CHAPTER SEVEN

Classification

Numerous schemes for classification have been proposed since Partsch (1843) and Shepard (1846) presented the first serious attempts, at that time on the basis of only about 65 stones and 25 irons. The system which has basically proved most efficient was suggested by Rose (1863). It has been revised and improved by Tschermak (1872a), Brezina (1896), Prior (1920), Yavnel (1968b) and Mason (1971). Basically different classifications have also been proposed. Daubrée (1867b) and Meunier (1884; 1893a) thus introduced a system which won wide support in France, Italy, Spain and most of the Latin-American countries. It has, however, been rightly criticized as rich in inconsistencies and superficial analogies (see e.g., Cohen 1905: 19); it has nevertheless persisted to our day as the basis for classification of some of the less important collections.

The scheme proposed below, Table 23a, adheres to Prior's system and comprises four main divisions. The number of classes has, however, been slightly altered partly because the iron division has been reworked, partly because it was felt that in a basic scheme comprising almost 1700 meteorites there should be no room for five old classes each of which contained only one or two known samples: thus the chassignites (1), angrites (1), nakhlites (2), siderophyrs (1) and lodranites (1) have been omitted, and, in their place, four, more extensive, "anomalous" classes have been introduced. The anomalous classes embrace meteorites which for one reason or another do not fit into the normal classes; with a negative criterion like this, individual members must necessarily be very different. Stone meteorites assigned to the anomalous classes are listed in the footnotes to the scheme, while the anomalous stony irons are briefly discussed below.

Just as there are stones which are unique and require individual recognition, e.g., Winona and Angra dos Reis, there are irons which are unique or at the most have one or two relatives, both in regard to structure and chemical composition. Such iron meteorites, e.g., Kodaikanal, Tucson and Mundrabilla, have been classed together as "anomalous irons." In the main part of this book and in Appendix 1, the reasons for the individual choices have been discussed and summarized.

In the scheme the number of falls and the total number of meteorites, i.e., falls plus finds, within each class are noted. The data are condensed from the more detailed compilation in Table 23b, where an attempt has been made to assemble the pertinent statistics as to falls, showers, finds and weights for all meteorites. A shower has, for this purpose, been defined as a fall that – in the air – decomposed into two or more fragments, which were subsequently recovered.

Also, the ratio between the number of finds and the number of falls has been calculated. This ratio mainly serves to indicate how easily meteorites will be recognized by layman: the higher the ratio, the easier the meteorite type will be distinguished from terrestrial rocks and reported. To a minor degree the ratio also reflects the resistance of meteorites to terrestrial weathering: the higher the ratio, the more stable the meteorite type.

Within the iron division, it was deemed necessary to exclude certain meteorites from those which were classified. Those excluded are insufficiently known, be it due to inaccessibility, state of corrosion or for other reasons; see page 37 and Appendix 2. By comparison, it is surprising to observe how homogeneous the chondritic classes apparently are, and how neatly all chondrites apparently can be referred to their pigeonholes in the classification system, leaving none unclassified and less than one percent anomalous. The system, as it stands here, has, in somewhat similar forms, won wide recognition; but it should be emphasized that it has not taken into account the often very complex nature of some stony meteorites, as for example several of the so-called polymict breccias discussed by Wahl (1952).

The meteoritic stones, or aerolites, are covered by the chondrite division and the achondrite division. The total of 634 falls have provided about 14.9 tons of material, i.e., on the average more than 23 kg per fall. However, to emphasize the fragmentary nature of our statistics it may be noted that until 1968 the carbonaceous chondrites C3-C4 comprised 11 falls, totaling less than 400 kg. Since then the Allende fall, on February 8, 1969, has alone added more than 2000 kg. A similar situation exists within iron meteorites: The Sikhote-Alin fall in 1947 (page 1123) added more than 23 tons to the previously rather rare group IIB. Nevertheless, the total quantity of meteorites recovered through the last some two hundred years amounts to no more than 485 tons, see Table 23b. The *annual* primary production of gold is about three times this amount; it is no wonder that meteorites are in demand and are expensive.

Chondrites

The Chondrites (Rose 1864a: 29, 84; Mason 1962a; Wood 1963; Van Schmus & Wood 1967) contain millimeter-sized silicate spherules, chondrules, and 19-35 weight percent iron, either as free nickeliferous iron or bound in troilite and silicates. The chondrites may be divided as shown in Table 24 into six classes according to their chemical composition. Within each class a range of textures exists which may be interpreted as representing progressive degrees of recrystallization, Table 24a (Van Schmus & Wood 1967; Dodd 1969). In Table 24b two typical

Table 23a. The Classification of Meteorites

Symbol	Class	Characteristic Minerals	Falls	Total	Example
E	Enstatite chondrites	Enstatite, nickel-iron	11	16	Hvittis
H	Olivine-bronzite chondrites	Olivine, bronzite, nickel-iron	224	450	Hessle
L	Olivine-"hypersthene" chondrites	Olivine, bronzite, nickel-iron	256	461	Bjurbole
LL	Amphoterites	Olivine, bronz-hyperst., plagioclase	49	64	Siena
C3-4	Carbonaceous, Type 3-4	Olivine, pyroxene, organics	12	15	Allende
C1-2	Carbonaceous, Type 1-2[1]	Chlorite[4], sulfates, organics	21	21	Orgueil
	Anomalous chondrites[2]		1	3	Winona
CHONDRITES		**Total:**	**574**	**1030**	
Au	Aubrites } Ca-poor (0.3-1.9%)	Enstatite, forsterite	8	9	Norton County
Di	Diogenites } Ca-poor (0.3-1.9%)	Bronzite, clinobronzite	8	8	Johnstown
U	Ureilites } Ca-poor (0.3-1.9%)	Olivine, nickel-iron, diamond	3	6	Novo-Urei
Ho	Howardites } Ca-rich (3-8%)	Hypersthene, bytownite	17	19	Kapoeta
Eu	Eucrites } Ca-rich (3-8%)	Pigeonite, bytownite	20	23	Stannern
	Anomalous achondrites[3]	Ti-augite; olivine; chromite	4	5	Nakhla
ACHONDRITES		**Total:**	**60**	**70**	
P	Pallasites	Olivine, nickel-iron	2	33	Imilac
M	Mesosiderites	Pyroxene, bytownite, nickel-iron	6	20	Estherville
	Anomalous stony irons	Pyroxene, nickel-iron; tridymite	1	6	Lodran
STONY IRONS		**Total:**	**9**	**59**	
I	Coarse inclusion-rich octahedrites	Kam., taen., graphi., silic., carbides	5	69	Canyon Diablo
I-An	Inclusion-rich irons	Kam., taen., graphi., silic., carbides	2	19	Copiapo
IIA	Hexahedrites	Kamacite, daubreelite	4	43	Coahuila
IIB	Coarsest octahedrites	Kamacite, taenite	1	14	Sikhote-Alin
IIC	Plessitic octahedrites	Kamacite, taenite	0	7	Ballinoo
IID	Medium octah. (10-11.5% Ni)	Kamacite, taenite	2	11	Carbo
IIIA	Medium octah. (7-8.8% Ni)	Kamacite, taenite, troilite	4	117	Cape York
IIIB	Medium octah. (8.6-10.6% Ni)	Kamacite, taenite, phosphates	1	40	Chupaderos
IIIC	Fine octah. (10.5-13.5% Ni)	Kamacite, taenite, carbides	1	6	Mungindi
IIID	Finest octahedrites	Kamacite, taenite, carbides	0	5	Tazewell
IIIE	Coarse octahedrites	Kamacite, taenite, cohenite, graphite	0	7	Kokstad
IVA	Fine octah. (7.5-10% Ni)	Kamacite, taenite	1	39	Gibeon
IVB	Ataxites	Kamacite, taenite	0	11	Hoba
	Anomalous irons	Kam., taen., silicate, graphite	4	92	Nedagolla
	Unclassified irons		7	52	Armanty
IRONS		**Total:**	**32**	**532**	
METEORITES		**Total:**	**675**	**1691**	

1) Also in some systems classified as olivine-pigeonite chondrites, or HL chondrites.
2) Kakangari, Winona, Mount Morris (Wisconsin).
3) Chassigny, Angra dos Reis, Nakhla, Lafayette, Shergotty
4) Chlorite or serpentine; identification very difficult (Mason 1972).

chondrites from each petrologic type have been selected for illustration. The numbers within the boxes indicate how many of the classified meteorites that had been studied, at the time of writing, with respect to their petrologic type. The systematic arrangement does not imply that, e.g., the meteorites Adhi-Kot, Abee, St. Marks and Hvittis necessarily represent a metamorphic rock sequence, since significant initial variations also seem to have been present within a class. In many instances chemical and textural similarities may only indicate formation of meteorites under similar conditions and from similar starting material, so it is possible that many of the recognized classes had already acquired their characteristic composition independently by differentiation in the solar nebula. One can still say with Wiik (1956):

"This [system] is intended only to give a picture of the

Table 23b. Statistical Data for All Meteorite Classes, as of Jan. 1, 1972

Class	Falls Number	Number of Shower-[2] producing falls	Falls kg[1]	Finds Number	Finds kg[1]	Finds / Falls	Total Number	Total kg[1]
E3	1	0	4	0	0	0.0	1	4
E4	2	0	142	3	1	1.5	5	143
E5	2	0	28	0	0	0.0	2	28
E6	6	2	52	2	7	0.33	8	59
Enstatites	11	2	226	5	8	0.46	16	234
H3	4	1	40	5	309	1.25	9	349
H4	16	6	985	21	266	1.31	37	1251
H5	53	23	1057	23	210	0.44	76	1267
H6	30	13	486	14	871	0.46	44	1357
H no specification	121	49	869	163	1305	1.35	284	2174
Bronz. chondr.	224	92	3437	226	2961	1.01	450	6398
L3	8	7	71	2	60	0.25	10	131
L4	11	4	719	10	478	0.91	21	1197
L5	23	13	862	21	494	0.91	44	1356
L6	107	48	3118	48	1555	0.45	155	4673
L no spec.	107	41	854	124	1299	1.16	231	2153
Hypers. chondr.	256	113	5624	205	3886	0.80	461	9510
LL3	5	4	90	0	0	0.0	5	90
LL4	1	1	80	1	44	1.0	2	124
LL5	7	4	181	2	3	0.29	9	184
LL6	16	10	669	4	46	0.25	20	715
LL no spec.	20	9	479	8	123	0.40	28	602
Amphoterites	49	28	1499	15	216	0.31	64	1715
C3-4	12	7	2378	3	34	0.25	15	2412
C1-2	21	13	165	0	0	0.0	21	165
Carbon. chondrites	33	20	2543	3	34	0.09	36	2577
Anom. chondrites	1	1	1	2	26	2.0	3	27
Chondrites	574	256	13330	456	7131	0.80	1030	20461
Aubrites	8	5	1200	1	5	0.13	9	1205
Diogenites	8	3	68	0	0	0.0	8	68
Ureilites	3	1	5	3	4	1.0	6	9
Howardites	17	5	34	2	7	0.12	19	41
Eucrites	20	7	207	3	24	0.15	23	231
Anom.- achondrites	4	1	51	1	1	0.25	5	52
Achondrites	60	22	1565	10	41	0.17	70	1606
Pallasites	2	0	45	31	7162	15.5	33	7207
Mesosiderites	6	3	479	14	1153	2.33	20	1632
Anom. siderolites	1	0	1	5	224	5.0	6	225
Siderolites	9	3	525	50	8539	5.6	59	9064
I	5	1	188	64	94500	12.8	69	94688
I-Anom.	2	1	107	17	7450	8.5	19	7557
IIA	4	2	304	39	3259	9.8	43	3563
IIB	1	1	23000	13	5089	12.0	14	28089
IIC	0	0	0	7	201	∞	7	201
IID	2	1	66	9	1100	4.5	11	1166
IIIA	4	1	32	113	100846	29.3	117	100878
IIIB	1	0	63	39	28045	42.0	40	28108
IIIC	1	0	1	5	144	5.0	6	145
IIID	0	0	0	5	54	∞	5	54
IIIE	0	0	0	7	705	∞	7	705
IVA	1	0	4	38	22250	38.0	39	22254
IVB	0	0	0	11	60487	∞	11	60487
Anom. irons	4	2	46	88	74396	21.5	92	74442
Irons	25	9	23811	455	398526	18.1	480	422337
Irons, no spec.	7	0	87	45	32200	6.3	52	32287
Irons total	32	9	23898	500	430726	15.5	532	454624

Footnotes: 1) Recovered weight. In many cases estimated; therefore, the figures must be taken with reservation.
2) A shower produced two or more fragments that were recovered.

chemical relations between the subgroups, and not intended to suggest the genesis. There is insufficient evidence at the moment to permit any clear conclusions regarding the genesis of various groups of meteorites."

This is perhaps particularly true of the carbonaceous chondrites, that in the future will require more subdivisions or classes to be introduced into the present system of classification (see, e.g., Yavnel 1968b; Van Schmus 1969; Mason 1970a). Again, however, the total number of carbonaceous chondrites is relatively small, so it is limited how specific one can be in a classification system.

In most chondrites the major minerals are olivine, orthopyroxene, albitic feldspar, troilite, calcic pyroxene, and metallic nickel-iron (Kamacite, taenite and their

Table 24. Classification and Composition of Chondrites

a. Chondrite Classification

	Petrologic Type					
	1	2	3	4	5	6
E			Enstatite chondrites			
H			Olivine-bronzite chondrites			
L			Olivine-hypersthene chondrites			
LL			Amphoterites			
C3-C4			Carbonaceous chondrites			
C1-C2	Carbonaceous chondrites					

← Increasingly unequilibrated — Progressively recrystallized →

b. Chondrite Examples. The number of chondrites so far identified to petrologic type is given in each case.

	1	2	3	4	5	6
E			Adhi Kot 1	Abee 5 Indarch	St. Marks 2 St. Sauveur	Hvittis 8 Pillistfer
H			Sharps 9 Tieschitz	Tysnes 37 Weston	Hessle 76 Pultusk	Guareña 44 Kernouvé
L			Hallingeberg 10 Mezö-Madaras	Bjurböle 21 Tennasilm	Farmington 44 Knyahinya	L'Aigle 155 Bruderheim
LL			Chainpur 5 Parnallee	Kelly 2 Soko-Banja	Olivenza 9 Krähenberg	Ensisheim 20 St. Severin
C3-4			Ornans 13 Vigarano	Coolidge 2 Karoonda		
C1-2	Alais 5 Ivuna	Murray 16 Murchison				

c. Chondrite Composition (some characteristic data)

	Metallic Fe[4]	Total Fe	Total S	Total P	Fe/Si	Si/Mg	Fayalite mole %	Spec. Grav. g/cm³
	weight %				atomic %			
E	19-28	22-35	2.6-6.1	0.04-0.26	0.83±0.32	1.27±0.10	–	3.45-3.65
H	14-19	25-31	0.9-2.6	0.00-0.23	0.83±0.08	1.04±0.03	16-20	3.40-3.90
L	4-11	20-23.5	0.8-3.0	0.00-0.30	0.59±0.05	1.07±0.03	22-26	3.25-3.75
LL[1]	0.5-4	18.5-21.5	1.8-2.6	0.06-0.18	0.53±0.03	1.06±0.03	27-32	3.45-3.55
C3-C4[2]	0-5	24-26	1.3-2.7	0.09-0.17	0.80±0.04	0.95±0.03	32-40	3.4-3.8
C1-C2[3]	0-0.1	18-24	2.8-6.7	0.05-0.18	0.85±0.05	0.95±0.03	–	2.2-2.9

1) Soko-Banjites of Craig (1964).
2) Ornansites of Craig (1964) and others.
3) The C1-C2 carbonaceous chondrites contain 10-20% water and 1-5% total carbon, but the analyses reported here are on a carbon- and water-free basis.
4) The data refer to the iron amount. Since nickel remains remarkably constant between 0.7 and 2.0 weight % and is present almost entirely in the metal phase, the structural ratio of taenite to kamacite may be expected to increase systematically from class to class. In those chondrites with little or no metal present, nickel is chalcophilic, occurring mainly in the nickel-iron sulfide pentlandite.

Data compiled from Wiik (1956), Pokrzywnicki (1957), Keil (1962), Craig (1964), Van Schmus & Wood (1967), Mason (1971) and Moore (1971).

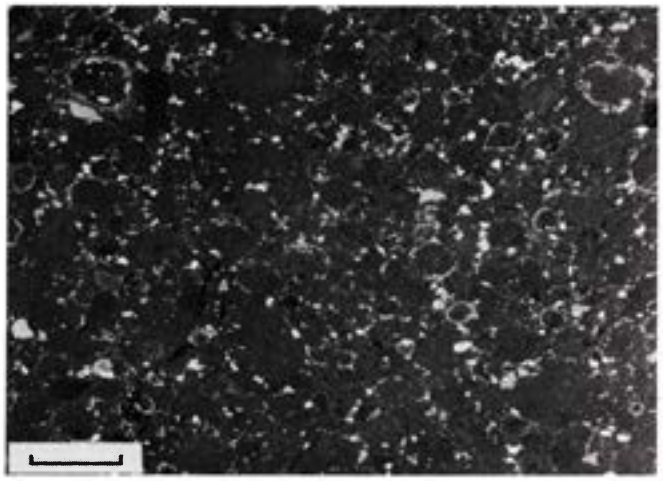

Figure 62A. The stone meteorite Mezö-Madaras fell in 1852 in Rumania (U.S.N.M. no. 3242). It is an olivine-hypersthene chondrite (L3). Tiny grains of nickel iron and troilite (white) are liberally sprinkled through the stone, sometimes enveloping the chondrules in discontinuous rings. Polished section. Scale bar 2 mm. S.I. neg. M-979.

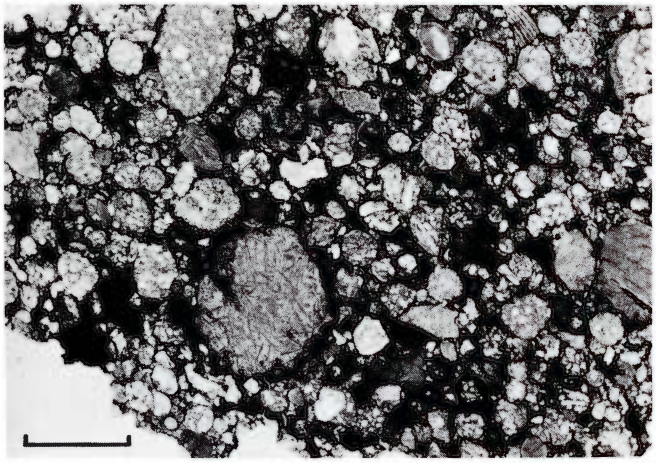

Figure 62B. Mezö-Madaras. In thin section the opaque minerals (nickel-iron and troilite) appear black, but the interior crystalline structure of the chondrules is distinctly seen. Polished thin section. Scale bar 2 mm. S.I. neg. M-1152. Compare Figure 62A.

plessite intergrowths). Minor minerals are graphite, oldhamite, daubreelite, schreibersite, tridymite, chromite, ilmenite, rutile, chlorapatite and whitlockite (see, e.g., Mason 1962b; 1972; Keil 1969). The kamacite of enstatite chondrites is remarkable by its high silicon content (1-4 weight %; Keil 1968), a composition which elsewhere is found only in some enstatite achondrites and a few iron meteorites, e.g., Tucson and Horse Creek. In carbonaceous chondrites, magnetite, epsomite (a magnesium sulfate), pyrrhotite, dolomite and other minerals occur, often with crystal water, but particularly interesting are the organic compounds. Aliphatic and aromatic hydrocarbons have been identified in significant numbers, e.g., n-alkanes, alkylbenzenes and alkylnapthalenes. Below C_8, branched alkanes, benzene and toluene dominate. Thiophenes, amino acids, porphyrin-like pigments and chlorobenzenes have also been found, particularly in C1 and C2. The C3 and C4 chondrites are apparently metamorphosed to a significant extent and contain little water and indigenous organic matter.

The presence of organic compounds and graphite may perhaps best be explained on the assumption that Fischer-Tropsch reactions were common in the primitive solar nebula: from simple molecules, like CO, H_2 and NH_3, the complexes were synthesized by the catalytic action of nickel-iron and magnetite on the surfaces of dust grains (Studier et al. 1968; 1972). A close study of 17 amino acids from Murchison (Kvenvolden et al. 1970) revealed these to be largely racemic; i.e., of abiological origin. They could, thus, not have been introduced by terrestrial contamination, but may well have been produced by a Fischer-Tropsch-like synthesis in the primitive solar system.

The compositions of the major silicate minerals are usually uniform within recrystallized chondrites and very similar for individual chondrites belonging to a given class (see, e.g., Mason 1965b, Yavnel 1968b). The olivine may thus be characterized by its fayalite content, as indicated in Table 24c. In unequilibrated chondrites the minerals are usually quite variable in composition and often zoned, and the primary structures of individual chondrules are well-preserved. The E6 enstatite chondrites have on the other side lost their chondritic structure, but their chemical and mineralogical similarities to E3, E4, E5 leave no doubt as to their classification. The C1 carbonaceous chondrites do not contain chondrules at all, but again because of chemical and mineralogical relationships to chondrites, they are tentatively classified with them.

Two principal hypotheses for the origin of the enigmatic chondrules have been proposed. One hypothesis suggests that chondrules are primary objects which condensed from a relatively slowly cooling gaseous nebula of solar composition and then agglomerated to form the meteorite parent bodies (Suess 1949; Blander & Katz 1967). The second hypothesis suggests that chondrules are secondary objects formed from preexisting solids by processes such as volcanism (Tschermak 1875), impact splattering (Fredriksson 1963), shock melting of primitive dust (Wood 1963), or electrical discharges through the primitive dust cloud (Whipple 1966). That glasses really can be produced in large concentrations by impact is proved by the surface samples recovered from the Moon (Chao et al. 1970; Glass 1971). The lunar soil, the so-called regolith, a few meters in depth, is observed to consist of from 10 to 60% glass, depending in general upon site and core sample. The glasses occur as coatings, ellipsoids, dumbbells, perfect spherules and as fragments of these, and the analystical data suggest that the glasses are mainly derived by impact from the lunar surface rocks and soil. Apparently, on the Moon, glass can remain metastable, without devitrification, through billions of years, possibly due to the extreme deficiency of water.

Many chondrites are not simple aggregates of perfect

chondrules and comminuted matrix. Commonly chondrules have been broken prior to, or during, accretion, and furthermore some chondrules show evidence of plastic deformation and chemical alteration, suggesting that they were exposed to mutual collisions while still hot. Finally, many polymict breccias also contain angular to rounded fragments of pre-existing chondritic or crystalline material. Also a few iron meteorites, such as Netschaevo, apparently include chondritic fragments. Although the question of the origin of chondrules is not solved, it appears that the observational data favor an origin as secondary objects in the top soil of a planet exposed to the infall of other bodies. For thorough discussions and references to the extensive literature on chondrules, the reader is referred to the above mentioned papers, and to Kurat (1967), Binns (1968), Fredriksson (1969), Van Schmus (1969) and Ahrens & O'Keefe (1972).

Achondrites

Achondrites (Cohen 1905: 13; Moore 1962; Mason 1962a; Wasson & Wai 1970) form a somewhat heterogeneous division, characterized by the absence of chondrules, by less iron – about 14 weight % – than in chondrites, and by analogies in both chemical, mineralogical and mechanical properties to some terrestrial rocks (diabases, dunite, pyroxenites); see Table 25. Their resemblance to terrestrial rocks also seems to be reflected in the low ratio, 0.17, between finds and falls (Table 23b). The total weight of all achondrite falls is about 1560 kg, but if the 1000 kg Norton County is subtracted, there remains 560 kg on 59 falls or on the average less than 10 kg per fall. The achondrites contain only small amounts of metallic nickel-iron and troilite. While analyzing one-half kilogram of the aubrite, Norton County, Wiik (1956) thus noted only three small rounded fragments of metallic nickel-iron, amounting to 0.73 weight %. The specific gravity of the achondrites ranges from about 3.00 (some eucrites) to 3.40 (some diogenites). The mineralogy and texture of many achondrites suggest that they at one time were entirely molten and crystallized from a magma, in contrast to the chondrites which never were molten, but acquired their final texture through varying degrees of metamorphism.

The ureilites form a distinct achondrite class of six meteorites, of which the most recent fall is that of Haverö, Finland, August 2, 1971, (Wiik 1972; Jedwab 1972). The ureilites, named after the fall of Novo-Urei in 1886, contain olivine, pigeonite and kamacite. The metal and some troilite are present as micron-sized globules and as polycrystalline flakes that constitute 3-6 weight % of the mass. Carbonaceous matter occurs as irregular inclusions between silicate, troilite and metal. Most of the carbon is in the form of graphite, while only trace quantities (~ 1 ppm) of hydrocarbons occur. In Haverö (Vdovykin 1972) 0.32% of the meteorite consists of hard polycrystalline aggregates of diamond and lonsdaleite microcrystals (< 1 μ). Diamonds have long been known from other ureilites (Jerofejef & Latsjinof 1888); their occurrence, together with lonsdaleite, is best interpreted as indicating formation under cosmic shock conditions from preexisting graphite.

Stony Irons

Pallasites form the most homogeneous class within the classification system. They are characterized by the presence of up to centimeter-sized, rounded or angular olivine crystals (11-13 or 18-20 mole % fayalite), embedded in an equal volume of nickeliferous iron (Rose 1864a: 28, 73; Mason 1963; Buseck & Goldstein 1969). Only two pallasite falls are recorded (Table 23b), that of Marjalahti 1902, which provided 45 kg, and that of the little known Laisho (1898?) which allegedly comprised only one mass of 330 grams. Although the present author originally planned to leave pallasites out of the handbook because they are not

Table 25. Composition of Achondrites and Stony-Irons

	Metallic Fe average	Total Fe	Total Ni[1]	Total S	Total P	Total Mg	Total Ca	Average Spec. Grav. g/cm^3
				Weight %				
Aubrites	2.3	0.5-3.0	0.04-0.1	0.2-0.5	0.01-0.03	22.5-24.6	0.5-1.2	
Diogenites	0.8	11.7-16.6	0.02-0.1	0.1-0.6	0.03-0.04	14.0-17.1	0.5-1.9	3.36
Ureilites	3.9	11.3-16.4	0.09-0.23	0.2-0.6	0.03-0.04	22.0-23.5	0.3-1.0	(3.29)
Howardites	0.3	13.7-14.1	< 0.01	0.1-0.5	0.04-0.07	7.2-12.4	2.9-5.8	3.23
Eucrites	0.8	12.2-15.8	< 0.01[2]	0.02-0.5	0.005-0.08	3.9-5.1	7.1-8.2	3.23
Pallasites	49	30-69	3-8	0.2-1.0	0.06-0.25	25.6-29.3[3]	0.002-0.008[3]	4.90
Mesosiderites	46	44-52	3.2-4.8	0.2-4.6	0.25-0.54	7.3-13.6[3]	2.0-5.7[3]	4.85

1) Bulk nickel values for achondrites are not known with great precision.
2) According to Duke (1965) even as low as 4 ppm and thus significantly lower than in terrestrial basalts, which contain 40-230 ppm Ni.
3) Data for the separated silicate phases.
Compiled from Urey & Craig (1953), Keil (1969), Mason (1971), Moore (1971) and Wiik (1972).

considered proper iron meteorites, a few (Glorieta Mountain, Hopewell Mounds, Imilac and Lazarev (?)) have been included, either because the metallic portion of these meteorites has become so significant that, in small samples, the meteorites could pass for undisputed irons, or because new field work and structural data could be reported (Imilac). Typical chemical data are summarized in Table 25.

Mesosiderites are composed of about equal weights of nickel-iron and silicates. The nickel-iron usually occurs as discrete blebs and grains that may reach centimeter-size and display Widmanstätten structure (Figure 64). The silicates are mainly orthopyroxene and anorthitic plagioclase, but olivine, clinopyroxene, troilite, schreibersite and chromite also occur. Several accessory minerals have been noted. The structure is often brecciated (Rose 1864a: 28; Mason 1962a: 125; Powell 1969). The six mesosiderite falls are Barea (1842: 3 kg), Estherville (1879: 300 kg), Veramin (1880: 54 kg), Dyarll Island (1933 ? 0.2 kg ?), Lowicz (1935: 59 kg) and Patwar (1935: 37 kg). Typical chemical data are summarized in Table 25.

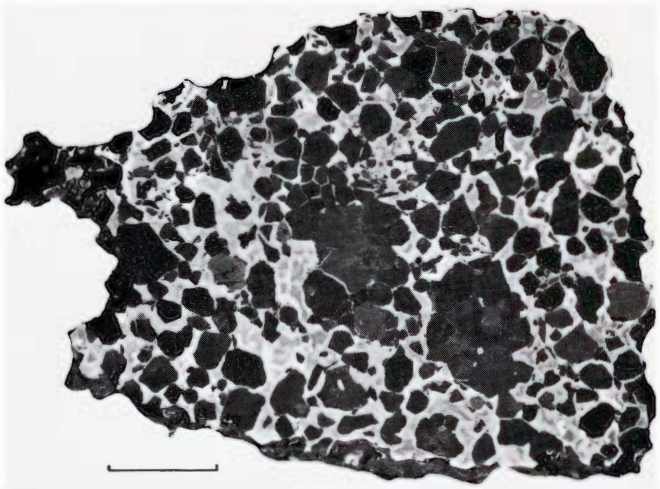

Figure 63. The pallasite Salta (U.S.N.M. no. 1333). One mass of 27.1 kg was found in Argentina and acquired by the Smithsonian Institution. The subangular olivine grains (black) have nucleated rims of swathing kamacite (white). The remaining metal has transformed into fine Widmanstätten patterns that indicate a large number of randomly oriented parent taenite grains. Salta is possibly a transported fragment of Imilac. Etched. Scale bar 3 cm. S.I. neg. M-1336A.

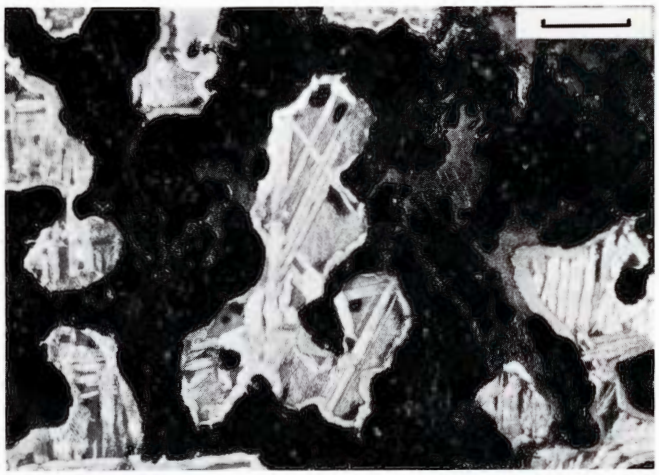

Figure 64. The siderophyre Steinbach (Copenhagen no. 1872, 2803) was found in Saxony. It is composed of about 50 weight % metal and 50% silicates. The silicate portion contains about 70% bronzite and 30% tridymite (Dörfler et al. 1965). The metal forms a spongy, almost continuous network. Its fine octahedral structure and its composition closely resemble that of many group IVA irons, such as Hill City and Duchesne. Etched. Scale bar 3 mm.

The *anomalous stony irons* comprise Lodran (one kilogram fell in 1868) and the finds Bencubbin, Enon, Mount Egerton, Weatherford and Steinbach. Lodran (the sole example of the Lodranites in the old system) consists of a friable aggregate of granular olivine and orthopyroxene in a discontinuous nickel-iron matrix with some troilite, chromite and anorthite. The structure approaches a pallasitic Widmanstätten structure, but the crystals are smaller than 1 mm (Tschermak 1870). Of the others, Steinbach has also previously been given its own class, siderophyrs; but, as noted above, there is little sense in retaining classes based upon only one example. Steinbach contains about 50% nickel-iron, 35% bronzite, 15% tridymite and some schreibersite, troilite and chromite (Götz 1962; Dörfler et al. 1965). It displays considerable similarity to the Gibeon meteorites and other fine octahedrites of group IVA (Schaudy et al. 1972).

The reader is referred to Cohen (1905:3), Prior (1920), Krinov (1960a), Yavnel (1962), Mason (1962a), Craig (1964), Hey (1966) and Keil (1969) for additional information regarding the development of the classification system and the precise composition of the silicates.

Iron Meteorites

Many modern classifications, e.g., by Lovering et al. (1957), have tended to reduce the number of classes of iron meteorites. This trend is an unwarranted oversimplification, only justified as long as insufficient information concerning the individual meteorites is available. More advanced schemes of classification were proposed as new and precise data were accumulated (Buchwald & Munck 1965; Yavnel 1965b; Wasson 1967a; Goldstein 1969). Basically two entirely different approaches have been used. The classic one is based upon the examination of the macrostructure of an etched section under a hand lens. The new one is based on accurate chemical analysis of the major element, nickel, plus the trace elements gallium, germanium and iridium. Let it be said immediately that the two approaches support and agree with each other very well, particularly if, in addition to the macrostructure, one also observes and utilizes the microstructure.

The problems associated with classifying iron meteorites on basis of their structure alone are mainly caused by the fact that solid state diffusion processes have been much more efficient in transforming and eliminating primary structures in irons than in stones. As a result of deformation and reheating – caused, e.g., by movement of the overburden and by shock, – original medium octahedrites, such as Cape York, may have been altered beyond

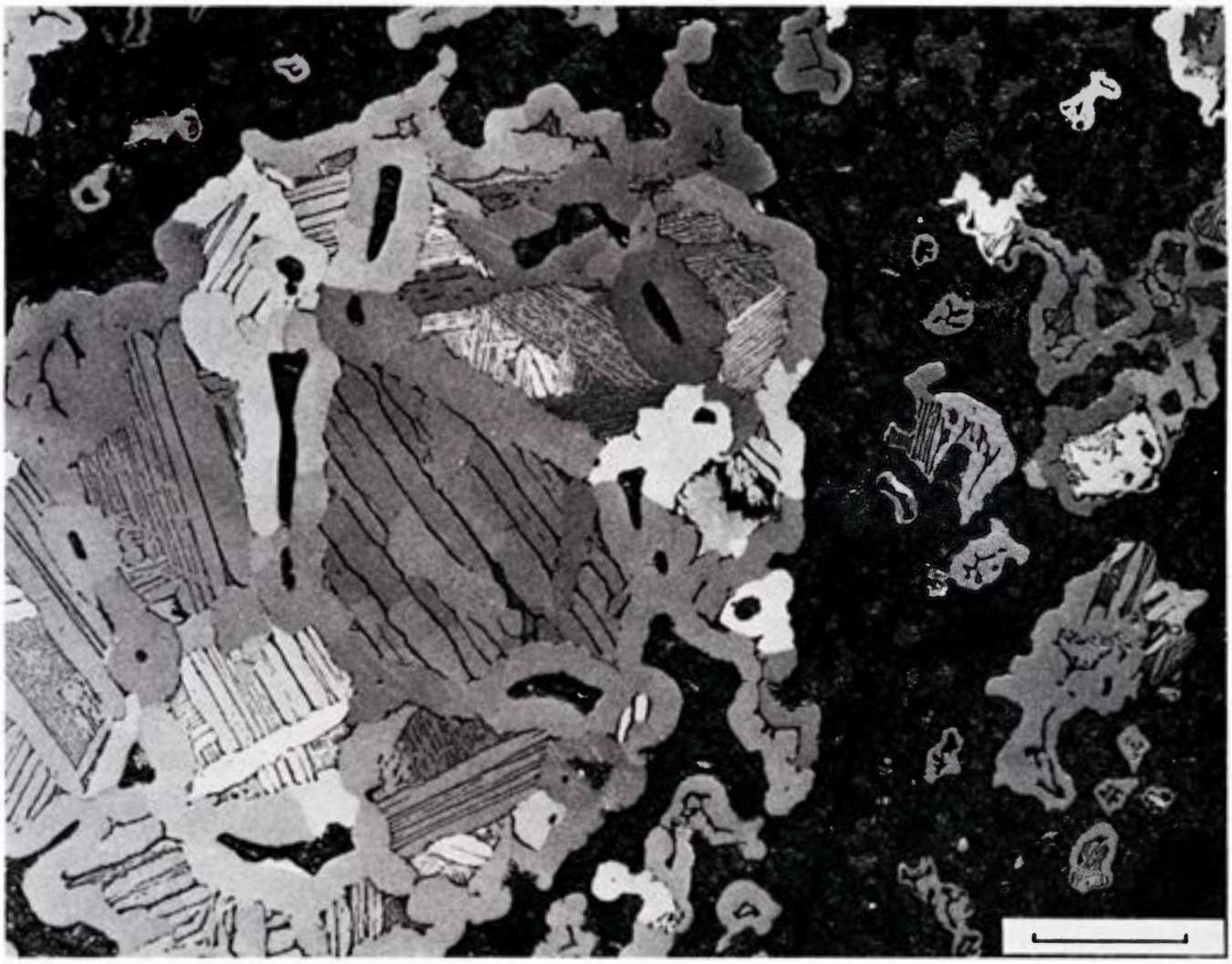

Figure 65. The mesosiderite Pinnaroo (U.S.N.M. no. 2312) was found in South Australia. The silicate portion consists of pyroxene and plagioclase. The metal, originally polycrystalline with a grain size about 5 mm, now displays swathing kamacite nucleated by the grain boundaries and their silicates. The grain interior subsequently decomposed in a Widmanstätten pattern. Etched. Scale bar 3 mm. S.I. neg. M-1052E.

recognition to structures like that of Juromenha. This fact makes any structural classification for genetic purposes very difficult, since meteorites with the same chemical composition of both main and trace elements may, under some circumstances, form a perfect medium octahedrite. Under other circumstances, however, they may form an ataxite; or, in one case, a hexahedrite (Boguslavka) and in another case a "nickel-poor ataxite" (Mejillones). However, having recognized this, it must be emphasized that a close study of the iron meteorites can penetrate and rationalize the structural alterations, and, therefore, the structural classification is not obsolete. The best classification for genetical purposes is that based upon Ni-Ga-Ge-Ir determinations as presented in Table 23a-b, while the structural classification serves as a guide to the initial cooling conditions and to the secondary stages of metamorphism, suffered over aeons of time.

The iron meteorites may be subdivided according to their primary structures as shown in Table 26a. The size and shape of the kamacite crystals are the decisive criteria.

Table 26a. Structural Classification of Iron Meteorites

Structural Class	Symbol	Bandwidth, mm	Type member	Approximate number Falls	Total
Hexahedrites	H	–	Coahuila	4	50
Coarsest Octahedrites	Ogg	> 3.3	Sikhote-Alin	1	20
Coarse Octahedrites	Og	1.3-3.3	Canyon Diablo	4	90
Medium Octahedrites	Om	0.5-1.3	Cape York	12	210
Fine Octahedrites	Of	0.2-0.5	Gibeon	4	55
Finest Octahedrites	Off	< 0.2, continuous	Tazewell	0	7
Plessitic Octahedrites	Opl	< 0.2, spindles	Ballinoo	2	20
Ataxites	D	–	Hoba	1	33
Anomalous	Anom	Various	–	3	40
				31	525

A typical kamacite lamella is a finger- to plate-shaped ferrite crystal which has the approximate ratios 30:3:1 between length, height and width. It is the average width of the largest kamacite lamellae that is to be used for classification purposes. Frost (1967a) has published correction factors for measurements taken on a single, arbitrary section. In the present work, the bandwidths have, however, usually been obtained as averages from the examination of mutually perpendicular sections. In order to arrive at true average values for the maximum bandwidths it was found necessary to work with sections with areas at least 1000 times the bandwidth, thus, e.g., at least 30× 30 mm sections for a medium octahedrite.

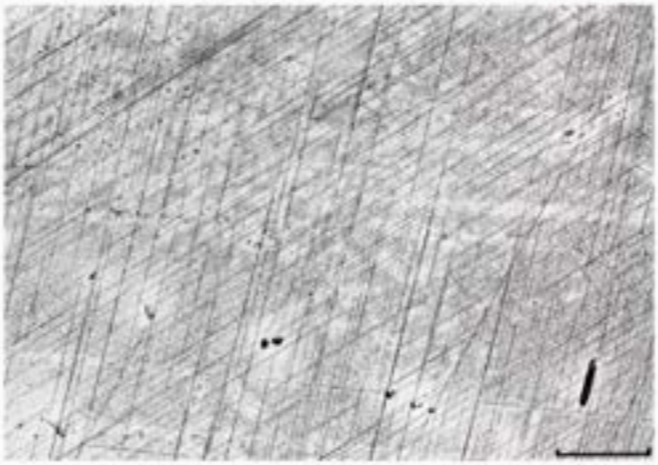

Figure 66. The hexahedrite Scottsville (Copenhagen no. 1891, 54). Neumann bands cross the entire section in at least seven directions, parallel to $(112)_{\alpha}$. Schreibersite crystals (dark) are surrounded by zones depleted in Ni and P (white). Etched. Scale bar 3 mm.

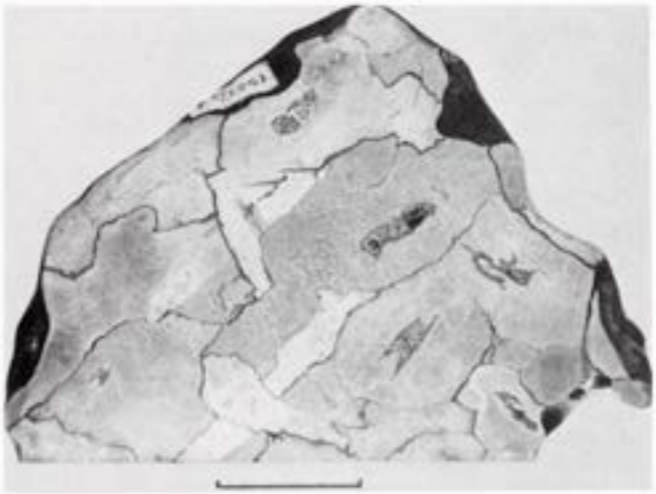

Figure 67. The coarsest octahedrite Sikhote-Alin (Moscow no. 1601). The Widmanstätten pattern is not very obvious in this meteorite class unless large sections are examined. Schreibersite crystals have nucleated wide rims of swathing kamacite. Etched. Scale bar 30 mm.

In hexahedrites the kamacite crystals are large (generally larger than the specimen) and equiaxial; in octahedrites they are distinctly visible as lamellae, while in ataxites no kamacite is visible to the naked eye.

The availability of a large number of bandwidth measurements has allowed a clearer definition of the bandwidth divisions, differing slightly from the earlier proposed system (Buchwald & Munck, 1965).

The observed range in kamacite widths has been subdivided into five steps, each formed from the previous by multiplication by 2.5. This number is a very convenient and psychologically attractive increment which is used in other sciences, too; for example, for classification of stellar magnitudes. The proposed system is felt to be superior to previously used structural systems because in a majority of cases it also coincides with the chemical groups as proposed by Wasson (1967a; 1969; 1970a). Structural classes and chemical groups coincide as follows:

Table 26b. Comparison of Structural and Chemical Classes

H	IIA	Of	IVA; IIIC
Ogg	IIB	Off	IIID
Og	I, IIIE	Opl	IIC
Om	IIIA, IIIB, IID	D	IVB

Notable exceptions occur; these are discussed under the individual descriptions. Since the kamacite bandwidths are primarily dictated by the initial bulk nickel content of the cooling taenite crystal *and* the cooling rate, it is obvious that a structural classification will not necessarily coincide with a chemical classification based on nickel, gallium, germanium and iridium. When, on the other hand, the present structural classification scheme happens to show

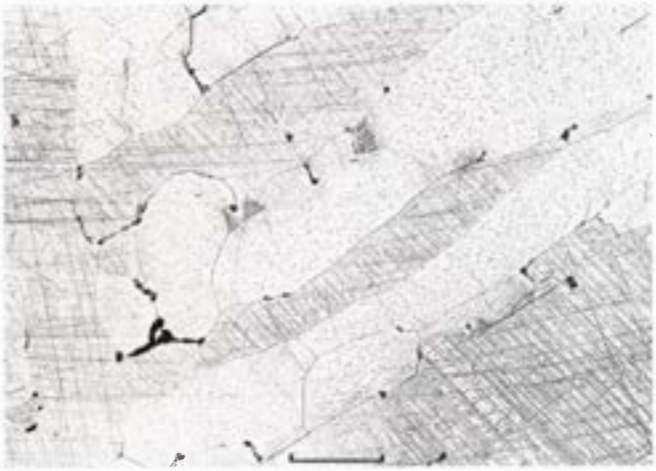

Figure 68. The coarse octahedrite Seeläsgen (Copenhagen no. 32). Neumann bands are present in all the kamacite lamellae but more easily etched in contrast within some orientations. Grain growth has occurred. Scale bar 3 mm.

Figure 69. The medium octahedrite Cape York (Ahnigito; A.M.N.H. no. 2688). The kamacite lamellae display subboundaries and Neumann bands. Comb and net plessite are common, while a few black taenite wedges may also be seen. Etched. Scale bar 3 mm.

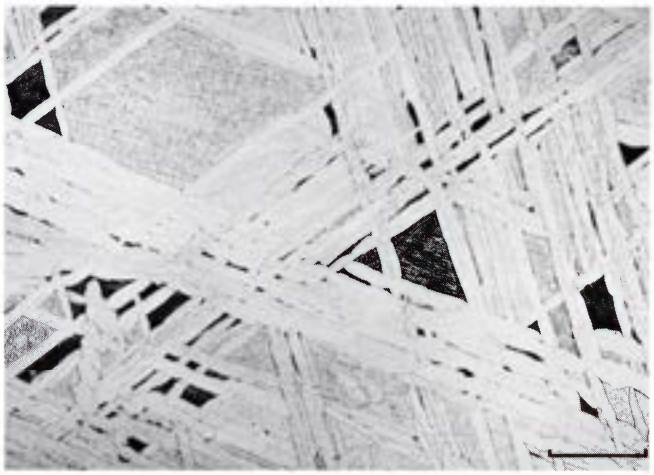

Figure 70. The fine octahedrite Gibeon (Copenhagen no. 1905, 1735). The kamacite displays subboundaries and Neumann bands. Taenite and plessite fields cover 40-50% by area. Etched. Scale bar 3 mm.

such close relationships, there is reason to use it and sustain it because, for the uninitiated and for preliminary examinations, it is so much easier to perform a structural than a chemical analysis. The least one can do in presenting data on a new iron meteorite is to report the kamacite bandwidth in mm.

The first seven structural classes, Table 26a, are each rather homogeneous, while the last two serve more as a kind of wastebasket in which many irons are included that have little other in common than that they do not fit the first seven classes.

The *hexahedrites* (H) are primarily large single crystals of kamacite, but grain boundaries appear in rare cases (Coahuila, Indian Valley). Almost all of them are members of the chemical group IIA. Due to shock or cosmic reheating, many of the hexahedrites are partially or completely altered, giving rise to polycrystalline kamacite aggregates like Mejillones, Bingera and Forsyth County. Such meteorites were previously classified as nickel-poor ataxites, but this term is unfortunate, since the meteorites in question are certainly not ataxitic, i.e., structureless to the naked eye.

The class of nickel-poor ataxites is further of little value, since in the past it has included, rather indiscriminately, pseudometeorites (some Siratik specimens), coarse octahedrites (Campo del Cielo), artificially reheated hexahedrites (Chesterville), cosmically reheated hexahedrites (Wathena), and coarsest octahedrites (Navajo). In other words, the nickel-poor ataxite class has been entirely eliminated here, and the meteorites included in it have been distributed in their proper classes.

The *octahedrites* display octahedral arrangement of the kamacite in the parent taenite crystal, at least when large sections are inspected. Sikhote-Alin, Mount Joy, Navajo, Nelson County and Auburn, all belonging to the class Ogg, are examples of octahedrites – small samples of which apparently show a random assemblage of kamacite without

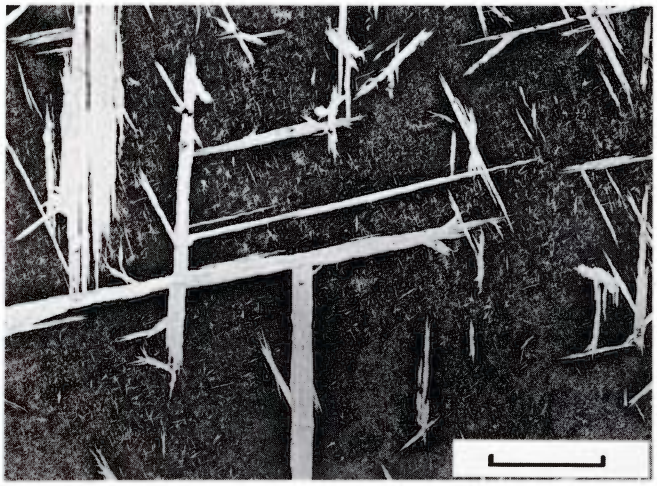

Figure 72. The plessitic octahedrite Butler (Copenhagen no. 1876, 2247). The kamacite forms discontinuous, bayonet-like spindles with widths below 0.2 mm. In the plessitic matrix the pattern is repeated on a ten times finer scale. Etched. Scale bar 3 mm.

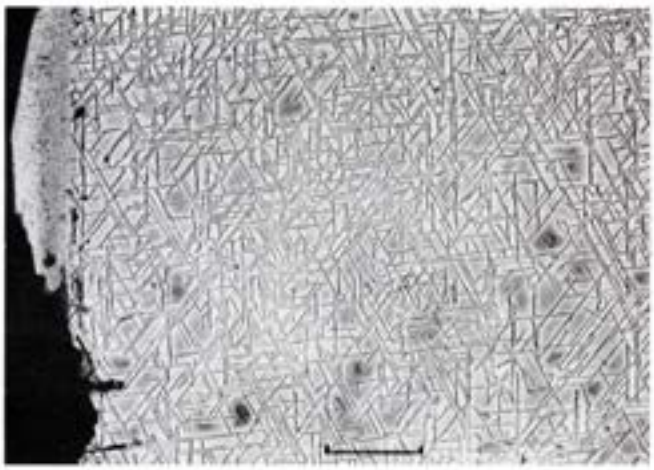

Figure 71. The finest octahedrite Föllinge (Stockholm). The kamacite lamellae have widths below 0.2 mm. Dense plessite fields cover 80-90% of the sections. To the left, remnants of the metallic fusion crust. Etched. Scale bar 3 mm.

Figure 73. The ataxite Kokomo (Copenhagen no. 1876, 2245). At this magnification the meteorite appears dense and homogeneous, except for the parallel bands which exhibit oriented sheen. Below left, a terrestrial corrosion attack has created concentric zones of different oxidation stages. Etched. Scale bar 3 mm.

taenite and plessite. Close examination of larger sections usually reveals the presence of taenite and plessite; moreover, these remnants will serve to indicate the orientation of the parent taenite crystal(s).

The classes Og, Om, Of, and Off display continuous kamacite lamellae between which retained plessite is squeezed in ever increasing proportions until – in meteorites such as Tazewell, Dayton and Föllinge – the kamacite part constitutes only about 15% by volume. These irons have 17-18 weight % Ni and so far represent the maximum in perfect octahedral structure. It was previously believed (Perry 1944: 48; Uhlig 1954; Mason 1962a: 139; Keil 1969) that bulk octahedral structure did not develop with more than 10-14% Ni in the meteorite, but this is certainly not the case.

The *plessitic octahedrites*, Opl, are transitional between octahedrites and ataxites. They display a plessitic matrix in which numerous pointed kamacite spindles, less than 0.2 mm wide, are scattered in octahedral arrangement. They normally require a hand lens for proper recognition.

The *ataxites* (Brezina 1896: 238, 295; previously termed "Dichte Eisen" i.e., dense irons, by Tschermak, 1872a, and Brezina, 1885: 220, – hence the symbol D) unfortunately must remain a rather heterogeneous group if we accept the old definition of "densely structured," i.e., a structure not resolvable to the naked eye or under a hand lens. A considerable number of ataxites belong to the chemical group IVB and are structurally characterized by the presence of centimeter-wide more or less diffuse bands that cross etched sections in octahedral directions and subdivide the surface into patches with differently oriented sheens. The ataxitic class includes, however, a number of irons which are not members of group IVB and are mutually unrelated genetically, such as Washington County, Arltunga, Juromenha, Smithland, Guffey, Nedagolla and the two Babb's Mill meteorites.

When the above classes have been established, a number of irons remain which are sufficiently anomalous to require individual recognition as unique specimens. Sometimes two or more appear to form doublets or triplets, but generally speaking the *anomalous irons* comprise meteorites which both structurally and chemically are easily recognized. They appear to be point samples of different, very small populations. N'Goureyma, Barranca Blanca, Zacatecas, Santa Rosa, Tucson and New Baltimore are good examples. The anomalous meteorites are often relatively fine-grained – i.e., the primordial taenite crystal size was of the order of 1-3 cm instead of the usual foot- to meter-sized. Sections through, e.g., Tucson, Mundrabilla, Santa Rosa and N'Goureyma clearly show the polycrystalline array of inch-sized crystals, often with copious amounts of silicates or troilite in the grain boundaries.

On the whole, there are fewer structurally anomalous meteorites than chemically anomalous meteorites, because many of the latter may be fitted into one of the octahedrite or ataxite classes, e.g., Mbosi (Om), Reed City (Og) and Morradal (D).

A number of irons were previously termed "brecciated," e.g., Holland's Store, Barranca Blanca, and N'Goureyma (Krinov 1960a: 488; Hey 1966; and elsewhere). The term is unfortunate and should be abandoned. The meteorites are not brecciated in the geological sense but are polycrystalline aggregates of ferrite or austenite grains that have grown to their present size by solid state diffusion. Holland's Store, originally a normal hexahedrite, probably acquired its peculiar structure by recrystallization of a shock-deformed single kamacite crystal. It is here classified as a hexahedrite, with the qualifying statement that it has been shocked and partially recrystallized. Barranca Blanca and N'Goureyma apparently still display their primary cosmic structure, formed by sintering and some grain growth. They are classified as anomalous; their grain size and inclusions are noted, and their possible relationships with other meteorites mentioned.

There are numerous irons which, upon sectioning, can be shown to be composed of several taenite crystals. As noted above, most of these are anomalous; however, others are normal members of their classes. Gibeon (Of), Bodaibo (Of), Arispe (Og), Mertzon (Om) and Toluca (Og) are thus

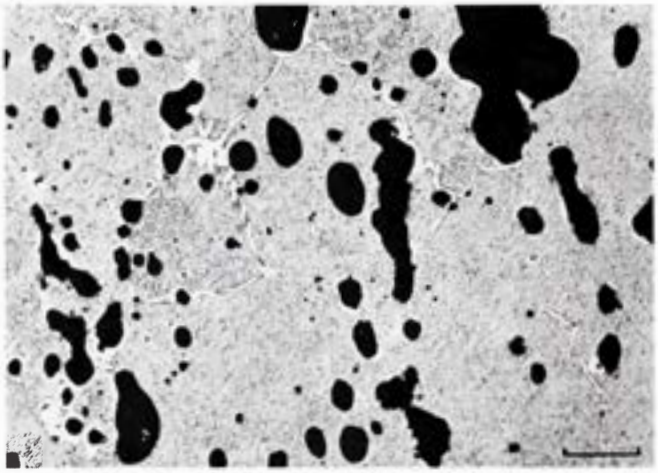

Figure 74. Tucson (U.S.N.M. no. 368; Ring mass). Individual parent taenite crystals are 2-8 mm in diameter. The grain boundaries and the silicate inclusions (black) have nucleated 20 μ wide rims of kamacite (white). Etched. Scale bar 0.5 mm.

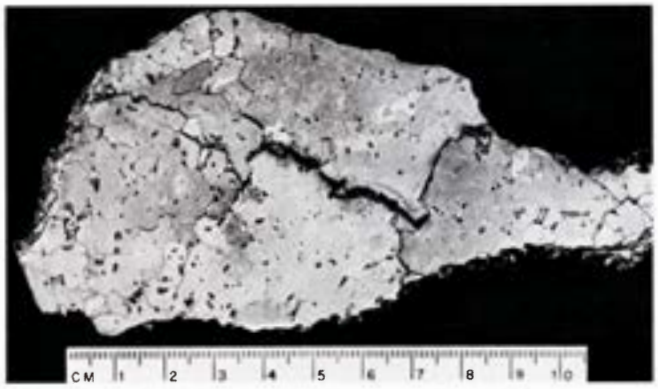

Figure 75. Barranca Blanca (Tempe no. 536.1). The anomalous macrostructure shows numerous troilite globules and taenite-plessite wedges enveloped by irregular kamacite grains of varying orientation. Etched. Scale in centimeters. Tempe neg. R6.24.

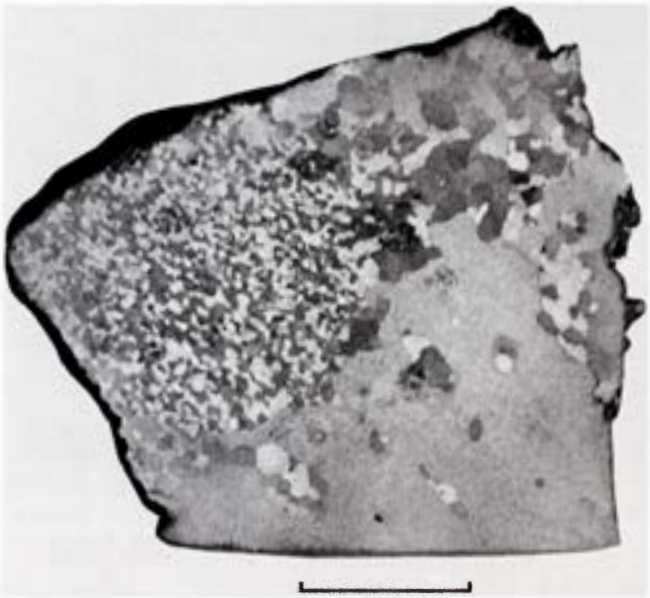

Figure 76. Holland's Store (Vienna no. F6482). Probably originally a normal hexahedrite. Plastic deformation and subsequent annealing caused the material to recover and recrystallize. Etched. Scale bar 20 mm.

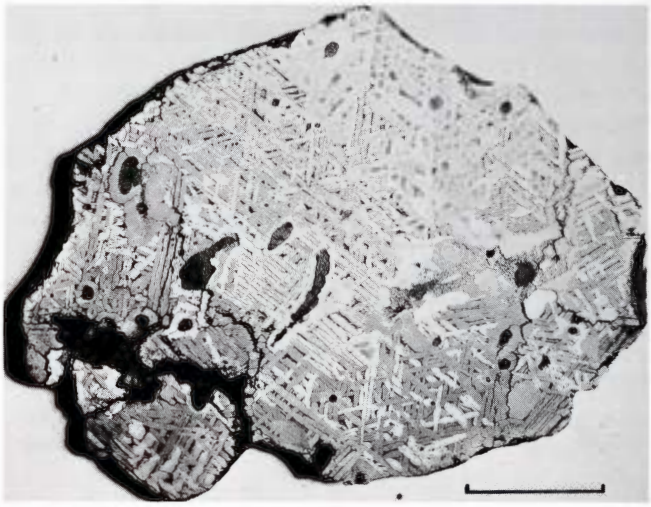

Figure 77. Mertzon. (U.S.N.M. no. 1435). A polycrystalline medium octahedrite related to group I. A large precursor taenite crystal is in the center, while at least six smaller ones are located left and right of it. Troilite and schreibersite inclusions (dark) are abundant, particularly in the grain boundaries. Etched. Scale bar 20 mm.

classified according to their bandwidth, but the prefix "polycrystalline" indicates that the samples examined were composed of several taenite crystals. If this prefix is not given, the meteorites in question are believed to be – or at austenitic temperatures have been – single taenite crystals larger than foot-sized. The largest documented single crystal is that of Cape York; the sectioning of the 20-ton Agpalilik fragment demonstrated that the parent taenite crystal measured at least 2 X 1.5 X 1.5 m. It may well have been larger if all of the Cape York fragments were uniformly oriented. On the other hand, the fragmentation may have taken place by preferential fracturing along inclusion-rich grain boundaries, so that the present fragments represent the true grain size.

Campo del Cielo, which has been in collections since about 1800, was, until 1967, only known as monocrystalline material. The cutting in Mainz of a 2 ton mass revealed, however, a polycrystalline array of 10-30 cm precursor taenite crystals with silicates in the grain boundaries. Further sectioning of other masses, particularly from the chemical group I and from the anomalous groups, will probably reveal other polycrystalline iron meteorites.

Table 27. Statistical and Analytical Data for 480 Iron Meteorites

Group	Number		Frequency	Bandwidth	Structural	Ni	P	Ga	Ge by weight	Ir	Ge-Ni
	Falls	Total	%	mm	class	Weight %	Weight %	ppm	ppm	ppm	correlation
I	5	69	14.4	1.1-3.2	Om-Og	6.5-8.5	0.12-0.40	55-100	190-520	0.6-5.5	neg.
I-Anom	2	19	4.0	0.01-4	Om-Og-Anom	6.2-25	0.12-0.50	12-80	25-350	0.2-10	neg.
IIA	4	43	9.0	>50	H	5.35-5.75	0.20-0.34	57-62	170-185	2-60	0
IIB	1	14	2.9	5-10	Ogg	5.5-6.9	0.3-0.9	45-60	105-185	0.01-0.5	neg.
IIC	0	7	1.4	0.03-0.07	Opl	8.9-11.6	0.3-0.5	35-40	85-115	4-11	pos.
IID	2	11	2.3	0.45-0.85	Of-Om	9.9-11.4	0.2-0.9	70-85	80-100	3-20	pos.
IIIA	4	117	24.4	0.9-1.5	Om-Og	7.1-8.8	0.06-0.35	17-22	32-46	0.15-20	pos.
IIIB	1	40	8.3	0.5-1.3	Om	8.6-10.6	0.25-1.0	16-22	28-46	0.01-0.15	neg.
IIIC	1	6	1.2	0.2-0.5	Of	11.3-13.3	0.3-0.6	11-26	8-35	0.07-0.55	0
IIID	0	5	1.0	0.01-0.05	Off-D	16-23	0.15-0.4	1-5	1-4	0.01-0.07	neg.
IIIE	0	7	1.5	1.3-1.6	Og	8.3-8.8	0.19-0.45	17-19	34-36	0.05-0.6	0
IVA	1	39	8.1	0.23-0.43	Of	7.5-9.5	0.02-0.18	1.6-2.4	0.09-0.14	0.1-4	pos.
IVB	0	11	2.3	0.006-0.03	D	16-18	0.05-0.20	0.17-0.27	0.03-0.08	4-36	pos.
Anom	4	92	19.2	All	All	5.1-6.1	0.01-2.1	0.05-87	0.005-2000	0.007-54	0
Total	25	480	100.0								

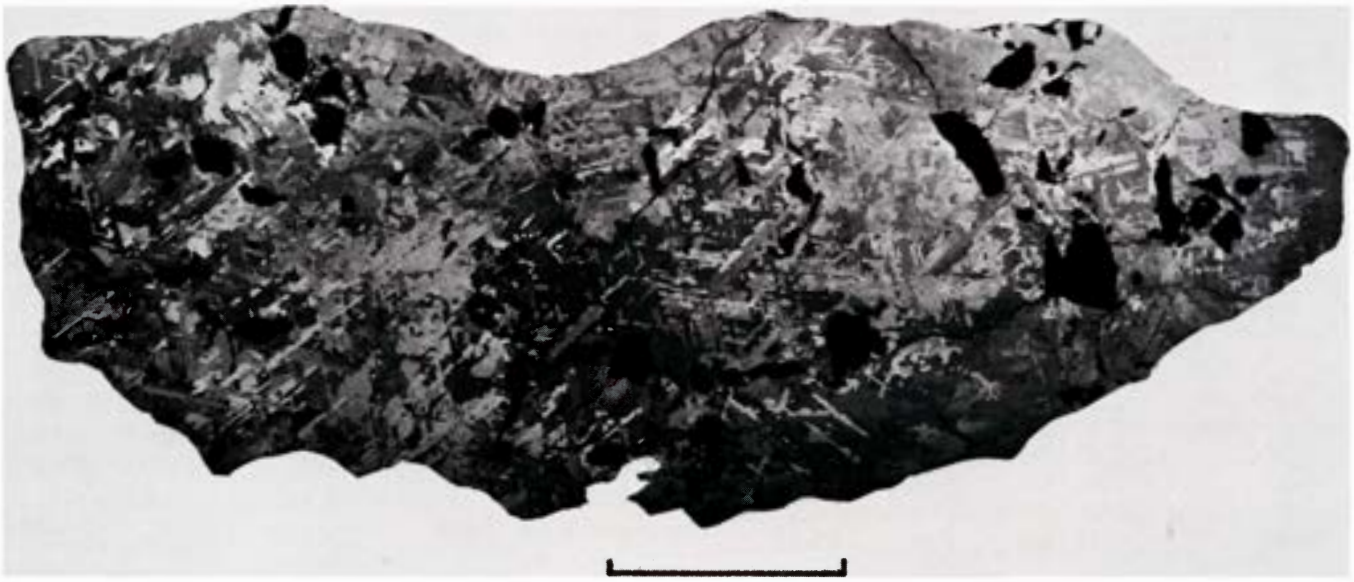

Figure 78. Campo del Cielo (U.S.N.M.). The 110 cm long El Taco slice displays numerous silicate inclusions (black). It is composed of many randomly oriented precursor taenite crystals, ranging from 2 to 30 cm in diameter. Etched. Scale bar 20 cm. S.I. neg. M-1464.

Under the individual meteorites, a qualifying statement as to amount and nature of inclusions (silicates, graphite, troilite) and to the state of recrystallization is given, if judged to be characteristic for the particular meteorite. While recrystallization and other signs of cosmic reheating may occur in each class or group, it appears that silicates in significant amounts are restricted to the coarse octahedrites of group I and to several anomalous irons.

The structural classification scheme, as developed above, is only slightly different from the classical ones. It is deliberately developed so as to remain a purely descriptive system, based upon morphological characters that are easily observed with the naked eye or a hand lens. Although coinciding with the chemical system below in numerous cases, it should not be used for "genetic studies." Its value lies in its simplicity. If it is further elaborated upon by introducing subclasses to indicate recrystallization, cooling rate or number of inclusions, it will, in my opinion, cease to be functional. On the other hand, used together with the chemical system, it provides a full guide to the iron meteorites.

The Chemical Classification of Iron Meteorites

In the chemical classification system, originally suggested by Goldberg et al. (1951), the elements nickel and gallium were selected to establish a new classification scheme of genetic importance – i.e., it was an attempt to group all iron meteorites of similar composition and, therefore, supposedly of similar origin in place and time. Later, additional parameters were included, first germanium (Lovering et al. 1957) and then iridium (Wasson & Kimberlin 1967). While iron meteorites have resisted satisfactory chemical classification for nearly two centuries, this impasse has now been breached, due particularly to the systematic work by Wasson and co-workers since 1967.

Accurate determination of Ni, Ga, Ge and Ir together with low-power microscopy have enabled Wasson to define 12 or 13 groups of chemically related meteorites. In 4-dimensional composition space (Ni, Ga, Ge, Ir), the groups form very compact well defined clusters. The clusters have limited concentration ranges of all elements compared to the range shown by all iron meteorites; they show smooth variations in the concentration of one element when plotted against that of another, and the members display similar structures (Wasson & Kimberlin 1967).

When each element is plotted against Ni on logarithmic scales, the groups are clearly resolved. All members of the same group fall, within the limits of sampling and analytical error, on a straight line. Similar correlations of a pair of elements may be observed in several groups, e.g., Ni-P

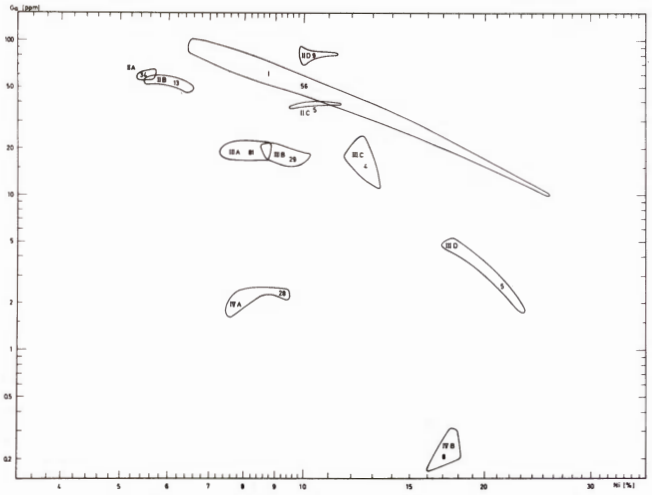

Figure 79. Log-log plot of gallium versus nickel. Eleven resolved chemical groups are labeled with Roman numerals and the number of meteorites within each group added. Up-to-date numbers are to be found in Table 27. See also Figures 189A and B.

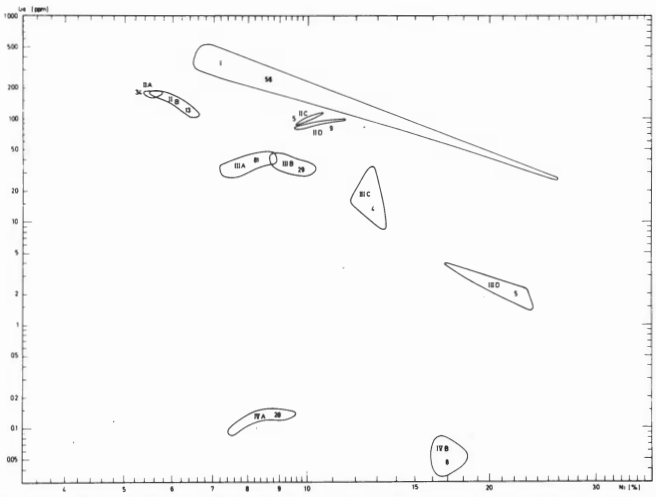

Figure 80. Log-log plot of germanium versus nickel. Compare Figure 79.

(Figure 81), P-Ir (Figure 82), Ni-Cr and Ni-As (not shown). In contrast to Ga and Ge, many of the elements show variations within a group which may approach the range of all iron meteorites. This is particularly true of Ni-P and Ni-Ir (Figure 92). The correlation of elements has, after the finishing of this manuscript, been discussed in great detail by Scott (1972).

Table 27 displays all the essential information accumulated concerning the chemical groups, their corresponding structural groups, their relative importance and the ranges observed in chemical analyses for selected elements. In Tables 23a-b details as to mineralogy and statistics of numbers and weights are developed. All data have been taken from the descriptive part of the book, and only the 480 best examined irons have been included. Numerous others were excluded because of insufficient information. See Appendix 2.

Five or more similar meteorites are required to form a group. The group "I-Anomalous" is related to group I but somewhat of a hybrid because structural observations indicate that the members do not correspond to the main sequence of group I. The nickel content in I-Anom increases to 25.6% in San Cristobal.

The last line of the table, the chemically anomalous meteorites, are those which do not fit the requirements of the other groups.

It should be noted that the symbols I, IIA, IIB etc. are rather arbitrarily chosen. Lovering et al. (1957) designated

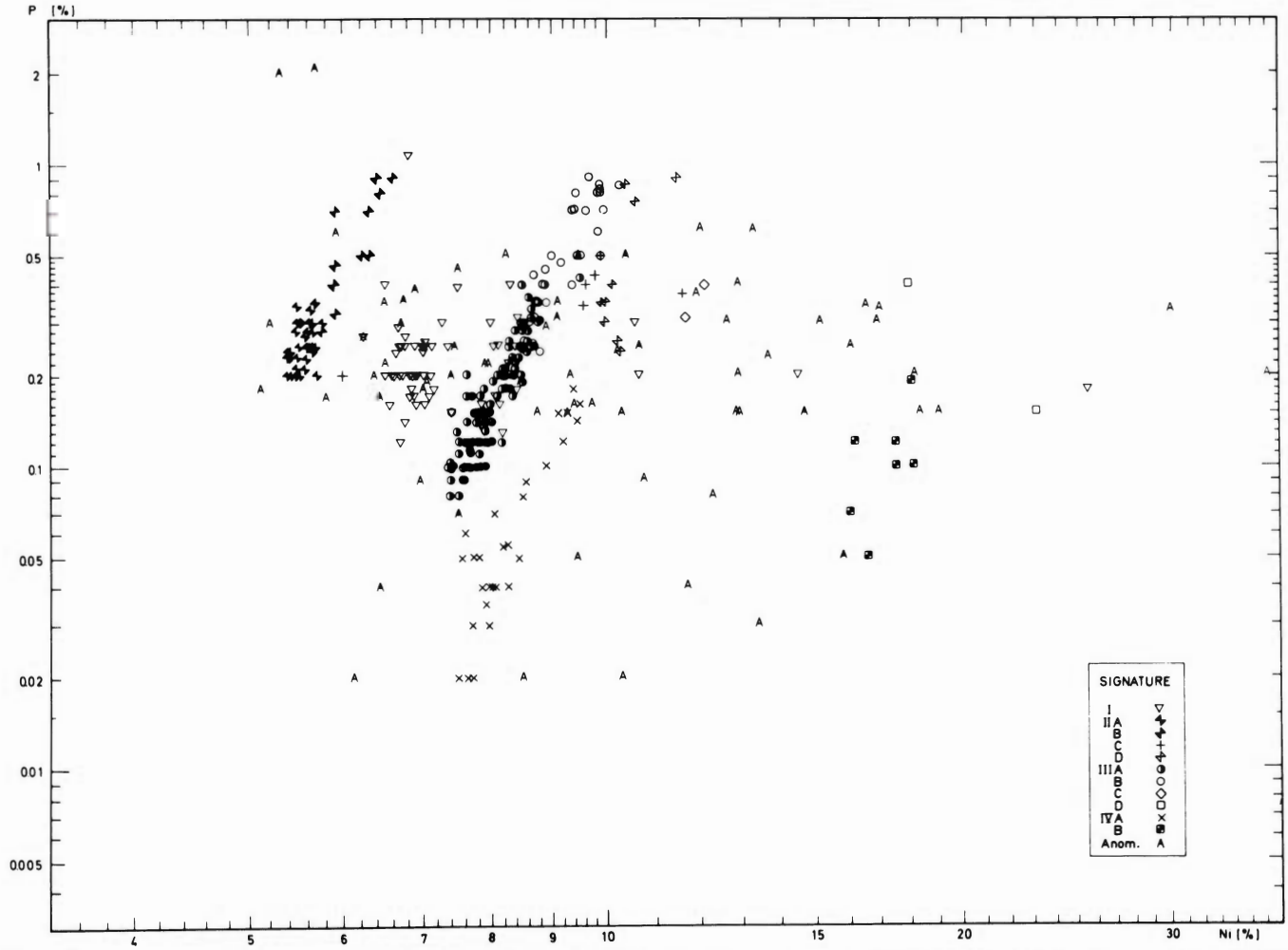

Figure 81. Log-log plot of phosphorus versus nickel. Genetically related meteorites plot within narrow bands. Anomalous meteorites, A, scatter all over. Data from descriptions in the handbook.

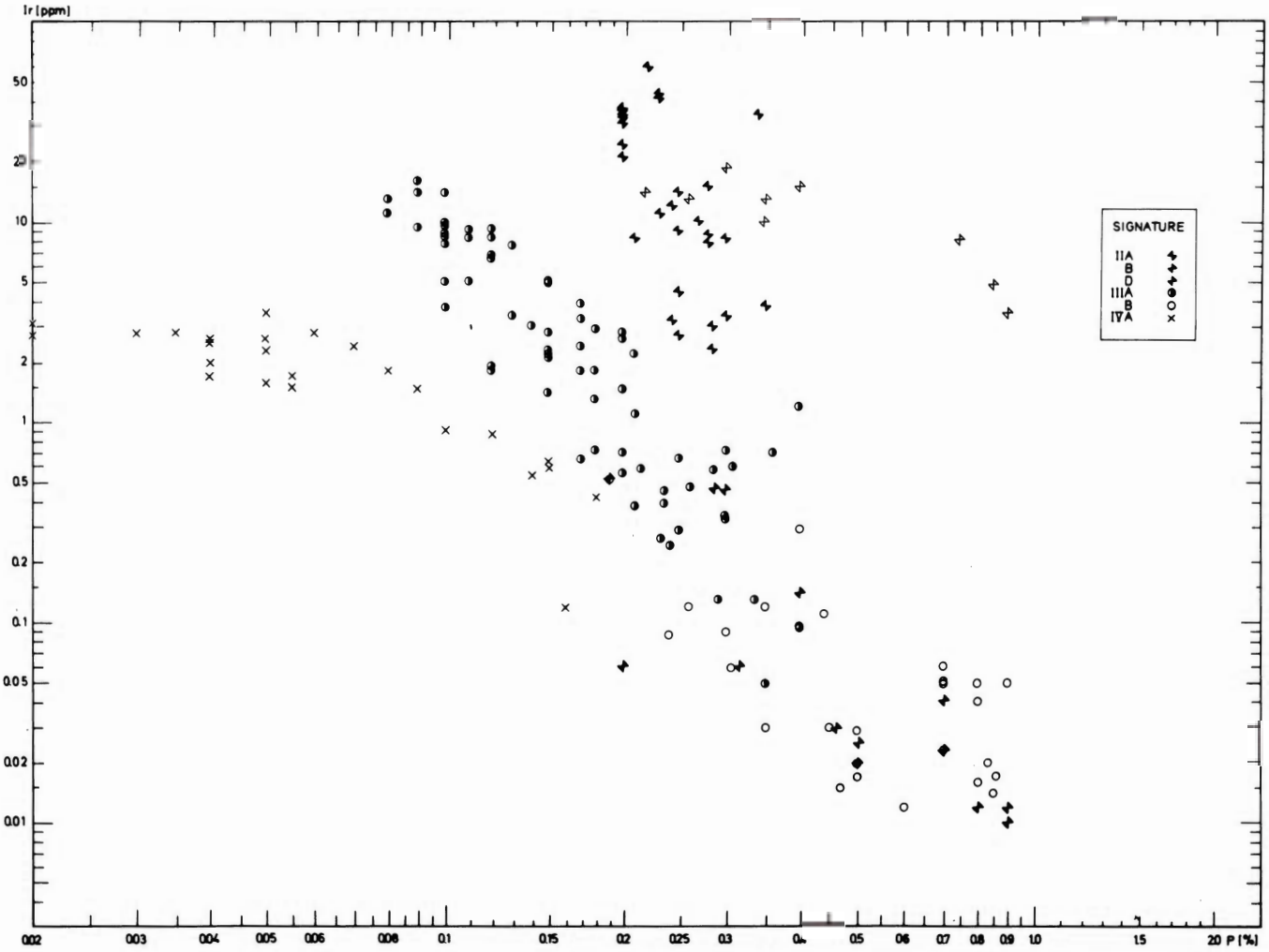

Figure 82. Log-log plot of iridium versus phosphorus (up to 2.0% P), for six resolved chemical groups. Ir and P are negatively correlated; i.e., increasing P means decreasing Ir. Correlation factors vary, however, from group to group. Data from descriptions in the handbook.

four Ga-Ge groups, I to IV, in order of decreasing abundance of these elements. When Wasson refined the system and introduced additional groups, the letters A, B, C, D and E were attached to the Roman numerals on the appropriate Ga-Ge level. Various considerations, both structural and chemical, indicate that the pairs I - I-Anom, IIA - IIB, IIIA - IIIB - IIIE and IIIC - IIID, although distinct, are genetically related, while all other groups are unrelated. See also Figures 79 and 80.

It is hoped that we will ultimately succeed in referring each group to a particular condition in time and space for its formation. Presumably each group formed in a separate environment with specified depth of burial, gravity field, age, initial and peak temperatures, and cooling rate. The size of the parent bodies may have varied by large factors, some perhaps having been the central nuclei of 100 km bodies, others, with higher cooling rates, perhaps having formed meter-sized raisins in the upper mantle of the same or another parent body. For recent reviews of these topics the reader is referred to Anders (1971b).