CHAPTER EIGHT

Chemical Composition

Since excellent discourses have been published by, e.g., Urey & Craig (1953), Suess & Urey (1956), Krinov (1960a), Ringwood (1961), Mason (1962a), Wood (1963), Ahrens (1965), Cameron (1968), Yavnel (1968b), Arnold & Suess (1969), Goles (1969), Anders (1971a), Mason (1971), Scott (1972) and Schmitt et al. (1972), only a brief survey and a few remarks will be presented here.

The meteorites as a whole contain no other elements than those known to exist on Earth. And virtually all known elements from Earth have been identified in meteorites, albeit sometimes in very small quantities. Studies of the isotopic compositions of iron meteorites have occasionally revealed differences from those of Earth, but not larger than can be explained in terms of different cosmic radiation exposures or in different initial content of radioactive elements. The meteorites have, since the classical works by Goldschmidt (1938; 1954) and Suess & Urey (1956), served as space probes that provided us with information of the interior of some unknown planets. Together with spectrographic data of the solar atmosphere, the meteorites have provided the basis for various estimates of the so-called "cosmic abundances." Solar and meteoritic data pertain, strictly speaking, only to our own solar system, but Unsöld (1969) has noted that more than 95% of all stars in our galaxy essentially have solar composition, so it is probably justified to speak of "cosmic" abundances.

Goldschmidt (1922; 1938; 1954) and Noddack & Noddack (1930; 1934) divided the elements into three major categories. See Table 28. *Lithophile* elements, such as Na, Ca and Al, are those with a great affinity for minerals rich in oxygen. *Chalcophile* elements, such as Cu, Mo and Pb, have a similar affinity for sulfur-bearing minerals. *Siderophile* elements such as Ni, Pt, Au, and P, have a great affinity for iron, entering into solid solution in the ferrite or austenite lattice. Natural processes on the Earth – weathering, sedimentation, metamorphism, melting, etc. – have a very strong tendency to fractionate these three element groups from one another. Therefore, we find the rocks of the Earth's oxidized crust generally composed of lithophile elements, while the chalcophile elements are

Table 28. Geochemical Classification of the Elements

Periodic group	Lithophile	Chalcophile	Siderophile
IA	Li, Na, K, Rb, Cs		
IIA	Be, Mg, Ca, Sr, Ba, Ra		
IIIA	B, Al, Sc, Yt, La		
IVA	Ti, Zr, Hf, Th		
VA	V, Nb, Ta		(V)
VIA	Cr, (Mo), W, U	Mo	(Cr), Mo
VIIA	Mn	(Mn)	Mn
IB		Cu, Ag, (Au)	Cu, (Ag), Au
IIB	(Zn), (Cd)	Zn, Cd, Hg	(Zn), (Cd)
IIIB	(Ga), (Tl)	Ga, In, Tl	Ga
IVB	Si, (Sn), (Pb)	Ge, (Sn), Pb	Ge, Sn, Pb
VB	(P), (As), (Sb)	As, Sb, Bi	P, As, Sb, Bi
VIB		S, Se	
VIIB	F, Cl, Br, I		
VIII	Fe, (Co), (Ni)	Fe, Co, Ni	Fe, Co, Ni
		(Ru), (Pd), (Os), (Pt)	Ru, Rh, Pd, Os, Ir, Pt

Parentheses indicate subsidiary tendencies. After Goldschmidt 1954.

highly concentrated in a few small areas (i.e., ores), and the siderophile elements are largely missing from the crust. Presumably the latter are concentrated in the core of the Earth which is believed to consist of iron-nickel metal.

In chondritic meteorites, and particularly in the subclass Cl of carbonaceous chondrites, lithophile, chalcophile and siderophile elements occur mixed together to a degree not matched in terrestrial rocks. The Cl chondrites show a remarkable correspondence in elemental abundances with the Sun. If elemental abundances were exactly the same in both, the points in Figure 83 would lie on the 45° line. As it is, there are small deviations in both directions. The most important discrepancy, iron (see below), has recently been solved and has improved the fit. It would appear that chondrites have not been subjected to chemical fractionation in the same way that the Earth's rocks have, and that they, therefore, may serve as probes of primordial material that has survived essentially unchanged since the time when planets formed (Urey 1967a; Wood 1968; Unsöld 1971; Grossman 1972).

Other classes of meteorites, such as irons and achondrites, might well be derived from the chondrites by melting. Thus the iron meteorites are usually thought to be fragments of cores or pools of iron which were produced by melting in the parent bodies. Some of the anomalous irons have probably not been melted but only subjected to sintering and presumably negligible differentiation.

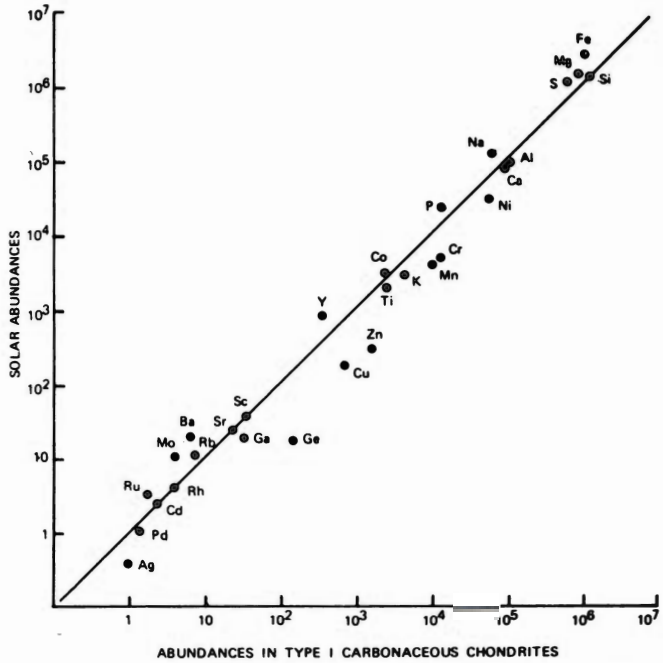

Figure 83. Comparison of elemental abundances in the primitive, highly oxidized Cl carbonaceous chondrites with those in the Sun. Abundances are relative to Si = 10^6 atoms in the Sun and in the meteorites. The close approach to the 45° line for most elements is the basis for considering the Cl carbonaceous chondrites as approximating in composition to the primordial non-volatile matter of the solar system. (From Mason (edit.) 1971.)

Concentration of Selected, Important Elements

It is somewhat futile to try to calculate the *average* composition of the iron meteorites. In order to do this we would have to calculate or estimate the total mass and the individual masses, or to define the total number and the frequency of the types; and both attempts are, for the time being, of little avail because the examination should be restricted exclusively to falls of which there are very few. These are, moreover, as evident from Table 10, often inadequately examined. Only very approximate "average" values will, therefore, be given in the following. Instead of the average composition, the range in composition for the various groups is given in Table 27. Comments on the individual elements follow, for the three major elements Fe, Ni and Co to begin with, then for a selection of other important elements. Much more information has been compiled in the handbooks edited by Wedepohl (1969) and Mason (1971).

Iron (26). After the gases H, He, O, N and Ne, and after C, Fe is the most abundant element in the solar system, occurring with about the same frequency as Si and Mg (Unsöld 1971). A confusing discrepancy of about a factor of ten between the solar iron abundance obtained by spectroscopy and the iron abundance in carbonaceous chondrites was pointed out by Urey (1967a). The problem was recently solved by Unsöld (1971) and co-workers who discovered a tenfold error in the oscillator strengths of the iron-I lines used by astronomers for solar abundance determinations; data from chondrites and from astronomical observations are now in excellent agreement. See Table 29 and Figure 83. The actual content of iron varies in stone meteorites from virtually nothing in enstatite achondrites (aubrites) to about 35% by weight in enstatite chondrites. In iron meteorites it varies from about 64% in Santa Catharina to about 94% in hexahedrites and some anomalous irons, e.g., Auburn. The iron is not pure, in that it is either encountered in solid solution with nickel, or in compounds, such as troilite, schreibersite, chromite, daubreelite, olivine and pyroxene. It may be estimated that the iron meteorites on the "average" contain 90.5-91.0% iron.

Nickel (28). Nickel accompanies iron, normally in solid solution, and is one of the celestial guarantees that a newly recovered find is a genuine meteorite. The average ratio of Fe to Ni in the solar photosphere is 17.8, in ordinary chondrites 19.5 (Unsöld 1971). In iron meteorites, nickel varies from a minimum of 5.1-5.3% (Tombigbee River, Auburn, Holland's Store) to a maximum of 35% (Santa Catharina). If Oktibbeha County, page 947, is confirmed as an independent meteorite, the nickel maximum increases to about 60%. Nickel percentages above 18% are, however, relatively rare. See Figure 84. The ratio of Fe to Ni varies in the iron meteorites from 18.0 in hexahedrites to 1.7 in Santa Catharina. "Average" values of 11.5 apply to a large number of medium octahedrites of groups IIIA, IIIB and IVA.

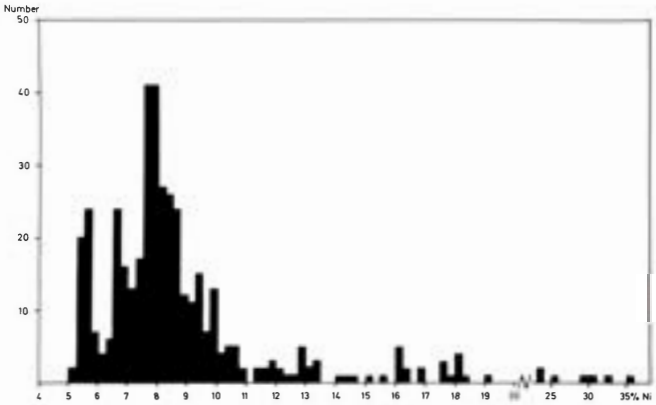

Figure 84. The frequency of distribution of nickel content in selected analyses of iron meteorites, plotted at 0.25% Ni intervals. No iron meteorite contains less than 5% Ni, and only seven contain more than 20%. This type of diagram was first used by Yavnel the selected analyses in the handbook. – Outside the histogram lie Dermbach (42%) and Oktibbeha County (61% Ni).

The rather confusing outline on Figure 84 that resembles the Manhattan skyline is analyzed in Figure 85. It is obvious that the ragged appearance is due to the histogram being a sum curve of several independent groups each of which displays a smoother distribution. The sum histogram is, therefore, in itself of little usefulness and meaning. The hexahedrites, group IIA, constitute a very narrow cluster, while on the other hand, groups I, IIIA-IIIB and IVA occupy a larger range in nickel values.

The nickel-poor members of each group are the most common, both in terms of number and cumulative weight. Thus in group I, the huge meteorites Magura, Campo del Cielo, Morasko, Youndegin, Cranbourne and Canyon Diablo all have less than 7.1% Ni. In group IIIA-IIIB, the crater-producing Wabar, Henbury and Boxhole meteorites and the monsters Morito, Willamette and Cape York all have less than 7.9% Ni. In group IVA, the only really large meteorite, Gibeon, with 7.9% Ni, is situated near the lower limit of the group. It appears, from various factors, that the "average" nickel content in iron meteorites is close to 7.9%.

Nickel is usually exclusively in the metal phase and thus strongly siderophile – in fact more so than iron itself! Kamacite of hexahedrites contains 5.3-5.7%; kamacite of octahedrites, 6.0-7.5%; while undecomposed taenite contains 30-50% Ni. Nickel is also very important as a substitutional element in schreibersite, cohenite and haxonite, but almost absent in chromite, olivine and pyroxenes. Schreibersite shows a range of about 10-45%, cohenite 0.7-2.3% and haxonite 3.5-5.5% Ni.

Reports by Nichiporuk & Chodos (1959) and others that up to 6% nickel should occur in the troilite are apparently erroneous, mainly because of the failure of separating troilite quantitatively from metallic admixtures. This is a pronounced difficulty in meteorites with shock-melted troilite that contains finely dispersed iron nickel droplets and schreibersite fragments. See, e.g., Bingera and Gibeon. Monocrystalline, undamaged troilite usually contains less than 0.3-0.9% Ni.

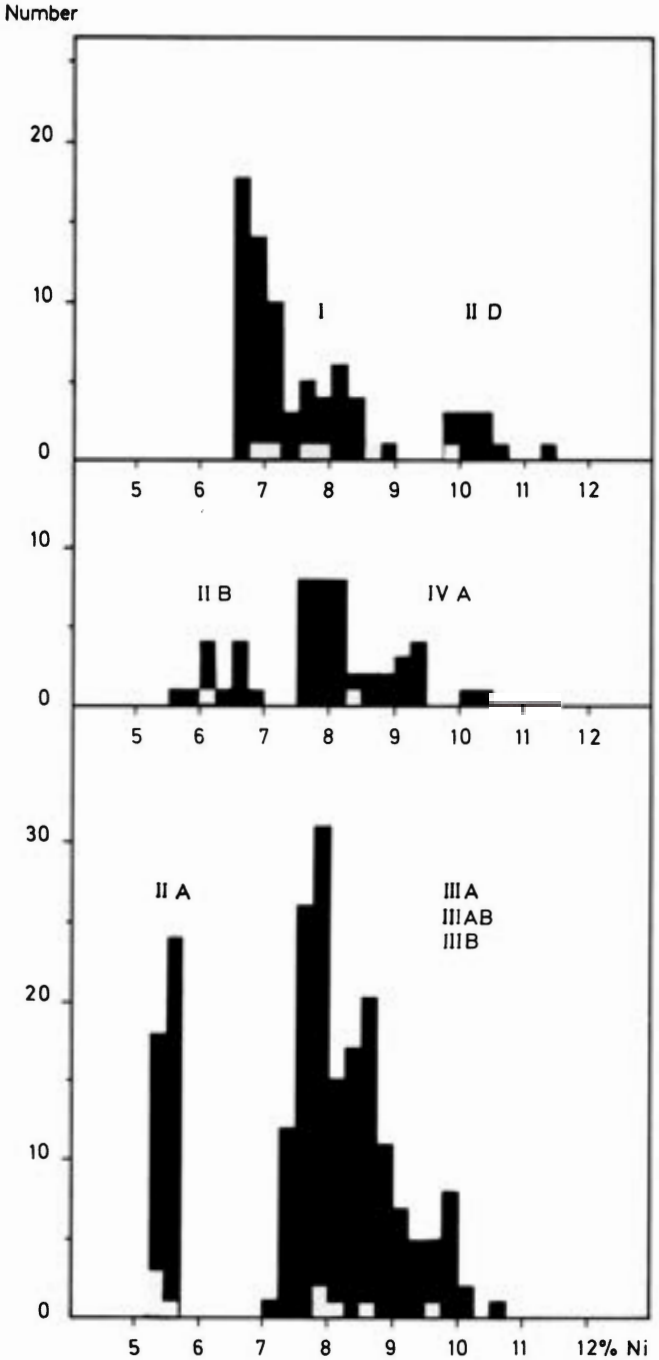

Figure 85. Analysis of Figure 84. The sharp peak at 5.5% Ni is caused by the hexahedrites of group IIA; the peak at 6.8% by the coarse octahedrites of group I; and the peak at 8.0% by the combined effects of group IIIA and IVA. Gray squares indicate observed falls.

Cobalt (27). This element, being odd-numbered, is less abundant that the even-numbered iron and nickel on either side. Wiik (1969) found a range of 0.02 to 0.13% Co in stone meteorites with virtually all Co present in the metallic phases. The average Ni/Co ratio was about 17 in chondrites, rather similar to the Fe/Ni ratio.

In iron meteorites, the cobalt ranges from about 0.32% (Clark County, Nelson County) to 1.0% (Babb's Mill, Troost's Iron) with average values of 0.4-0.6%. See Figures 86 and 87. Since the cobalt atom is similar to iron and

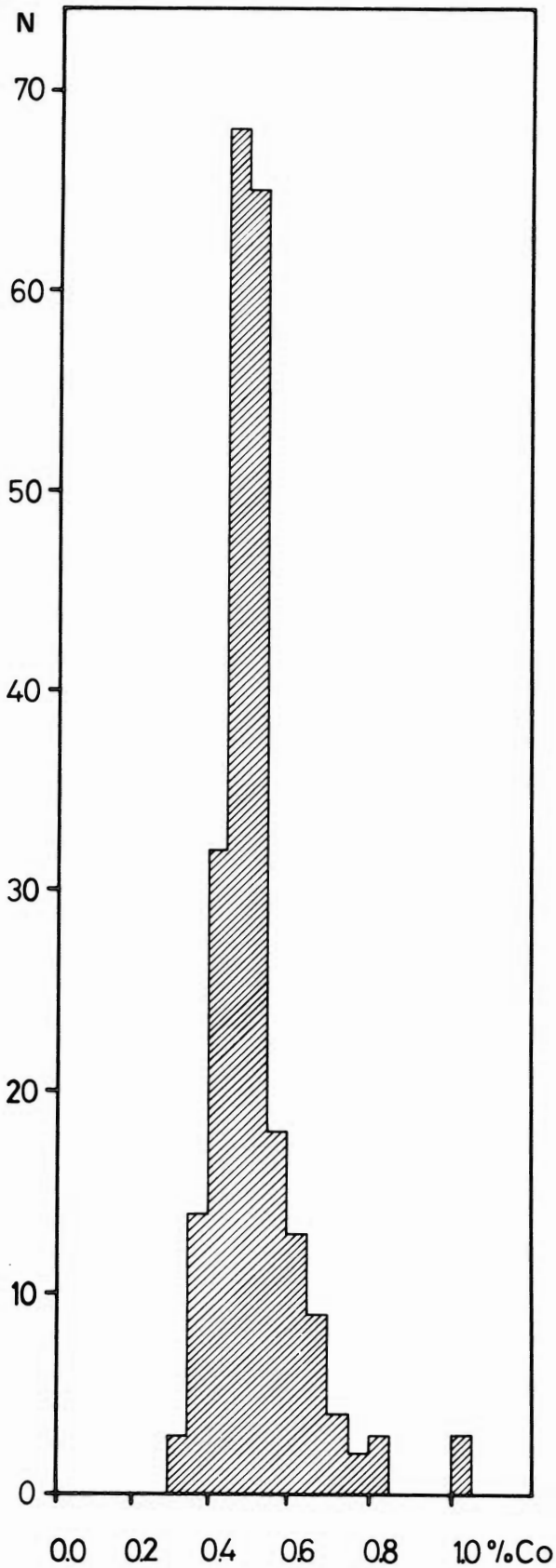

Figure 86. The frequency of distribution of cobalt content in selected analyses of iron meteorites. Values above 1% are very rare. Low values (~ 0.4%) occur particularly in group IVA and IIA, high (~ 0.7%) in IVB.

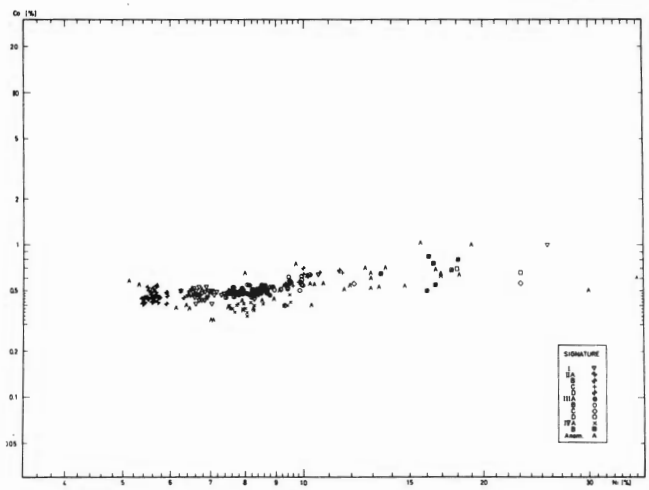

Figure 87. Log-log plot of cobalt versus nickel. There is a weak positive correlation between cobalt and nickel, and the correlation is best within the resolved chemical groups.

nickel, it is usually found substitutionally in the iron- and nickel-rich phases and minerals. Kamacite contains about 0.6% Co, while taenite shows only about 0.3% Co. Cohenite shows a range in cobalt of about 0.02-0.3%. Haxonite has a range of 0.05-0.4% (Scott, personal communication). Schreibersite usually contains about 0.1% Co, and most other minerals still less.

Hydrogen (1). It is the most common element of our solar system and astronomers use it as a reference, listing the abundance of other elements as a number of atoms relative to 10^{12} hydrogen atoms. The determination of H in meteorites is difficult, because finds are always contaminated with terrestrial water; see, e.g., the discussion by Boato (1954). The most reliable data probably come from the recent falls, e.g., Allende (Clarke et al. 1971a). In Allende, water and hydrated minerals are absent, while the analytically determined H_2 ($< 0.01\% H_2$) is believed to be combined with carbon and oxygen in organic C,H,O-compounds. Significant amounts of water (0.2-5%) and organic compounds, e.g., N-methylalanine, α-aminoisobutyric acid and other aminoacids not known from terrestrial proteins, have been reported from carbonaceous chondrites, e.g., Ivuna, Felix (Boato 1954), Murchison and Murray (Lawless et al. 1971). These organic compounds are certainly not due to contamination but indicate an extraterrestrial milieu in which D and L isomers were produced in equal abundances.

Organic compounds are absent in iron meteorites. H occurs as interstitially dissolved atoms in the kamacite and taenite, and perhaps also in some of the minerals and in the grain boundaries. It is further possible that it occurs as trapped gases (H_2, CH_4) in the numerous microfissures which have here been proved to exist in many iron meteorites. The most efficiently sealed fissures are probably the narrow cracks in the kamacite of both hexahedrites and octahedrites. The fissures are of preatmospheric age and probably date from cosmic collisions, remote in time and space.

Edwards (1955) extracted H from 14 iron meteorites and found a range of 0.7-54 ppm. Older data were reviewed by Farrington (1915).

Helium (2). The most important reaction in our Universe is the hydrogen burning in the stars, converting hydrogen into helium and releasing heat energy (Bethe 1968). The cosmic abundance of He is at present about 1/6 that of H. The helium in meteorites is (i) primordial – i.e., was incorporated at the time of meteorite formation, or (ii) radiogenic – i.e., produced in situ by radioactive decay of U or Th, or (iii) cosmogenic – i.e., produced by cosmic ray spallation from, e.g., Fe. Helium in iron meteorites is almost exclusively of the third category. Chackett et al. (1953), Paneth (1954), Signer & Nier (1962), Bauer (1963), Hintenberger & Wänke (1964), Hintenberger et al. (1967) and many others have reported total helium and $^3He/^4He$ ratios for numerous iron meteorites (Appendix 7). Total He ranges from less than 10^{-9} to about 7×10^{-5} cm^3 per gram, the $^3He/^4He$ ratio from 0.3 to 0.04. See also page 142.

Carbon (6). Carbon atoms are about eight times more abundant than iron atoms on a cosmic basis. In stone meteorites carbon occurs in widely varying amounts, from 0.01-0.1% in ordinary chondrites, through 0.3% in enstatite chondrites, to 2-5% in carbonaceous chondrites (Moore & Lewis 1965; Wiik 1969). A similar large range is met with in iron meteorites (Moore et al. 1969). Group IVA and IVB are low in carbon, about 0.005%, IIIA and IIA-IIB intermediate, about 0.01%, while group I is carbon-rich, 0.2-2%. Since the carbon is very inhomogeneously distributed in iron meteorites it is unfortunately difficult to arrive at true bulk analytical data.

In carbon-poor iron meteorites the carbon is in solid solution in the taenite (0.1-0.5%) and to a minor extent in the kamacite (< 0.01%) (Figure 88). Adjacent taenite and plessite fields may display widely varying C amounts. In carbon-rich irons, minerals such as graphite, cliftonite, cohenite or haxonite are formed. Amorphous carbon and diamond and lonsdaleite also occur but rarely; see, e.g., Canyon Diablo and Magura.

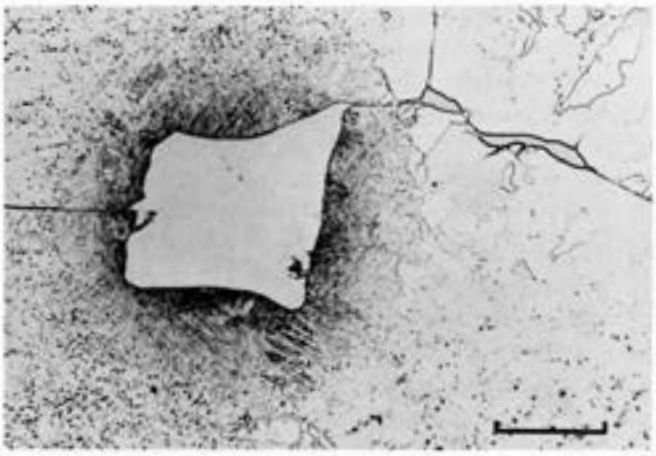

Figure 88. Odessa (Copenhagen no. 1961, 557) Reheated for 10 minutes to 850° C in the laboratory. The central taenite island homogenized slightly, and carbon diffused about 50 μ outwards into the surrounding metal, which at this temperature was also austenitic. Air cooling sufficed to create bainitic carbon-nickel structures (dark). The experiment serves to indicate where a significant portion of the analytically determined carbon in iron meteorites is located. Etched. Scale bar 100 μ.

Nitrogen (7). Nitrogen atoms are about 2.5 times more common than iron atoms on a cosmic basis. In stone meteorites Wiik (1969) reported 0.01-0.29%, the maximum values occurring in carbonaceous chondrites. In these, the nitrogen is present as water soluble NH_4 compounds, pyrimidines (Folsome et al. 1971) and as amino acids, 17 of which have been identified (Lawless et al. 1971). In enstatite chondrites, sinoite, Si_2N_2O, occurs (Andersen et al. 1964), and in the enstatite achondrite, Bustee, osbornite, TiN (Bannister 1941). N is also present in iron meteorites but on a low level. Buchwald (1961b) found 44 ppm in Thule, and Gibson & Moore (1971) recently found a range of 2-130 ppm in 123 iron meteorites. In Odessa and Canyon Diablo large variations, from 25 to 340 ppm N (Goel 1970) exist in adjacent samples. In irons, nitrogen occurs in solid solution in the metal phases and as

Table 29. Abundances of Some Elements in the Solar Photosphere and in a carbonaceous chondrite, (Orgueil (C1)

Atomic number	Element	Atoms per 10^{12} H atoms Solar Photosphere log	Orgueil log
1	H	12.00	
2	He	11.2	
6	C	8.5	
7	N	8.0	
8	O	8.83	
10	Ne	9.0	
11	Na	6.2	
12	Mg	7.50	7.62
13	Al	6.4	
14	Si	7.60	7.60
15	P	5.4	
16	S	7.3	
20	Ca	6.3	
24	Cr	5.0	
25	Mn	4.9	
26	Fe	7.60	7.55
27	Co	(4.7)	
28	Ni	6.25	6.29
29	Cu	4.16	4.28
30	Zn	3.52	
31	Ga	2.7	
32	Ge	2.5	
41	Nb	2.3	
42	Mo	2.3	
47	Ag	0.75	
51	Sb	1.94	
82	Pb	1.63	

Relative to hydrogen, normalized to 10^{12} H atoms. From Unsöld 1969; 1971.

the newly detected mineral carlsbergite, CrN (Buchwald & Scott 1971). Carlsbergite is particularly common in low-nickel irons of group IIIA, in group IIA and group I.

Oxygen (8). Oxygen atoms are 16-17 times more abundant than iron on a cosmic basis. It is a major element of the stone meteorites where – mainly combined in silicates but also as water, carbonates and organic compounds – it constitutes between 28% (Rose City) and 47% (carbonaceous chondrites) (Wiik 1969). The oxygen weight percentage is usually a calculated figure, being the difference between 100% and the sum of all analytically determined elements. See also H and N. In iron meteorites, O occurs in chromite, phosphates, and silicate inclusions, but bulk quantitative data are absent. Krinov (1960a: 287) mentions magnetite as a component of iron meteorites. It must be on a very low level, since the present author never observed it.

Sodium (11). According to Bauer & Schaudy (1970) this element can only be detected in iron meteorites provided these contain an appreciable amount of silicate inclusions. Also, a sodium content less than 1 ppm cannot readily be determined because this element may have been introduced into the sample as an impurity. The authors therefore suggest that the sodium content of iron meteorites can only be specified as less than 5 ppm with the available techniques.

Magnesium (12). Magnesium atoms show the same cosmic abundancy as iron atoms. It is a major element in stone meteorites where – mainly as olivine, pyroxene, mixed sulfides and serpentine – it constitutes between 9 (carb. chondrites) and 25% (some achondrites) (Wiik 1969). In iron meteorites it occurs in silicate inclusions and substitutional for iron in chromite (Bunch & Keil 1969). There is less than 0.001% Mg in the kamacite of Sikhote-Alin (Yavnel, in Fesenkov & Krinov 1963: 351), and this low Mg content is probably general for the metallic phases.

Silicon (14). Silicon atoms show the same cosmic abundance as iron atoms. Si is a major element in stone meteorites, constituting from 10 (carbonaceous chondrites) to 25% (some achondrites) of the total weight (Wiik 1969). Si is normally combined in silicates but also occurs as sinoite (Andersen et al. 1964) and, rarely, in solid solution in the metal phase. Ringwood (1961) considered that the hexahedrites and the enstatite achondrites were complimentary differentiates from the enstatite chondrites and that silicon consequently might be present in the hexahedrites. However, this is not the case; the kamacite phase of Sikhote-Alin contains less than 0.001% Si (Yavnel, in Fesenkov & Krinov, 1963), and Wai & Wasson (1969) found less than 30 ppm Si in the metal of a series of iron meteorites. Silicon is thus only present in the silicate inclusions of iron meteorites. There are, however, a few anomalous, highly reduced iron meteorites. Horse Creek (page 661) has a kamacitic matrix with about 4% Ni and 2.5% Si, in which precipitates of a nickel silicide are abundantly scattered. Tucson and Nedagolla are other anomalous irons with Si in solid solution in the metal phase, 0.8% and 0.14% Si, respectively.

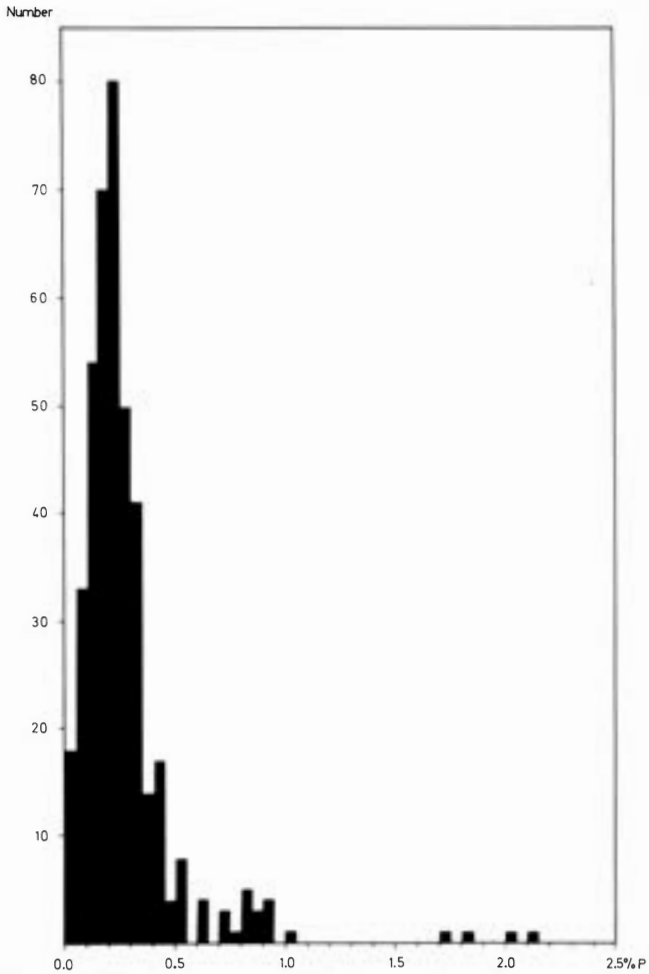

Figure 89. The frequency of distribution of phosphorus content in iron meteorites, plotted at 0.05% P intervals. Meteorites with 0.15-0.25% P are most common, while bulk phosphorus contents above 1% are rare.

Phosphorus (15). Phosphorus atoms are 160 times less abundant than iron atoms on a cosmic basis. P in stone meteorites ranges from 0.01 in Norton County to about 0.25% in some chondrites with the bulk of the values lying between 0.1 and 0.2% (Wiik 1969). P occurs mainly as phosphates, such as apatite, whitlockite, brianite and others (Fuchs 1969).

In iron meteorites it ranges from 0.01-0.02% (Santiago Papasquiaro, Arlington, Nedagolla, nickel-poor members of IVA) to about 2% (Bellsbank, Tombigbee River, Soper). Phosphorus-poor irons have P in solid solution, up to 0.05-0.1%, depending on the cooling rate. Phosphorus-rich irons display schreibersite and rhabdites, $(Fe,Ni,Co)_3P$, in varying amounts. In addition, phosphates are present in several members of group IIIA-IIIB (e.g., Cape York, Grant, Chupaderos, Bella Roca) and in Dayton. It appears that phosphates are also present as accessories in some group I irons, particularly in association with the troilite inclusions. When P is plotted against Ni on logarithmic scales (See

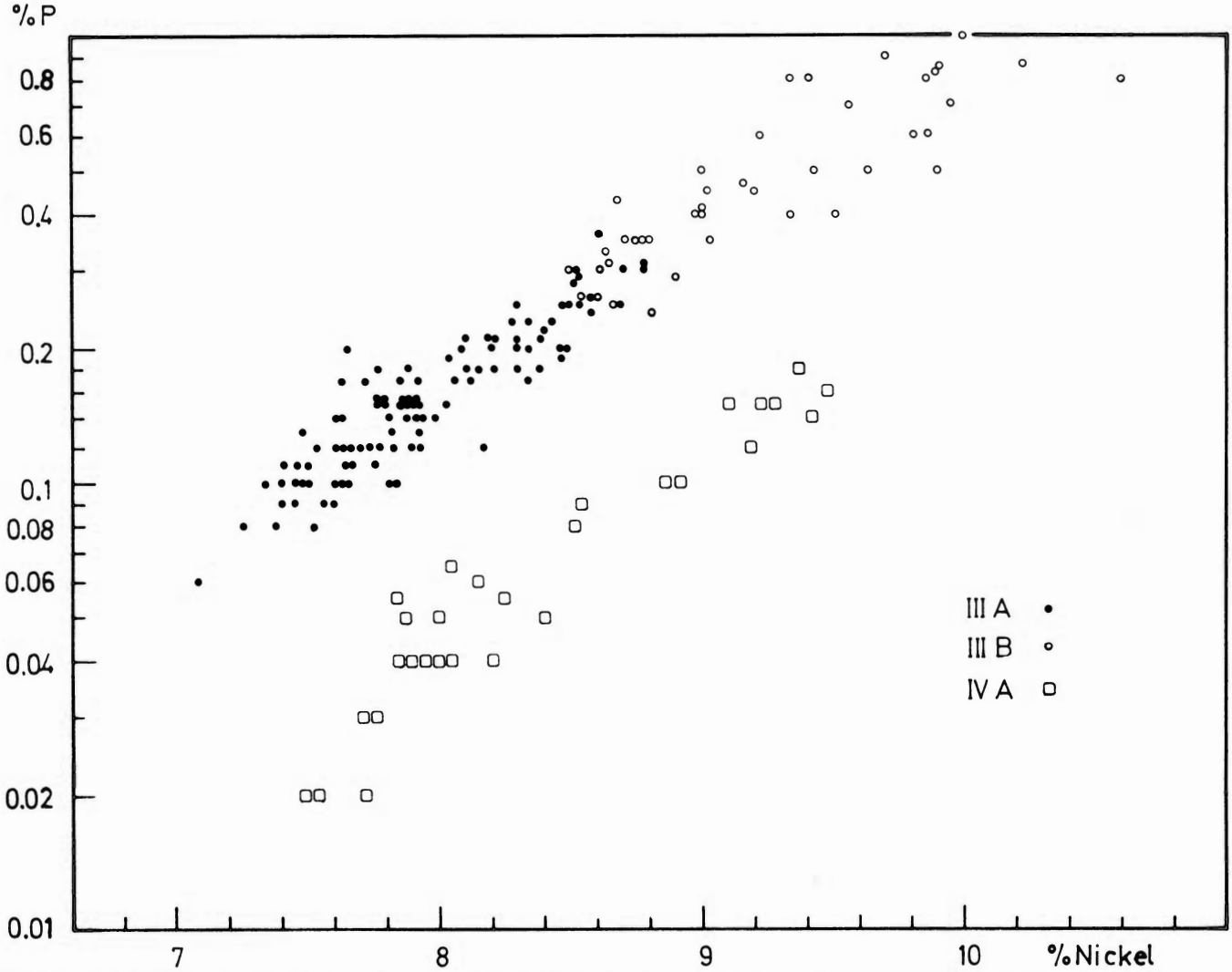

Figure 90. A more detailed plot of phosphorus versus nickel than Figure 81. For a given Ni content a meteorite in group IIIA-IIIB will have about four times the phosphorus content of a group IVA iron.

Figure 81), strong positive correlations are observed in the groups IIA-IIB, IIIA-IIIB, IVA and IVB. Group I alone is remarkable by the absence of any correlation, a fact which is also observed for many other plots of elements (e.g., As, Au, Ir, Pt) versus nickel. For a given Ni content, a meteorite in group IIIA-IIIB will have about four times the phosphorus content of a group IVA member. See Figure 90. Detailed examinations of the phosphorus partition between kamacite and taenite have been presented by Reed (1965a, b; 1967; 1969).

Sulfur (16). Sulfur is only slightly less abundant than iron on a cosmic scale. It appears to be omnipresent in meteorites. For stone meteorites Wiik (1969) found a range from 0.25 (Frankfort, achondrite) to 6.7% (Ivuna, carbonaceous chondrite), the variation probably mainly caused by the varying abundance of the major mineral troilite, FeS. Ramdohr (1963a) found troilite to be present in all of the 135 stone meteorites he examined. Other sulfides are daubreelite, oldhamite and pentlandite.

In iron meteorites the sulfur content is usually underestimated, as it was in the series of analyses by Smales et al. (1967) and Moore et al. (1969). Their sampling technique did not allow visible inclusions in the material to be included. Values of 10-100 ppm may, therefore, be interpreted as the sum of sulfur present in microscopic inclusions (10-100 μ daubreelite and troilite grains) and in solid solution in the nickel iron. For a true bulk value, it is necessary either to dissolve several hundred grams of the meteorite or – better still – to resort to planimetry. In the descriptive part of the book I have shown that sulfur is much more abundant than would appear from the normal wet chemical analyses, values of 0.2-1% being quite common, and cases above 1% (Cape York) not infrequent. In Soroti, Mundrabilla, Santa Catharina and others, the sulfur content is very much higher. See Table 30.

Most remarkable is the absence of troilite in Tucson and Nedagolla. Instead, Tucson has a minor accessory brezinaite, Cr_3S_4 (Bunch & Fuchs 1969), and Nedagolla has daubreelite, $FeCr_2S_4$, an otherwise very common mineral in irons.

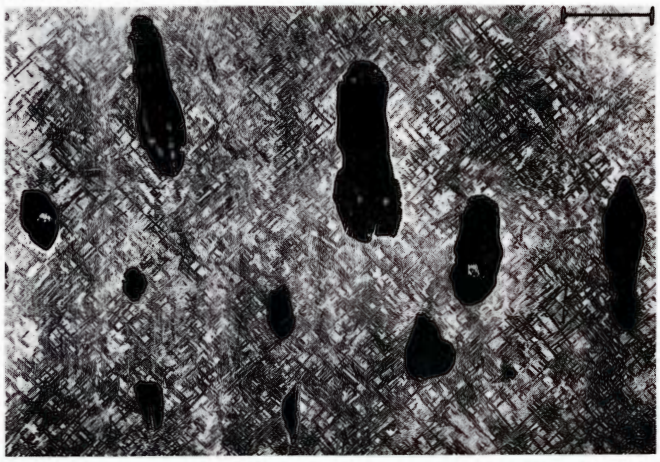

Figure 91. Cape York (Agpalilik, Copenhagen no. 1967, 410). The large section parallel to $(100)_\gamma$ revealed a number of oriented, sausage-shaped troilite inclusions (black). Planimetry of several square meters yielded an average of 1.3% S in the meteorite. Etched. Scale bar 50 mm.

Chlorine (17). The cosmic abundance of chlorine is not very well known (approximately 10 times scarcer than iron), and the data on meteorites are somewhat conflicting. Some of the best values are those of Goles et al. (1967) who studied Cl, Br and I, and found a range of 40 to 800 ppm for chlorine, the highest values occurring in C2 carbonaceous chondrites. In the iron meteorites Odessa and Sardis they found a range of 24 to 82 ppm. Numerous analysts have reported still more chlorine in iron meteorites, in fact up to several percent. In the present work I have noted that such determinations were always on finds, i.e., weathered material, exposed for countless generations to ground water. The analytical values are no doubt high due to chloride ions that have penetrated along grain boundaries in the weathering meteorite. Berkey & Fisher (1967) have, in fact, presented some chlorine analyses that can be interpreted in this way. Presumably the chlorine content in irons is below 1 ppm, the excess in the presented analyses being due to contamination. It is recommended that this problem be solved by the accurate analysis of new iron meteorite falls, the interiors of which should be sampled. The supposed chlorine mineral lawrencite, $FeCl_2$, (Daubrée 1877c; Mason 1962a: 60; Strunz 1970: 157) appears to be a cosmic ghost that has never been adequately defined in iron meteorites and probably does not exist (Buchwald 1971c). In the present work I have searched for it, particularly in the meteorites in which it allegedly occurred, but I have never found anything except rust stains due to terrestrial chloride in near-surface cracks and limonitic veins.

Potassium (19) and *calcium* (20). These elements are important in stone meteorites but only occur on a low and somewhat unknown level in iron meteorites. With potassium and calcium one has to be careful, as with chlorine, because in finds substantial amounts may have been introduced along cracks and grain boundaries from ground water. The elements occur (i) as primordial substitutional atoms in compounds of mainly silicates and phosphates, or segregated to the metallic grain boundaries; or (ii) they are to be found as lattice atoms produced by cosmic irradiation. The accurate method by Voshage (1967) for cosmic ray age determinations of iron meteorites is based upon the separate determination by mass spectroscopy of about 10^{-9} g/g of the spallation-produced isotopes ^{39}K, ^{40}K and ^{41}K. See page 141.

Titanium (22) and *vanadium* (23). These elements are apparently lithophile since they occur on the 50-500 ppm level in stone meteorites (Wiik 1969) but on a 100 times lower level in iron meteorites. Small amounts of Ti and V are present in the chromite inclusions of iron meteorites, substituting for Cr (Bunch & Keil 1969).

Chromium (24). Chromium atoms are about 40 times less abundant than iron on a cosmic basis. Chromium is a lithophile element and the Cr content of stone meteorites is remarkably constant, showing a range of only 0.2-0.9% in 100 meteorites (Wiik 1969). In iron meteorites the "average" concentration is about 100 times lower, but the range is from < 5 ppm (Tombigbee River, Santa Catharina) to 2500 ppm (0.25%, Tucson, Nedagolla). See, e.g., Smales et al. 1967. Some Cr (< 5 ppm) may be present in solid solution in the metallic matrix, while a significant portion occurs bound in carlsbergite CrN, daubreelite $FeCr_2S_4$, and chromite $FeCr_2O_4$, all of which are common accessory minerals in the iron meteorites.

It is remarkable that the anomalous irons, Nedagolla and Tucson, combine high Cr content with low S content and absence of troilite. In Tucson, the rare sulfide brezinaite Cr_3S_4 occurs. Apparently then, chromium is generally lithophile in character but also shows chalcophile behavior in the various sulfides. Under circumstances when Si, S and O are low, Cr may enter into solid solution in the metal or form carbides, thus showing a siderophile trend.

On a logarithmic plot of Cr versus Ni there is a negative correlation within groups IIA-IIB, IIIA-IIIB and IVA. The curves (not shown) are similar to those of an Ir-Ni plot (See Figure 92) but with Cr on an approximately 10 times higher level.

Manganese (25). Mn is on a cosmic basis only slightly less abundant than chromium. Like chromium, it is lithophile and shows a very small range, 0.12-0.43%, in 100 stone meteorites (Wiik 1969). In iron meteorites it plays a very insignificant role and is rarely determined. Kaye & Cressy (1965) analyzed the exceedingly small quantities of Mn in Ider and gave an improved estimate of the half life of the ^{53}Mn nuclide: $(1.9 \pm 0.5) \times 10^6$ years. Mn, a lithophile element, mainly occurs in combined form, in phosphates (sarcopside, graftonite) and in chromite, where it occurs substitutional for Fe II. In the Sikhote-Alin kamacite and schreibersite phases less than 10 ppm Mn was reported, while troilite contained 230-290 ppm (Yavnel, in Fesenkov & Krinov 1963:351). Bauer & Schaudy (1970) reported a range of 9.8-22 ppm Mn for 21 iron meteorites, representing the most important chemical groups and also including

Table 30. Total Sulfur Content of Selected Iron Meteorites

Estimated on basis of planimetry of large sections.

	Name	Class	Weight %
Group I	Bogou	Og	2.0
	Burkett	Og	0.17
	Canyon Diablo	Og	1.0
	Gladstone	Og	1.1
	Odessa	Og	0.5
	Toluca	Og	0.7
	Wichita County	Og	1.2
	Youndegin	Og	0.4
Group I-Anom	Bendego	Og	0.3
	Mertzon	Om	1.4
	Persimmon Creek	Opl	3.0
	Pitts	Of	5.0
	San Cristobal	D	3.0
Group IIA	Boguslavka	H	0.1
	Braunau	H	0.08
	Bruno	H	0.18
	Calico Rock	H	0.15
	Keen Mountain	H	0.3
	North Chile	H	0.1
Group IIB	Ainsworth	Ogg	0.14
	Sikhote-Alin	Ogg	0.3
Group IIC	Ballinoo	Opl	0.3
Group IID	Carbo	Of	0.5
	Wallapai	Of	<0.1
Group IIIA	Angelica	Om	0.4
	Cape York	Om	1.3
	Casas Grandes	Om	0.1
	Costilla Peak	Om	0.2
	Cumpas	Om	0.35
	Dalton	Om	0.3
	Youanmi	Om	0.5
	Tamarugal	Om	0.1
Group IIIB	Apoala	Om	0.6
	Augustinovka	Om	0.9
	Bear Creek	Om	2.0
	Bella Roca	Om	2.0
	Chupaderos	Om	1.4
	Grant	Om	0.6
	Joe Wright Mt.	Om	0.6
	Wonyulgunna	Om	1.0
Group IVA	Altonah	Of	0.5
	Gibeon	Of	0.1
	Yanhuitlan	Of	0.04
Group IVB	Cape of Good Hope	D	0.02
	Hoba	D	0.03
	Tlacotepec	D	0.05
Anomalous	Arltunga	D	0.02
	Barranca Blanca	Anom	0.9
	Butler	Opl	0.35
	Cambria	Of	1.8
	Chihuahua City	Anom	0.25
	De Hoek	Anom	1.2
	La Primitiva	H	0.2
	Mundrabilla	Anom	8
	Nedogolla, Tucson, Washington Co.	Anom	<0.05
	N'Goureyma	Anom	0.6
	Rafrüti	D	0.1
	Santa Catharina	Anom	1.8
	Santa Rosa	Anom	0.3
	Soroti	Off	12
	Waterville	Anom	3.0
	Zacatecas (1792)	Anom	0.5

several anomalous irons. Manganese evidently shows very little group specificity.

Iron (26), *cobalt* (27), *nickel* (28). See above, page 76.

Copper (29). Copper atoms are about 1500 times less abundant than iron atoms on a cosmic basis. In both stone and iron meteorites the range is quite limited. Wiik (1969) found 50-420 ppm in 25 stones, and Smales et al. (1967) and Moore et al. (1969) found 1-1000 ppm in about 150 iron meteorites. While the common chemical groups I, IIA-IIB, IIIA-IIIB and IVA show very little, if any, differentiation and all have 100-200 ppm Cu, it is remarkable that IVB (e.g., Hoba) is very low in Cu, having less than 10 ppm. Some anomalous meteorites particularly of group I-An, have a rather high Cu content. In stones, Cu often occurs as native grains, 5-10 μ across (Ramdohr 1963a, b; Koritnig 1964); in irons, the copper is in solid solution in kamacite and troilite, or occasionally forms grains of native copper adjacent to troilite (Morito, Cape York, Toluca), or forms djerfisherite and chalcopyrrhotite.

Zinc (30). On a cosmic scale Zn atoms are about 10^4 less abundant than iron. In 44 stone meteorites Wiik (1969) found a range of 4-370 ppm, the highest values occurring in carbonaceous chondrites. Iron meteorites are low in Zn; in one-half of 67 examined Smales et al. (1967) found less than 1 ppm, and maximum values of 20-40 ppm occurred only in coarse octahedrites of group I. Similar results, but deviating in detail, were reached by Nishimura & Sandell (1964), Nava (1968), Rosman (1972), and Rosman & De Laeter (1974). Zn occurs in combined form as tiny sphalerite grains, particularly in group I, and it substitutes for Fe in chromite, troilite, and probably daubreelite and phosphates. It may be estimated that less than 10 ppm is in solid solution in the metal.

Gallium (31). On a cosmic scale Ga atoms are about 7.5×10^4 less abundant than iron atoms. In carbonaceous chondrites the range is 6-14 ppm Ga, in other stones 4-22 ppm (Wasson, personal communication). Ga ranges in iron meteorites from 0.05 to 100 ppm and is of particular interest because the concentration range is much smaller, generally less than a factor 2 (See Table 27) within any group of irons which are genetically related. Gallium minerals have not been reported; Ga appears to be siderophile and in solid solution in the metallic phases and in chromite. Nichiporuk (1958) found Ga to be enriched in taenite, relative to kamacite. The extensive works by Goldberg et al. (1951), Lovering et al. (1957), Cobb (1967), Wasson & co-workers (1967 and following years), and Smales et al. (1967) are quoted in numerous places in this work and should be consulted for more details. The isotopic composition of gallium in meteorites and terrestrial samples has been studied by De Laeter (1972a).

Germanium (32). Germanium atoms are about 1.2×10^5 less abundant than iron atoms on a cosmic basis. In stone meteorites Ge shows a small range from about 4 to 50 ppm (Fouché & Smales 1967), but in iron meteorites strong fractionation must have occurred since the observed range

is from 0.005 (Nedagolla) to 2000 ppm (Butler), a factor of 4×10^5. Within structurally and otherwise chemically related irons the Ge concentration range is narrow (See Table 27), a fact which has enabled Wasson & co-workers to refine the chemical classification greatly. See page 71. Ge is found almost exclusively in the kamacite and taenite phases, and it is usually concentrated by factors of 1.5-4 in the taenite phase (Goldstein 1967). Ge is a siderophile element, and chromite, schreibersite and troilite appear to be depleted (at least) 4 times relative to kamacite (Yavnel, in Fesenkov & Krinov 1963: 351). For references, compare Gallium.

Arsenic (33). The cosmic abundance is about 6.6 arsenic atoms per 10^6 iron atoms. The geochemical behavior of the element is perhaps best demonstrated by the distribution pattern noted by Onishi & Sandell (1955) when they analyzed separate metal, sulfide and silicate portions of seven group H and seven group L chondrites. While the bulk values showed a very small range of 0.9-4.0 ppm, the metal, sulfide and silicate portions contained 12, 10 and 0.3 ppm As, respectively. In iron meteorites the range of arsenic is 0.43-31 ppm (Cobb 1967; Smales et al. 1967). In groups I and IIA the arsenic content is rather constant, at 12±2 ppm and 4.5±1 ppm, respectively. In group IIIA-IIIB, however, there is a strong positive correlation with nickel, from 3 ppm As at 7.5% Ni (Henbury) to 16.5 ppm As at 10.2% Ni (Sams Valley). Similarly, within group IVA there is a strong positive correlation, from 1.8 ppm As at 7.5% Ni (Obernkirchen) to 10.0 ppm As at 9.23% Ni (Smithland). There are too few published data to determine the behavior within other resolved chemical groups, but the highest values reported (26.3 and 30.7 ppm) occur in the very nickel-rich meteorites San Cristobal and Santa Catharina.

Niobium (41). On a cosmic scale niobium is about 10^6 times less abundant than iron. Very little information is available regarding its behavior in meteorites, but it appears to be lithophile and chalcophile, rather than siderophile. Rankama (1948) who examined five stone meteorites, three iron meteorites and a pallasite found a range from <0.002 ppm Nb (Plainview, H5) to 1 ppm Nb (Lake Labyrinth, LL6). The iron meteorites Casas Grandes and Kyancutta (both of Group IIIA) showed <0.03 and < 0.003 ppm Nb, respectively, while Coolac (group I) showed < 0.02 ppm. The niobium concentration in troilite was reported to be < 20 ppm, suggesting an enrichment factor in troilite of about 1000 relative to the metallic phases.

Molybdenum (42). On a cosmic scale molybdenum is about 2×10^5 times less abundant than iron. It shows a remarkable constancy in iron meteorites, ranging only from 2.2 to 25 ppm, and with most values between 5 and 9 ppm in 67 samples (Smales et al. 1967). It probably mainly occurs in solid solution in the metal phases.

Antimony (51). The cosmic abundance is about 0.3 antimony atoms per 10^6 iron atoms. Antimony is about equally lithophile and siderophile in geochemical behavior, although the latter may predominate. It shows a range of 0.03-0.3 ppm in stone meteorites (Fouché & Smales 1967; Tanner & Ehmann 1967), and a range of 0.003-2.2 ppm in iron meteorites (Smales et al. 1967). As pointed out by the latter authors, there is a strong correlation between arsenic and antimony and between arsenic and palladium. In groups I and IIA the antimony content is remarkably constant, at 0.38±0.10 ppm and 0.05±0.01 ppm, respectively. In group IIIA-IIIB there is, however, a strong positive correlation between nickel and antimony, ranging from 0.03 ppm Sb at 7.5% Ni (Henbury) to 0.15 ppm Sb at 10.2% Ni (Sams Valley). Also in group IVA this positive correlation may be present, but there are too few published data and the concentrations in group IVA (< 0.012 ppm) are near the limit of detection. It is noteworthy that the As/Sb ratios vary considerably, yet are rather constant within each group: about 30 in group I; about 100 in groups IIA, IIIA and IIIB; and about 500 in group IVA.

Tungsten (74). According to references in Mason (1962a: 178) W appears to be entirely siderophile in meteorites, and its amount in any meteorite is directly related to its nickel-iron content. Average contents of stone meteorites are about 0.14 ppm; for eight irons a range of 0.76 to 2.6 ppm is reported.

Iridium (77). Like germanium, Ir shows a small range (0.18-1.3 ppm) in stone meteorites but a large range in irons (0.007-60 ppm; Table 27). Cobb (1967) presented an initial series of analyses of iron meteorites, and Wasson (1968), Schaudy et al. (1972), Scott et al. (1973) presented a large number and rationalized the interpretation, greatly facilitating the definition of resolved chemical groups. Within each group, with the exception of group I, Ir varies systematically with Ni, especially smooth negative correlations being visible in groups IIIA-IIIB and IIA-IIB, IID, IIIA-IIIB and IVA (Figure 92). In group I, Ir is remarkably constant at 1-5 ppm.

Platinum (78). Attempts to determine platinum, a trace element in iron meteorites, were made at an early stage by assayers on such iron meteorites as Delegate, Bingera (Mingaye 1916; 1921), Weaver Mountains, Tlacotepec, Arispe and Canyon Diablo (Hawley 1939). Improved results are now available (Baedecker & Ehmann 1965; Nichiporuk & Brown 1965) showing a range of 0.5 (Tazewell) to 30 ppm (Indian Valley). Recently, Crocket (1972) determined platinum, iridium, gold, osmium and ruthenium in a series of iron meteorites. Seven group I meteorites had 9±2 ppm Pt with no Ni-Pt correlation. Six group IIIA-IIIB irons showed strong negative correlation as in the Ir-Ni plot (Figure 92); and five group IVA irons showed a similar correlation, except Gibeon which plotted off the line. It also appears that there is a strong negative correlation in group IIA-IIB.

Gold (79). The cosmic abundance is about 0.2 gold atoms per 10^6 iron atoms. Gold is strongly siderophile and when present in the stone meteorites may be assumed to be

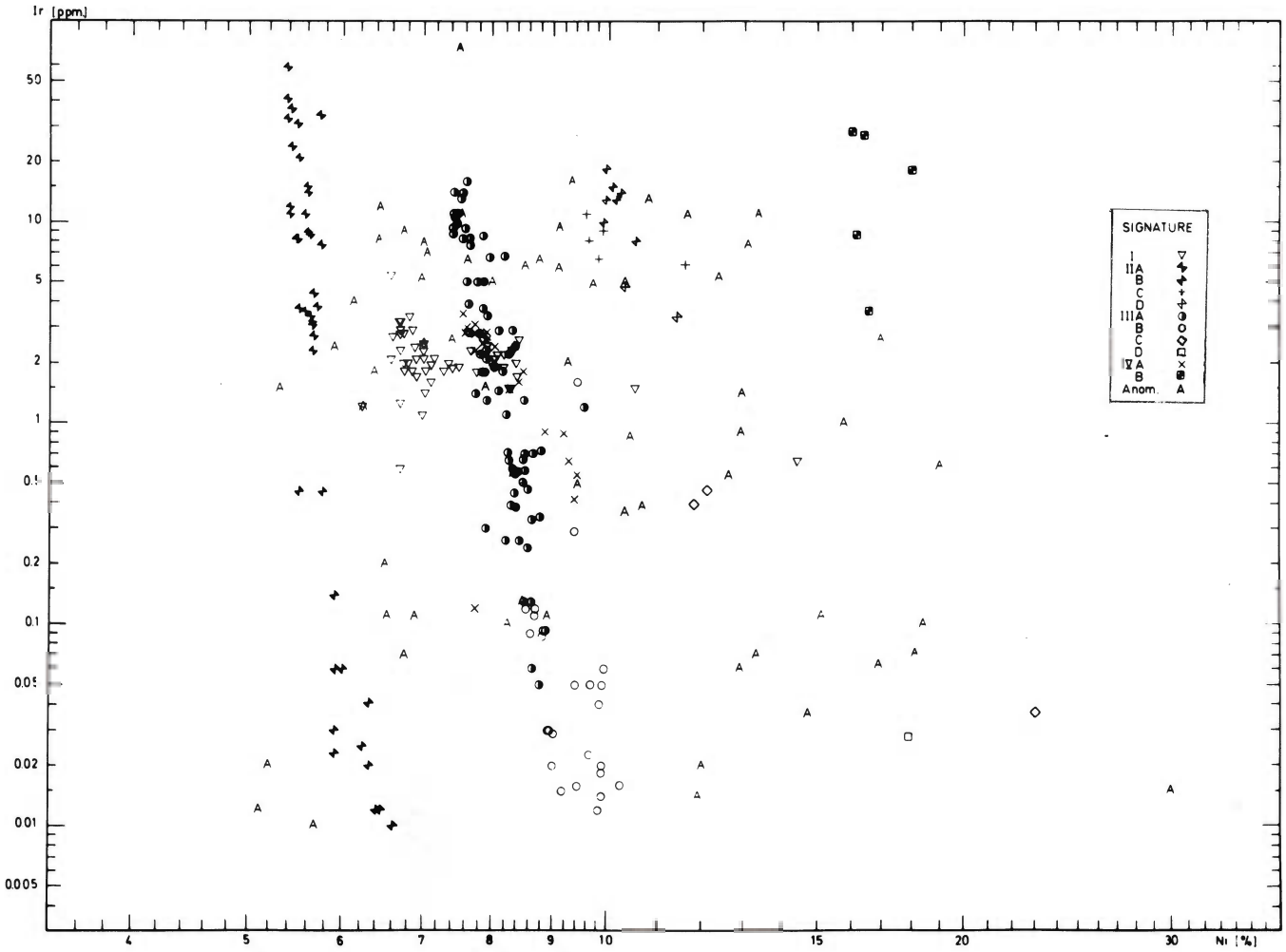

Figure 92. Log-log plot of iridium versus nickel for the resolved chemical groups. (Data mainly from Wasson and co-workers.)

almost entirely in solid solution in the metallic inclusions. Concentration ranges for stones are about 0.1-0.3 ppm. For iron meteorites extensive series of analyses have been carried out, by Goldberg et al. (1951), Fouché & Smales (1966), Cobb (1967), Linn & Moore (1967), Bauer & Schaudy (1970) and Crocket (1972) covering over 100 iron meteorites. Au ranges from 0.05 ppm (group IVB) to over 4 ppm (some anomalous irons). If Au is plotted against Ni, smooth variations occur within the groups IIA-IIB, IIIA-IIIB, IIIC and IVA with positive correlation coefficients as for the P-Ni plot (Figure 81).

Lead (82). Lead atoms are on a cosmic basis about 10^6 times less abundant than iron atoms, and since it is chalcophile – or rather immiscible with iron, – it is not expected to be present in iron meteorites, except at a low level and then chiefly in the troilite. Patterson (1956) and Starik et al. (1960; 1961) thus reported a range of 0.02-0.40 ppm in the metal and 1-8 ppm in the troilite. The lowest concentrations – 0.03 ppm in metal and 1.0 ppm in troilite – were found in Sikhote-Alin, a fall. Discrepancies in data for the meteorite finds may be due to terrestrial contamination during weathering as pointed out by Anders (1962).

Uranium (92). The uranium content of meteorites is of particular interest because it enables us to estimate the solidification age of the meteorite; i.e., the time that has elapsed since the parent material last underwent extensive melting. Unfortunately, the analytical difficulties are so great that few reliable data exist for iron meteorites in which the maximum U concentration appears to be 0.3 ppb (3×10^{-10} g/g) and usually is 10-100 times lower (Reed & Turkevich 1957). Goles & Anders (1962) found a very small range of 8-28 ppb in 12 chondrites, a result which was supported by Morgan & Lovering (1967) who found 8-24 ppb in ten carbonaceous chondrites. These authors estimate a cosmic abundance of about 0.6 U-atom per 10^6 Si (or Fe) atoms. Levsky (pers. comm. 1974) found 0.4 ppb and < 0.05 ppb U in troilite inclusions of Sikhote-Alin and Cape York, respectively.

Concluding Remarks

The elements selected for presentation under the individual descriptions in the following volumes are Ni, Co, P, C, S, Cr, Cu, Zn, Ga, Ge, Ir and Pt. The analytical results are derived from various sources, but a large proportion

come from Wasson (1967, etc; and personal communications), Moore and co-workers (1969 etc.), Smales et al. (1967), Moss (in Hey 1966), Lovering et al. (1957 and Goldberg et al. (1951). About 20 are from the author's own laboratory where troilite, schreibersite, graphite and cohenite were also often measured by planimetry of representative sections in order to arrive at good bulk values for S, P and C.

Numerous old analyses exist; those by J. Lawrence Smith, Whitfield, Cohen, Weinschenck, Sjöström, Fahrenhorst, Eakins and Hawley are usually of good quality and have been accepted if no other analyses were available. However, those by Shannon, Tassin, Nichols, Gonyer and several others were usually of inferior quality and have been rejected here. For the evaluation, the author has mainly used macro- and microstructural criteria in association with electron microprobe work.

The 12 elements selected are believed to be of considerable value, serving as "fingerprints" in the identification of individual meteorites. *It is recommended that any iron meteorite always be analyzed for Ni and P.* These two major elements, together with the structure, are in 90% of all cases sufficient to classify the meteorite. Since C and S are also of primary significance for the development of the structure, they should be analyzed next, and the determination should be supported by planimetry of representative sections. Co, Cu and Zn, which are usually rather constant are perhaps the least informative or useful of the elements selected. Cr is included because a metallurgist acquainted with steels and stainless steels will always want to know to what extent the iron-nickel meteorites are influenced by chromium. As it is, Cr is generally on such a low level that it only occasionally influences the structure. Ga, Ge and Ir – and to a minor degree Pt – are invaluable, since they serve to identify and classify the meteorite unambiguously. However, they usually require refined neutron activation analysis. They are present on such low levels that they apparently do not influence the structure. The remaining elements, other than the 12 selected, are, in iron meteorites, present on the ppm or even ppb level. They usually add up to less than 100 ppm, or 0.01%. They are normally not reported at all in the handbook section, although they are known quantitatively in a significant number of iron meteorites. The interested reader should be able to find the relevant literature, either on basis of the preceding paragraphs or from consultation of modern compilations, in, e.g., Wedepohl (1969) and Mason (1971).

Table 31. The "Average" Iron Meteorite*

percentage (weight)							
Fe(26)	Ni(28)	Co(27)	C(6)	P(15)	S(16)		
90.6	7.9	0.5	0.04	0.2	0.7		

ppm (weight)									
N(7)	Mg(12)	Al(13)	Si(14)	Cl(17)	Ti(22)	V(23)	Cr(24)	Mn(25)	Cu(29)
50	1	1	10	1	5	0.5	50	1	150

ppm (weight)								
Zn(30)	Ga(31)	Ge(32)	As(33)	Nb(41)	Mo(42)	Pd(46)	Ag(47)	Cd(48)
1	50	150	5	<0.03	6	3	0.03	0.005

ppm (weight)							
Sb(51)	W(74)	Ir(77)	Pt(78)	Au(79)	Pb(82)	Th(90)	U(92)
0.05	1	2	10	1	0.2	0.00001	0.00003

*Bulk values, including troilite, schreibersite and other meteoritic minerals.

To conclude the survey of the chemical elements, the author would like to present an estimate of the composition of the "average" iron meteorite. As noted above, any "average" is dependent on many assumptions not easily weighed against each other. The "average iron meteorite" described above can be called the intuitive result based upon the acquaintance with a large number of iron meteorites, and it is difficult to maintain that it is based on strictly scientific calculations. The composition is close to that of Cape York, the average iron meteorite par excellence (Table 31).