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Petrography, geochemistry and classification of ten new iron meteorites from Northwest Africa and Chile

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ABSTRACT

I present detailed petrographic descriptions and major- and trace-element data on a set of ten new iron meteorites (irons) from Nortwest Africa and the Atacama Desert (Chile). Part of these data were used to classify the meteorites upon their submission to the Nomenclature Committee of the Meteoritical Society for official approval. The studied irons belong to the following groups: IAB-complex (2 meteorites), IC (1), IIAB (1), IIE (1), IIIAB (1), IVA (1). Three irons do not fall in any compositional group and, therefore, are classified as ungrouped iron meteorites. Based on their structure, the ten irons were subdivided into plessitic octahedrites (1 meteorite), fine octahedrites (2), medium octahedrites (1), coarse octahedrites (1), ataxites (1) and in iron with anomalous structure (4). The distribution of the studied irons among the chemical groups is consistent with what has already been observed by other authors, that is, irons from northern Africa and Antarctica have a high frequency of ungrouped irons and of members of the IAB-complex with respect to irons from other parts of the world. This biased distribution is discussed in relation to the smaller median size of irons from northern Africa and Antarctica in comparison with meteorites from other parts of the world.

Keywords: iron meteorite; asteroid; siderophile elements; geochemistry; classification.

INTRODUCTION

Iron meteorites (hereafter irons) are meteorites mostly consisting of Fe-Ni alloys, such as kamacite, taenite, tetrataenite, awaruite, accompanied by a series of accessory mineral phases, most commonly troilite, schreibersite, daubréelite, cohenite, graphite, etc. (Mittlefehldt et al., 1998; Haack and McCoy, 2003). Less reduced irons may also contain oxides (e.g., chromite) and phosphates (e.g. sarcopside, graftonite, etc.). Several groups of irons are notable because they contain minor proportions of silicates, like olivine, pyroxenes and silica minerals, that are main components of stony and stony-iron meteorites.

Currently, there are 1024 different iron meteorites classified and officially approved by the Nomenclature Committee of The Meteoritical Society, and 41 of them are witnessed falls (https://www.lpi.usra.edu/meteor/, Meteoritical Bulletin Database accessed on February 25, 2019). Although irons constitute only 3.6% of the total witnessed meteorite falls, they are the most abundant extraterrestrial material available for study. Indeed, they are easier to recognize, have higher resistance during ablative flight through Earth's atmosphere, and are more durable to weathering in the Earth physical-chemical environment. Indeed the seventeen largest meteorites found on Earth (weighting between $60 \cdot 10^3$ and $5.3 \cdot 10^3$ kg) are all irons (Meteoritical Bulletin Database).

Most irons are thought to be fragments of the cores of asteroids that have undergone internal differentiation, whereas other types are interpreted as the crystallization product of immiscible liquid metal originated by impact melting of chondritic material close to the surface of asteroids (e.g., Buchwald, 1975; Wasson and Wang, 1986). The study of the structure, chemistry and isotopic composition of iron meteorites is fundamental for understanding the process of planetary differentiation, including Earth, and the chemical evolution of the Solar System.

Over the period 2004-2018, sixteen iron meteorites were analyzed an classified at the Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) Laboratory of the Dipartimento di Scienze della Terra (University of Pisa; Table 1). Fourteen are newly recovered meteorites, whereas Bagnone (D'Orazio et al., 2004) and Bendegò (Carvalho et al., 2011) are historical meteorites that have not been fully analyzed for trace elements, yet.

While the irons Bagnone, Miller Butte 03002, Sahara 03505, Bendegó, Gebel Kamil and Northwest Africa 6583 (hereafter Nortwest Africa=NWA) have been investigated in detail (D'Orazio et al., 2004, 2006, 2009; Carvalho et al., 2011; D'Orazio et al., 2011; Fazio et al., 2013, respectively), the irons Ilafegh 018, Los Vientos 188, NWA 5289, NWA 6163, NWA 6164, NWA 6165, NWA 6166, NWA 6167, NWA 6716, NWA 11404 have been only preliminarly described in the Meteoritical Bulletin (Table 1). This paper is therefore addressed to the full petrographical and geochemical characterization of these ten iron meteorites.

STRUCTURAL AND CHEMICAL CLASSIFICATION OF IRON METEORITES

Irons are classified both on structural and chemical grounds. The structure of irons is the final result of the very complex interplay between chemical variables (in particular Fe, Ni and P content) and physical variables (in particular the cooling rate and the eventual shock metamorphism). Octahedrites (O) consist of kamacite (α-Fe-Ni phase) lamellae oriented along octahedral planes separated by Ni-rich fields (plessite) composed of several

Table 1. The sixteen iron meteorites analyzed in the ICP-MS Laboratory of the Department of Earth Sciences, University of Pisa, over the period 2004-2018.

Name	Mass (kg)	Structure	Classification	Place	Year found	Type Specimen location	Reference
Bagnone	48	Om	IIIAB	Bagnone, Italy	1904/1905	MSN-UNIPI	D'Orazio et al. (2004)
Bendegó	5360	Og	IC	Bahia, Brasil	1784	-	Carvalho et al. (2011)
Gebel Kamil	> 1600	D	UNGR	Al Wadi al Jadid, Egypt	2009	MNA-UNISI	MB (98) D'Orazio et al. (2011)
Ilafegh 018	11.1	Om	IIIAB	Adrar, Algeria	2001	CEREGE	MB (107)
Los Vientos 188	0.806	A	IIAB	Antofagasta, Chile	2017	CEREGE	MB (106)
Miller Butte 03002	0.083	Om	IID	Antarctica	2003	MNA-UNISI	MB (88) D'Orazio et al. (2006)
Sahara 03505	0.065	A	UNGR	Sahara	2003	MNA-UNISI	MB (91) D'Orazio et al. (2009)
NWA 5289	0.296	Of	IVA	Northwest Africa	2007	MSN-UNIPI	MB (94)
NWA 6163	0.358	A	UNGR	Northwest Africa	2008	MSN-UNIPI	MB (99)
NWA 6164	0.726	Og	IAB-MG	Northwest Africa	2007	MSN-UNIPI	MB (99)
NWA 6165	0.029	Of	IAB-sLM	Northwest Africa	2003	MSN-UNIPI	MB (99)
NWA 6166	0.144	Opl	UNGR	Northwest Africa	2005	MSN-UNIPI	MB (99)
NWA 6167	0.500	D	UNGR	Northwest Africa	2003	MSN-UNIPI	MB (99)
NWA 6583	1.825	A	UNGR	Northwest Africa	2010	MSN-UNIPI	MB (100) Fazio et al. (2013)
NWA 6716	0.293	Og r	IIE	Northwest Africa	2010	MSN-UNIPI	MB (100)
NWA 11404	1.096	A	IC	Northwest Africa	2016	CEREGE	MB (106)

Abbreviations: Om, medium octahedrite; Of, fine octahedrite; Og, coarse octahedrite; Opl, plessitic octahedrite; D, ataxite; Og r, recrystallized coarse octahedrite; A, anomalous structure; UNGR, ungrouped iron; NWA, Northwest Africa; MB, Meteoritical Bulletin (in parentheses the issue number); MSN-UNIPI, Museo di Storia Naturale - University of Pisa; MNA-UNISI, Museo Nazionale dell'Antartide - University of Siena; CEREGE, Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement.

phases. This structure, revealed by grinding and etching the surfaces of irons, is known as the Widmanstätten pattern. Octahedrites are subdivided according to the width of the kamacite lamellae from coarsest (Ogg, lamellae width >3.3 mm) to finest (Off, lamellae width <0.2 mm). Ataxites (D) show only microscopic spindles of kamacite. Hexahedrites (H) consist almost entirely of kamacite often exhibiting rectilinear features known as Neumann bands. Plessitic octahedrites show a structure intermediate between Off and D. Some irons show secondary structures, due to the effect of re-heating and/or mechanical deformation, that modify or completely obliterate the original ones. Re-heating of meteoroids may occur during their repeated passage close to the Sun, during shock events, and during their ablative flight through Earth's atmosphere. Mechanical deformation may originate during impact and ejection of meteoroids from their parent bodies, during collisions between meteoroids in space, and finally as a consequence of the hypervelocity impact of meteoroids with Earth's surface.

Usually, more than 99.5% of the mass of the metallic fraction of irons consists of Fe, Ni, Co, S, P, C while the remaining mass is made of siderophile and chalcophile trace-elements showing a widely variable relative distribution. Besides Ni and Co, the trace elements Ga, Ge, Ir and Au have the greatest taxonomic significance. Based on the concentration of these elements (plus Cr, Cu, As, Mo, Sb, Ru, Rh, Pd, Os, Pt, W, Re, irons are classified into thirteen chemical groups (IAB complex, IC, IIAB, IIC, IID, IIE, IIF, IIG, IIIAB, IIIE, IIIF, IVA, IVB) (Wasson et al., 1998 and references therein). Each group should contain at least five distinct meteorites. Irons that do not fall in any of these chemical groups (about 12%) are named ungrouped, while irons that have concentrations of only one or two element outside the range typical of a specific group are called "anomalous".

EXPERIMENTAL

Samples of the studied meteorites have been obtained cutting small slices from the main masses using a diamond blade or a diamond wire saw. Subsamples for the chemical analyses were obtained cutting again the original slices and avoiding visible accessory minerals as much as possible. Two very small cubes, each weighting from 200 to 300 mg, for each meteorite, were repeatedly washed in acetone and ultrapure water (Milli-Q, resistivity >18.2 MΩ cm). Following the procedure described by D'Orazio and Folco (2003), one of the small cubes was dissolved in 5 ml 6 N HNO_3 (Aristar ultrapure) and used for the determination of Cr, Co, Ni, Cu, As, Mo, and Sb; the other subsample was dissolved in 4 ml Aqua Regia and used for the determination of Ru, Rh, Pd, W, Re, Ir, Pt and Au. The final sample solutions were diluted with ultrapure water and analyzed by ICP-MS (VG PQ2 Plus and Perkin Elmer NexION 300x). The calibrations were performed with synthetic solutions made by diluting and mixing 10 μg/ml single- and multi-element stock solutions (Inorganic Ventures).

The microstructure and the mineral chemical composition of the studied meteorites have been investigated through scanning electron microscopy coupled with energy-dispersive microanalytical systems (Philips XL30 SEM equipped with EDAX DX4 detector and FEI Quanta 450 ESEM FEG equipped with Bruker, QUANTAX XFlash Detector 6|10). The concentration of Ni and Co of Ilafegh 018 was determined by hand-held X-ray fluorescence (Gemelli et al., 2015).

All the analytical data were acquired at the Dipartimento di Scienze della Terra of the University of Pisa, except for the ESEM FEG data that were obtained at the Centro Interdipartimentale di Scienza ed Ingegneria dei Materiali of the University of Pisa.

RESULTS

Ilafegh 018

This iron was found as a single mass of 11.1 kg by nomadic Berbers in 2001 in southern Algeria (Adrar Province), close to the Mali border. Only in 2015 it was recovered by Moroccan meteorite dealers and recognized as an iron meteorite. It is a compact, heavily sculpted mass with well-preserved fusion crust on large parts of the surface and only a thin layer of surface oxidation (Figure 1a). The mass shows distinct large regmaglypts and heavy ablation of edges. The etched section shows an octahedrite texture with ~2 mm-thick heat-affected zone. Only eight kamacite lamellae are visible in the available section, with an average width of 1.1±0.3 mm (Om; Figure 2a). Kamacite is polycrystalline and in the ε form. Comb, black and net plessite are present (Figure 2 a,b). Large (up to 300 μm) fractured crystals of schreibersite are preferentially located at the interfaces between kamacite lamellae and plessite fields (Figure 2c). Within the heat-affected zone the schreibersite crystals melted forming amoeboidal or subspherical particles made of dendritic crystals of P-bearing and Ni-rich metal set in an extremely fine-grained phosphide groundmass with eutectic texture (Figure 2d). These textures have been described in the heat-affected zone of many irons (e.g., Buchwald, 1975) and are due to the rapid solidification of the schreibersite melt that has dissolved part of the surrounding kamacite.

The medium octahedrite structure and the composition of the metal (Table 2) are those typical of IIIAB irons (Figure 3).

Los Vientos 188

This meteorite was found on February 20, 2017 by dr. Svend Buhl in the Atacama Desert, Antofagasta, Chile

Figure 1. The main masses of Ilafegh 018 (a), Los Vientos 188 (b), NWA 5289 (c), NWA 6163 (d), NWA 6164 (e), NWA 6165 (f) iron meteorites. Photo credit: Ilafegh 018 and Los Vientos 188, Svend Buhl (Meteorite-Recon.com); NWA 5289, NWA 6163 and NWA 6164, Mirko Graul (meteorite-mirko.de); NWA 6165, Fabien Kuntz (WWMeteorites.com). The side of the scale cube is 1.0 cm.

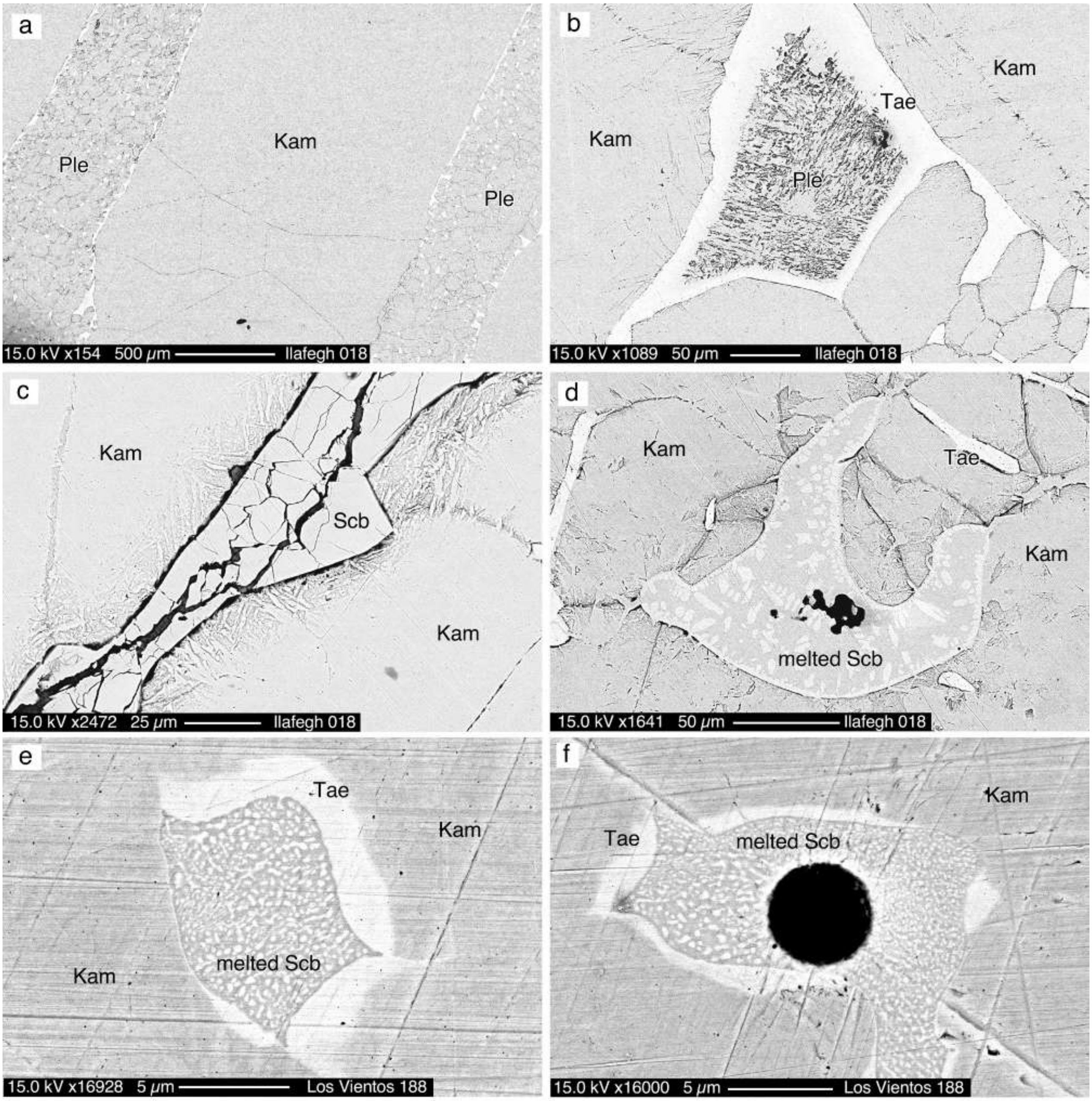

Figure 2. Back-scattered electron images of polished sections of Ilafegh 018 (a, b, c, d) and Los Vientos 188(d, e) iron meteorites. a) Polycrystalline kamacite lamella between two plessite fields; b) finger plessite bordered by taenite surrounded by polycrystalline kamacite; c) fractured crystal of schreibersite within kamacite; d) amoeboidal particle of melted schreibersite showing Ni-rich metal dendrites; e) cuspate particle of melted schreibersite rimmed by Ni-rich metal; f) cuspate particle of melted schreibersite rimmed by Ni-rich metal showing a shrinkage bubble. Abbreviations: Kam, kamacite; Ple, plessite; Scb, schreibersite; Tae, taenite.

(24°40'03.7''S, 69°55'37.3''W). It was recovered as a single 806 g individual sitting on fine grained granodiorite pediment. The shield-shaped mass was stuck vertically in the ground, one third of the mass protruding from the soil. The surface is mostly brown with darker patches and partially covered with caliche (Figure 1b). A cut face reveals a metallic unweathered interior. The etched section shows a polycrystalline kamacite aggregate with crystal size up to 550 μm. Euhedral tetragonal prisms of schreibersite (rhabdite), 10-20 μm in size, are extremely

Table 2. Chemical composition of the ten iron meteorites studied in this work.

Element	Unit	Ilafegh 018	Los Vientos 188	NWA 5289	NWA 6163	NWA 6164	NWA 6165	NWA 6166	NWA 6167	NWA 6716	NWA 11404
Ni	mg/g	77.0*	55.4	90.2	84.3	70.1	107.9	178.1	190.4	77.7	63.2
Co	mg/g	4.41*	4.55	4.04	4.27	5.02	4.92	5.97	9.29	4.22	4.64
Cu	µg/g	184	125	111	258	122	214	499	302	147	142
Ga	µg/g	20.3	67	2.0	15.1	74	18.0	4.4	11.3	24.3	61
Ge	µg/g	41	191	< 1	54	281	24.2	< 1	51	62	254
As	µg/g	4.9	4.4	12.0	11.1	14.9	21.2	34.5	14.5	12.9	5.0
Mo	µg/g	6.5	6.2	5.4	6.6	6.4	4.2	2.20	17.1	10.0	6.3
Ru	µg/g	10.8	25.8	2.32	6.9	4.6	2.66	0.10	22.0	6.4	14.2
Rh	µg/g	1.85	2.72	0.78	1.42	1.22	0.93	0.05	3.35	1.40	2.32
Pd	µg/g	3.10	1.67	6.5	3.8	3.9	6.2	8.8	7.2	3.6	2.09
Sb	µg/g	n.d.	0.05	< 0.05	n.d.	n.d.	0.35	0.77	0.17	0.12	n.d.
W	µg/g	n.d.	3.33	0.36	1.55	1.23	0.72	0.02	2.68	1.05	2.16
Re	µg/g	0.48	1.94	0.08	0.48	0.20	0.03	< 0.01	1.73	0.48	0.16
Ir	µg/g	5.5	22.6	0.80	4.2	1.99	0.40	0.02	18.7	4.4	2.42
Pt	µg/g	11.5	29.0	3.76	9.6	5.8	3.45	0.04	26.4	9.1	16.6
Au	µg/g	0.67	0.39	2.33	1.08	1.49	1.60	1.51	1.12	0.97	0.53

*Determined by hand-held X-ray fluorescence. n.d., not determined.

abundant. They have a high Ni content (33-37 wt%) and sometimes include tiny (2-3 µm), euhedral, chromite crystals. Close to the external surface, the schreibersite crystals melted forming amoeboidal, cuspate particles with a cellular texture of phosphide and Ni-rich metal, and surrounded by Ni-rich metal (Figure 2e). Many of this melted particles have a shrinkage bubble (Figure 2f). The melted schreibersite particles of this iron differ from that observed in Ilafegh 018, and commonly occurring in the heat-affected zone of many irons, because they lack the dendrites of Fe-Ni metal, are surrounded by a well-developed zone of Ni-rich metal, and frequently have a shrinkage bubble. This type of structure recalls those formed by unmixing of two immiscible liquids accompanied by a volume decrease during rapid cooling.

The composition of the metal (Table 2) of Los Vientos 188 is that of IIAB irons (Figure 3).

NWA 5289

A single iron mass was purchased from a Moroccan dealer in August 2007 by Mirko Graul (Bernau, Germany). The 296 g mass, measuring approximately 81×54×30 mm, has a flattened shape (Figure 1c). The portion of the surface originally sitting into the soil is partially covered with caliche deposit, whereas the remaining portion appears to be polished by wind-driven sand. No fusion crust is preserved. Etched sections show a fine octahedrite structure with kamacite lamellae (bandwidth=0.32±0.04 mm, Of) and cellular plessite fields in approximately 1:1 volumetric ratio (Figures 4a, 5a). The kamacite lamellae show abundant Neumann bands and occasionally are displaced along shear planes (Figure 5b). Accessory phases are schreibersite, troilite, chromite (tiny euhedral crystals included in troilite; Figure 5c) and anhydrous Fe-phosphate (up to 1.3 mm in maximum length and surrounded by swathing kamacite; Figure 5d).

The fine octahedrite structure and the composition of the metal (Table 2) are those typical of IVA irons (Figure 3).

NWA 6163

A single iron mass was purchased from a Moroccan dealer in October, 2008 by Mirko Graul. The 358 g mass, measuring 70×57×35 mm, has a cone-like shape with a surface roughly flat and one more convex. The surface is partially (>50%) covered by a brown fusion crust and presents several roughly circular depressions up to 1 cm in diameter (Figure 1d). Etched sections show a well-preserved heat-affected rim and a peculiar internal structure of sub-equant, 5 to 10 mm kamacite grains with prominent Neumann bands between which are comb-

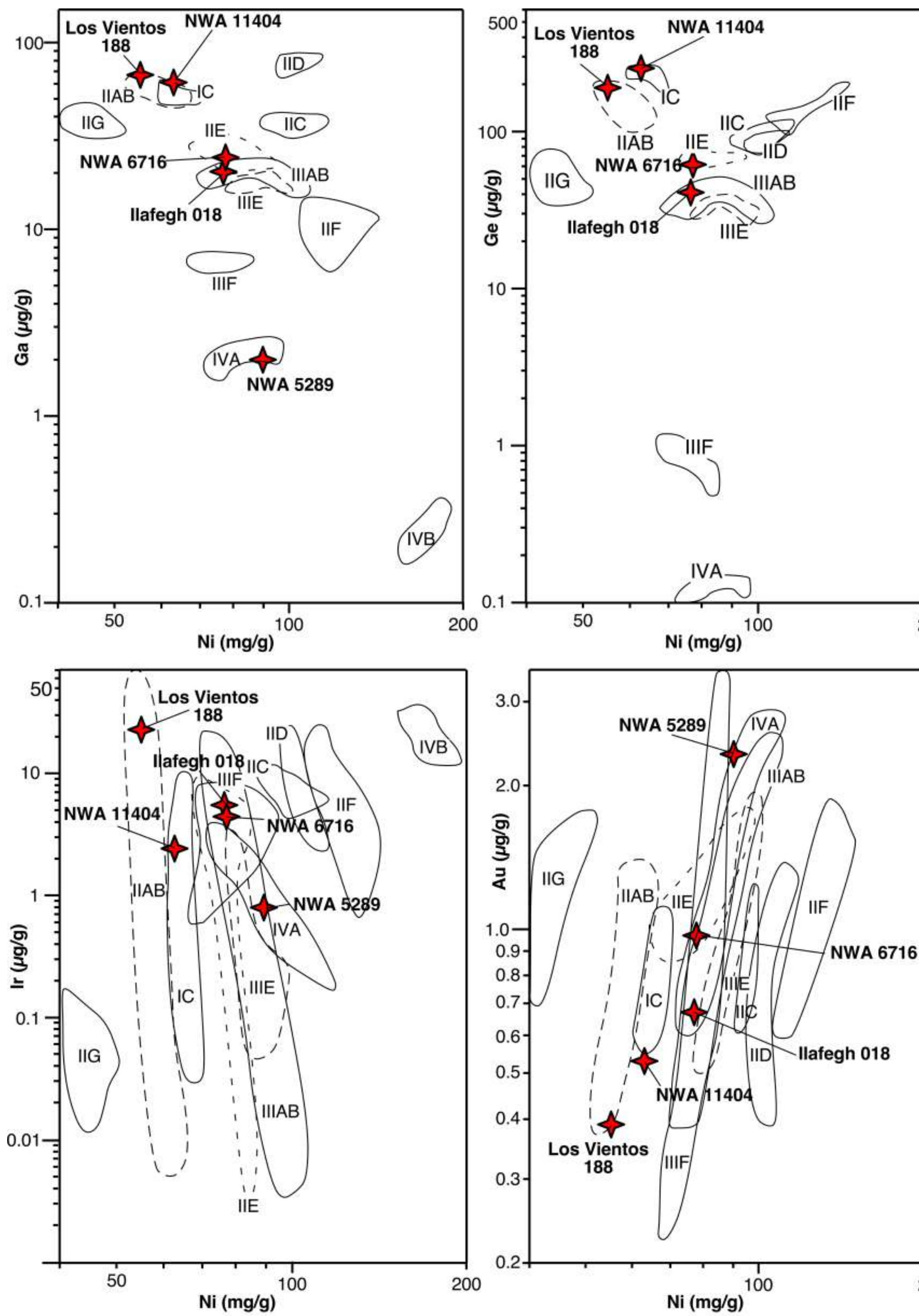

Figure 3. Ga (a), Ge (b), Ir (c), Au (d) vs Ni diagrams showing the fields of the iron meteorite groups IC, IIAB, IIC, IID, IIE, IIF, IIG, IIIAB, IIIE, IIIF, IVA, IVB (data source: MetBase) and the compositions of the studied irons.

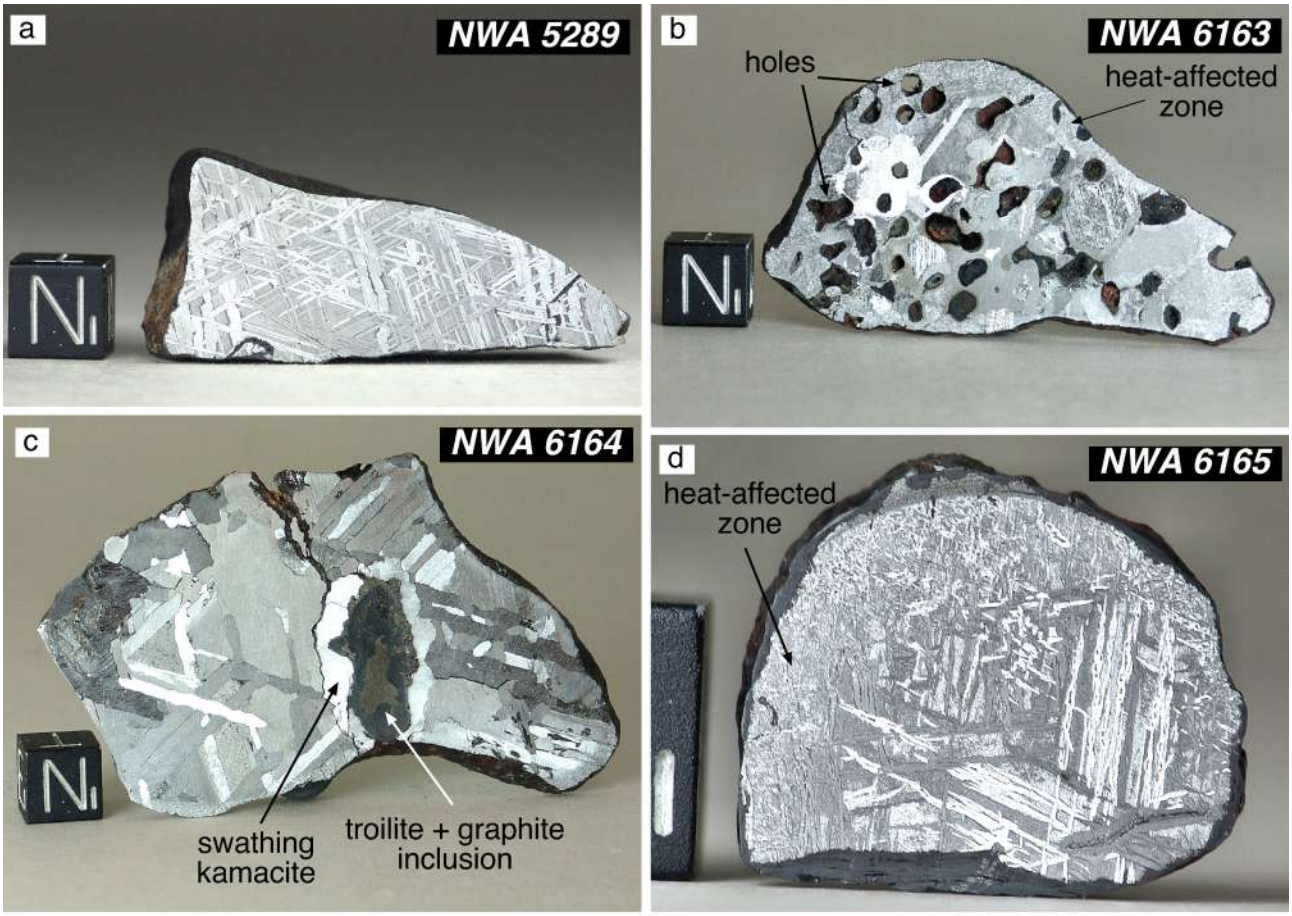

Figure 4. Etched slices of the main mass of NWA 5289 (a), NWA 6163 (b), NWA 6164 (c) and NWA 6165 (d). The side of the scale cube is 1.0 cm. Photo credit: Mirko Graul (meteorite-mirko.de).

net plessite bodies (Figure 4b). Troilite occurs within kamacite as 1 to 6 mm rounded inclusions showing lamellar twinning, whereas schreibersite forms 100 to 500 µm subhedral, elongated crystals often grown at the troilite-kamacite interface (Figure 5e). Several inclusions of troilite show, towards their contact with the host kamacite, replacements by chalcopyrite (Figure 5f). Many small hollow spaces (from 0.5 to 10 mm in length), sometimes lined with black iron hydroxides, characterize the internal structure of this meteorite (Figure 4b). Close to the external surface these cavities are filled with rounded, sand-sized, grains of quartz from the desert soil.

Though similar to IIIAB irons, the composition of this meteorite does not fit any group; therefore NWA 6163 is classified as an ungrouped iron meteorite with anomalous structure (Figure 6).

NWA 6164

A single, irregular-shaped, iron mass weighting 726 g and measuring 88×70×55 mm was purchased from a Moroccan dealer in December, 2007 by Mirko Graul (Figure 1e).

The portion of the surface originally sitting in the soil is partially covered with light-brown caliche, whereas the remaining portion is glossy dark-brown due to polishing by wind-driven sand. No fusion crust is preserved. Etched sections show a coarse Widmanstätten pattern with kamacite lamellae (bandwidth=1.6±0.2 mm, coarse octahedrite; Figure 4c) and comb-net plessite fields in approximately 9:1 volumetric ratio (Figure 7a). Large (up to 2 cm) inclusions of troilite + graphite enclosed in swathing kamacite are also present (Figure 4c). The heat-affected rim (≤1.5 mm) is partially preserved. Kamacite lamellae show abundant Neumann bands and host crystals of cohenite (up to 4 mm in length) with inclusions of schreibersite (Figure 7b) and taenite.

The composition of the metal is that of IAB-Main Group irons (Wasson and Kallemeyn, 2002; Figure 8).

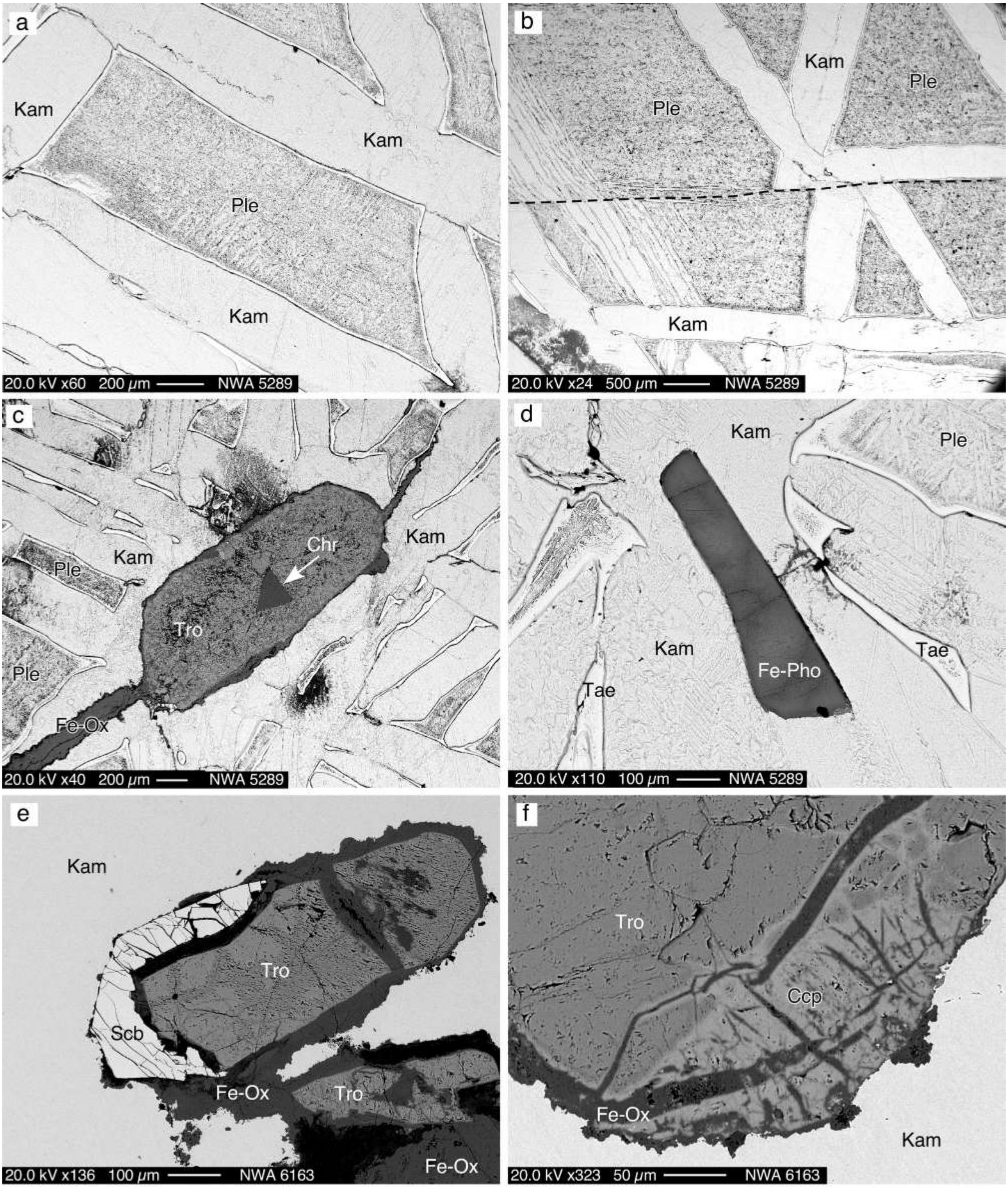

Figure 5. Back-scattered electron images of polished sections of NWA 5289 (a, b, c, d) and NWA 6163 (d, e) iron meteorites. a) Cellular plessite field surrounded by kamacite lamellae; b) Kamacite lamellae displaced along a shear plane; c) Rounded crystal of troilite including a tiny, euhedral chromite crystal ; d) Rounded crystal of an undetermined iron-phosphate; e) Anhedral crystal of troilite partially enveloped in euhedral schreibersite within a kamacite matrix; f) Anhedral crystal of troilite partially replaced by chalcopyrite. Abbreviations: Ccp, chalcopyrite; Chr, chromite; Fe-Ox, iron oxi-hydroxides; Kam, kamacite; Ple, plessite; Scb, schreibersite; Tae, taenite; Tro, troilite.

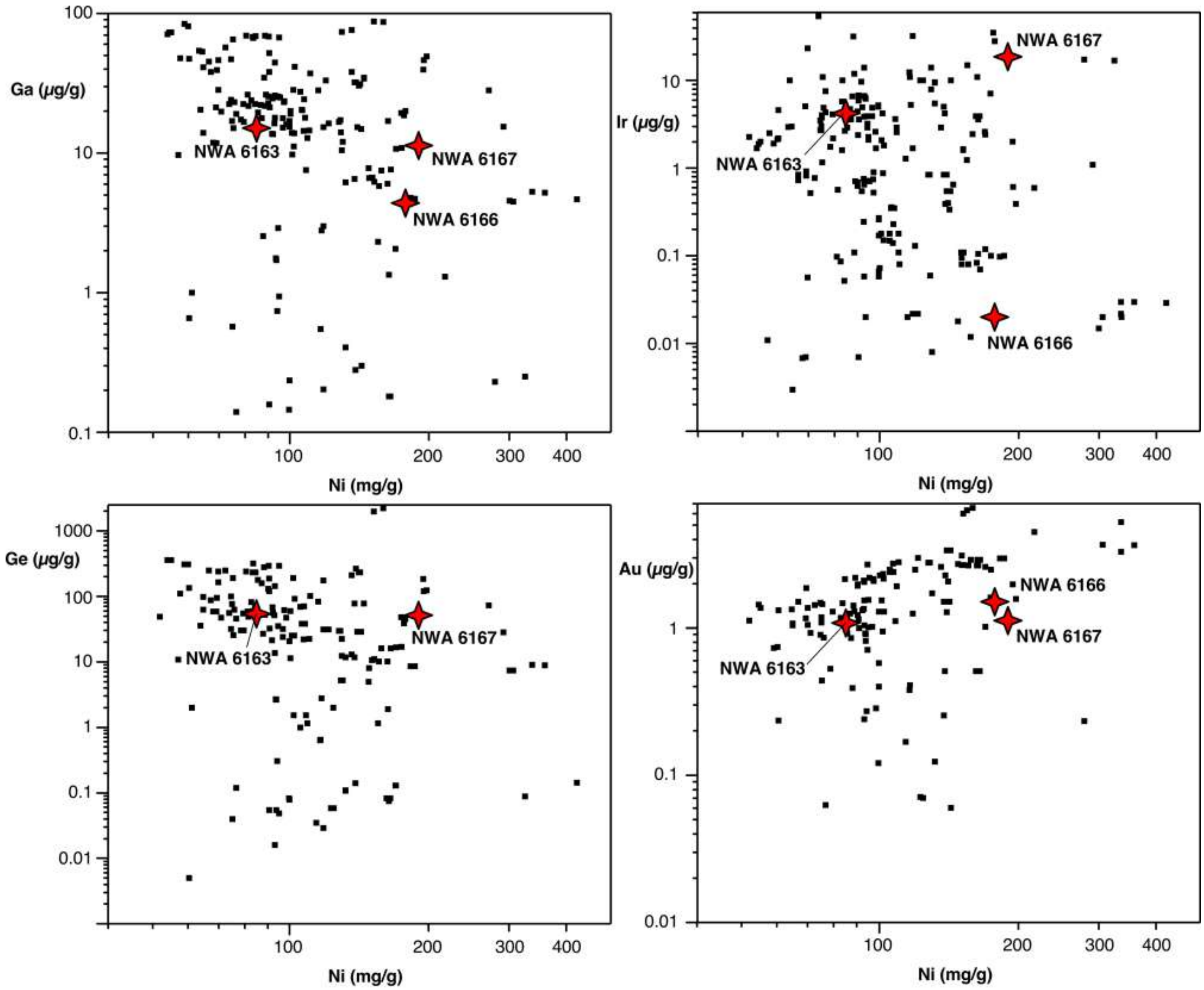

Figure 6. Ga (a), Ir (b), Ge (c), Au (d) vs Ni diagrams showing the ungrouped iron meteorites taken from the literature (data source: MetBase) and the compositions of the studied ungrouped irons.

NWA 6165

A single small iron mass was purchased in Erfoud, Morocco, in December, 2003, by Fabien Kuntz (Besançon, France). The 29 g mass, measuring 3.5×1×1, cm is covered by terrestrial iron oxidation products and lacks fusion crust (Figure 1f). Etched sections display a fine Widmanstätten pattern of straight kamacite lamellae with a bandwidth of 0.25±0.05 mm (fine octahedrite; Figure 4d). Kamacite lamellae show Neumann bands and sub-boundaries. Schreibersite is common as large skeletal crystals (to 1.5 cm) enveloped in swathing kamacite. They are frequently brecciated and cemented by terrestrial oxidation products. The heat-affected zone is locally very well preserved (Figure 7c). Close to the heat-affected rim are found melted schreibersite crystals with dendritic texture and the kamacite is recrystallized into serrated α_2 grains.

The composition of the metal is that of IAB-sLM irons, which is a subgroup of the IAB-complex characterized by low Au and intermediate Ni contents (Wasson and Kallemeyn, 2002; Figure 8).

NWA 6166

A single iron mass was purchased in Erfoud, Morocco, in 2005 by Fabien Kuntz. The 144 g mass measures 5×5×1.5 cm and is lens-shaped. The surface of the meteorite is covered by terrestrial iron oxidation products and lacks fusion crust (Figure 9a). Etched sections show a

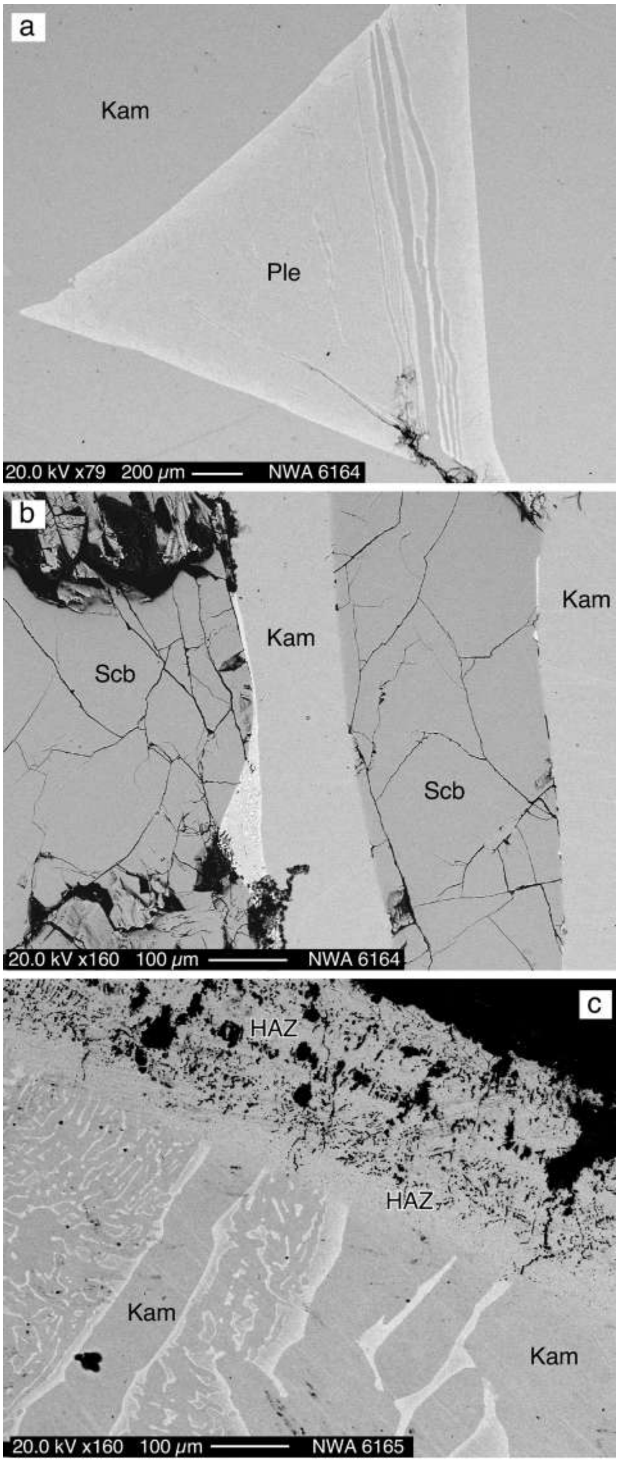

Figure 7. Back-scattered electron images of polished sections of NWA 6164 (a, b) and NWA 6165 (c) iron meteorites. a) Comb-net plessite field surrounded by kamacite lamellae; b) Large fractured crystals of schreibersite; c) Detail of the heat-affected zone of NWA 6165. Abbreviations: Kam, kamacite; Ple, plessite; Scb, schreibersite; HAZ, heat-affected zone.

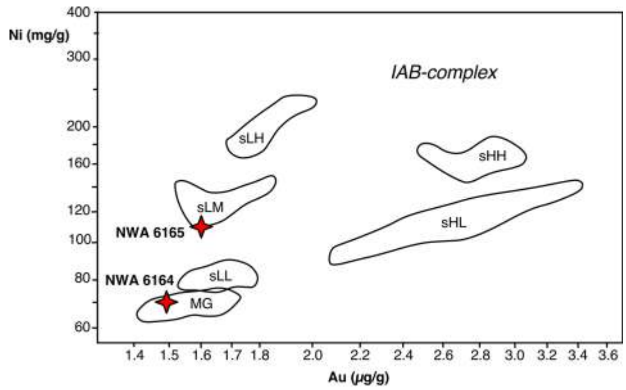

Figure 8. Ni vs Au diagram showing the fields of the Main Group and the sub-groups of the IAB-complex iron meteorites (Wasson and Kallemeyn, 2002). The compositions of NWA 6164 and NWA 6165 are also shown. Abbreviations: MG, Main Group; sLL, sub-group low-Au low-Ni; sLM, subgroup low-Au medium-Ni; sLH, subgroup low-Au high-Ni; sHL subgroup high-Au low-Ni; sHH subgroup high-Au high-Ni.

plessitic octahedrite structure given by pointed kamacite spindles 30-70 μm wide (Figure 10a). Swathing kamacite, nucleated around primary euhedral crystals of schreibersite (100-250 μm in maximum length), is also widespread. The matrix surrounding the kamacite occurs in two different types: some zones have an homogeneous Ni-rich metal matrix; other zones are made of a rather coarse (10-50 μm) intergrowth of Ni-rich and Ni-poor metal arranged into irregular but continuous ribbons (Figure 11 a,b). The heat-affected rim is partially preserved and contains some melted schreibersite crystals showing dendritic structures. The weathering grade of this iron is quite low.

The composition of the metal of this structurally anomalous plessitic octahedrite does not fit any group; therefore NWA 6166 is classified as an ungrouped Ni-rich iron meteorite (Figure 6).

NWA 6167

A single iron mass was purchased in Erfoud, Morocco, in December 2003, by Fabien Kuntz.

The 500 g mass, measuring about 7×4×4 cm, has a bullet-shaped morphology with some regmaglypts and remnants of the fusion crust (Figure 9b). Etched sections show an ataxitic texture (Figure 10b). Under high magnification the metal shows a very fine (1-5 μm) intergrowth of kamacite and taenite arranged into a micro-Widmanstätten pattern. Small globular inclusions (up to 2 mm) of sulfide-rich material are scattered in the metal (Figure 11c). These inclusions are made of a heterogeneous intergrowth of very small (1-10 μm) crystals of kamacite, taenite and schreibersite with interstitial troilite. Some of these

Figure 9. The main masses of NWA 6166 (a), NWA 6167 (b) and NWA 6716 (c) iron meteorites. The side of the scale cube is 1.0 cm. Photo credit: NWA 6166 and NWA 6167, Fabien Kuntz (WWMeteorites.com); NWA 6716, Mirko Graul (meteorite-mirko.de).

inclusions also host small euhedral elongated crystals of chromite (Figure 11d). The studied 16.5 cm^2 surface contains five rounded silicate inclusions (up to 6.8 mm). They consist of prevailing crystals of olivine ($Fo_{79.1-80.6}$), low-Ca pyroxene ($En_{78-80}Wo_{2.2-3.1}$), high-Ca pyroxene ($En_{49-51}Wo_{41-42}$), plagioclase (An_{78-85}), Ca-phosphate and chromite. Close to the boundary with the Fe-Ni metal, the silicate crystals are crossed by tiny veinlets of very fine-grained Fe-Ni metal+troilite or iron oxyhydroxides. The weathering grade of this iron is very low.

The composition of the metal does not fit any group; therefore NWA 6167 is classified as an ungrouped, silicated, Ni-rich ataxite (Figure 6).

NWA 6716

A single iron mass was purchased from a Moroccan dealer in August 2010 by Mirko Graul.

The 293 g wedge-shaped mass measures 110×35×5-30 mm and has a glossy-brown external surface (Figure 9c). Etched section show a polycrystalline texture composed of 0.1 to 2 mm grains of kamacite often showing 120° triple junctions and Neumann bands (Figure 10c). Ghosts of the pre-existing Widmannstätten pattern (bandwidth= 1.5±0.2 mm, Og) are still visible (Figure 10d). Plessitic fields showing comb-net structure are preserved. The sections show three large (to 4.5 mm) rounded inclusions of Cl-rich Ca-phosphate, with rims of Cl-free Ca-Mg-Na-phosphate and tiny inclusions of Cl-free Mg-Ca-Fe-Na-Mn phosphate. Schreibersite is relatively common as elongated (to 8 mm) skeletal crystals. A well-preserved heat-affected zone (Figure 10c) is marked by an 1.5-2.0 mm-thick band showing serrated texture and grain-size (50-100 μm) significantly smaller that the meteorite interior. Terrestrial weathering is low.

The composition of the metal falls in the field of IIE iron meteorites (Figure 3).

NWA 11404

A single iron mass weighting 1096 g was bought in Zagora, Morocco, in June 2016. The etched section shows a fine-scale struture of interlocking ~2 μm thick curved metal spindles. This indicates decompositon of the original metal into $\alpha+\gamma$ phases, and heavy plastic deformation. The Widmanstätten structure has been entirely obliterated by these processes. Schreibersite occurs as fractured euhedral grains (2-5 μm, up to 100 μm; Figure 11e) or needles up to 200 μm long. Chromite occurs as extremely thin (<1 μm) and up to 20 μm long needles (Figure 11f).

The composition of the metal falls in the field of IC irons (Figure 3).

DISCUSSION AND CONCLUSIONS

The ten iron meteorites described in this study were all

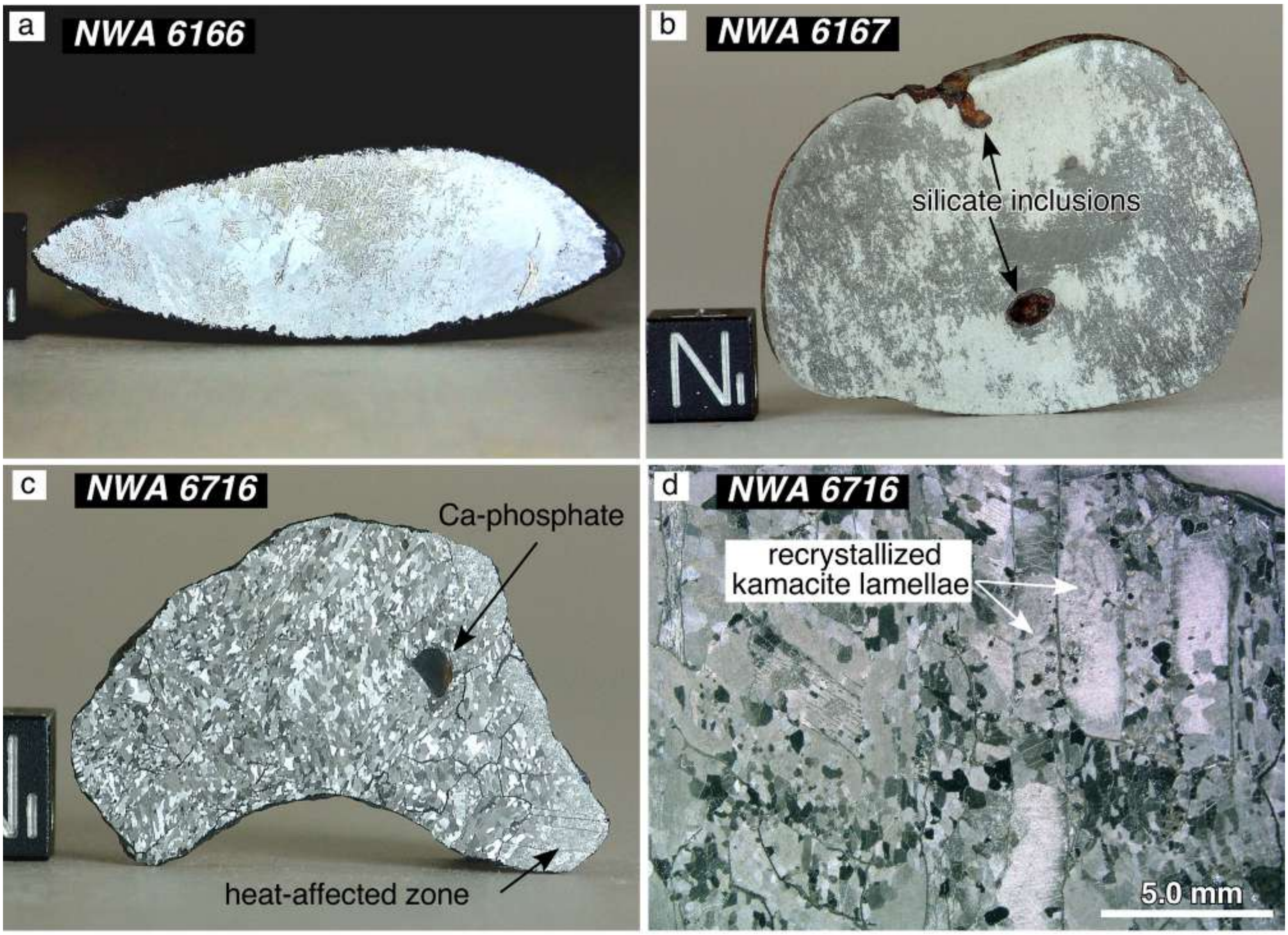

Figure 10. Etched slices of the main mass of NWA 6166 (a), NWA 6167 (b) and NWA 6716 (c, d). The side of the scale cube is 1.0 cm. Photo credit: Mirko Graul (meteorite-mirko.de).

recovered in hot-desert environments (western Sahara and Atacama Desert), and they were all found as single pieces. With the exception of Ilafegh 018, weighting 11.1 kg, they have small masses (from 29 to 1096 g). Seven meteorites still preserve the heat-affected zone or remnants of the fusion crust, indicating a low level of alteration/erosion. As 12 out of the 16 irons analyzed in our laboratory were recovered in northern Africa (Table 1), it is interesting to compare the distribution within the different groups of irons from northern Africa (Algeria, Chad, Egypt, Libya, Mali, Mauritania, Morocco, Niger, Tunisia, Western Sahara) with those from Antarctica and from other parts of the world. Indeed, over the last forthy years a very large number of meteorites have been collected from hot and cold desertic regions, Sahara and Antarctica being the most prominent. Table 3 reports the distribution of the iron meteorites into groups in the northern Africa, Antarctica and other parts of the world. As already observed by Wasson (2011), there is a much higher frequency of IAB-complex in the iron meteorites from northern Africa (46.8%) with respect to Antarctica (30.1%) and the rest of the world (27.4). Ungrouped irons are much more frequent in Antarctica (34.9%) than in northern Africa (13.7%) and the rest of the world (9.3%). These distributions of irons into groups have to be compared to the distributions of sizes (represented by mass). The median mass of the 83 different Antarctic irons is 171 g, that of the 124 irons from northern Africa is 1620 g, and that of the irons from the rest of the world is 15300 g (Figure 12). These different size distributions reflect both the ease with which small meteorites are spotted and recovered in hot- and cold-desert environments and their higher resistance to oxydation in dry climates. Accordingly, it seems that small meteorites, being constituted by a higher proportion of IAB-complex plus ungrouped irons, sample a larger number of parent asteroids. According to Wasson (2011), this could be due the fact that: i) small (centimeter-to-meter) lumps of

Table 3. Distribution of iron meteorites into groups in northern Africa, Antarctica and the rest of the world.

Group	northern Africa (N=124)	northern Africa (%)	Antarctica (N=83)	Antarctica (%)	Rest of the world (N=817)	Rest of the world (%)
IAB	58	46.8	25	30.1	224	27.4
IC	2	1.6	-	-	11	1.3
IIAB	15	12.1	6	7.2	85	10.4
IIC	-	-	-	-	8	1.0
IID	4	3.2	1	1.2	22	2.7
IIE	2	1.6	4	4.8	16	2.0
IIF	-	-	-	-	6	0.7
IIG	-	-	-	-	6	0.7
IIIAB	19	15.3	11	13.3	253	31.0
IIIE	1	0.8	-	-	14	1.7
IIIF	-	-	-	-	9	1.1
IVA	6	4.8	6	7.2	72	8.8
IVB	-	-	1	1.2	15	1.8
UNGR	17	13.7	29	34.9	76	9.3

liquid metal can form by impacts on the regolithic surface of chondritic asteroids generating the precursors of the IAB-complex irons (Wasson and Kallemeyn, 2002); ii) small fragments are more efficiently ejected from asteroids during collisions; iii) small meteoroids evolve more rapidly than larger ones to Earth-crossing orbits (e.g., Farinella et al., 1998). Eight out of the fourteen irons from hot and cold deserts analyzed in our laboratory are ungrouped or IAB-complex irons. Therefore, our set of data, though very small, seems to confirm the trend observed in the world collections.

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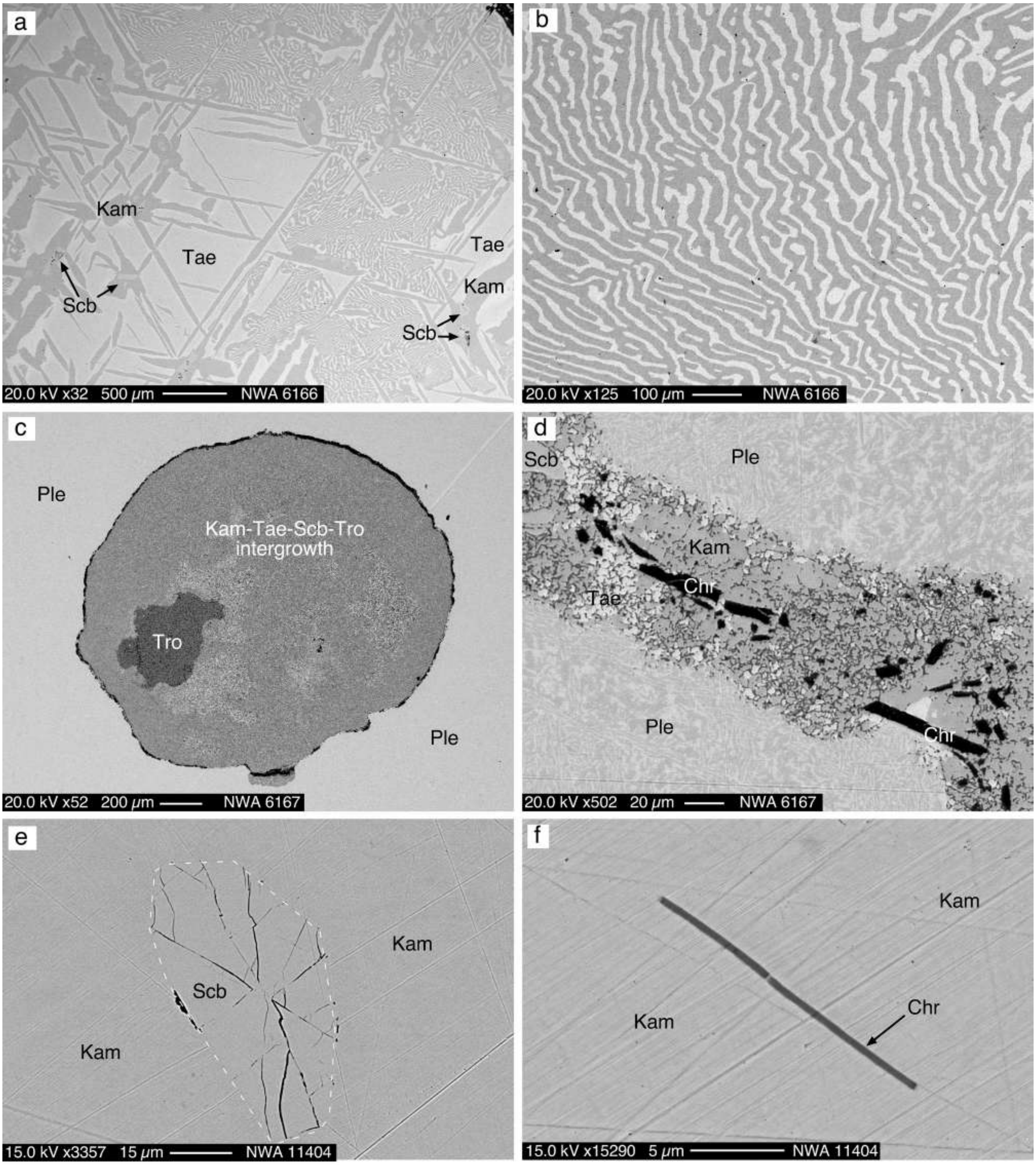

Figure 11. Back-scattered electron images of polished sections of NWA 6166 (a, b), NWA 6167 (c, d) and NWA 11404 (e, f) iron meteorites. See text for explanation. Abbreviations: Chr, chromite; Kam, kamacite; Ple, plessite; Scb, schreibersite; Tro, troilite.

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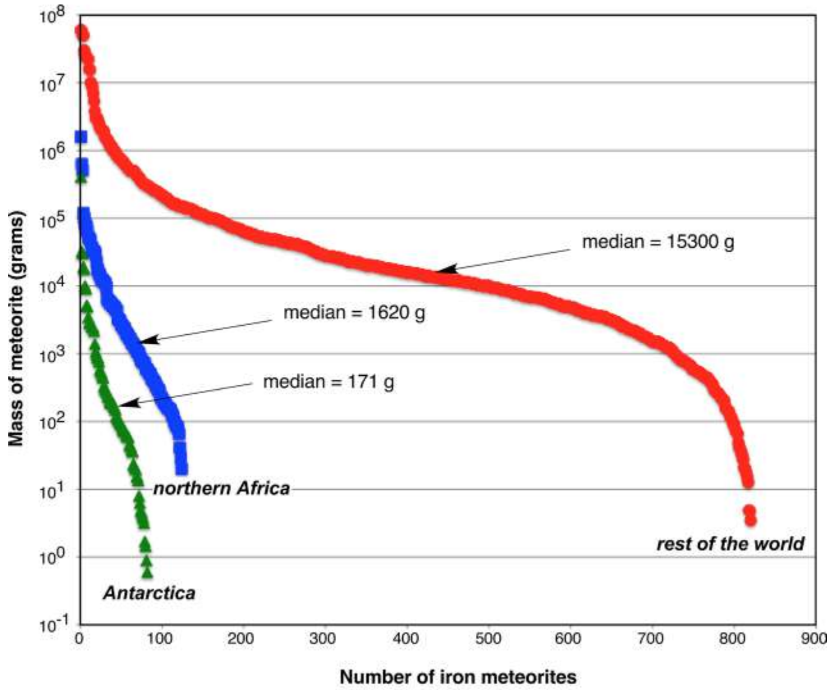

Figure 12. Distribution of iron meteorites from Antarctica, northern Africa and other parts of the world as a function of their sizes.

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