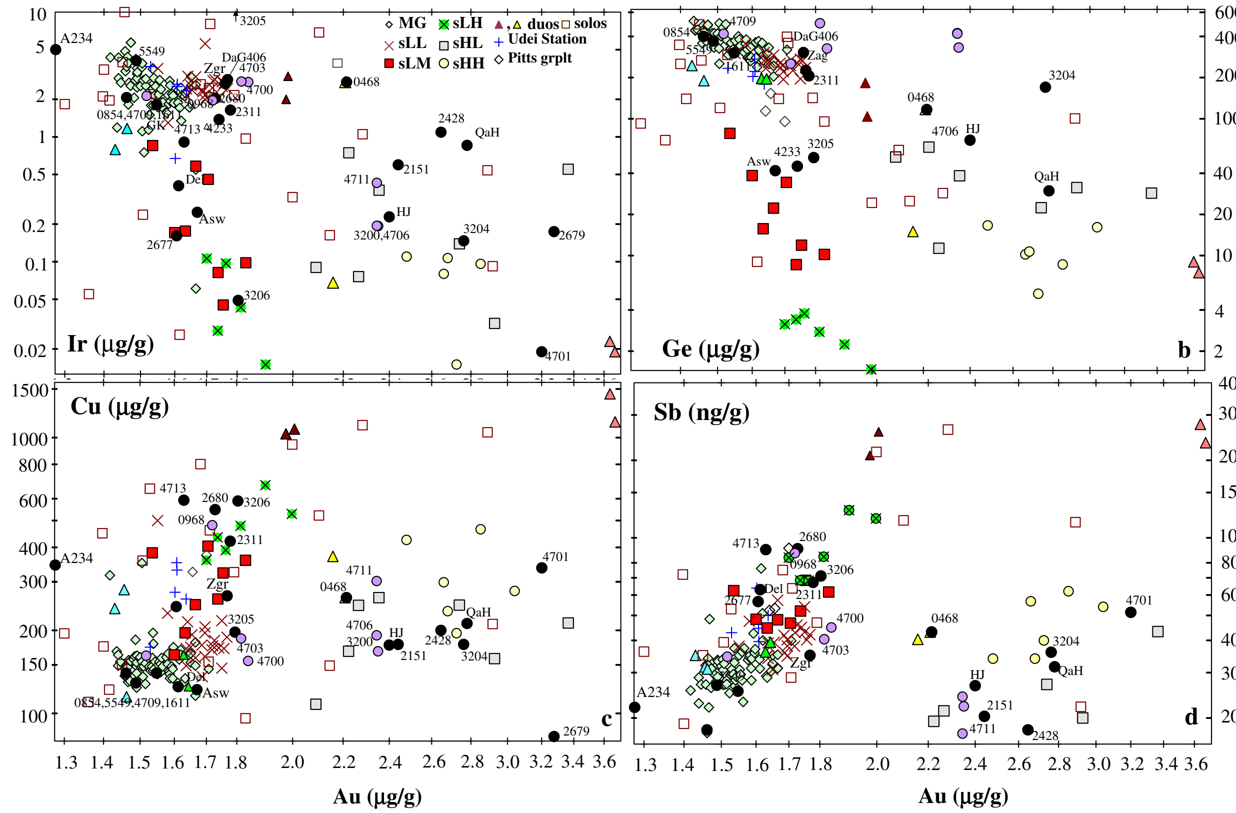

Fig. 4. Log element-log Au diagram for Ir, Ge, Cu and Sb showing the positions of irons in the IAB complex. All Ge data <100 μg/g were determined by radiochemical neutron-activation analysis; irons for which only Ge upper limits are available are not plotted. As in Fig. 3, the North African members of the IAB complex are shown as black-filled circles with labels giving abbreviations of their names; secondary paired irons are the lightly shaded circles plotting near the point for the primary.

between sLL and sLM on Ni, As and Ga diagrams but its Co content is the highest in a IAB iron and its Ir content (15 μg/g) is off the plotted area.

NWA 0468 is plotted on top of a triangle (the symbol for duos) because, as discussed by Wasson and Kallemeyn (2002) it forms a tentative duo with Grove Mountains 98003; there are, however, large differences in Ga and Ir values that make this relationship tenuous at best. NWA 0176 is a silicate-bearing and is assigned to the IAB complex based on its O-isotopic composition ($\Delta^{17}O = -5.2‰$); its As and Au values are below our suggested IAB limits.

In summary, the addition of new members has not resulted in a clearer resolution of the IAB subgroups; there remains the serious possibility that the three pairs of groups (sLH and sLM, MG and sLL, sHH and SHL) should eventually be merged.

The fraction of the IAB-complex irons assigned to the main group is much smaller in the North African set than in common irons. The 71 IAB-MG irons described by Wasson and Kallemeyn (2002) accounted for 45% of the 157 members of the complex then known. This contrasts with our observation of four MG irons in the North African set, only 17% of this set of 25 irons. This difference is discussed in the final section of this paper.

Perhaps the most surprising observation is that six (24%) of the IAB irons belong to the sHL subgroup. In the Wasson–Kallemeyn (2002) study nine (6% of 157) sHL were listed, and two of these HJ and QaH are from N. Africa. The four remaining North African sHL are NWA irons thus these four (and the four paired with them) may have all been recovered within 200 km of Erfoud, Morocco (located within the cluster of points on the Morocco-Algeria border in Fig. 1). As discussed in Section 7, this raises the possibility of a combined fall event.

5. CLASSIFICATION OF THE NON-IAB IRONS FROM NORTH AFRICA

The remaining North African irons are members of the magmatic groups with the exception of two small IIE (41- and 65-g) non-magmatic irons. Because most magmatic groups are now well defined the classification of these irons is relatively straightforward. I show the locations of most of the magmatic groups on Co–Au and Ga–Au diagrams in Fig. 6. These irons also fall within the group fields on Ni–Au, As–Au and Ir–Au diagrams but I do not show these diagrams because there is so much overlap between groups that these offer little additional information regarding

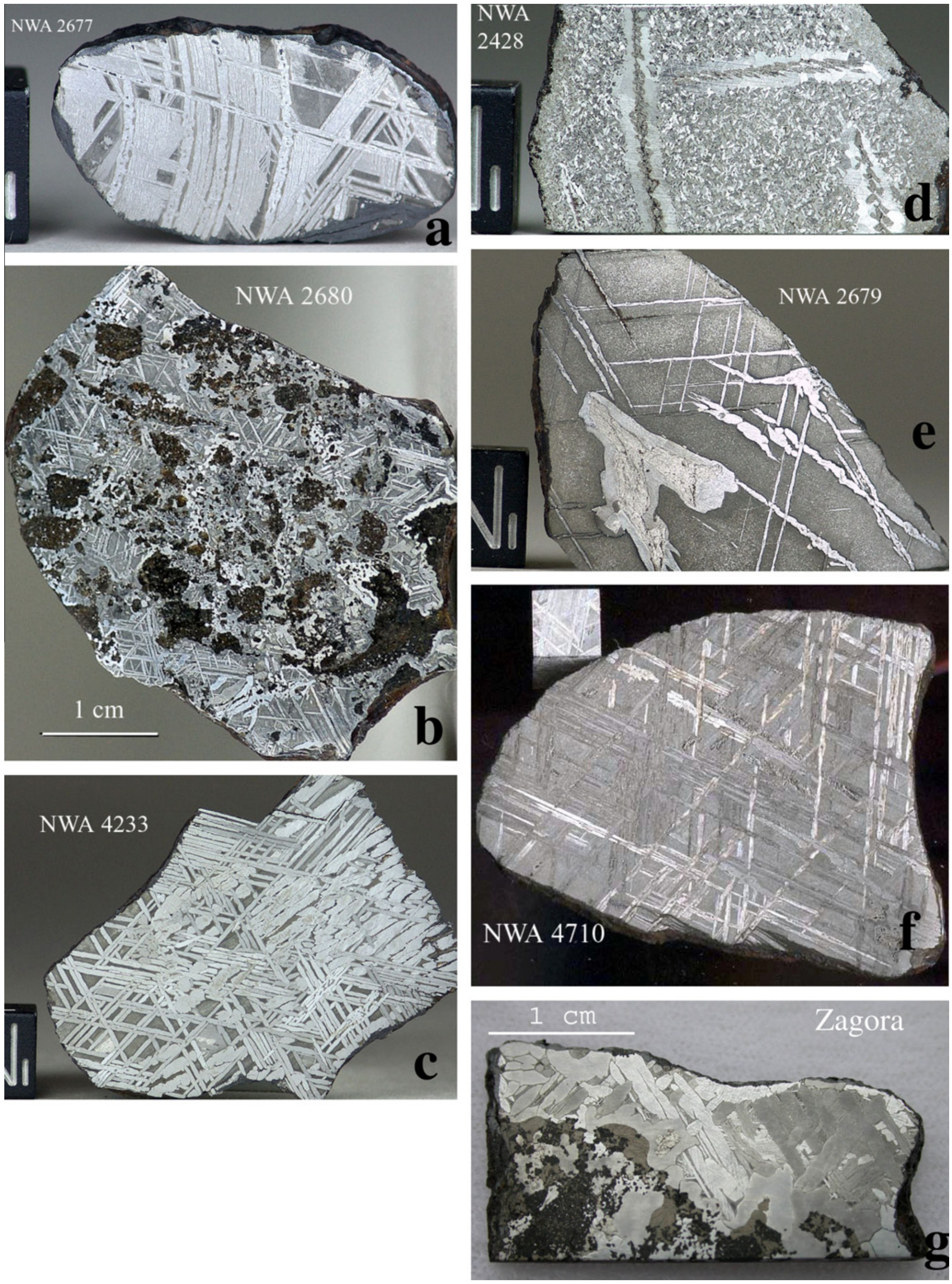

Fig. 5. Structures of North African irons that are members of the IAB complex. See text for more details. (a) NWA 2677 (IAB-sLM Of). Plastic deformation has resulted in the curvature of the most prominent set of kamacite bands, vertical in this image. Edge of block on left 1 cm. (b) NWA 2680 (IAB-sLM Off). Dark areas are silicates. Orientations of the octahedral patterns in cm-size domains vary across the section. (c) NWA 4233 (IAB-sLM Of). No inclusions are visible in this section; one set of kamacite lamellae is broad because its plane is nearly coincident with the plane of the section. Block edge 1 cm. (d) NWA 2428 (IAB-sHL, Opl). This iron mainly consists of large schreibersite crystals surrounded by swathing kamacite and interstitial regions with a plessitic octahedrite structure. An impact has sheared the meteorite; after annealing there are interesting en-echelon offsets in the schreibersite and swathing kamacite. Block edge 1 cm. (e) NWA 2679 (IAB-sHL Off). The structure mainly consists of long narrow kamacite lamellae in fine plessite; one lamellae set is nearly in the plane of the section, and one of these is swathing a large phosphide crystal. Block edge 1 cm. (f) NWA 4710 (IAB-sHL Of). This low-inclusion iron has suffered impact-induced recrystallization giving it a sparkle. Block edge 1 cm. (g) Zagora (IAB-sLL Om). The lower left portion of this specimen shows the high abundance of fine silicates typical of Zagora. However, most of this specimen is free of silicates demonstrating that the two lithologies were close together in the parent asteroid. Images a–e from M. Graul, image f from A. Schlazer, image g from F. Vignato.

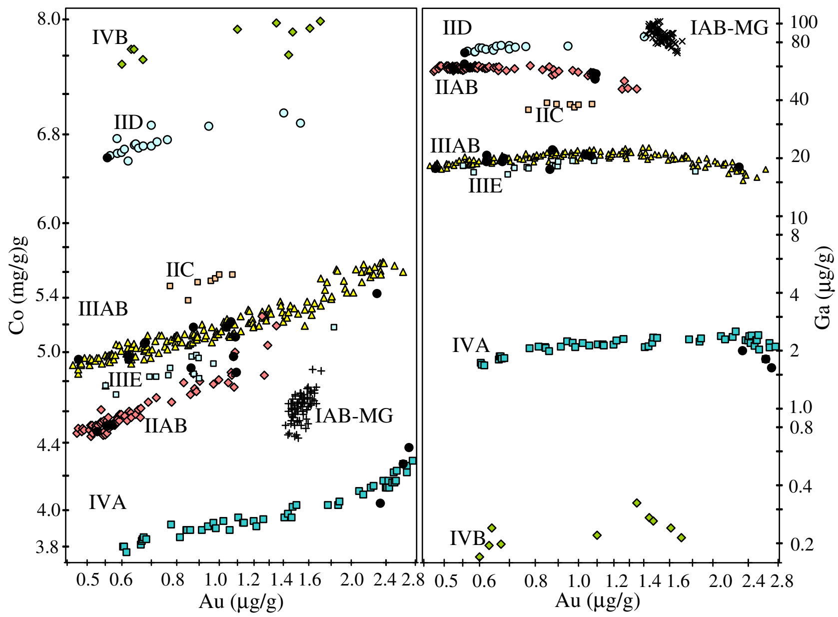

Fig. 6. Log element-log Au diagram for Co and Ga showing locations of seven large magmatic groups. North African irons that are members of these groups are shown as black-filled circles with labels giving abbreviations of their names; secondary paired irons are the lightly shaded circles plotting near the point for the primary. Not shown, these irons plot in or near the group fields for other taxonomic elements including Ni, As and Ir.

group membership. I will discuss the non-IAB irons in the order that they appear in Table 2.

Group IC shows considerable scatter, so much so that it may not be a true group. Nonetheless, NWA 2743 has concentrations of all the taxonomic elements similar to those of other IC irons having similar Au contents. It plots at the high-Au end of the group and is very similar in composition to Chihuahua City. Because IC strongly overlaps with group-IIAB irons of Fig. 6a and b, the field is not plotted to reduce clutter. Most IC irons can be distinguished from the IIAB set on the basis of their higher Ni and Ge contents. The sample imaged in Fig. 7a shows ca. 2 mm kamacite bands, plessite with a striking octahedral pattern, a 1-cm FeS nodule surrounded by schreibersite and another lamellar schreibersite wrapped in swathing kamacite.

There are six IIAB irons listed in Table 2. Two (3201 and 6279) are paired with Foum Zguid (FZ), which plots towards the high-Au end of the group. These form a tight cluster at Au ~1.1 μg/g on Fig. 6b; they scatter vertically on Fig. 6a with the highest Co plotting at the edge of the IIIAB field, which is not resolved from IIAB at Au $\geqslant$1.1 μg/g. The other three are the low-Au, high-Ir hexahedrites 2678 (now a recrystallized Ni-poor ataxite, Fig. 7b), 3202 and Dar al Gani 413 (DaG413), listed near the bottom of Table 2. Each is compositionally distinct.

One IID (NEA 002) iron was studied; it plots at the low-Au (and high-Ir) extreme of the group. It is especially important because of its extreme composition and its fine structure (bandwidth ~0.2 mm) and centimeter-size parental γ-iron domains (Fig. 7c). In typical low-Au IID irons bandwidths are ca. 0.9 mm and the parental γ-iron domains are >50 cm. Because of its atypical structure it was designated IID-an (Wasson and Huber, 2006).

The non-magmatic IIE irons are characterized both by the silicate petrology and by the metal composition although the silicates show large variations in texture and the element–element diagrams do not always form smooth trends. I studied a single metal sample of the tiny (41 g) NWA 5608 and found its content of the five taxonomic elements to fall within or near the border of the data fields formed by other IIE irons. I tentatively also list the sulfide-rich iron SAH 03505 as IIE because its structure is similar to that IIE HOW 88403, most elements fall within IIE compositional fields, and the D17O value of 0.3‰ is IIE-like (D'Orazio et al., 2009). Because some elements fall outside IIE fields (Co, W are low, Ni high) more studies are needed.

Group IIIAB is the largest group of iron meteorites, accounting for about 30% of known irons. The North African sample set (Table 2) includes 8 and possibly 9 independent IIIAB irons, one (4708) that is paired with 1430 (also known as Tata), and one (Dor el Gani) for which only the Ni content has been reported and thus one cannot judge possible pairing (or even if it is really a IIIAB). Even if Dor el Gani is independent, the calculated fraction of IIIAB irons in the North African set is only 17% of the 52 independent irons here discussed, a fraction much smaller than 30% for the entire set of iron meteorites.

Our set included one member (4704) of the rare-group IIIE; it is plotted in Fig. 6. Group IIIE irons have compositions very close to IIIAB for all elements, as shown (with lower quality data) by Malvin et al. (1984). The present, more precise, data set leaves no serious doubt that the groups are distinct. In addition to the small differences in metal compositions, the IIIE irons differ from IIIAB in containing carbides and having swollen kamacite bands. NWA

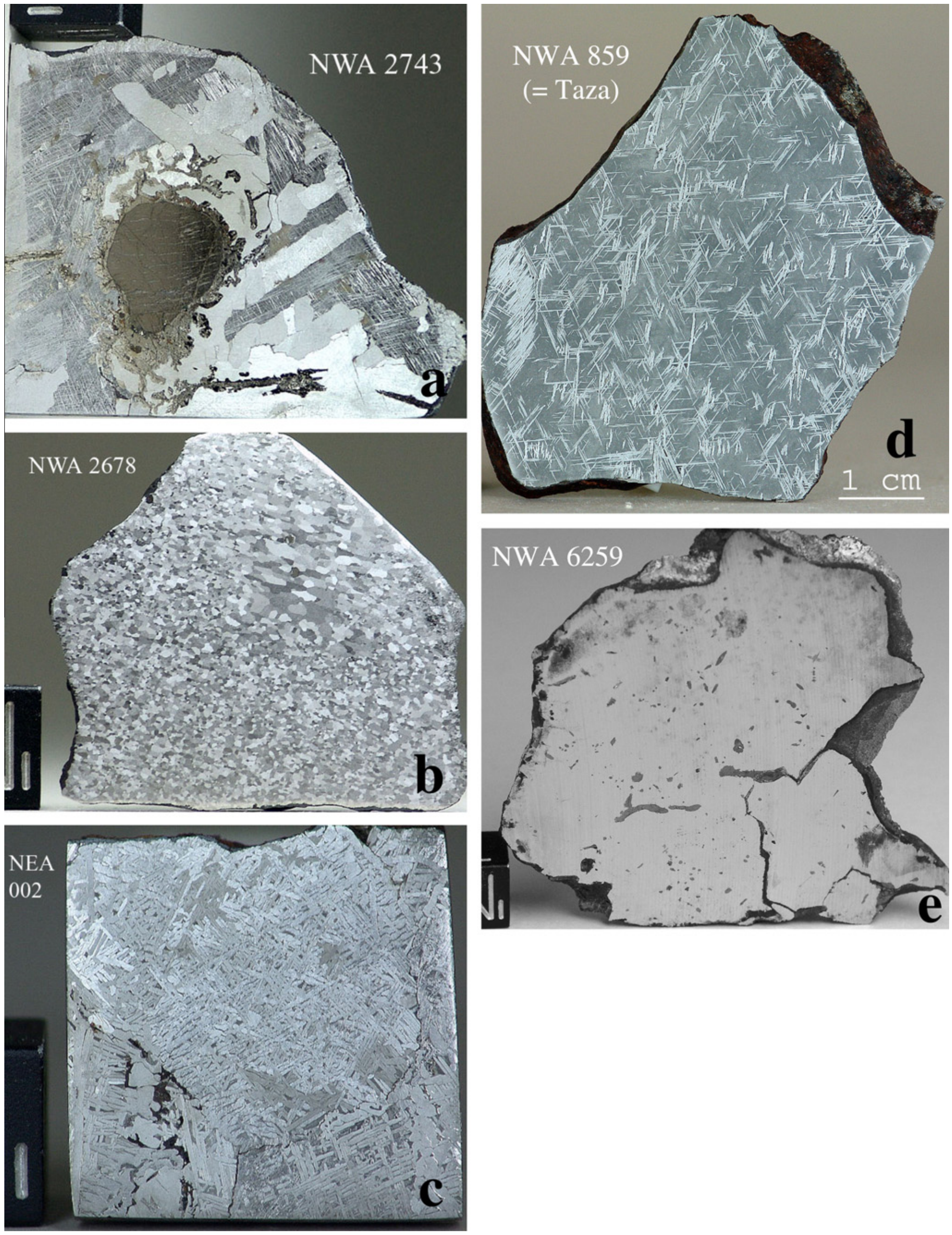

Fig. 7. Structures of North African irons that are not members of the IAB complex. See text for additional details. (a) NWA 2743 (IC, Og). Section includes a large ellipsoidal FeS inclusion surrounded by schreibersite and swathing kamacite; some kamacite shows impact-induced Neumann lines. Block edge on upper left 1 cm. (b) NWA 2678 (IIAB, anom.). Impact and subsequent annealing has transformed this former hexahedrite into a carpet of more-or-less equiaxed kamacite grains with sizes ranging from ~0.05 to ~4 mm. Block edge 1 cm. (c) NEA 002 (IID, Of). This iron has a much finer bandwidth than other IID irons and also shows evidence that the precursor γ-iron crystals were only 1 cm across. Block edge 1 cm. (d) NWA 0859 = Taza (ungr Opl). This specimen is dominated by the spindles and sparks that define plessitic octahedrites. The small ellipsoidal patch on the left side of the specimen has a differently oriented octahedral structure and thus formed from a different parental γ-iron crystal. (e) NWA 6259 (ungr, D). This iron has a very high (~420 mg/g) Ni content in the metal. The dark inclusions are FeS; the stringy shapes of some of them seem to reflect impact melting and migration of an FeS rich melt. Block edge 1 cm. All images from M. Graul.

4704 has swollen bands and falls in or near the IIIE compositional fields on element-Au diagrams for all the taxonomic elements. The three North African members of group IVA are all located near the high-Au extreme of the fields on Fig. 6. One, Kharga, is from Egypt, the other two are NWA irons. The point that plots below the Co–Au trend is 5289, which is not a UCLA analysis, this raises the possibility of interlaboratory biases. On the Ga-Au plot all three points plot below the previous data for IVA irons having similar Au values.

Table 3
Comparison of two independent means of Campo del Cielo data with the mean of NWA 5549. The upper values are Campo del Cielo data published by Wasson and Kallemeyn (2002). The next line gives the mean of four Campo irons received at UCLA under pseudonyms after 2002. The final line shows that mean NWA 5549 data differ from Campo del Cielo in terms of Cr, Ga, W and Ir; relative 95% confidence limits on the listed values for these elements are <8% for Cr and W, and <4% for Ga and Ir.

	Cr µg/g	Co mg/g	Ni mg/g	Cu µg/g	Ga µg/g	Ge µg/g	As µg/g	Ru µg/g	Sb ng/g	W ng/g	Re ng/g	Ir µg/g	Pt µg/g	Au µg/g
Campo WK	38	4.58	66.8	140	93.0	394	11.8		270	1.31	370	3.55	7.6	1.490
Campo new	33	4.54	66.9	146	91.1	374	11.2	8.1	258	1.36	428	3.67	7.9	1.474
NWA 5549	191	4.55	68.8	129	81.6	370	11.9	7.3	268	0.96	399	4.08	7.1	1.488

Six North African irons are classified as ungrouped (Table 2). Two have low As and Au values and are therefore not part of the IAB complex; El Qoseir is from Egypt, the other, 4702, is from Northwest Africa. El Qoseir and 4702 have no close relatives.

The other four irons have very interesting compositions and structures. Their As and Au contents are above the IAB threshold values but, in three of them, As, Au and some other elements are so high that it seems better to treat them as special cases. Future studies (including the determination of O-isotopic compositions) are needed to determine whether they should be considered ungrouped members of the IAB complex.

The first, NWA 0859, also known as Taza, is chemically related to Butler. Both irons have beautiful plessitic octahedrite structures (Fig. 7d) and extremely high Ge (2000–2300 µg/g), As (48–54 µg/g) and Au (6.5–6.8 µg/g) contents. It is not yet clear whether or not Taza formed magmatically. Because I cannot recognize magmatic trends (such as negative Ir–Au and Ir–As trends) in the Butler-0859 data set, it seems probable that they are non-magmatic irons formed by impacts.

The second high-Au ungrouped iron is 4705; it is a plessitic octahedrite distinguished by having one the highest known Ir contents and by far the highest Pt (83 µg/g) and Ru (76 µg/g) values in my iron-meteorite data set (which, however, is very incomplete for Ru). The Ge content of 1300 µg/g is exceptionally high; The Ge/Ga ratio is 87, far above the working upper limit of 7 for IAB irons (Wasson and Kallemeyn, 2002).

The third high-Au ungrouped iron is the high-Ni ataxite NWA 6259; it is distinguished by having the second highest Ni content (426 mg/g) known in an iron meteorite (Oktibbeha County has ~600 mg/g Ni); Dermbach, with 419 mg/g is similar. Its structure is irregular with many small squiggly FeS inclusions (Fig. 7e), probably reflecting impact melting. Curiously the mass is highly magnetic, capable of picking up large steel objects; this is presumably an effect introduced by humans.

I also list metal from one mesosiderite (2676) in Table 2. The concentrations of taxonomic elements all fall within the scatter fields of mesosiderite metal (e.g., Hassanzadeh et al., 1990).

6. THE DIVERSITY OF DESERT IRONS

It is useful to compare the taxonomy of irons from the North African hot desert with that for the irons from the cold desert of Antarctica. Wasson (1990) noted that studies of Antarctic irons revealed a much larger fraction of the ungrouped irons than present in the 600 irons previously studied. At that time 15% (88 of 574) of known non-Antarctic irons were listed as ungrouped versus 39% (12 of 31) of Antarctic irons.

Wasson (2000) reexamined the taxonomic data for Antarctic irons. From a set of 40 irons he deleted six that had total recovered masses ⩽21 g; he noted that these were so small that they could easily be metal nuggets from impact-altered chondrites such as those studied by Widom et al. (1986). In this set of 34 he classified 13, or 38% as ungrouped.

For comparison with the North African data set I applied modern taxonomic rules to the current set of 52 independent Antarctic irons having masses >30 g (set this high to help avoid impact nuggets from chondrites). Table 4 shows the group and subgroup assignments for these together with the statistics for the irons from North Africa. Some related groups and subgroups have been combined to simplify the discussion. Also listed in Table 4 is a column giving the combined statistics for these two sets of desert irons, and (from Wasson, 1985) a slightly reconstituted list showing the "classic" distribution prior to the recovery of large numbers of desert irons. The latter requires some clarification. The irons that were called ungrouped at the time of the Wasson (1985) compilation are now divided into ungrouped, IAB-ungrouped, and IAB sHH and IAB sHL. The classic value for IAB on Table 4 and 0.211, is the sum of what Wasson (1985) listed for IAB and the (now defunct) IIICD.

The distribution of the desert irons is very different than the classic distribution. The combination of the MG group and the sLH, sLM and sLL subgroups is 0.250, about 1.2 times larger than the IAB and IIICD value just discussed. But more remarkable is the fact that the total abundance of IAB sHH, sHL and ungrouped together with the non-IAB ungrouped among desert irons is about 35% of the total whereas the ungrouped fraction on the Wasson (1985) list is about 13%.

Wasson (1990, 2000) considered and rejected the possibility that the very high fraction of ungrouped (now including IAB-ungr and the sHx subgroups) irons in Antarctica might be the result of latitudinal effects on accretion, a reflection of stochastic effects associated with a few anomalous accretional events in Antarctica, or the result of a temporal fluctuation in the nature of earth-crossing debris coming to light because Antarctic irons tend to have shorter median terrestrial ages (~110 ka) than those from the rest of the world (~200 ka). He concluded that the difference was associated with the much smaller median mass observed in Antarctic irons, 300–400 g, nearly 100 times smaller than that (~30 kg) for "common" irons from the remainder of the world. The North African irons are also relatively small; the median mass is 1200 g, 3–4 times larger than the Antarctic irons but 25 times smaller than that of common irons.

In the case of the North African irons latitude is not a factor because the range covered (22° to 37°) strongly overlaps that for the "common", pre-1970 museum set.

Although stochastic variations in accretionary events cannot account for the differences if each of these events drops meteoroids of a single class, Wasson (2000) noted that porous asteroids or comets that make many passages through the asteroid belt could serve as collectors of tough metallic objects, and the accretion of such a body could deposit a variety of materials in a single strewn field. A similar suggestion had been made earlier by Cintala (1981), who suggested that highly porous comets could collect meteoroids.

A simpler and more plausible scenario can be proposed to account for the exceptionally high fraction (6 of 51) of IAB-sHL irons in the North African set. Wasson and Kallemeyn (2002) noted that metallic materials formed by impacts will each have formed under somewhat differing conditions that will have affected both their compositions and structures. Because the elements were distributed among several phases in the pre-impact, presumably chondritic, precursor materials, the fraction entering the impact generated melt would have depended on the temperature history of the shock-altered materials. Processes such as the diffusion of elements out of non-metallic phases or chondrule interiors in the chondritic host into the metallic melt or loss of volatiles by vaporization followed by transport to another location and condensation there would have depended on these detailed histories.

Wasson and Kallemeyn (2002) noted that it is not yet possible to determine how many parent asteroids were involved in the formation of the IAB main group and the subgroups; they suggested that a simple working hypothesis is that all IABs having similar metal and O-isotopic compositions formed on a single asteroid. This model is supported by the fact that O isotope studies of silicates from the

Table 4
Distribution of iron meteorites into classes in the two main deserts of North Africa and Antarctica. For comparison, the distribution given in Wasson (1985) is listed. See text for details. Fraction is abbreviated fract.

Group	Subgroup	N. Africa		Antarctica		Two deserts		Wasson 85
		Total	fract.	Total	fract.	Total	fract.	fract.
IAB		25	0.481	28	0.538	53	0.510	–
IAB	MG,sLL sLM,sLH	13	0.250	15	0.288	28	0.269	0.211
IAB	ungr	5	0.096	11	0.212	16	0.154	–
IAB	sHH and sHL	7	0.135	2	0.038	9	0.087	–
IC		1	0.019	0	0.000	1	0.010	0.021
IIAB		4	0.077	3	0.058	7	0.067	0.108
IIC, IIF		0	0.000	0	0.000	0	0.000	0.024
IID		1	0.019	0	0.000	1	0.010	0.027
IIE		2	0.038	1	0.019	3	0.029	0.025
IIIAB		9	0.173	8	0.154	17	0.163	0.323
IIIE		1	0.019	0	0.000	1	0.010	0.027
IVA		3	0.058	4	0.077	7	0.067	0.083
IIIF,IVB		0	0.000	0	0.000	0	0.000	0.023
ungr		6	0.115	8	0.154	14	0.135	0.128
	Total irons	52		52		104		

main-group and subgroups sLH, sLM and sLL all have similar O-isotopic compositions of $\sim -0.5‰$ (e.g., Clayton and Mayeda, 1996). However, until now, there are few isotopic data available for the sHH and sHL irons; the one available value is for sHL Sombrerete, with $\Delta^{17}O = -1.39‰$ (Clayton and Mayeda, 1996), much more negative than the common IAB value. If this value is characteristic of sHL (or sHH) irons, it is unlikely that these subgroups formed on the same asteroid as the MG and the three low-Au subgroups.

I therefore suggest that the exceptional concentration of sHL irons in the area near Erfoud may partly reflect that these represent small masses of metal formed by impacts into the regolith of a single asteroid, and that one asteroidal fragment may be responsible for all or most of the four independent (and four paired) sHL members of the North African set. It is also not out of the question that Hassi Jekna, recovered about 600 km ESE of Erfoud, could also have been deposited in the same accretionary event, particularly if one allows for the possibility that Hassi Jekna could have been transported by humans (despite the hearsay reports regarding the fall site). This hypothesis can be tested by obtaining cosmic-ray-exposure ages for the various sHL irons.

7. SUMMARY

During the past three decades the hot and cold deserts have provided many meteorites. In earlier studies of iron meteorites from Antarctica Clarke (1986) and later authors (Wasson et al., 1989; Wasson, 1990, 2000) showed that there are many more ungrouped irons in Antarctica that in the "common" irons present in the world's museums prior to 1980. A major change in the classification of iron meteorites by Wasson and Kallemeyn (2002) has made it necessary to reassign meteorites related to the group originally designated IAB, a group that is now widely accepted to be melts produced by impacts into a carbonaceous-chondritic regolith (Wasson et al., 1980; Wasson and Kallemeyn, 2002). Some meteorites originally designated ungrouped are now recognized to be members of the IAB complex.

The present study is the first comprehensive study of the iron meteorites of North Africa. I report data obtained by neutron-activation analysis for 45 independent iron meteorites, one mesosiderite and 11 paired irons. I also discuss 8 irons from the literature. This data set confirms earlier conclusions based on the study of Antarctic irons (e.g., Wasson, 1990); the distribution among classes is very different from that observed in the common irons. There is a much larger fraction of irons from the IAB complex and of non-IAB ungrouped irons. A large fraction of these "extra" irons are small and probably the result of impact-melting of a chondritic regolith.

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APPENDIX A. PAIRING OF NORTH AFRICAN IRONS

A.1. Pairings among irons in the IAB complex

The six main taxonomic elements (Co, Ni, Ga, As, Ir and Au) were used to test for pairing. Clusters of points on all five element-Au diagrams in a set of samples from the same general geographic region (in this case, parts of North Africa) constitutes strong evidence that they are paired.

One of the more intriguing sets of paired irons is one that is closely similar in composition to Hassi Jekna (HJ) which is reported to have fallen a few years before it was purchased in 1890 by a French officer serving in southern Algeria (Buchwald, 1975). It was reportedly recovered by nomads who were camped near the Hassi Jekna well in north central Algeria. Buchwald noted that "corrosion has superficially attacked the fusion crust and some of the cracked grain boundaries but the general appearance is not inconsistent with the report that the meteorite was observed to fall in the 1880s".

Three small irons from North Africa (3200, 4706 and 4710) have compositions quite similar to that of HJ on all five element-Au diagrams (Figs. 3 and 4a). Estimated bandwidths for these are 0.4 mm, the same within the uncertainties as the width of 0.47 mm reported for HJ by Buchwald (1975); the structure of 4710 is illustrated in Fig. 5f. I did not recognize fusion crust or heat altered zones on our specimens, which, depending on local conditions, could survive for 125 years in the Sahara. However, I only made low-power microscopic observations and cannot rule out that these may be present. Based on presently available chemical and structural evidence it seems probable that these three irons are paired with Hassi Jekna.

Two additional irons (2151 and 4711) fall into the HJ cluster on element-Au diagrams for Ni, Co and Ga but deviate on those for As and Ir (by a factor of 2 on the latter). They have much coarser structures, with bandwidths of 1.2 mm. I conclude that they are paired with each other, but not with HJ. As noted above, although it seems possible to have substantially different cooling rates recorded in meteorites that were formed in the same impact but stored at different locations in a megaregolith, it is implausible that such different Ir contents and cooling rates would be recorded in a meteoroid having maximum dimensions of about 2 m.

The possible exception to using a factor 2 in Ir contents as sufficient grounds for resolving potentially paired IAB irons would be if the meteoroid had dimensions larger than the mean diffusion distance for Ir during the metamorphism recorded by the Widmanstätten pattern. The preservation of compositional gradients in IIIAB Cape York specimens (Esbensen et al., 1982) implies that the mean diffusion length in this body was on the order of 2 m. It is important to note that the total known range in Ir in extensively studied IAB irons such as Canyon Diablo (Wasson and Ouyang, 1990) and Campo del Cielo, Odessa and Toluca (Wasson and Kallemeyn, 2002) is only a factor of 1.2–1.3.

Many masses of the silicate-bearing sLL iron Zagora are known; most samples are rich is silicate clasts and dust with typical clast sizes of ~0.3 mm. Although most specimens do have silicates, two of our samples (4700 and 4703) plot together with Zagora on the five element-Au diagrams although no silicates have been recognized. However, the image of Zagora by Vignato shown in Fig. 5g shows that silicate-free regions can be found adjacent to regions containing abundant dusty silicates. It therefore, seems best to treat 4700 and 4703 as paired with Zagora. Another North African iron, 2311, plots near the Zagora cluster on 4 of the 5 taxonomic diagrams, but because its Ir is a factor of 2 lower, it is probably not part of the same fall.

The two sLM irons 0968 and 2680 plot close together on the five taxonomic diagrams. The greatest deviation is 13% on the As–Au diagram. It appears that they are paired. As noted above, they both have Ir values 2.3 times higher than the highest in other members of subgroup sLM leading to designation as anomalous members of sLM. The iron NWA 4233 (Fig. 5c) analyzed by B. Spettel (MBDB, 2010) is relatively similar to this pair but the structure is very different and Spettel's analyses of As and Ir are much (33%) lower; it is not part of this pairing cluster. The structure of the 2680 set is so unique that, based on images posted on the web, one can confidently state that the so-called winonaites NWA 4024 and 5980 are also paired with 2680.

The two relatively similar sLH irons 2677 and 3206 are not paired. The first analysis of 2677 was by ICP-MS by A. Campbell; I reanalyzed it by neutron activation to better assess its classification and possible pairing. The Ir content differs from that in 3206 by a factor of 3, excluding a pairing relationship.

It is well recognized that several pieces of the iron meteorite NWA 0854 (also know as Ziz) have been recovered. One that I have analyzed is 4709, which plots close to 0854 on the five taxonomic diagrams and thus 4709 is probably part of the Ziz shower. Ziz specimens are known for the beautiful regmaglypts decorating their exterior surfaces.

During the last few years several specimens of the silicate-rich iron NWA 5549 have been recovered but most have not been accorded separate NWA names. I have analyzed two such specimens and combined the data in our tables and diagrams. The NWA 6203 iron (MBDB, 2010) also appears to be a member of this shower; it was reportedly recovered from "the Algerian side of the Ziz river". Because the Ziz River crosses the border, I infer that this means "near the Ziz River on the Algerian side of the border".

I have been sent a number of supposedly new iron meteorites during the past several years that have compositions very similar to the members of the huge shower that fell at Campo del Cielo (Campo); based on their compositions I have concluded it probable that all were mislabeled. It is therefore of importance to note that 5549 has a composition close to but resolvable from that of Campo; I summarize the two compositions in Table 3. The 5549 means are based on four analyses of two separate masses thus the ranges are not as well defined as those for Campo which are based on about 20 analyses of about 10 separate masses. The differences between 5549 and Campo for Cr, Ga, W and Ir are all resolvable, with the largest differences for Cr and W. This is the first time that Cr and W have been shown useful for resolving differences between compositionally similar IAB-complex irons.

It would be good if all specimens of paired NWA meteorites were reported to the Meteorite Nomenclature Committee and included in the Meteoritical Bulletin Database. Such information may lead to the belated identification of recovery locations.

The fact that two closely related irons could have such large (factor of five) differences in Cr contents is interesting. In magmatic irons high Cr values appear to reflect the fact that a Cr-rich phase (generally chromite) was on the liquidus during crystallization and that this phase was finely dispersed in the metal. If the chromite had precipitated as inclusions coarse enough for the analyst to avoid, the concentration in the "metal" samples would have been much lower.

A.2. Pairings among irons not in the IAB complex

There are three sets of paired magmatic irons, one set of three from IIAB, one large set within IIIAB of which I have analyzed two members, and the numerous small irons paired with NWA 0859. Because the magmatic irons are compositionally better behaved than the IAB irons, I am quite confident that the members of each of these clusters are paired.

The high-Au, low-Ir IIAB cluster consists of Foum Zguid, NWA 3201 and NWA 6279. Within experimental error concentrations of the six taxonomic elements Co, Ni, Ga, As, Ir and Au are the same in these three irons.

It has been recognized for some time that there are numerous specimens of the IIIAB iron NWA 1430 (also known as Tata). Our data for NWA 4708, a 9.6-kg specimen, agree with that of NWA 1430 for all taxonomic elements. I carried out only one analysis and averaged the data in with our replicate data for NWA 1430. Several other Tata specimens in private hands do not have NWA numbers.

Among the ungrouped irons we know of only one shower, NWA 0859, also known as Taza. We have analyzed only one specimen. Because of the identical striking textures of other masses posted on the web there is no doubt regarding their identification as paired masses of this iron.

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