Data of Geochemistry
Sixth Edition

Chapter B. Cosmochemistry
Part 1. Meteorites

GEOLOGICAL SURVEY PROFESSIONAL PAPER 440-B-1

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

1879 · CENTENNIAL · 1979

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MICHAEL FLEISCHER, *Technical Editor*

Chapter B. Cosmochemistry
Part 1. Meteorites

By BRIAN MASON

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Tabulation and discussion of elemental abundances in the different classes of stony and iron meteorites, and in their constituent minerals

U.S. DEPARTMENT OF THE INTERIOR
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DATA OF GEOCHEMISTRY, SIXTH EDITION

Michael Fleischer, *Technical Editor*

The first edition of the Data of Geochemistry, by F. W. Clarke, was published in 1908 as U.S. Geological Survey Bulletin 330. Later editions, also by Clarke, were published in 1911, 1916, 1920, and 1924 as Bulletins 491, 616, 695, and 770. This, the sixth edition, has been written by several scientists in the Geological Survey and in other institutions in the United States and abroad, each preparing a chapter on his special field. The current edition is being published in individual chapters, titles of which are listed below. Chapters already published are indicated by boldface.

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ABBREVIATIONS

The following abbreviations for the meteorite classes are used throughout the tables and elsewhere; for the chondrites a digit after the symbol indicates the petrographic type.

Chondrites

C	carbonaceous
H	bronzite
L	hypersthene
LL	amphoterite
E	enstatite

Calcium-poor achondrites

Ae	aubrites
Ah	diogenites
Ac	chassignite
Au	ureilites

Calcium-rich achondrites

Aa	angrite
An	nakhlites
Aho	howardites
Aeu	eucrites

DATA OF GEOCHEMISTRY

COSMOCHEMISTRY
PART 1. METEORITES

By BRIAN MASON[1]

ABSTRACT

Meteorites are the least-differentiated rocks in the solar system, and can thus provide a reasonable approximation to the relative and absolute abundances of the nonvolatile elements. This was first recognized by V. M. Goldschmidt, who in 1937 used data from meteorites to compile the first table of cosmic abundances of the elements in "Geochemische Verteilungsgesetze der Elemente." The great expansion and improvement in analytical techniques, coupled with a growing interest on space research, have resulted in an enormous expansion in the data on elemental abundances in meteorites. These data (to 1976) are summarized herein. An introductory section discusses the phase composition and classification of meteorites, and the factors governing the distribution of the chemical elements within them. This is followed by sections, one for each element (groups of elements for the noble gases and the lanthanides), in which the specific abundances are tabulated and discussed. A concluding section compares meteoritic and solar abundances, using Type I carbonaceous chondrites as the best approximation for average meteoritic matter. In this class of meteorites the order of abundance of the elements (by weight) is: O, Si, Fe (>10 percent); Mg, S, Ca, Ni (1-10 percent); Al, Na, Cr, Mn (0.1-1 percent); P, Cl, K, Co, Ti, Zn, Cu (0.01-0.1 percent); all others (<0.01 percent). A list of meteorite minerals is provided, and a tabulation of elemental abundances in 35 stony meteorites represents most of the recognized classes.

INTRODUCTION

HISTORICAL BACKGROUND

The systematic investigation of elemental abundances in meteorites can be said to date from 1923. In that year V. M. Goldschmidt, in the initial part of his great work "Geochemische Verteilungsgestze der Elemente," pointed out the significance of meteorites for elucidating the geochemistry of the elements. He proposed a classification of the elements into siderophile, chalcophile, lithophile, and atmophile groups, according to their affinity for metallic iron, for sulfides, for silicates, and for the atmosphere, respectively. He remarked that meteorites, with their nickel-iron, troilite (FeS), and silicate (plus oxide) phases, provided a readily available "fossilized" experiment in the distribution of the elements among these phases. During the following years, Goldschmidt and his coworkers made many determinations of specific elements in meteorites. These results, and those of other investigations such as I. and W. Noddack and G. von Hevesy, were summarized in the final part of "Geochemische Verteilungsgesetz der Elemente" (1937), and were used by Goldschmidt to prepare the first comprehensive table of elemental abundances in meteoritic matter. In this table (1937, p. 99-101) he introduced the convention of referring atomic abundances to silicon as the reference element, primarily in order to relate terrestrial and meteoritic abundances to solar abundances, a convention which has since become standard practice.

On the basis of the meteoritic data, supplemented by information from solar spectra, Goldschmidt also prepared a table of cosmic abundances of the elements (1937, p. 120-122). This table and many revised versions (such as Cameron, 1973) have formed the basis for theoretical studies of cosmochemistry and for the testing of hypotheses of nucleosynthesis. As Cameron stated (1973, p. 121):

> In the field of cosmochemistry, these abundances determine the mineral phases which will condense from the primitive solar nebula under different conditions of temperature and density, so that by examining the bulk compositions and individual mineral phases of planetary and smaller bodies in the solar system, much can be deduced about the conditions in the original primitive solar nebula. As our knowledge of the abundances improves, more stringent boundary conditions can be placed on the mechanisms of nucleosynthesis which produced these elements in stars, particularly in short-lived phases such as supernova explosions, thus allowing better tests of theoretical astrophysical calculations in this field.

For some years the propriety of using data from

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meteorites for establishing cosmic abundances of the elements was questioned, largely on an apparent fivefold to tenfold discrepancy between the iron abundance in the solar photosphere and in chondritic meteorites (Urey, 1967; Arnold and Suess, 1969). This discrepancy has been eliminated by the discovery of a tenfold error in the oscillator strengths of the Fe spectrographic lines used for solar abundance determinations (Garz and Kock, 1969). Anders (1971a) provided a detailed discussion of this problem, and concluded that a particular group of meteorites, the Type I carbonaceous chondrites, closely approximates the condensible fraction of primordial solar-system matter. Figure 1 shows the correlation between solar abundances and those in Type I carbonaceous chondrites for 29 elements for which adequate data are available. If abundances for individual elements were the same in both, the points in figure 1 would lie on the 45° line. The close approach to this line is the basis for considering Type I carbonaceous chondrites as approximating in composition the unfractionated nonvolatile matter of the solar system.

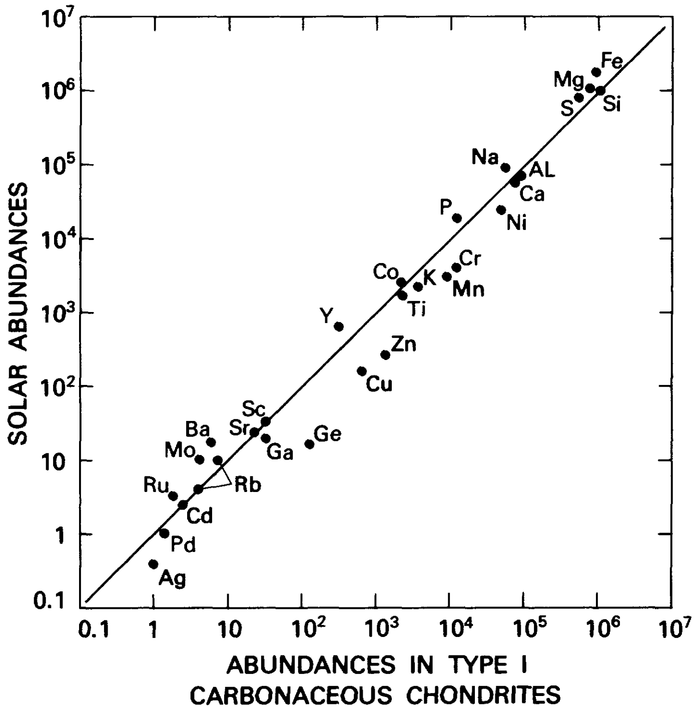

FIGURE 1.—Comparison of elemental abundances (normalized to Si=10^6 atoms) in Type I carbonaceous chondrites with abundances in the Sun. Reprinted from Mason (1971) and published with permission.

PHASE COMPOSITION OF METEORITES

More than 80 minerals are known from meteorites (tables 1 and 83), but many of these are rare acces-

TABLE 1.—*The common minerals of meteorites*

Kamacite	α-(Fe,Ni)	(4-7 percent Ni)
Taenite	γ-(Fe,Ni)	(30-60 percent Ni)
Troilite	FeS	
Olivine	$(Mg,Fe)_2SiO_4$	
Orthopyroxene[1]	$(Mg,Fe)SiO_3$	
Pigeonite	$(Mg,Fe,Ca)SiO_3$	(About 10 mole percent $CaSiO_3$)
Diopside	$Ca(Mg,Fe)Si_2O_6$	
Plagioclase	$(Na,Ca)(Al,Si)AlSi_2O_8$	

---

[1] Divided into enstatite, with 0-10 mole percent $FeSiO_3$, bronzite 10-20 percent, and hypersthene, >20 percent; these minerals are orthorhombic, and have monoclinic polymorphs known as clinoenstatite, clinobronzite, and clinohypersthene. It should be noted that the boundary between bronzite and hypersthene in meteorites, established by Prior (1920), is not the same as current mineralogical usage (30 mole percent $FeSiO_3$), following Poldervaart (1947).

TABLE 2.—*Classification of meteorites*

Class[1]	Symbol	Principal minerals
	Chondrites	
Enstatite (11)	E	Enstatite, nickel-iron
Bronzite (224)	H	Olivine, bronzite, nickel-iron
Hypersthene (256)	L	Olivine, hypersthene, nickel-iron
Amphoterite (49)	LL	Olivine, hypersthene, nickel-iron
Carbonaceous (33)	C	Serpentine, olivine
	Achondrites[2]	
Aubrites (8)	Ae	Enstatite
Diogenites (8)	Ah	Hypersthene
Chassignite (1)	Ac	Olivine
Ureilites (3)	Au	Olivine, clinobronzite, nickel-iron
Angrite (1)	Aa	Augite
Nakhlite (1)	An	Diopside, olivine
Howardites (17)	Aho	Hypersthene, plagioclase
Eucrites (20)	Aeu	Pigeonite, plagioclase
	Stony-irons	
Pallasites (2)	P	Olivine, nickel-iron
Siderophyre (1)(find)	S	Orthopyroxene, nickel-iron
Lodranite (1)	Lo	Orthopyroxene, olivine, nickel-iron
Mesosiderites (6)	M	Pyroxene, plagioclase, nickel-iron
	Irons	
Hexahedrites (4)	Hx	Kamacite
Octahedrites (27)	O	Kamacite, taenite
Ataxites (1)	D	Taenite

[1] Figures in parentheses are the numbers of observed falls in each class. (Buchwald, 1975, Table 23a, p. 60).

[2] Generally subdivided into calcium-poor achondrites (aubrites, diogenites, chassignite, ureilites) and calcium-rich achondrites (angrite, nakhlite, howardites, eucrites).

sories. The common and abundant minerals are listed in table 1. Some contrasts to terrestrial mineralogy may be pointed out: nickel-iron is practically absent from terrestrial rocks; the common minerals in meteorites are largely magnesium-iron silicates, whereas, in the Earth's crust, the commonest minerals are quartz and aluminosilicates; the common meteorite minerals are anhydrous, whereas hydrated minerals are common and abundant on Earth. These features indicate that most meteorites formed in a highly reducing environment, in which nickel and iron were largely in the metallic state. The carbonaceous chondrites, a small but remarkable class of meteorites, differ fundamentally: they consist largely of serpentine, $(Mg, FE)_6Si_4O_{10}(OH)_8$ (or related layer-lattice silicates), the nickel is present mainly in silicates and sulfides, and they contain considerable amounts of organic compounds of extraterrestrial origin. A notable feature of the overall mineralogy of meteorites is the absence of phases, such as pyrope garnet and jadeitic pyroxenes, indicative of high pressures (that is, large parent bodies); the origin of the diamond in the Canyon Diablo iron has been plausibly ascribed to the shock of impact with the Earth that formed the Arizona Meteor Crater, and the presence of diamond in the small group of ureilites appears to be due to extraterrestrial shock effects.

CLASSIFICATION OF METEORITES

Current classifications of meteorites are based on mineralogy and structure. The major groups and classes are listed in table 2. It is obvious from the figures for observed falls that the populations of the different classes vary widely. The figures for observed falls are used as being the best approach to actual extraterrestrial abundances; irons dominate meteorite finds since they are resistant to weathering and are readily recognized as meteorites or at least as very unusual objects. More than 80 percent of meteorite falls are chondrites, and 84 percent of these belong to two classes, frequently referred to jointly as the ordinary or common chondrites. Of the other classes of meteorites, some are represented by a single fall, which suggests that additional classes, as yet unknown, may well exist.

CLASSIFICATION OF CHONDRITES

Chondrites are characterized by the presence of chondrules, which are small (~1 mm diameter) spheroidal aggregates, usually of olivine and (or) pyroxene. Chondrules are unique to chondritic meteorites [2], being unknown in terrestrial rocks, which suggests that they were formed by some exotic process. That they originated as molten silicate droplets is generally agreed, although where and under what circumstances is still a controversial subject. Current ideas include volcanism on the meteorite parent bodies, splash droplets formed in collisions between asteroids, condensation of liquid droplets from a hot gas of solar composition, and fusion of dust in the primordial solar nebula.

Not only are the chondrites the most abundant meteorites, but many features indicate a primary origin for them and a derivative origin for the other meteorite groups. As a consequence, compositional data are far more extensive for the chondrites than for any other meteorite group. However, although the chondrites may have originated from comparatively undifferentiated parent material, they can be subdivided into several classes and subclasses, marked off by distinct mineralogical and chemical hiatuses.

This subdivision is illustrated in figure 2, which plots chemical analyses of individual chondrites in the form of weight percent iron as metal and sulfide (that is, reduced iron) against weight percent oxidized iron (essentially iron combined in silicates). The trend is clear, from meteorites in which all the iron is in the reduced form (the enstatite chondrites) to meteorites in which all or nearly all is in the oxidized form (the carbonaceous chondrites). But the sequence is not a continuous one, and the five classes of chondrites form discrete clusters in this diagram. The classes are also distinguished by their total iron content. Urey and Craig (1953), in the original version of figure 2, noted a bimodal clustering of points corresponding to average total iron contents of approximately 22 percent and 28 percent, and named these the low-iron (L) and high-iron (H) groups respectively. The present figure 2, based on a more rigid selection of analyses and a considerable number of superior analyses made since 1953, shows that the H group comprises the bronzite chondrites and the L group the hypersthene chondrites. In the enstatite chondrites the iron content ranges from values corresponding to the L group to higher figures than those characteristic of the H group. Carbonaceous chondrites cannot be directly compared with the other classes of chondrites, since they contain a large amount of combined water and other volatiles; on a volatile-free basis (used in fig. 1) they belong to the H group.

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[2] Chondrite-like structures have been identified in some lunar rocks.

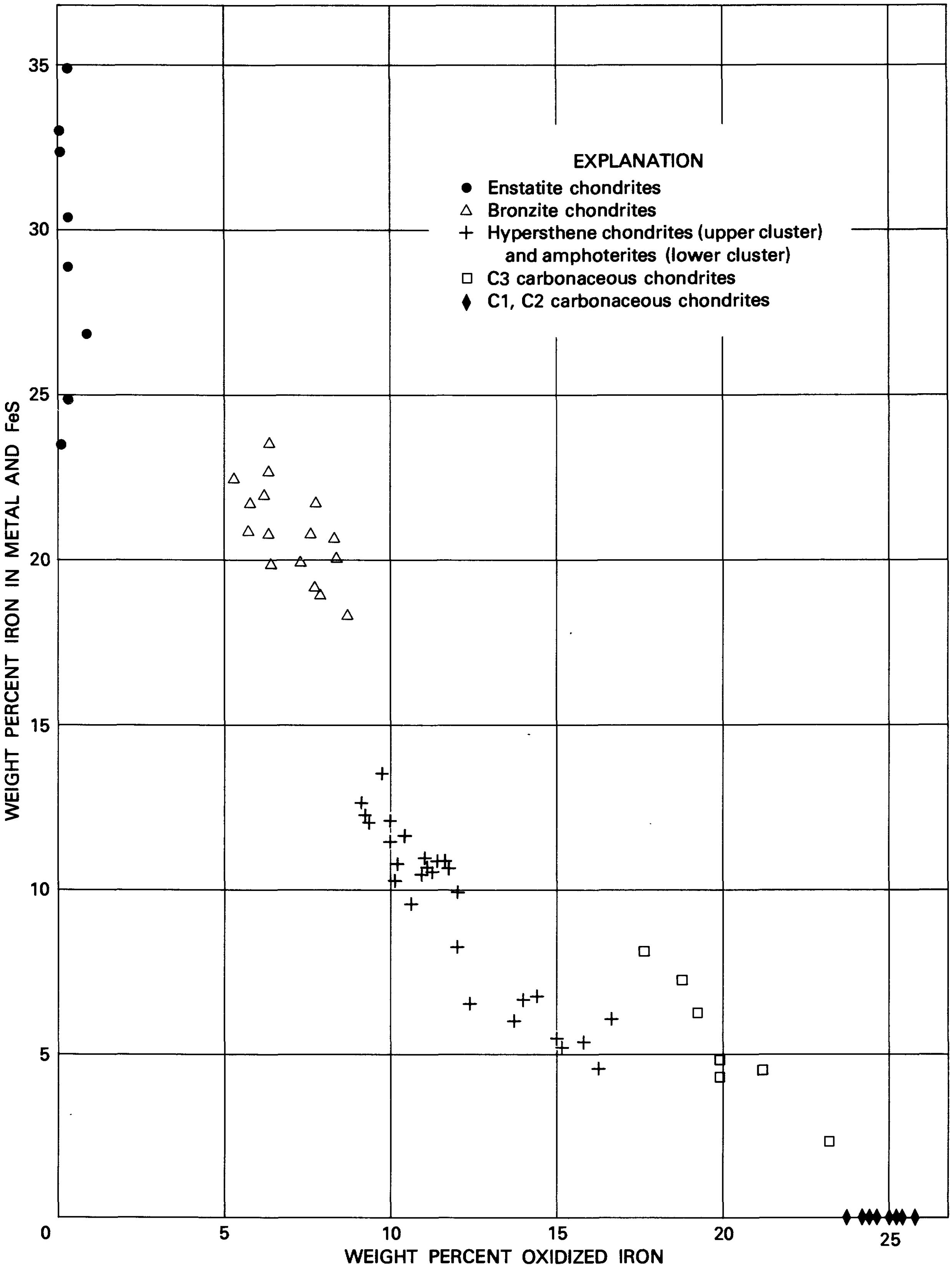

FIGURE 2.—Relationship between oxidized iron and iron as metal and sulfide in analyses of chondrites, illustrating the separation into distinct classes and the variation within the classes. Reprinted from Mason (1967b) and published with permission.

TABLE 3.—*Chemical analyses of chondritic meteorites*

	1	2	3	4	5	6	7
	Weight percent						
Fe	0.00	0.00	0.00	2.28	8.37	16.30	22.05
Ni	.00	.00	.00	.97	1.21	1.74	1.68
Co	.00	.00	.00	.05	.06	.09	.08
FeS	---	---	6.74	5.84	6.42	5.48	9.02
SiO_2	22.56	27.81	33.40	40.81	40.32	36.74	39.83
TiO_2	.07	.08	.10	.17	.12	.12	---
Al_2O_3	1.65	2.15	2.51	2.12	2.19	2.04	2.17
Cr_2O_3	.36	.36	.52	.51	.52	.55	.21
FeO	23.70	27.34	25.43	18.51	12.43	10.24	---
MnO	.19	.21	.19	.40	.34	.32	< .02
MgO	15.81	19.46	23.98	25.32	24.94	23.44	20.94
CaO	1.22	1.66	2.56	1.85	1.82	1.60	.62
Na_2O	.74	.63	.51	.97	1.00	.90	.80
K_2O	.07	.05	.04	.11	.11	.09	.09
P_2O_5	.28	.30	.38	.18	.18	.27	---
H_2O	19.89	12.86	2.07	.15	.05	.15	.12
C	3.10	2.48	.47	.03	.08	.02	.18
NiO	1.23	1.53	1.64	---	---	---	---
CoO	.06	.07	.08	---	---	---	---
S	5.49	3.66	---	---	---	---	---
Total	96.42	100.65	100.62	100.27	100.16	100.09	99.65

TABLE 3.—*Chemical analyses of chondritic meteorites*—Continued

Si	10,000	10,000	10,000	10,000	10,000	10,000	10,000
Mg	10,400	10,400	10,700	9,240	9,240	9,510	7,760
Fe	8,730	8,220	7,750	5,380	5,920	8,140	7,540
Al	860	910	890	610	640	660	630
Ca	580	640	820	490	480	470	350
Na	630	440	300	460	480	480	390
Ni	440	440	400	240	310	480	430
Cr	130	104	122	100	100	120	85
Mn	71	60	50	82	71	74	79
P	106	91	97	38	38	62	44
K	38	22	16	36	36	33	30
Ti	29	28	28	31	22	25	30
Co	22	19	19	12	14	25	22

Key to analyses:

1. Carbonaceous chondrite,Type I: Orgueil.(Wiik, 1956). Deficiency in summation can be ascribed to reporting all Fe as FeO and all S as S, although both ferric iron and sulfate are present in considerable amounts.

2. Carbonaceous chondrite, Type II: Mighei (Wiik, 1956, recalculated with all Fe as FeO).

3. Carbonaceous chondrite, Type III: Mokoia (Wiik, 1956).

4. Amphoterite: Cherokee Springs (Jarosewich and Mason, 1969).

5. Hypersthene chondrite: Leedey (Jarosewich, 1967).

6. Bronzite chondrite: Guarena (Jarosewich and Mason, 1969).

7. Enstatite chondrite: Pillistfer (Jarosewich and Mason, 1969). Includes Si 0.18, TiS 0.14, Cr_2S_3 0.29, MnS 0.26, CaS 0.90, P 0.09.

The individual classes can be divided into subclasses by the use of chemical, mineralogical, and structural distinctions. On the basis of his numerous chemical analyses, Wiik (1956) divided the carbonaceous chondrites into Types I, II, and III, some of the principal distinguishing factors being C, H_2O, total S, and specific gravity, the mean values being:

	C	*H_2O*	*S*	*Sp gr*
Type I	3.54	20.08	6.04	2.2
Type II	2.46	13.35	3.16	2.7
Type III	.46	.99	2.21	3.4

These three types are clearly demarcated by both chemical and mineralogical criteria, and appear to be discrete groups, meteorites of intermediate composition being unknown. One unique carbonaceous chondrite, Renazzo, cannot be readily classified; its mineralogy resembles that of Type II, except for the presence of 12 percent free nickel-iron. Type III carbonaceous chondrites have been called olivine-pigeonite chondrites, but the mineral identified as pigeonite is now known to be a pyroxene of the clinobronzite-clinohypersthene series, so the term "olivine-pigeonite chondrite" should be abandoned.

The existence of an amphoterite group distinct from the hypersthene chondrites has been the subject of some controversy. Inspection of figure 2 shows a cluster of hypersthene chondrite analyses around 10 percent oxidized iron, and a smaller cluster around 15 percent oxidized iron, with possibly a hiatus between them. This clustering was first perceived by Prior (1916), and he called them the Baroti type and Soko-Banja type respectively, after two analyzed meteorites. In the 1920 paper in which Prior established the current classification, he placed these two types in a single class of hypersthene chondrites; the overall chemical composition of the two types is very similar, except for the degree of oxidation of the iron. As figure 2 shows, the greater amount of oxidized iron in the Soko-Banja type is compensated by a concomitant decrease in the amount of iron in the metal phase. Mason and Wiik (1964) studied a number of meteorites of the Soko-Banja type and found that chemically and mineralogically they correspond to the amphoterites, then considered a class of achondrites, evidently because they contain few and poorly defined chondrules; Mason and Wiik therefore considered the amphoterites as a subclass of the hypersthene chondrites. Independently, Keil and Fredriksson (1964) pointed out some distinctive features of the Soko-Banja type chondrites, in particular: "The total iron content of the Soko-Banja group is almost the same as in the L-group chondrites, whereas the mettalic nickel-iron content is considerably lower. For this reason the group constituted of Soko-Banja chondrites should properly be designated the low-iron-low metal (or LL group) of chondrites" (p. 3493-4). Thus the terms Soko-Banja type (or group), LL group, and amphoterite refer to a single group of meteorites. A compositional hiatus probably exists between this group and the hypersthene chondrites (Fredriksson and others, 1968), but the hiatus is a narrow one, much narrower than those between the other chondrite classes and between the Type I, II, III carbonaceous chondrites.

The bronzite chondrites form a very coherent group and are not readily subdivided on chemical or mineralogical criteria. The enstatite chondrites, however, show a wide spread in chemical composition, their total iron content ranging from 20 to 35 percent. They can be divided into two subclasses, sometimes called Type I and Type II (Anders, 1964). Type I enstatite chondrites contain more than 30 percent Fe and more than 5 percent S; the principal mineral is clinoenstatite; and chondritic structure is well developed. Type II enstatite chondrites contain less than 30 percent Fe and 5 percent S; the principal mineral is enstatite; and chondritic structure is poorly developed. Type I and Type II enstatite chondrites show characteristic differences in minor- and trace-element contents (Larimer and Anders, 1967).

The similarities and differences in overall chemical composition between chondrites of the different classes and subclasses is illustrated in table 3. The variation in nickel and cobalt are clearly seen. The carbonaceous chondrites, the common chondrites, and the enstatite chondrites have distinctive Si/Mg ratios, as pointed out originally by Urey (1961). Fractionation of the major lithophile elements between different classes of chondrites is the subject of a paper by Ahrens and others (1969).

Van Schmus and Wood (1967) developed a classification scheme for the chondrites that has been widely adopted. They distinguished six petrologic types on the basis of mineralogical and structural criteria (table 4). They then constructed two-dimensional classification grid (table 5), using these six petrologic types and five chemical groupings [enstatite chondrites (E), carbonaceous chondrites (C), bronzite chondrites (H), hypersthene chondrites (L), and amphoterites (LL)]. No carbonaceous chondrites of types 5 and 6 are known, and there are no representatives of types 1 and 2 in the remaining chemical groups. Their C1, C2, and C3 classes correspond closely to Wiik's Type I, II, and III carbonaceous chondrites. Their E3 and E4 classes correspond to the Type I enstatite chondrites, E5 and E6 to the Type II. The Van Schmus-Wood clas-

TABLE 4.—*Petrologic types of chondrites*

[From Van Schmus and Wood, 1967]

	Petrologic types					
	1	2	3	4	5	6
Homogeneity of olivine and pyroxene composition	-	Greater than 5 percent mean deviations		Less than 5 percent mean deviations to uniform	Uniform	
Structural state of low-Ca pyroxene	-	Predominantly monoclinic		Abundant monoclinic crystals	Orthorhombic	
Degree of development of secondary feldspar	-	Absent		Predominantly as microcrystalline aggregates		Clear, interstitial grains
Igneous glass	-	Clear and isotropic primary glass; variable abundance		Turbid if present	Absent	
Metallic minerals (maximum Ni content in percent)	-	(<20) Taenite, **absent** or very minor		Kamacite and taenite present (>20)		
Sulfide minerals (average Ni content) in percent	-	>0.5		<0.5		
Overall Texture	No chondrules	Very sharply defined chondrules		Well-defined chondrules	Chondrules readily delineated	Poorly defined chondrules
Texture of matrix	All fine-grained, opaque	Much opaque matrix	Opaque matrix	Transparent microcrystalline matrix	Recrystallized matrix	
Bulk carbon content (percent)	∿2.8	0.6-2.8	0.2-1.0	< 0.2		
Bulk water content (percent)	∿20	4-18		<2		

TABLE 5.—*Classification of the chondrites*

[From Van Schmus and Wood, 1967]

CHEMICAL GROUP	PETROLOGIC TYPE 1	2	3	4	5	6
E	E1 —	E2 —	E3 1*	E4 4	E5 2	E6 6
C	C1 4	C2 16	C3 8	C4 2	C5 —	C6 —
H	H1 —	H2 —	H3 7	H4 35	H5 74	H6 44
L	L1 —	L2 —	L3 9	L4 18	L5 43	L6 152
LL	LL1 —	LL2 —	LL3 4	LL4 3	LL5 7	LL6 21

*Number of examples of each meteorite type now known is given in its box.

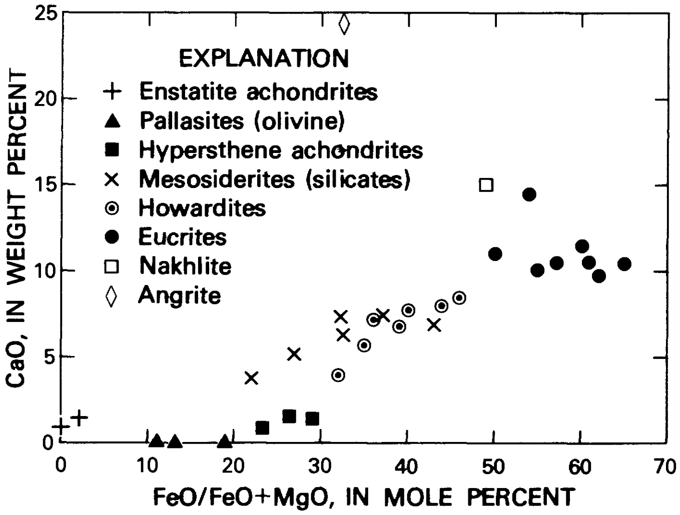

FIGURE 3.—Plot of CaO (weight percent) against FeO/(FeO+MgO) (mole percent) for the achondrites and stony-irons.

sification implies that each chemical group is essentially an isochemical sequence, and that the classes within each group are genetically related; they suggested that (except for the carbonaceous chondrites) the sequence may represent progressive recrystallization. The interpretation is not universally accepted. However, the classification stands independently of its genetic implications; it provides a workable scheme for subdividing the larger chondrite classes, and has shown its utility in the interpretation of minor- and trace-element data.

CLASSIFICATION OF ACHONDRITES AND STONY-IRONS

Superficial examination of a collection of achondrites and stony-irons reveals a great diversity and an apparent lack of any unifying features. Some of them, especially the mesosiderites, are obviously breccias made up of fragments of widely different chemical and mineralogical composition, cemented together by a nickel-iron matrix. However, a closer examination does indicate relationships that imply common processes of genesis for most of them. The composition and structure of the silicate material indicate original crystallization from a melt, similar to the magmas that gave rise to terrestrial mafic and ultramafic igneous rocks.

These relationships can be most readily visualized in the form of a diagram (fig. 3). This shows a regular trend, from calcium-poor, magnesium-rich compositions to compositions richer in calcium and ferrous iron. The enstatite achondrites can plausibly be accounted for by the partial melting of a parent body of enstatite chondrite composition, whereby metal and sulfide were melted and removed by gravitational forces, leaving a residue of coarsely-crystallized enstatite and a little sodic plagioclase. Most of the other achondrites and stony-iron may have been derived by the melting and fractional crystallization of one or more parent bodies with the overall composition of the common chondrites. Such a melt would begin to crystallize at about 1,500°C with the separation of magnesium-rich olivine, similar in composition to that found in pallasites. This olivine together wth the molten nickel-iron would sink and eventually form a core of pallasitic composition. The crystallization of olivine would be followed by that of hypersthene, with a higher Fe/Mg ratio, as occurs in the hypersthene achondrites. At a slightly later stage, plagioclase would begin to crystallize, giving the association hypersthene-plagioclase characteristic of the howardites. This fractional crystallization would result in a steady increase in the concentration of calcium and ferrous iron in the melt, and eventually pigeonite, a pyroxene richer in iron and calcium than hypersthene, would be the stable ferromagnesian silicate, producing the association pigeonite-plagioclase characteristic of the eucrites. Mesosiderites appear to be breccias of all these achondrite types, together with nickel-iron and olivine.

CLASSIFICATION OF IRON METEORITES

The traditional basis for classifying iron meteorites is their structure, specifically the relationship between kamacite, taenite, and plessite (a fine intergrowth of kamacite and taenite). This classification

TABLE 6.—*Structural classification of iron meteorites*

[From Buchwald, 1975]

Structural class	Symbol	Kamacite Bandwidth, mm	Type member	Falls	Total
Hexahedrites	Hx	--	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	.5-1.3	Cape York	12	210
Fine octahedrites	Of	.2-.5	Gibeon	4	55
Finest octahedrites	Off	<.2 continuous	Tazewell	0	7
Plessitic octahedrites	Opl	<.2 spindles	Ballinoo	2	20
Ataxites	D	----	Hoba	1	33
Anomalous	Anom	various	----	3	40
				31	525

TABLE 7.—*Structural and compositional properties of iron meteorite groups*

[From Scott and Wasson, 1975]

Group	Number	Frequency (percent)	Bandwidth (mm)	Structure	Ni (percent)	Ga (ppm)	Ge (ppm)
1A	82	17.0	1.0-3.1	Om-Ogg	6.4-8.7	55-100	190-520
1B	8	1.7	.01-1.0	D-Om	8.7-25	11-55	25-190
1C	10	2.1	<3	Anom.-Og	6.1-6.8	49-55	212-247
11A	39	8.1	>50	Hx	5.3-5.7	57-62	170-185
11B	13	2.7	5-15	Ogg	5.7-6.4	46-59	107-183
11C	7	1.4	.06-.07	Opl	9.3-11.5	37-39	88-114
11D	13	2.7	.4-.8	Of-Om	9.6-11.3	70-83	82-98
11E	12	2.5	.7-2	Anom[1]	7.5-9.7	21-28	62-75
111A	120	24.8	.9-1.3	Om	7.1-9.3	17-23	32-47
111B	36	7.5	.6-1.3	Om	8.4-10.5	16-21	27-46
111C	7	1.4	.2-.4	Off-Of	10-13	11-27	8-70
111D	5	1.0	.01-.05	D-Off	16-23	1.5-5.2	1.4-4.0
111E	8	1.7	1.3-1.6	Og	8.2-9.0	17-19	34-37
111F	5	1.0	.5-1.5	Om-Og[2]	6.8-7.8	6.3-7.2	.7-1.1
IVA	40	8.3	.25-.45	Of	7.4-9.4	1.6-2.4	.09-.14
IVB	11	2.3	.006-.03	D	16-26	.17-.27	.03-.07

[1] Also Om and Og.

[2] Also Ogg and Of.

is presented in table 6, and its significance was discussed in detail by Buckwald (1975).

A more detailed chemical classification of the irons [based on chemical parameters], has been developed by J. T. Wasson and coworkers, and is described by Scott and Wasson (1975). This work is a refinement and extension of the earlier Ga-Ge divisions of Goldberg, Uchiyama, and Brown (1951) and Lovering and others (1957). This classification is based on structural data and accurate analyses for Ni, Ga, and Ge. Sixteen groups of irons have been defined, each of which shows limited ranges of these and other elements, and very similar structures (table 7). Scott and Wasson believe there is good evidence for genetic relationships between groups IA-IB, IIA-IIB, IIIA-IIIB, and IIIC-IIID, and each of these pairs is considered as a single group, giving 12 distinct groups. As can be seen from table 7, the groups are very unevenly populated, two of them (IA and IIIA) comprising over 40 percent of the whole. The relationship of Co, Ga, Ge, As, Ru, Sb, Re, Os, Ir, Pt, and Au to Ni is shown in diagrams under each of these elements.

CHEMICAL FRACTIONATIONS IN CHONDRITES

The abundance variations between different classes and subclasses of chondrites were carefully reviewed by Larimer and Anders (1967). Figure 4, taken from their report, relates the abundances of a considerable number of elements, of differing degree of volatility, in Type I, II, and III carbonaceous chondrites, and in the ordinary chondrites. For the carbonaceous chondrites, abundances decrease from Type I through Type II to Type III by rather constant factors, in the ratio 1.0:0.6:0.3; Type I enstatite chondrites, with a factor 0.7, resemble Type II carbonaceous chondrites. In ordinary chondrites and Type II enstatite chondrites, 9 elements (Au, Cu, F, Ga, Ge, S, Sb, Se, and Sn) are depleted by factors of 0.2–0.5, whereas 12 elements (Te, Ag, Zn, Cd, Hg, Cl, Br, I, Pb, Bi, In, Tl) show more drastic depletions, to factors of 0.002. Larimer and Anders considered that chondrites are a mixture of two types of material: a low-temperature fraction (=matrix) that retained most of its volatiles, and a high-temperature fraction (=chondrules, metallic grains) that lost them. They concluded that these fractionations occurred in the solar nebula as it cooled from high temperatures, and could not have been produced in the meteorite parent bodies. They correlated the different compositions of the chondrite classes with different regions of aggregation within the ancestral solar nebula: enstatite chondrites come from the inner fringe of the asteroidal belt; ordinary chondrites

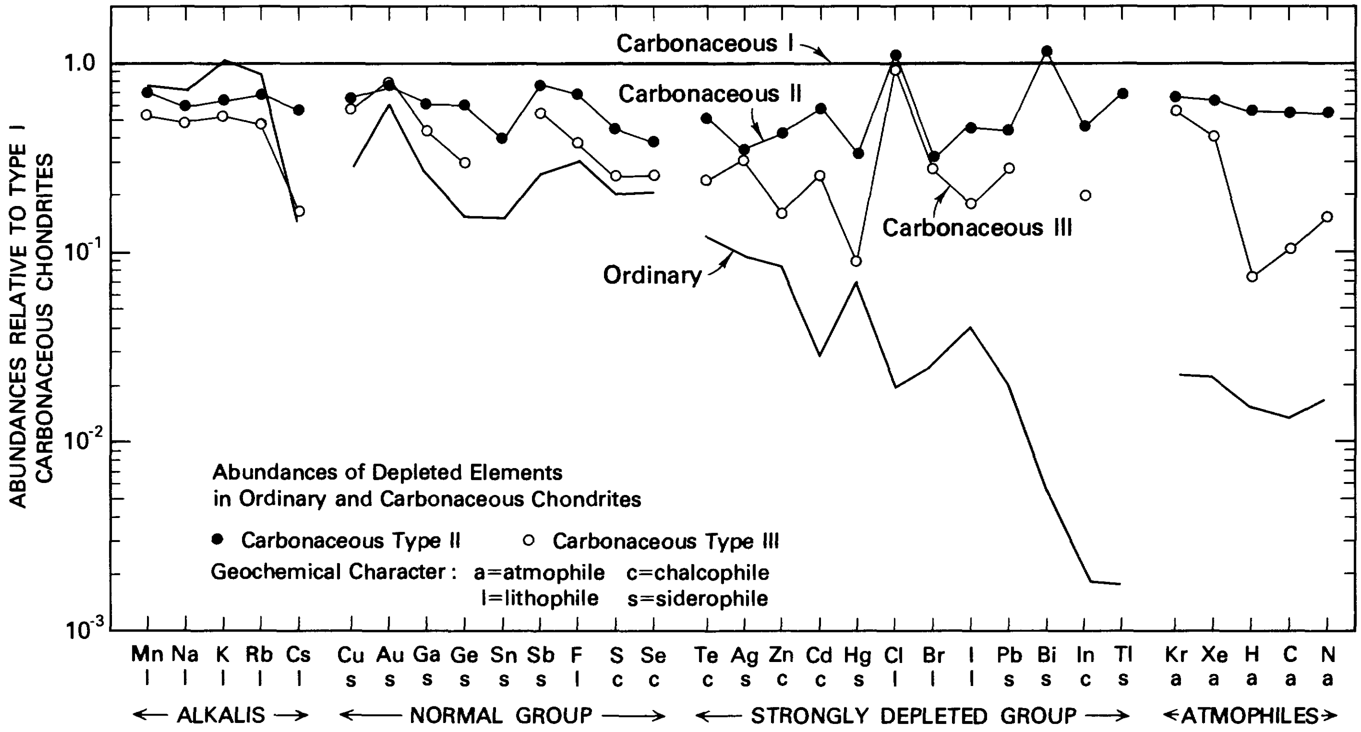

FIGURE 4.—Relative abundances of selected elements in Type II and III carbonaceous chondrites and in ordinary chondrites, normalized to Type I carbonaceous chondrite abundances=1.0. Reprinted from Larimer and Anders (1967) and published with permission.

from the center and inner half; carbonaceous chondrites from the outer fringe or from comets.

Goles (1969, p. 123) commented: "While the model of Larimer and Anders (1967) is an engagingly simple approach to the systematization and, hopefully, understanding of geochemical fractionations among meteorites, much further work must be done before it can be accepted as valid." This seems to be a reasonable statement of the present situation. The existence of fractionation, both of major and minor elements, between different classes of chondrites is beyond dispute; how and where these fractionations took place, and their significance for the early history of the solar system, are certainly open for further elucidation. Clearly, however, the different classes of chondrites are not a simple genetic sequence in the sense that one class represents the parent material from which the others were derived. Instead, they appear to be samples from different regions of an ancestral nebula which was somewhat differentiated chemically, and possibly mineralogically. Carbonaceous chondrites, usually considered more "primitive" or "undifferentiated" with respect to other chondrites, are so only to the extent that their elemental abundances approximate solar abundances more closely; they are presumably coeval, not ancestral, to the other classes.

THE GEOCHEMICAL BEHAVIOR OF ELEMENTS IN METEORITES

When Goldschmidt proposed his geochemical classification of the elements in 1923, few data were available for many of the minor and trace elements. This situation has been largely remedied, but thorough investigation has revealed some surprising variations of geochemical behavior under special circumstances, particularly in some of the less common meteorite classes. For example, potassium, normally a completely lithophile element, occurs as an essential component of the sulfide djerfisherite, $K_3CuFe_{12}S_{14}$, in some enstatite chondrites. For many elements, therefore, it is necessary to qualify their geochemical classification according to the specific environment. Table 8 gives the geochemical behavior as seen in the ordinary chondrites, with appropriate qualifications where called for. Some elements show multiple affinity, even in a single class of meteorite. In ordinary chondrites, iron shows lithophile, chalcophile, and siderophile affinities, whereas in the enstatite chondrites it is essentially chalcophile and siderophile, and in the Type I carbonaceous chondrites it is essentially lithophile, because these meteorites contain no free metal and little or no sulfide. Variations in behavior occur within a single class of meteorites; for example, titanium is progressively more chalcophile and less lithophile in going from the more chondritic to the more recrystallized members of the enstatite chondrites (Easton and Hey, 1968).

LOCATION OF MINOR AND TRACE ELEMENTS IN METEORITES

The location of a specific element in a meteorite is of course conditioned by its geochemical character. Siderophile elements are present in the nickel-iron, chalcophile elements in the troilite, lithophile elements in the silicates (and accessory minerals such as phosphates and oxides). However, the quantitative expression of this is only partly explored, and is a promising field for further investigation. Some of the possible ways a minor or trace element may be incorporated in a meteorite are: (1) as a minor constituent of a major phase; for example, in the common chondrites the manganese is present in solid solution in the olivine, pyroxene, and chromite, (2) as a major constituent of a minor phase; for example, zirconium has been found to occur as rare grains of zircon ($ZrSiO_4$), (3) as a minor constituent of a minor phase; for example, most of the chlorine in stony meteorites is present in chlorapatite ($Ca_5(PO_4)_3Cl$, (4) possibly as a constituent of an intergranular film; for example, water-soluble bromine and iodine. Other mechanisms can be postulated. For example, the noble gases have been found to be concentrated in the surface layers of meteorite minerals, and emplacement by the solar wind has been advanced as an explanation.

HYDROGEN

The occurrence and distribution of hydrogen in meteorites has been extensively reviewed by I. R. Kaplan, in Mason (1971). Although hydrogen is the most common element in the solar system and in the universe as a whole, it is essentially absent from most meteorites, because of the high-temperature conditions under which they formed. Only the carbonaceous chondrites contain hydrogenated compounds of undoubted extraterrestrial origin—the small amount of H_2O sometimes reported in analyses of other stony meteorites is probably terrestrial, acquired since the meteorite entered the Earth's atmosphere. The C1 and C2 carbonaceous chondrites contain hydrogen in a number of forms: water of crystallization in gypsum and hydrated magnesium sulfate, OH groups in serpentine or related layer-lattice silicates, hydrogen in a variety of organic

TABLE 8.—*The geochemical behavior of the elements in chondritic meteorites*

= Atmophile: $\underline{\text{N}}$
= Lithophile: Na
= Chalcophile: $\underline{\underline{\text{In}}}$
= Siderophile: $\underline{\underline{\underline{\text{Fe}}}}$

H																	$\underline{\text{He}}$
Li^{1}	Be											B	$\underline{\text{C}}$	$\underline{\text{N}}$	O	F	$\underline{\text{Ne}}$
Na^{1}	Mg^{1}											Al	Si	P	$\underline{\underline{\text{S}}}$	Cl	$\underline{\text{Ar}}$
K^{1}	Ca^{1}	Sc	Ti^{1}	V	Cr^{1}	Mn^{1}	$\underline{\underline{\underline{\text{Fe}}}}^{3}$	$\underline{\underline{\underline{\text{Co}}}}$	$\underline{\underline{\underline{\text{Ni}}}}^{4}$	$\underline{\underline{\underline{\text{Cu}}}}$	Zn^{1}	$\underline{\underline{\underline{\text{Ga}}}}^{3}$	$\underline{\underline{\underline{\text{Ge}}}}$	$\underline{\underline{\underline{\text{As}}}}$	$\underline{\underline{\text{Se}}}$	Br	$\underline{\text{Kr}}$
Rb	Sr^{1}	Y	Zr	Nb	$\underline{\underline{\underline{\text{Mo}}}}^{2}$		$\underline{\underline{\underline{\text{Ru}}}}$	$\underline{\underline{\underline{\text{Rh}}}}$	$\underline{\underline{\underline{\text{Pd}}}}$	$\underline{\underline{\text{Ag}}}$	$\underline{\underline{\text{Cd}}}$	$\underline{\underline{\text{In}}}$	$\underline{\underline{\underline{\text{Sn}}}}$	$\underline{\underline{\underline{\text{Sb}}}}$	$\underline{\underline{\text{Te}}}^{5}$	I^{6}	$\underline{\text{Xe}}$
Cs	Ba	La-Lu	Hf	Ta	$\underline{\underline{\underline{\text{W}}}}$	$\underline{\underline{\underline{\text{Re}}}}$	$\underline{\underline{\underline{\text{Os}}}}$	$\underline{\underline{\underline{\text{Ir}}}}$	$\underline{\underline{\underline{\text{Pt}}}}$	$\underline{\underline{\underline{\text{Au}}}}$	$\underline{\underline{\text{Hg}}}$	$\underline{\underline{\text{Tl}}}^{5}$	$\underline{\underline{\text{Pb}}}$	$\underline{\underline{\text{Bi}}}$			
			Th		U												

1. Partly chalcophile in enstatite chondrites.
2. Also moderately chalcophile.
3. Also chalcophile and lithophile.
4. Chalcophile and lithophile in carbonaceous chondrites.
5. Also moderately siderophile.
6. Possibly chalcophile.

TABLE 9.—*Hydrogen released as water from carbonaceous chondrites*
[In weight percent]

Meteorite	Type	H_2O-	H_2O+	Reference
Orgueil	C1	6.10	10.55	Jarosewich, unpub. data
Pollen	C2	.62	12.95	Wiik, unpub. data
Murray	C2	2.44	9.98	Wiik, 1956
Santa Cruz	C2	1.10	9.23	Wiik, 1956
Murchison	C2	1.14	8.95	Jarosewich, 1971
Essebi	C2	3.72	7.67	Wiik, unpub. data
Ornans	C3	.18	.25	Wiik, 1956
Warrenton	C3	.00	.10	Wiik, 1956

compounds, and presumably acquired terrestrial H_2O as well. Some analytical data are given in table 9. Many of the C3 chondrites have no detectable combined hydrogen, which is consistent with the absence of hydrated minerals; the small amounts reported in some of them may be partly terrestrial and partly derived from organic compounds.

Boato (1954) concluded from his studies that all H_2O liberated by heating in a vacuum up to 180°C was terrestrial water absorbed by different minerals in the meteorite. This conclusion was reached by measuring the D/H ratio of the liberated water at a series of temperatures from 25°C to 800°C. For the Ivuna, Orgueil, and Mokoia meteorites, water released above 180°C gave values that fell outside the range of atmospheric water. Some of the H_2O extracted from the carbonaceous chondrites has the highest deuterium content ever found in natural material.

Edwards (1955) extracted hydrogen from 14 iron meteorites, and found a range of 0.7–54 ppm.

THE NOBLE GASES: HELIUM, NEON, ARGON, KRYPTON, XENON

The noble gases have especial significance in the geochemistry of meteoritic matter. Their gaseous nature and inertness simplify analytical procedures, and the volume of data on their abundance in meteorites exceeds that for most other elements. By using modern techniques, a determination of their concentration and their isotopic composition can be carried out with high precision on small samples. They may have originated from a variety of sources, and the identification of these sources enables significant deductions regarding the origin and evolution of the meteorites.

Neglecting terrestrial atmospheric contamination (usually small and readily removed by gentle heating), the noble-gas content of a meteorite may comprise several different components, as follows:

Trapped.—Divided into two types, (1) solar, implanted in the surface layers of mineral grains directly from the solar wind; (2) planetary, occluded from the primitive solar nebula during the initial condensation of solid matter. The trapped component is sometimes referred to as the primordial component.

Cosmogenic.—Produced by cosmic-ray-induced spallation reactions; dominantly He, Ne, and Ar produced by spallation of the abundant elements up to Fe and Ni. Heavy elements that produce Kr and Xe by spallation are of low abundance in meteorites, and hence cosmogenic Kr and Xe occur only in very minor amounts.

Radiogenic.—Decay products of radioactive isotopes; ^{4}He from U and Th, ^{40}Ar from ^{40}Kr, and ^{129}Xe from extinct ^{129}I.

Fissionogenic.—Isotopes of Kr and Xe produced by spontaneous (for example, ^{244}Pu) or neutron-induced (for example ,^{235}U) fission. Anders and others (1975) have provided evidence that Xe of peculiar isotopic composition in the Allende meteorite is derived from the fission of an extinct superheavy element, probably element 115.

An indication of the concentration range of the noble gases in meteorites is provided by the data in table 10 (from Dieter Heymann, in Mason (1971)). Grant is an iron meteorite and contains only cosmogenic gas. Bruderheim contains principally cosmogenic gas and radiogenic ^{4}He and ^{40}Ar, and small amounts of trapped ^{36}Ar, ^{84}Kr, and ^{132}Xe. Chainpur differs from Bruderheim in containing substantial

TABLE 10.—*Noble gases in five meteorites*

[In 10-8 ccSTP/g]

Meteorite	Class	^{3}He	^{4}He	^{20}Ne	^{21}Ne	^{22}Ne	^{36}Ar	^{38}Ar	^{40}Ar	^{84}Kr	^{132}Xe
Grant	Of	490	1,880	5.89	5.95	6.25	18.8	30.0	27.6		
Bruderheim	L6	52.4	561	8.8	9.90	10.9	1.56	1.56	1,155	.015	.013
Chainpur	LL3	48	2,080	13.8	10.6	11.8	51	10.5	4,940	.31	.24
Orgueil	C1	6.1	10,800	31.2	.80	4.3	77	15.9	518	.58	.18
Fayetteville(light)	H4	54	1,880	12	8.6	8.4	1.50	1.23	2,450	.055	.022
Fayetteville(dark)	H4	474	1,410,000	5,450	21.4	450	286	58	6,100	.17	.10

amounts of trapped Ar, Kr, and Xe; the same is true for Orgueil, which also contains a large amount of trapped He. Fayetteville typifies a small group of chondritic meteorites with light-dark structure (light- and dark-gray areas of essentially the same composition except for their noble-gas content). In Fayetteville, the light parts have gas contents similar to Bruderheim, but the dark part contains vast amounts of trapped He, Ne, and Ar of solar wind origin.

This brief review clearly shows that no purpose is served in attempting to give mean concentrations of the noble gases in meteorites since each meteorite is essentially unique, and its noble-gas content reflects its individual history. Cameron (1973) gave the following cosmic atomic abundances for the noble gases (normalized to $Si=10^6$): He, $2{\cdot}21\times10^9$; Ne, $3{\cdot}44\times10^6$; Ar, $1{\cdot}172\times10^5$; Kr, 46·8; Xe 5·38.

Wasson (1974) provided a comprehensive account of noble gases in meteorites and their significance in problems of genesis and subsequent history.

LITHIUM

Lithium is a trace element that shows remarkably little variation in abundance between different classes of chondritic meteorites (table 11), except in the enstatite chondrites of petrologic types 5 and 6, in which this element is notably diminished. The same is true for the single analysed aubrite (enstatite achondrite). In terms of atoms/10^6Si, some diminution in abundance is evident in going from C1 to C2 to C3, and thence to the ordinary chondrites. The highest concentrations are found in the eucrites, at about twice chondritic levels.

Lithium is essentially a lithophile element; Fireman and Schwarzer (1957) found less than 0.01 ppm in several iron meteorites. However, Shima and

TABLE 11.—*Lithium in stony meteorites*

[From Walter Nichiporuk, in Mason, 1971; Nichiporuk and Moore, 1974; Nichiporuk, 1975; and table 84]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
C1	2	1.52-1.61	1.6	60
C2	5	1.61-1.86	1.7	52
C3	11	1.43-3.83	1.9	49
H	13	1.2-2.1	1.7	40
L	19	1.3-2.6	1.8	39
LL	21	1.7-2.7	2.1	45
E4	2	1.3-2.9	2.1	47
E5,6	2	.44-.64	.58	13
		Calcium-poor achondrites		
Ae	1	.33	--	5.3
Ah	1	2.20	--	36
Au	1	1.84	--	40
		Calcium-rich achondrites		
Aa	1	2.02	--	40
Aeu	3	5.07-7.27	6.1	106

Honda (1967) showed that, in the enstatite chondrite Abee, about two-thirds of the lithium is in the sulfide phases; evidently under conditions of extreme reduction and relatively high sulfur fugacity, lithium, like sodium and potassium, has chalcophile affinities. Shima and Honda also showed that in ordinary chondrites most of the lithium is in the HCl- soluble fraction (after treatment with bromine water to remove troilite); this indicates that in these meteorites the lithium probably resides in olivine, replacing magnesium. ($LiFePO_4$ is isostructural with olivine.)

BERYLLIUM

The limited data on the abundance and distribution of beryllium in meteorites are derived from the work of Sill and Willis (1962) and Quandt and Herr (1974). Sill and Willis analyzed 12 chondrites, 4 achondrites, and 1 iron by a fluorometric procedure; Quandt and Herr analyzed 73 chondrites, 1 achondrite, and 4 irons by photon activation. Their results are generally consistent, although Quandt and Herr recorded some unusually high values for chondrites—those >100 ppb have been omitted from table 12. The single enstatite chondrite and enstatite achondrite (aubrite) analyzed show relative depletion in this element, as does the Johnstown diogenite; one eucrite, Sioux County, is relatively enriched. Beryllium is a lithophile element; Sill and Willis recorded <1 ppb in the Aroos iron, Quandt and Herr <8 ppb in the four irons they analyzed. The abundance of Be is remarkably low, lower even

TABLE 12.—*Beryllium in meteorites*

Class	Number analyzed	Range (ppb)	Mean (ppb)	Atoms/10^6Si	Source[1]
		Chondrites			
C2	1	35	--	0.81	S
C2	1	41	--	.94	Q
C3	3	43-93	62	1.25	Q
H	4	30-48	38	.69	S
H	23	30-88	51	.93	Q
L	6	32-58	43	.72	S
L	25	26-92	52	.87	Q
LL	1	33	--	.58	S
LL	4	41-62	51	.85	Q
E4	1	20	--	.36	S
		Calcium-poor achondrites			
Ae	1	6-13	8	0.10	S
Ah	1	13	--	.16	Q
		Calcium-rich achondrites			
Aeu (Pasamonte)	1	37-40	39	0.63	S
Aeu (Sioux County)	1	272-276	274	3.69	S

[1] S, Sill and Willis (1962); Q, Quandt and Herr (1974).

than the abundances of the neighboring odd-numbered elements.

BORON

Data on the concentration of boron in meteorites are sparse, and have been summarized and discussed by P. A. Baedecker (in Mason, 1971). See table 13. Practically all the data are derived from the work of Quijano-Rico and Wänke (1969), who used a fluorometric method of determination. The concentration in carbonaceous chondrites is notably higher than in most other stones, suggesting that in these meteorites the boron may be associated with the carbonaceous matter, or that it is combined in volatile compounds. Quijano-Rico and Wänke noted a correlation between boron content and petrologic type in chondrites, boron behaving like other volatile elements (and noble gases) by diminishing in concentration with increasing type number. Two iron meteorites, Canyon Diablo and Toluca, contained 0.02 and 0.03 ppm boron, confirming the lithophile nature of this element. Mason and Graham (1970) found that in mineral separates from meteorites boron is concentrated in plagioclase and olivine.

CARBON

Carbon in small amounts is universally present in meteorites, but until the work of Moore and Lewis (1965, 1966, 1967) no systematic investigation of a large number of specimens had been undertaken. Their results, along with some additional data, are summarized in table 14 and figure 5. The carbonaceous chondrites, as implied by their name, are richest in carbon; the abundance ranges of the four types overlap, and the lower limit of C3 and C4 overlaps the higher limits for the ordinary and enstatite chondrites. Thus, the distinction between carbonaceous and other classes of chondrites cannot be based on carbon content alone. Figure 5 illustrates the distribution of carbon in the ordinary chondrites in relation to the petrologic types established by Van Schmus and Wood (1967). High carbon contents are clearly confined to the so-called unequilibrated chondrites, the petrologic type 3 of Van Schmus and

TABLE 13.—*Boron in meteorites*

[From P. A. Baedecker, in Mason, 1971]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6
		Chondrites		
C1	2	5.1-7.1	5.7	144
C2	1	9.4	--	186
C3	3	5.6-9.6	7.2	121
H	25	.14-6.0	1.0	15
L	10	.14-1.70	.74	10
LL	1	1.4	--	19
E4	1	.77	--	12
E6	1	.43	--	5.7
		Calcium-poor achondrites		
Ae	1	0.42	--	3.9
Ah	1	.34	--	3.6
		Calcium-rich achondrites		
Aeu	1	0.63-1.1	0.83	9.4

Wood. A good median figure for the ordinary chondrites is 0.1 percent C.

The carbonaceous material in stony meteorites has been exhaustively discussed in a book by Nagy (1975). In the carbonaceous chondrites, some of the carbon is present as extractable organic compounds, but most is combined in a black insoluble complex of high molecular weight compounds. This complex is probably the carbonaceous material in most of the ordinary chondrites, judging by the results of Hayes and Biemann (1968). They found that the carbonaceous material in Holbrook, a hypersthene chondrite, is largely polymeric, the most abundant compounds being evolved at 200°–500°C. The pyrolysis compounds are predominantly alkylbenzenes, but various aromatic C-H-O, C-H-N, C-H-S compounds are also present, along with some more highly condensed aromatic hydrocarbons.

Carbon contents are low in the achondrites, except for the ureilities, which have carbon contents as high as the carbonaceous chondrites.

The results of Moore, Lewis, and Nava (1969) on iron meteorites (the samples selected to avoid inclusions of graphite and cohenite) show generally low figures for carbon (table 15). Slow cooling has evidently favored the segregation of carbon into specific phases, such as graphite and cohenite. Within the metal phases the carbon is in solid solution in the taenite (0.1–0.5 percent) in preference to the kamacite (<0.01 percent), according to Buchwald (1975).

NITROGEN

Nitrogen in meteorites has been systematically studied by Moore and his coworkers; the total nitrogen contents were determined by an inert gas-

TABLE 14.—*Carbon in stony meteorites*

[From Vdovykin and Moore, in Mason, 1971]

Class	Number of determinations	Range (weight percent)	Median (weight percent)	Atoms/10^6Si
		Chondrites		
C1	5	2.70-4.83	3.19	720,000
C2	9	1.30-4.00	2.48	440,000
C3	9	.35-2.49	.56	85,000
C4	2	.07-.20	.14	20,000
H	35	.02-.35	.11	15,000
L	43	.03-.53	.09	11,000
LL	16	.03-.44	.12	15,000
E4	4	.36-.56	.39	53,000
E5	2	.37-.54	.45	58,000
E6	7	.06-.43	.36	43,000
		Calcium-poor achondrites		
Ae	2	0.04-0.10	0.07	59,000
Ah	1	--	.04	3,800
Au	5	1.94-4.10	3.00	370,000
		Calcium-rich achondrites		
Aho	3	0.02-0.25	0.11	11,000
Aeu	4	.04-0.47	.06	6,100

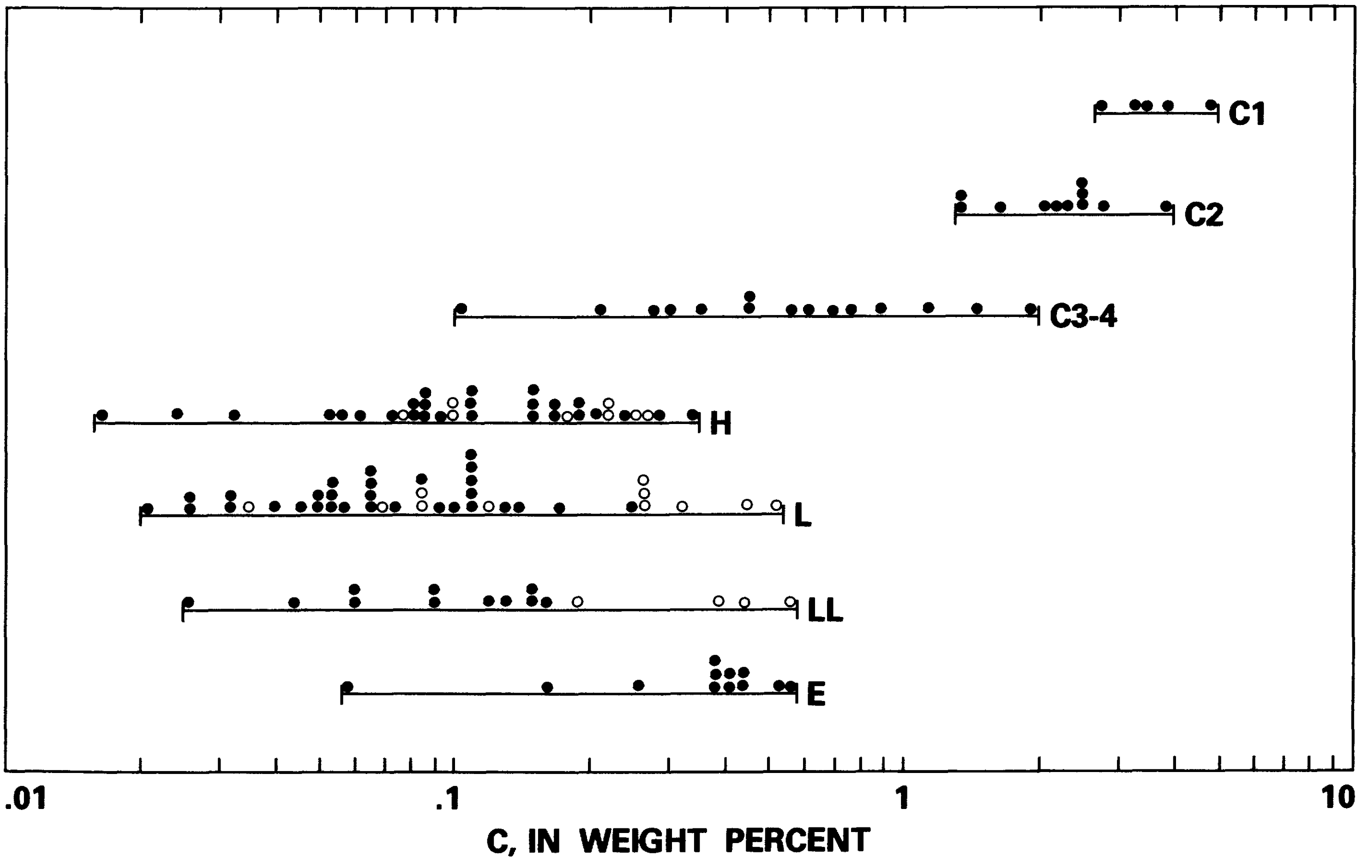

FIGURE 5.—Frequency distribution of carbon in chondrites; open circles indicate unequilibrated ordinary chondrites, petrologic type 3; solid circles indicate all other chondrites. Reprinted from Vdovykin and Moore *in* Mason (1971) and published with permission.

TABLE 15.—*Carbon in iron meteorites*

[In weight percent. From Moore, Lewis, and Nava, 1969]

Class	Number of meteorites	Range	Median
Hx	8	0.005-0.013	0.009
Ogg	3	.009-.022	.013
Og	10	.004-.18	.012
Om	42	.002-.06	.014
Of	17	.005-.046	.011
Off	6	.010-.042	.030
D	6	.003-.051	.007

fusion gas chromatographic technique (Gibson and Moore, 1970). Some additional determinations have been provided by Kothari and Goel (1974), who used a neutron activation technique. Results on the same meteorite by the two techniques are fairly consistent, although the figures obtained by Kothari and Goel are generally somewhat lower. The data are summarized in tables 16 and 17.

Nitrogen is strongly enriched in C1 and C2 carbonaceous chondrites with respect to other classes of stony mateorites. This can be ascribed to the presence in C1 and C2 meteorites of nitrogen-bearing organic compounds; Hayatsu and others (1968) have identified the nitrogen-bearing organic compounds adenine, ammeline, guanine, guanylurea, and melamine in the Orgueil (C1) meteorite; and amino acids have been found in several C1 and C2 meteorites—more than 30 different amino acids have been identified in the Murchison (C2) meteorite (Lawless, 1973).

The state of combination of the small amounts of nitrogen in noncarbonaceous meteorites is not well known. Kothari and Goel (1974) found that nitrogen is enriched in the nonmagnetic relative to the magnetic (metallic) fractions in ordinary chondrites. Some of the enstatite chondrites contain trace amounts of the minerals osbornite (TiN) and sinoite (Si_2N_2O); sinoite-bearing meteorites have notably enhanced nitrogen contents (Moore, Gibson, and Keil, 1969).

The nitrogen content of iron meteorites is low and variable as shown in table 17. The mineral carlsbergite (CrN) is an accessory in some irons. Gibson and Moore (1971a) showed that sulfide inclusions in iron meteorites contain notably higher concentrations of nitrogen than the metal itself.

Injerd and Kaplan (1974) determined the isotopic composition of nitrogen in some carbonaceous chondrites, and found that it is enriched in ^{15}N; $\delta^{15}N$ relative to air ranges from +5.6 to +46.3 (‰).

OXYGEN

Until 1964, no direct measurements had been made on the amount of oxygen in any meteorite, oxygen

TABLE 16.—*Nitrogen in stony meteorites*

[Data from Moore and Gibson, 1969; Moore, Gibson, and Keil, 1969; Gibson and Moore, 1971; Gibson and others, 1971a, b; Gibson and Moore, 1970;. Au is from Kothari and Goel, 1974]

Class	Number analyzed	Range (ppm)	Median (ppm)	Atoms/10^6Si
		Chondrites		
C1	1	3,090-3,280	3,185	59,000
C2	6	950-2,000	1,500	22,000
C3	10	55-242	105	1,200
H	20	18-121	48	570
L	28	17-109	43	480
LL	11	36-298	70	740
E	9	54-780	260	3,000
		Calcium-poor achondrites		
Ae	1	44	--	340
Ah	1	31	--	250
Au	2	13-46	27	290
		Calcium-rich achondrites		
Aho	3	40-66	56	490
Aeu	3	24-45	39	360

being a calculated figure, arrived at by difference in a classical chemical analysis; the oxygen percentages for individual meteorites given in table 84 have been calculated on this basis. This procedure, of course, throws all the errors and omissions of the analysis onto the figure for oxygen. Wing (1964) and Vogt and Ehmann (1965) directly measured oxygen in stony meteorites by neutron-activation analysis. Vogt and Ehmann's work is the more extensive, giving oxygen abundances for 39 meteorites, representing a total of 421 separate analyses; they estimated the absolute accuracy as probably better than ±5 percent. Their results for different classes of meteorites are summarized in table 18.

The state of combination of the oxygen presents problems in interpreting analytical data on meteorites. The standard procedure is to allot the requisite amounts to form the standard oxides of those elements more electropositive than iron, and then to add the amount required to form FeO from the iron not present as sulfide or nickel-iron. This procedure is reasonably satisfactory for most classes of stony and stony-iron meteorites, but may be unsatisfactory for the carbonaceous chodrites (which contain organic compounds, ferric iron, and oxidized sulfur compounds) and the enstatite chondrites (in which some of the Si, Ca, Cr, Mn, Mg, and Ti may not be present as oxidic compounds).

Taylor and others (1965) made an extensive series of measurements of oxygen isotopes in stony meteorites, and their results are summarized in figure 6. The common chondrites, the enstatite chondrites and enstatite achondrites, and the nakhlites are isotopically very similar to their terrestrial counterparts, the ultramafic igneous rocks, with δ values (relative to standard mean ocean water) about 5.7 per mil. Eucrites, howardites, diogenites, and mesosiderites have δ values about 4.0 per mil. The δ values of the carbonaceous chondrites are highly variable, showing a range of -2 to +12 per mil. The isotopic relationships among coexisting minerals in meteorites follow the same pattern observed in terrestrial rocks. In the eucrites and howardites, the small differences between pyroxene and plagioclase imply a high temperature of formation, consistent with a magmatic origin for these meteorites.

Intriguing anomalies have been found in the oxygen isotopic composition components of the Allende meteorite (C3). Clayton, Grossman, and Moyeda (1973) found that Ca,Al-rich chondrules and aggregates are strongly depleted in ^{17}O and ^{18}O; other carbonaceous chondrites also show this feature. These meteorites have lower $^{18}O/^{16}$ and $^{17}O/^{16}O$ ratios than all other meteorites studied. The depletion pattern is one in which ^{17}O and ^{18}O are equally depleted, whereas chemical processes that produce a 1 percent increase or decrease in the $^{17}O/^{16}O$ ratio produce a 2 percent or decrease in the $^{18}O/^{16}O$ ratio (since chemical isotope effects are almost linearly proportional to the relative mass difference of the isotopes). This indicates that the depletion pattern is the result of nuclear rather than chemical proc-

TABLE 17.—*Nitrogen in iron meteorites*

[From Gibson and Moore, 1971a. Median value for 123 meteorites equals 18 ppm nitrogen]

Group	Structure class	Number analyzed	Range (ppm) N	Median (ppm) N
I	Off-Ogg	17	2-131	35
IIA	H	11	4-26	15
IIB	Ogg-Oge	5	16-27	18
IIC	Opl	3	11-16	14
IID	Of-Om	2	32-44	38
IIIA	Om-Og	33	2-80	25
IIIB	Of-Om	7	22-70	46
IVA	Of	13	2-34	4
IVB	D	4	2-9	2

TABLE 18.—*Oxygen in stony meteorites*

[From Vogt and Ehmann, 1965; only data from observed falls are used because finds have suffered terrestrial oxidation]

Class	Number analyzed	Range (weight percent)	Mean (weight percent)	Atoms/10^6Si
		Chondrites		
C1	1	---	46.2	7,870,000
C2	3	42.0-43.8	43.2	5,790,000
C3	3	35.8-38.9	37.1	4,200,000
H	3	34.3-37.3	35.7	3,670,000
L	10	35.3-40.0	37.7	3,540,000
LL	1	38.4	---	3,590,000
E	2	27.0-31.6	29.3	2,860,000
		Calcium-poor achondrites		
Ae	2	47.3-48.0	47.7	3,020,000
Ah	1	47.7	---	3,400,000
		Calcium-rich achondrites		
Aeu	1	42.4	---	3,260,000

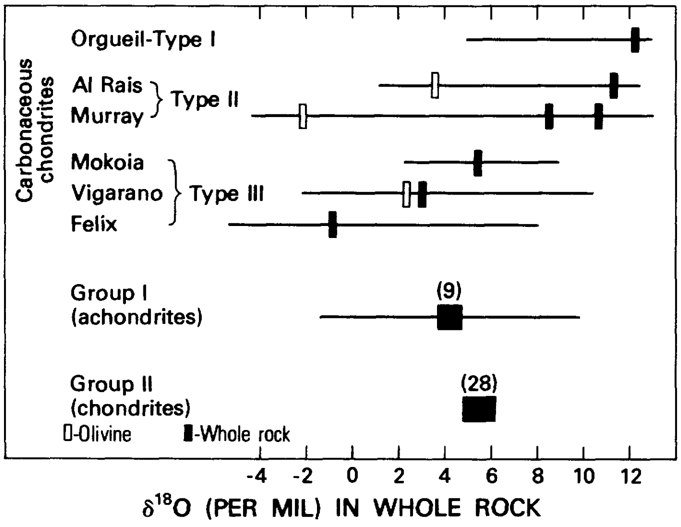

FIGURE 6.—Graphical comparison of $^{18}O/^{16}O$ analyses of whole-rock samples and olivines from carbonaceaus chondrites with whole-rock analyses of other meteorites. Reprinted from Taylor and others (1965) and published with permission.

esses; Clayton, Grossman, and Mayeda interpreted it as resulting from the admixture of a component of almost pure ^{16}O. They suggested that this component may predate the solar system and may represent interstellar dust with a separate history of nucleosynthesis

These investigations of variations in oxygen isotope ratios have been extended to all classes of meteorites (Clayton and others, 1976). On the basis of the data obtained, they presented a classification of meteorites into six categories: (1) H chondrites; (2) L and LL chondrites; (3) anhydrous minerals of C chondrites; (4) hydrous matrix minerals of C2 chondrites; (5) ureilites; (6) stony-irons, achondrites other than ureilites, and E chondrites (this group also including terrestrial and lunar rocks). They believe that meteorites of one category cannot be derived by fractionation or differentiation from the source materials of any other category.

FLUORINE

Data on the abundance of fluorine are rather sparse, and the accuracy of many of the data is questionable. This is illustrated in table 19, where results obtained by different investigators from the same meteorite are compared. Greenland and Lovering (1965) used emission spectrography; Reed (1964) and Fisher (1963) used different neutron-activation techniques; Goldberg and others (1974) used a proton-activation technique; Sen Gupta (1968b) used a spectrophotometric procedure; and Allen and Clark (1977) used a proton activation technique. Reed determined fluorine in the rock standards G-1 and W-1 by his technique and obtained 1,124 ppm and 490 ppm respectively; these figures are considerably higher than the current recommended values (700 ppm and 250 ppm), suggesting that his meteorite results may be consistently too high. Therefore, the data provided in table 20 on the average content of fluorine in stony meteorites must be interpreted with caution. However, there is a moderate diminution in fluorine concentration from C1 through C3 carbonaceous chondrites to the H, L, LL chondrites is evident; enstatite chondrites are relatively enriched in F. The anchondrites are depleted in fluorine relative to the chondrites, especially the calcium-poor achondrites (aubrites and diogenites).

Little is known about the distribution of fluorine in meteorites. Meteoritic apatite is chlorapatite that has a minor F content (0.4 percent), according to Van Schmus and Ribbe (1969). If all the phosphorus in a chondrite is present as apatite, this mineral would amount to 0.6 percent, and thus contribute 24 ppm F to the meteorite; this is clearly insufficient to account for even the minimum recorded fluorine content. Trace amounts of amphibole are an intriguing possibility. Olsen and others (1973) discovered trace amounts of fluor-richterite (4.6 percent F) in the Abee enstatite chondrite. Reference to table 19 shows that this meteorite has the highest F content of those analyzed by Greenland and Lovering (1965). Allen and Clark (1977) noted a correlation between F and Al in meteorite minerals, and suggested therefore that F may be enriched in the plagioclase.

SODIUM

Sodium is determined as a matter of course in most analyses of stony meteorites, but many of these determinations, especially in older analyses, are unreliable. Schmitt and others (1972) made an extensive series of instrumental neutron activation analyses for sodium in meteorites, and their results are summarized in table 21. For the common chondrites (H, L, LL), sodium abundances are very uniform. Eugene Jarosewich of the Smithsonian Institution has analyzed a large number of chondrites since 1965, and for sodium (analyzed by flame photometry) he reported (written commun., 1976) as follows (class, number analyzed, range and mean (weight percent)): H(17), 0.61–0.70, 0.62; L(23), 0.66–0.78, 0.71; LL(4), 0.70–0.74, 0.72. His results show less variability and slightly higher means than those of Schmitt and others (1972); the higher variability in the results of Schmitt and others can probably be ascribed to their use in some instances of

TABLE 19.—*Comparison of fluorine determinations in chondrites*

[In parts per million. 1. Greenland and Lovering, 1965; 2. Reed, 1964; 3. Fisher, 1963; 4. Goldberg and others, 1974; 5. Sen Gupta, 1968b; 6. Allen and Clark, 1977]

Meteorite	1	2	3	4	5	6
Orgueil(C1)	190	206	405	74	-	-
Mighei(C2)	-	-	220	66	-	-
Abee(E4)	280	228	-	-	275	-
Indarch(E4)	220	246	136	-	-	-
Hvittis(E6)	250	122	-	-	-	-
Allegan(H5)	170	114	-	-	-	32
Holbrook(L6)	130	-	189	-	-	43
Mocs(L6)	160	119	147	-	-	-

TABLE 20.—*Fluorine in stony meteorites*

[References are: 1. Goldberg and others, 1974; 2. Reed, 1964; 3. Greenland and Lovering, 1965; 4. Sen Gupta, 1968b; 5. Reed and Jovanovic, 1969; 6. Allen and Clark, 1977]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si	Reference
		Chondrites			
C1	2	70-74	72	1,000	1
C2	4	59-80	68	780	1
C3	1	59	---	550	1
H	5	21-41	32	320	6
L	8	32-52	41	330	6
LL	1	60-66	63	490	4
E4	2	205-246	238	1,950	2
E6	3	100-250	180	1,410	3
		Calcium-poor achondrites			
Ae	3	6.8-11	10.4	56	5
Ah	2	12.1-12.4	12.2	73	5
		Calcium-rich achondrites			
Aeu	6	23-90	60	390	5

TABLE 21.—*Sodium in stony meteorites*

[Data from Schmitt and others, 1972, excep tfor Ah, Ac, Aa, which are from table 84]

Class	Number analyzed	Range (weight percent)	Mean (weight percent)	Atoms/10^6Si
		Chondrites		
C1	3	0.45-.54	0.51	60,000
C2	7	.14-.46	.38	35,000
C3	9	.25-.44	.35	28,000
H	45	.41-.74	.57	41,000
L	50	.45-.83	.65	43,000
LL	20	.44-.87	.66	43,000
E4	2	.67-.86	.82	59,000
E5,6	5	.44-.63	.52	34,000
		Calcium-poor achondrites		
Ae	5	0.03-0.99	0.35	17,000
Ah	4	.02-.08	.03	1,500
Ac	1	.11	---	7,800
Au	2	.02-.04	.03	1,800
		Calcium-rich achondrites		
Aa	1	.026	---	1,600
An	2	.30-.39	.33	18,000
Aho	8	.11-.31	.18	9,300
Aeu	20	.25-.41	.31	17,000

very small samples (<100 mg) that may not have been representative. The relative constancy of sodium content is consistent with the relative constancy in the amount (~10 percent) and composition (An_{10-12}) of chondrite plagioclase. This mineral (or maskelynite, its glassy equivalent) contains essentially all the sodium in these meteorites.

Carbonaceous chondrites have more variable sodium contents than the common chondrites. The C1 and C2 chondrites contain no feldspar, and the state of combination of the sodium is not well understood. Jarosewich (written commun., 1976) has found that practically all the sodium in Orgueil (C1) and about half that in Murchison (C2) is water soluble (probably as sulfate). Sodium also appears to be very irregularly distributed in some of these meteorites; Fuchs, Olsen, and Jensen (1973) analyzed separate fragments from five different pieces of Murchison and found that the Na_2O content ranged from 0.19 percent to 0.71 percent. The C3 chondrites contain plagioclase, but it is usually close to anorthite in composition, and most of the sodium must be in other minerals; the Allende meteorite contains both nepheline and sodalite.

The sodium content of enstatite chondrites is comparable to that of the common chondrites. Van Schmus and Ribbe (1968) showed that the plagioclase in enstatite chondrites is slightly more calcic (An_{15}) than that in the common chondrites (An_{10-12}). Moss and others (1967) detected sodium in the sulfide phases of several enstatite chondrites, demonstrating that this element shows chalcophile tendencies in a highly reducing and sulfide-rich paragenesis.

Achondrites have variable sodium contents, generally considerably lower than in the chondrites. Schaudy, Kiesl, and Hecht (1967) analyzed two irons and found the sodium content to be less than 10 ppm.

MAGNESIUM

Magnesium is a major element in all classes of stony and stony-iron meteorites, and as a consequence the abundance data are very extensive. Von Michaelis, Ahrens, and Willis (1969) pointed out that the older data on chondrites summarized by Urey and Craig (1953) show a greater spread of values than more recent analyses, indicating an improvement in overall quality in recent years. The figures presented in table 22 are derived as far as possible from recent analyses of observed falls.

The data for the chondrites show that the Mg/Si ratio (atomic) is fairly uniform at 0.934–0.965 for the common (H, L, LL) chondrites, although the difference between the L and LL groups on the one hand and the H group on the other is probably greater than the experimental error, and hence may be significant (Ahrens, 1970). The differences between the common chondrites and the carbonaceous and enstatite chondrites are considerably larger than those within the common chondrites. The Mg/Si ratio for the carbonaceous chondrites is consistently slightly greater than unity, whereas for the enstatite chondrites this ratio is considerably less than unity and notably lower than for the common chondrites. The difference between the Type I and Type II enstatite chondrites is also significant. The range of values of Mg/Si ratios for the enstatite chondrites is considerably wider than for the other classes of chondrites.

The differences between the Mg/Si ratios for the different classes of chondrites were first pointed out by Urey (1961), and were further discussed by Ahrens (1964). These differences are illustrated in a simple plot of weight percent SiO_2 against weight percent MgO (fig. 7). The significance of this fractionation remains to be fully elucidated. The close approach to unity of the Mg/Si ratio for the carbonaceous and the common chondrites is consistent with their derivation from relatively unfractioned material that still retained the Mg/Si ratio established by nucleosynthesis. The fractionation shown by the enstatite chondrites may be related to the high degree of reduction shown by these meteorites, one of the features being the presence of elemental silicon in solid solution in their metal phase. Magnesium is not reduced to the elemental state in any class of meteorites. Thus, the enstatite chondrites may actually be enriched in silicon (incorporated in the metal phase) rather than depleted in magnesium, relative to the common and carbonaceous chondrites.

The calcium-poor achondrites show a considerable range of Mg/Si ratios. Since the enstatite achondrites consist almost entirely of enstatite, $MgSiO_3$, this ratio should be close to unity; the exact figure in the table is coincidental owing to the balancing of the contribution of magnesium and silicon by minor minerals such as plagioclase and forsterite. The lower Mg/Si ratio for the hypersthene achondrites results from the introduction of ferrous iron partly replacing magnesium in the pyroxene. The chassignite and the ureilites show an enhancement of the Mg/Si ratio because of their high content of olivine, $(Mg, Fe)_2SiO_4$.

The calcium-rich achondrites are notably depleted

TABLE 22.—*Magnesium in stony meteorites*

[Modified from Mason, 1971, and additional data]

Class	Number analyzed	Range (weight percent)	Mean (weight percent)	Atoms/10^6Si
		Chondrites		
C1	3	9.44-9.70	9.56	1,060,000
C2	9	10.79-14.19	11.80	1,040,000
C3	6	13.31-14.66	14.53	1,060,000
H	36	13.25-14.97	14.20	965,000
L	68	14.05-15.99	15.19	941,000
LL	14	14.48-15.75	15.29	934,000
E3,4	3	10.05-11.49	10.70	727,000
E5,6	5	11.62-14.01	13.31	809,000
		Calcium-poor achondrites		
Ae	4	22.49-24.58	23.20	1,000,000
Ah	5	15.55-17.03	16.16	758,000
Ac	1	19.80	--	1,320,000
Au	3	22.02-23.49	22.60	1,370,000
		Calcium-rich achondrites		
Aa	1	6.06	--	341,000
An	1	7.52	--	386,000
Aho	5	7.48-12.13	10.36	507,000
Aeu	11	3.54-6.85	4.60	233,000

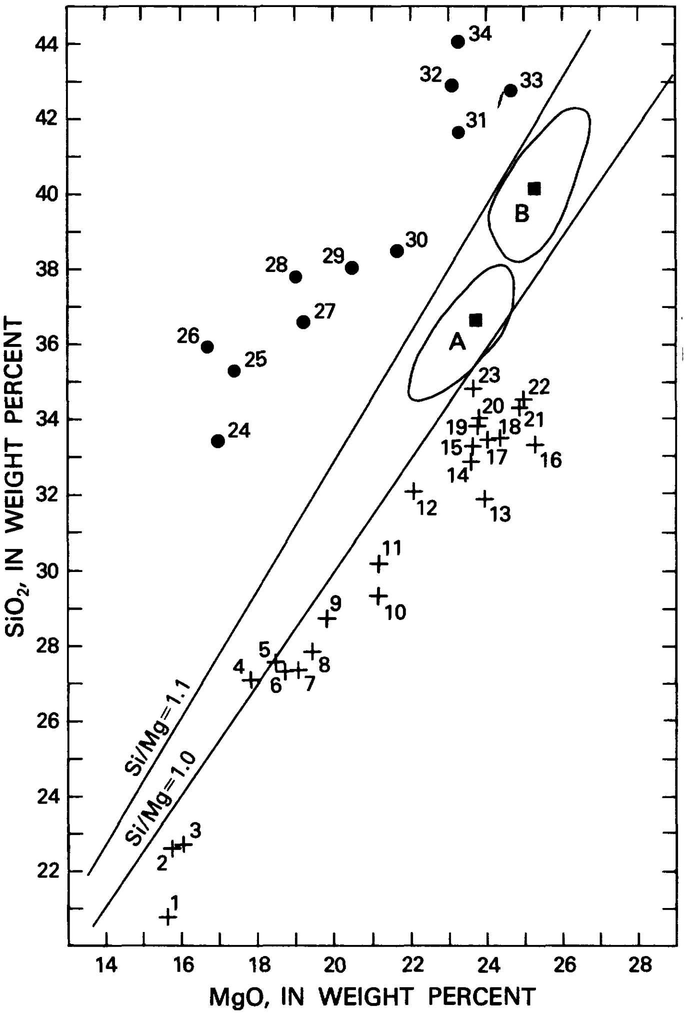

FIGURE 7.—SiO_2 plotted against MgO (weight percentages) for chemical analyses of chondrites; the diagonal lines are for Si/Mg atomic ratios of 1.0 and 1.1. A is the field for 36 analyses of bronzite (H) chondrites, B the field for 68 analyses of hypersthene (L and LL) chondrites, the black squares being the means for each group. The analyses of carbonaceous chondrites (1-23) and enstatite chondrites (24-34) are plotted individually. Reprinted from Mason 1967b) and published with permission.

in magnesium relative to the chondrites. The howardites and the eucrites form a sequence in which the silicon and ferrous iron contents remain practically constant and the magnesium content decreases (fig. 3), hence the marked diminution in the Mg/Si ratio. Among the stony-irons, the mesosiderite silicates are essentially similar to those in the howardites, hence the similarity in Mg/Si ratios between these two classes. The silicate material in the pallasites is magnesium-rich olivine, hence the Mg/Si ratio is much higher than in other classes of meteorites and approaches 2:1.

Magnesium is usually considered to be entirely lithophilic in character; however, in the extremely reduced and sulfide-rich enstatite chondrites, a small amount of the total magnesium is present in solid solution in alabandite, (Mn,Fe)S, or as niningerite, (Mg,Fe)S. In most classes of meteorites the magnesium is combined almost entirely in the minerals olivine and (or) pyroxene. The C1 and C2 carbonaceous chondrites are unique in having much of their magnesium present as the hydrated magnesium-iron silicate serpentine (or related layer-lattice silicates); C1 carbonaceous chondrites also contain notable amounts of hydrated magnesium sulfate.

ALUMINUM

Aluminum is a minor constituent in all stony and stony-iron meteorites (except the pallasites, in which it is present in trace amounts only). It has therefore been determined in all complete chemical analyses of these meteorites. However, many of the data in the literature are unreliable, because the accurate determination of small amounts of aluminum (especially in the presence of much iron, as in meteorites) is extremely difficult by standard wet-chemical procedures. To obviate these difficulties, Loveland, Schmitt, and Fisher (1969) applied neutron-activation analysis to the determination of this element in some 120 stony meteorites, and their results are used in table 23, along with selected data for a few classes which they did not analyze.

Loveland, Schmitt, and Fisher reported that their average aluminum abundances were lower, in general, than those previously reported, and that the individual determinations showed a much smaller dispersion around the mean value for each class than earlier determinations. For the common chondrites (H, L, LL) they reported relative standard deviations of 6 percent, 7 percent, and 6 respectively, considerably less than earlier dispersion values of 25 percent, 28 percent, and 28 percent. Their low dispersion values indicate that, within specific chondrite classes, aluminum concentrations are remarkably uniform from one meteorite to another. This has been confirmed by Von Michaelis, Ahrens, and Willis (1969), who used X-ray fluorescence to analyze for aluminum and other elements in 69 meteorites.

The data for the chondrites show that the Al/Si ratio (atomic) is uniform at 0.061–0.062 for the common chondrites, whereas it is much greater for the carbonaceous chondrites (average 0.087), and somewhat lower for the enstatite chondrites (0.048). The lower ratio for the latter parallels a corresponding diminution of the Mg/Si ratio from the common chondrites to the enstatite chondrites, and can probably be ascribed to an absolute enhancement of Si in the enstatite chondrites. The higher Al/Si ratios for the carbonaceous chondrites are significant. The site of the aluminum in C1 and C2 chondrites is poorly known, but it is probably combined in the serpentine or other layer-lattice silicates that form the matrix of these meteorites. The C3 chondrites contain a variety of aluminum-rich minerals, the commonest being aluminous pyroxene, spinel ($MgAl_2O_4$), anorthite ($CaAl_2Si_2O_8$), and melilite ($Ca_2(Mg,Al)(Si,Al)_2O_7$, which are rarely found in other classes of chondrites. Loveland, Schmitt, and Fisher pointed out that the Al/Na ratio increases progressively from 1.42 to 2.40 to 3.29 through the C1, C2, C3 carbonaceous chondrites, whereas this ratio is very uniform at about 1.45 in the ordinary chondrites.

The calcium-poor achondrites are somewhat lower in aluminum than the chondrites, especially the enstatite achondrites and the ureilites; this can be correlated with their lower content of plagioclase feldspar. The calcium-rich achondrites (except the nakhlite) are notably enriched in aluminum; in the angrite this element is present in an aluminum-rich pyroxene, and in the howardites and eucrites as plagioclase.

Ahrens and others (1969) have pointed out that for all the chondrite classes, and for the eucrites and howardites, the Ca/Al ratio is remarkably uniform at 1.00-1.19 (by weight), and averages 1.10.

As far as is known, aluminum is entirely lithophilic in meteorites, and lacks chalcophilic or siderophilic tendencies; Fisher (1969b) has shown by activation analysis of 11 iron meteorites that they

TABLE 23.—*Aluminum in stony meteorites*

[Modified from Loveland and others, 1969; and additional data]

Class	Number analyzed	Range (weight percent)	Mean (weight percent)	Atoms/10^6Si
		Chondrites		
C1	3	0.80-.87	0.85	85,000
C2	7	.98-1.21	1.08	84,000
C3	7	1.27-1.64	1.37	92,000
H	15	.89-1.12	1.01	61,000
L	23	1.00-1.31	1.10	61,000
LL	13	1.07-1.20	1.12	62,000
E3,4	2	.71-.84	.79	48,000
E5,6	2	.76-.93	.85	48,000
		Calcium-poor achondrites		
Ae	5	.10-1.40	.50	20,000
Ah	5	.27-1.04	.55	23,000
Ac	1	.19	--	17,000
Au	3	.17-.46	.30	16,000
		Calcium-rich achondrites		
Aa	1	4.62	--	233,000
An	1	.77	--	36,000
Aho	5	2.57-5.27	3.71	164,000
Aeu	11	6.11-6.88	6.62	302,000

contain less than 10 ppm Al. In most meteorites, aluminum is present almost entirely in plagioclase feldspar; meteoritic pyroxenes [except in the angrite and in Allende (C3)] contain only small amounts of aluminum, and olivine only trace amounts. As mentioned above, C3 carbonaceous chondrites are noteworthy for containing aluminum-rich minerals rarely found in other meteorites.

SILICON

Silicon is a major element in stony and stony-iron meteorites, in which it is present in the common silicate minerals olivine, pyroxene, and plagioclase, and some rarer species. The rare minerals perryite, $(Ni,Fe)_5(Si,P)_2$ and sinoite, Si_2N_2O, are known as minor constituents in a few enstatite chondrites (and for perryite, in enstatite achondrites also). The concentration and distribution of silicon in meteorites has been thoroughly covered by C. B. Moore (in Mason, 1971); a selection of his data is provided in table 24.

Because of its high and relatively constant abundance and the availability of high-quality analytical data, silicon is extensively used as the basis for comparison of atomic abundances in stony meteorites. Most of the lithophile elements show relatively small variations with respect to the silicon abundances, but careful evaluation of the data indicates significant fractionation between chondrite classes. The extent of Mg/Si fractionation is illustrated in figure 7. Ahrens and Von Michaelis (1968) discussed the variation in the Mg/Si, Ca/Si, Al/Si, and Ti/Si ratios between the different chondrite classes.

TABLE 24.—*Silicon in stony meteorites*

[In weight percent. From C. B. Moore, in Mason, 1971; and additional data]

Class	Number analyzed	Range	Mean
		Chondrites	
C1	3	9.7-10.5	10.3
C2	9	12.7-13.7	13.1
C3	6	14.9-15.9	15.5
H	36	16.0-17.7	17.1
L	68	17.8-19.5	18.7
LL	12	18.1-19.3	18.8
E4	3	15.6-17.7	16.6
E5	2	17.2-17.7	17.4
E6	6	18.0-20.5	19.4
		Calcium-poor achondrites	
Ae	9	27.2-28.1	27.7
Ah	5	24.1-25.6	24.6
Ac	1	17.3	---
Au	3	18.6-19.6	19.1
		Calcium-rich achondrites	
Aa	1	20.5	---
An	1	22.5	---
Aho	5	23.0-24.2	23.6
Aeu	11	22.5-23.2	22.8

Silicon is an entirely lithophile element in most meteorites, but in the highly reduced enstatite chondrites and enstatite achondrites minor amounts of the element are present in the metal phase. Detailed investigation of the enstatite chondrites by Keil (1968) showed that the E4, E5, and E6 chondrites have an average of 3.2 3.3, and 1.3 weight percent silicon in their nickel-iron. Most iron meteorites contain only trace amounts of silicon; Moore (in Mason, 1971) reported that of 93 irons, 8 percent contained more than 10 ppm, 10 percent contained 5–10 ppm, and 2 percent less than 5 ppm; the median value was 3 ppm.

PHOSPHORUS

Phosphorus is a ubiquitous element in meteorites, present in minor to trace amounts (tables 25 and 26). Collections of analyses of chondrites, especially older ones, show a considerable variability for this element, which is negated by recent work; the data of Von Michaelis, Ahrens, and Willis (1969), reported

TABLE 25.—*Phosphorus in stony meteorites*

[From VonMichaelis and others, 1969; and additional data]

Class	Number analyzed	Range (weight percent)	Mean (weight percent)	Atoms/10^6Si
		Chondrites		
C1	1	0.080	---	7,000
C2	3	.089–.093	0.091	6,200
C3	4	.102–.107	.105	6,400
H	12	.104–.113	.108	5,800
L	20	.081–.112	.095	4,800
LL	4	.044–.13	.087	4,200
E4	2	.196–.209	.203	11,200
E5	1	.193	---	10,200
E6	4	.105–.134	.117	5,600
		Calcium-poor achondrites		
Ae	1	0.008	---	290
Ah	4	.001–.006	.003	110
Ac	1	.018	---	940
Au	4	.030–.040	.034	1,600
		Calcium-rich achondrites		
Aa	1	0.057	---	2,500
An	1	.054	---	2,200
Aho	5	.017–.039	.024	920
Aeu	11	.016–.048	.037	1,500

in table 25, show that within individual chondrite classes the variability is quite small. Achondrites, especially the calcium-poor achondrites, are notably depleted in phosphorus relative to the chondrites; the nonmetallic part of the mesosiderites appears to be relatively enriched in this element.

Phosphorus is a significant constituent of iron meteorites, but its true abundance is difficult to determine. Much of the phosphorus is present as schreibersite, $(Fe,Ni)_3P$, frequently as macroscopic inclusions; when an iron meteorite is sampled for analysis these inclusions are usually avoided, so the analyses are not representative of the whole meteorite but only of the metallic component (and microscopic inclusions). This selectivity is reflected by the data in table 26. The amount and size of schreibersite inclusions depend on both the bulk phosphorus content and the cooling history, since most if not all schreilbersite in iron meteorites has formed by solid-state diffusion during cooling. Doan and Goldstein (1969) showed that the phosphorus solubility in α (kamacite) and γ (taenite) nickel-iron decreases from 2.7 and 1.4 weight percent at 1,000°C to 0.25 and 0.08 weight percent at 550°C; the exsolved phosphorus combines with nickel and iron to form schreibersite. Doan and Goldstein estimated the total amount of phophorus in a number of iron meteorites from measurements of the percentage of screibersite, and obtained a range of 0.50–1.3 percent P.

Besides schreibersite, the common phosphorus minerals of meteorites are chlorapatite, $Ca_5(PO_4)_3Cl$, and merrillite, $Ca_9MgNa(PO_4)_7$. Merrillite has been generally identified with the terrestrial mineral whitlockite, but Prewitt and Rothbard (1975) produced evidence indicating that the two minerals are distinct but closely related species, being compositional and structural variants of β-$Ca_3(PO_4)_2$. Merrillite and chlorapatite commonly occur together in stony meteorites, and their relative amounts are probably controlled by the available chlorine. The state of combination of phophorus in carbonaceous chondrites is not well known. In the common chondrites, phosphorus is present as merrillite and chlorapatite; schreibersite is absent or present only in traces, and the metal is essentially phosphorus free (<45 ppm in five chondrites, according to Reed (1969)). The enstatite chondrites contain no phosphates, the phosphorus being present as schreibersite and in solid solution in the nickel-iron (Keil, 1968). Some iron meteorites contain assemblages of schreibersite and phosphate minerals, and Olsen and Fuchs (1967) deduced that these metallic meteorites represent approximately the same degree of oxidation as the ordinary chondrites; the enstatite chondrites clearly are much more highly reduced.

Ahrens (1970) pointed out that phosphorus shows a slight but consistent enrichment in H chondrites relative to L chondrites, and noted that this indicated a positive Fe-P correlation, which also applied to the E chondrites. He commented, "Perhaps P was associated with Fe in the early stages of the formation of the common chondrites and later events,

TABLE 26.—*Phosphorus in iron meteorites*

[In weight percent. From Moore, Lewis, and Nava, 1969]

Meteorite group	Number analyzed	Range	Mean
IIA	7	0.39-0.46	0.44
IIB	2	.18-.24	.21
I	6	.15-.34	.20
IIIA	13	.09-.36	.15
IIIB	2	.20-.63	.41
IIIAB	2	.51-.52	.52
IVA	10	.02-.16	.05
IVB	2	.04-.10	.05
IIC	1	---	.30
IID	2	.61-.65	.63

whatever they may be, produced minerals in which P was associated with oxygen" (p. 346). The fact that achondrites, which are almost or entirely metal free, are relatively depleted in phosphorus, and mesosiderites, which contain large amounts of metal, are relatively enriched in this element, further supports Ahrens' concept. Fuchs (1969) noted that the phosphate minerals in the mesosiderites are closely associated with the metal phase, and suggested that they originated by reaction of phosphorus in solid solution in the metal with the silicate minerals. These observations suggest that phosphorus was taken up originally in solid solution in nickel-iron, and was redistributed during later reequilibration.

SULFUR

Sulfur is ubiquitous in meteorites, most of it occurring as troilite (FeS), although a considerable variety of sulfide minerals is known from them. In C1 and C2 carbonaceous chondrites this element is mainly present as free sulfur and inorganic sulfates, with small amounts of organic sulfur compounds; in C3 carbonaceous chondrites pentlandite, $(Ni,Fe)_9S_8$, is an important sulfide phase. Troilite is the principal sulfide in the enstatite chondrites and enstatite achondrites, but these meteorites may contain a variety of unusual sulfides, such as oldhamite, CaS; niningerite, (Mg,Fe)S; alabandite, (Mn,Fe)S; daubreelite, $FeCr_2S_4$; sphalerite, (Zn,Fe)S; djerfisherite, $K_3CuFe_{12}S_{14}$, and heideite, $(Fe,Cr)_{1+x}(Ti,Fe)_2S_4$.

The data in table 27 show marked depletion of sulfur in the sequence C1–C2–C3–ordinary chondrites; a similar depletion is evident in the sequence E4–E5–E6 chondrites. For the ordinary chondrites the range in values for individual analyses

TABLE 27.—*Sulfur in stony meteorites*

[From C. B. Moore in Mason, 1971; and additional data]

Class	Number analyzed	Range (weight percent)	Mean (weight percent)	Atoms/10^6 Si
		Chondrites		
C1	5	5.01-6.70	5.90	502,000
C2	9	2.80-5.44	3.42	229,000
C3	9	1.31-2.66	2.19	124,000
H	87	1.30-2.64	2.00	102,000
L	110	1.73-2.74	2.22	104,000
LL	32	1.08-5.47	2.34	109,000
E4	3	5.65-6.12	5.85	301,000
E5	2	5.50-5.82	5.66	283,000
E6	6	2.62-4.44	3.32	149,000
		Calcium-poor achondrites		
Ae	3	.14-.70	.45	14,000
Ah	5	.13-.63	.38	13,000
Au	4	.19-.63	.50	23,000
		Calcium-rich achondrites		
Aa	1	.46	---	20,000
Aho	6	.25-.40	.34	13,000
Aeu	5	.02-.26	.13	4,900

may be largely due to analytical error and inadequate sampling; however, the mean values are probably good approximations, although inadequate to tell whether the small difference between H and L, LL means is significant.

Achondrites contain considerably less sulfur than the chondrites. The figures for sulfur in pallasites and mesosiderites range widely, because of both heterogeneous distribution of sulfide minerals and sampling problems; no attempt has been made to derive means for these meteorites.

Moore, Lewis, and Nava (1969) determined sulfur in 93 different iron meteorites (the samples selected to avoid visible inclusions of troilite) and found a range of 0.001–0.50 percent. Most figures are between 0.001 and 0.01 percent, and the median is 0.004 percent. This is a measure of the solubility of sulfur in the metal phase. The sulfur content in iron meteorites is best determined by planimetric analysis of large slices; determinations by Buchwald (1975) on 64 irons gave sulfur contents ranging from 0.02 to 5.0 percent, with two exceptionally S-rich meteorites, Mundrabilla (8 percent) and Soroti (12 percent).

The isotopic composition of sulfur in meteoritic troilite is remarkably uniform, the S^{32}/S^{34} ratio being 22.22. Kaplan and Hulston (1966) studied the isotopic composition of sulfur in compounds from carbonaceous chondrites and found a variation from +2.5 to −5.5 parts per thousand for the δS^{34} content with respect to troilite.

CHLORINE (17)

The chlorine content of stony meteorites (table 28) has been studied by a number of investigators, and the results have been collated and discussed by G. W.

TABLE 28.—*Chlorine in stony meteorites*

[From G. W. Reed, in Mason, 1971]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
C1	2	720-840	773	5,700
C2	2	190-510	335	2,050
C3	2	260-288	273	1,350
H	24	7-210	80	370
L	8	27-212	76	320
LL	2	121-131	126	530
E4	2	570-750	660	3,150
E5	1	210	---	960
E6	3	160-250	210	860
		Calcium-poor achondrites		
Ae	1	3.8	---	12
Ah	1	13	---	41
Au	1	35	---	150
		Calcium-rich achondrites		
Aho	1	14.9	—	51
Aeu	3	8-34.5	20	69

Reed, in Mason (1971). The results are rather sparse, sometimes conflicting, and difficult to interpret. Great variations are found in different samples of the same meteorite; for example, six samples of the Bruderheim chondrite measured by Goles, Greenland, and Jérome (1967) gave figures from 66 ppm to 130 ppm, and six samples of the same meteorite measured by Reed and Allen (1966) gave figures from 2.5 ppm to 50.0 ppm. The widely varying results suggest an inhomogeneous distribution of chlorine within the meteorites. Reed and Allen found that considerable amounts of the chlorine in enstatite and carbonaceous chondrites were leachable in hot water, whereas little was leachable from the ordinary chondrites. Clorapatite is an accessory mineral in the ordinary chondrites, and the amount of P_2O_5 shown by analyses is more than sufficient to bind all chlorine as this mineral. Lawrencite, $(Fe,Ni)Cl_2$, may account for some of the chlorine; although its validity as a meteorite mineral has been questioned, most recently by Buchwald (1975), its presence is suggested by the rapid rusting of grains of nickel-iron in some freshly fallen chondrites. Keil (1968) has presented evidence, including microprobe data, for the occurrence of lawrencite as a primary mineral in enstatite chondrites. Lawrencite would account for the small amounts of water-soluble chloride found by Reed and Allen in the ordinary chondrites, and possibly for the larger amounts in carbonaceous and enstatite chondrites. Fuchs (1966)

TABLE 29.—*Potassium in stony meteorites*

[From Edwards, 1955; Kirsten and others, 1963; and additional data]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
C1	3	380-570	500	3,500
C2	10	270-490	370	2,000
C3	5	250-420	370	1,700
H	17	710-920	800	3,400
L	28	720-998	870	3,300
LL	5	855-950	910	3,500
E4	2	822-905	860	3,700
E5	1	757	---	3,200
E6	5	670-874	730	2,700
		Calcium-poor achondrites		
Ae	5	70-550	330	860
Ah	5	3-80	29	85
Ac	1	270	---	1,100
Au	2	60-97	80	300
		Calcium-rich achondrites		
Aa	1	12.9	---	45
An	1	810	---	2,600
Aho	7	165-470	290	910
Aeu	9	236-600	400	1,250

described djerfisherite, a potassium copper iron sulfide, as an accessory mineral in some enstatite chondrites; the microprobe analyses show 1 percent Cl, which Fuchs believed may be in the structure. Sodalite, $Na_4Al_3Si_3O_{12}Cl$, has been recorded as an accessory mineral in the Allende (C3) chondrite. Some of the chlorine in carbonaceous chondrites may be present in organic compounds; Mueller (1953) recorded 4.8 percent Cl in the organic material extracted by solvents from Cold Bokkeveld.

Berkey and Fisher (1967) studied the abundance and distribution of chlorine in irons. Chlorine content of finds is usually profoundly influenced by terrestrial weathering. In falls, they obtained figures from <0.1 to 20 ppm; the chlorine is inhomogeneously distributed in the metal phase, being strongly depleted in kamacite and being concentrated at grain boundaries and around inclusions. Mason and Graham (1970) measured chlorine in the metal phases of the Modoc and St. Severin chondrites, obtaining 74 ppm and 52 ppm respectively; they suggested that this was due to occluded lawrencite.

POTASSIUM

Potassium is present in trace to minor amounts in meteorites, the concentration seldom exceeding 0.1 percent. On this account many of the older gravimetric analyses for this element are unreliable. The data in table 29 are mostly taken from the analyses of Edwards (1955), who used flame-spectrophotometry, and Kirsten, Krankowsky, and Zähringer (1963), who used isotope dilution. The common chondrites show slightly increasing K contents in the sequence H–L–LL, but in terms of atoms/10^6Si the abundances are not significantly different, and are equal to that in C1 chondrites. Carbonaceous chondrites show a marked diminution in K content in the sequence C1–C2–C3, as do the enstatite chondrites to a lesser degree in the sequence E4–E5–E6. The achondrites are depleted in potassium relative to the chondrites, especially the feldspar-free diogenites and angrite. The data in table 29 omit some anomalous figures for LL meteorites; Kirsten, Krankowsky, and Zähringer (1963) recorded 199 ppm in Ensisheim, and Zähringer (1968) found a dark inclusion in Krähenberg with 1.2 percent K.

In most chondrites (and other stony meteorites), the potassium is contained in plagioclase feldspar. The potassium-iron silicate merrihueite was discovered in the Mezö-Madaras (L3) chondrite, and the potassium-magnesium silicate roedderite and the complex potassium-bearing sulfide djerfisherite are rare accessories in some enstatite chondrites. Small amounts of potassium feldspar have been recorded in silicate inclusions in iron meteorites.

CALCIUM

Calcium is a minor element in most classes of stony and stony-iron meteorites, being present at about the 1 percent level; exceptions are the calcium-rich achondrites and mesosiderites, which contain considerably greater amounts, and the pallasites, in which this element is present in trace amounts only. Calcium is determined in all complete analyses of these meteorites, so the data on this element in the literature are very extensive; however, the quality is not good, as has been demonstrated by Von Michaelis, Ahrens, and Willis (1969). Classical wet-chemical analysis for calcium at the 1 percent level, especially in the presence of much magnesium (as in meteorites), may produce poor results unless great care is taken. An extensive series of X-ray fluoresence analyses by Nichiporuk and others (1967) and Von Michaelis, Ahrens, and Willis has shown very uniform calcium concentrations within the specific chondrite classes; their results are extremely consistent, and those of Von Michaelis, Ahrens, and Willis are used in table 30, except for the carbonaceous chondrites and the amphoterites (LL), for which a broader cover of reliable analyses is obtainable from the literature.

The Ca/Si ratios are remarkably uniform and distinctive for the three major groups of chondrites, as follows: carbonaceous, 0.073; ordinary (hypersthene, bronzite, amphoterite), 0.048; enstatite, 0.036. For the classes within these major groups the differences in this ratio are small and probably not significant. In the C3 chondrites the enrichment in calcium is manifested by the presence of calcium-rich minerals such as anorthite and melilite, not found in other classes of chondrites.

The calcium-poor achondrites, as their name implies, are notably depleted in calcium in relation to the chondrites, whereas the calcium-rich achondrites show a notable enrichment; the individual calcium values for many meteorites in these groups are illustrated in figure 3. The two meteorites richest in calcium are the angrite Angra dos Reis and the nakhlite Nakhla; in both of these the calcium is present as a calcium-rich pyroxene. In the other meteorites of these groups most of the calcium is present as calcic plagioclase. In the stony-irons, the pallasites contain only traces of calcium, in solid solution in olivine; the mesosiderite silicates resemble those of the howardites, and have comparable calcium contents.

Calcium is usually considered to be entirely lithophilic in character; however, in the extremely reduced and sulfide-rich enstatite chondrites and enstatite achondrites, some of the calcium is present as the sulfide oldhamite. In the common chrondites the calcium is distributed over a number of minerals—as the calcium phosphates chlorapatite and (or) merrillite, as the pyroxene diopside, and in solid solution in orthopyroxene and sodic plagioclase. As mentioned above, the C3 chondrites are characterized by the presence of some calcium-rich minerals; the distribution of calcium in the C1 and C2 chondrites is not well known, but gypsum, calcite, and dolomite have been recorded from some meteorites in these classes.

SCANDIUM

Scandium is a dispersed trace element in stony meteorites. A very extensive set of data has been provided by Schmitt and others (1972), who analyzed 180 stony meteorites by instrumental neutron-activation analysis; their results are summarized in table 31. The total range of variability over all chondrite classes is small, and the atomic abundances (effectively, Sc/Si ratios) are indistinguishable from one another on a rigorous statistical basis. Abundances in the calcium-poor achondrites are comparable with those in the chondrites; the calcium-rich achondrites are notably enriched in this element relative to the chondrites.

TABLE 30.—*Calcium in stony meteorites*

[From Von Michaelis and others, 1969; and additional data]

Class	Number analyzed	Range (weight percent)	Mean (weight percent)	Atoms/10^6Si
		Chondrites		
C1	3	0.87-1.34	1.06	72,100
C2	9	1.11-1.63	1.34	71,900
C3	6	1.40-1.87	1.70	74,300
H	12	1.15-1.22	1.19	49,800
L	19	1.22-1.35	1.28	48,400
LL	9	1.07-1.43	1.25	46,400
E4	2	.81-.87	.84	35,700
E6	5	.94-1.24	1.07	38,600
		Calcium-poor achondrites		
Ae	4	.47-1.16	.80	21,000
Ah	5	.52-1.27	.79	22,000
Ac	1	.54	---	22,000
Au	3	.31-0.97	.62	23,000
		Calcium-rich achondrites		
Aa	1	17.52	---	598,000
An	1	10.78	---	336,000
Aho	5	2.94-5.76	4.16	124,000
Aeu	11	6.49-7.63	7.23	222,000

In terrestrial rocks, scandium is enriched in pyroxene, and this appears to be true of meteorites also. The calcic pyroxenes of the calcium-rich achondrites evidently contain more scandium than the orthopyroxenes of the calcium-poor achondrites. The highest content in any meteorites is in Angra dos Reis, which consists almost entirely of a titanian fassaite. Most of the scandium in chondrites is evidently present in the pyroxenes; Allen and Mason (1973) recorded 96 ppm Sc in diopside and 12.1 ppm in orthopyroxene from the Modoc chondrite, and relatively little in the other minerals.

TITANIUM

Titanium is a minor element in stony and stony-iron meteorites, usually in the range of 500–5,000 ppm by weight. It is normally determined by standard colorimetric methods in complete analyses of these meteorites, but was frequently omitted in older analyses. Moore and Brown (1962), by spectrographical analysis of a large number of chondrites, found a rather constant titanium content. For 19 bronzite chondrite falls, the mean was 620 ppm Ti, equivalent to 0.103 percent TiO_2; for 23 hypersthene chondrite falls, the mean was 660 ppm Ti, equivalent to 0.110 percent TiO_2. These figures are in agreement with recent wet-chemical analyses of ordinary chondrites.

The data on titanium classes of stony meteorites are summarized in table 32. These determinations have been made by standard wet-chemical procedures (usually colorimetric), except for the figures

TABLE 31.—*Scandium in stony meteorites*

[From Schmitt and others, 1972]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
C1	3	4.8-8.1	5.1	31
C2	7	6.0-10.6	7.4	35
C3	9	5.8-14.0	9.1	36
H	46	5.0-11.6	7.6	28
L	50	5.4-12.1	8.2	28
LL	21	5.9-11.6	7.8	26
E4	2	6.2-7.5	6.7	25
E5,6	4	5.5-10.8	7.6	24
		Calcium-poor achondrites		
Ae	5	5.0-8.5	6.4	16
Ah	2	9.8-14	11.9	30
Ac	1	5.6	---	20
Au	2	6.8-8.8	7.9	26
		Calcium-rich achondrites		
Aa	1	57	---	170
An	2	47-53	49	140
Aho	8	15-26	20	53
Aeu	20	14-41	29	79

for the bronzite and hypersthene chondrites, which are spectrographic. This table shows a fairly uniform level of titanium in the chondrites at 2,000–3,000 atoms/10^6Si, although the data suggest a moderate degree of enrichment in the C3 chondrites. Titanium contents are somewhat lower in the calcium-poor achondrites than in the chondrites, except for the enstatite achondrites, which show a marked depletion; in the latter meteorites, the titanium resides almost entirely in the troilite, which is small in amount and irregularly distributed. The calcium-rich achondrites show a marked enrichment in titanium, both absolutely and relative to silicon. The unique meteorite Angra dos Reis shows extreme enrichment; this meteorite consists almost entirely of a calcium-rich aluminous pyroxene, in which titanium is present in atomic substitution, probably as the component $CaTiAl_2O_6$. Among the stony-irons, the pallasites are notably deficient in titanium, because this element does not readily enter olivine, the silicate mineral; the mesosiderites contain silicates similar to the howardites, and the titanum content is comparable in these two classes.

In most meteorites, titanium is mainly lithophile, but it also has moderate chalcophile affinity; in enstatite chrondites and enstatite achondrites, however, it is almost completely chalcophile. Titanium is considered to have little or no siderophile tendency, and is seldom looked for in analyses of meteoritic iron; A.A. Moss (oral commun., 1965) reported it to be below the limit of detection (<5 ppm) in several irons.

TABLE 32.—*Titanium in stony meteorites*

[From Mason, 1971; and additional data]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
C1	3	400-450	430	2,400
C2	9	480-700	540	2,900
C3	6	600-1,400	870	3,600
H	19	510-780	620	2,100
L	23	460-810	660	2,100
LL	11	540-1,300	840	2,600
E4	3	400-800	570	2,000
E5,6	7	300-900	620	1,900
		Calcium-poor achondrites		
Ae	4	160-480	340	750
Ah	5	340-720	460	1,100
Ac	1	400	---	1,350
Au	3	720-1,100	880	2,700
		Calcium-rich achondrites		
Aa	1	14,300	---	41,000
An	1	1,700	---	4,400
Aho	5	1,400-2,930	1,990	4,900
Aeu	11	1,000-5,880	3,820	9,800

Titanium may be present in several phases in a single meteorite. The only meteoritic minerals in which this element is an essential constituent are ilmenite ($FeTiO_3$), rutile (TiO_2), perovskite ($CaTiO_3$), rhönite ($CaMg_2TiAl_2SiO_{10}$), osbornite (TiN), and heideite $[(Fe,Cr)_{1+x})Ti,Fe)_2S_4]$ Ilmenite is not uncommon as an accessory mineral; Ramdohr (1963, p. 2028) reported, "It was observed in more than 50 percent of all the stony meteorites examined. It appears to be absent in some of the strongly reduced chondrites and in carbonaceous chondrites. Usually it occurs in very small quantities, only a few grains being found in sections of normal size." Th ecomposition of meteoritic ilmenite is reported by Snetsinger and Keil (1969). Rutile is a rare accessory mineral (in some meteorites as exsolution lamellae in ilmenite and chromite), in a few chondrites and some mesosiderites (Buseck and Keil, 1966). Osbornite was described many years ago from the Bustee enstatite achondrite, and may occur in other enstatite achondrites and enstatite chondrites in trace amounts. Perovskite and rhönite occur as accessory minerals in calcium-rich inclusions in C3 chondrites, along with pyroxene containing up to 17.7 percent TiO_2 (Mason, 1974). However, most of the titanium in meteorites is dispersed in the more abundant minerals in substitution for the major elements. Olivine contains little titanium, probably in the 10–100 ppm range. Orthopyroxene contains about 1,000 ppm (except for enstatite from

TABLE 33.—*Vanadium in stony meteorites*

[From Walter Nichiporuk in Mason, 1971; and additional data from Baedecker and Wasson, 1975, and Jérome, 1970]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
C1	1	41-57	49	254
C2	2	56-71	64	270
C3	6	50-117	88	312
H	32	44-88	61	196
L	49	45-94	65	193
LL	7	53-93	74	217
E4	3	56-58	57	189
E5	1	55	--	176
E6	4	64-80	68	193
		Calcium-poor achondrites		
Ae	4	14-21	17	34
Ah	3	133-260	180	393
Ac	1	50	--	159
Au	3	78-147	110	318
		Calcium-rich achondrites		
Aa	1	150	---	393
An	2	169-210	190	466
Aho	7	105-178	140	327
Aeu	9	84-115	95	230

enstatite chondrites and enstatite achondrites, which contains less than 100 ppm), whereas the clinopyroxenes diopside and pigeonite can take up considerably larger amounts, usually up to about 5,000 ppm; the clinopyroxene from the Angra dos Reis meteorite is exceptional with 15,000 ppm. Plagioclase may contain a little titanium, but no measurements in meteoritic plagioclase have been reported; in terrestrial plagioclase, the maximum appears to be about 400 ppm. Chromite ($FeCr_2O_4$) is an accessory mineral in stony meteorites, usually in the 0.1–0.5 percent range, and it contains significant amounts of titanium; in the common chondrites it contains 2–4 percent TiO_2 (Snetsinger and others, 1967). In the enstatite chondrites and enstatite achondrites, almost all the titanium is present in solid solution in troilite; usually about 0.5 percent is present in enstatite chondrites (Keil, 1968), but as much as 4.1 percent was recorded in troilite from the Norton County enstatite achondrite (Keil and Fredriksson, 1963), and up to about 10 percent in this mineral from the Khor Temiki enstatite achondrite (Keil, 1969). In the common chrondites Moss and others (1967) found 192, 100, and 132 ppm Ti in troilite from three hypersthene chondrites, and 398 ppm in troilite from a bronzite chondrite. Titanium has not been recorded from other sulfide minerals except daubreelite ($FeCr_2S_4$), in which Keil (1968) found up to 1,500 ppm.

Titanium is clearly a dispersed element in stony meteorites, but the major amount is probably contained in the pyroxenes, except in the enstatite chondrites and enstatite achondrites.

VANADIUM

Vanadium is a trace element in stony meteorites. Its distribution has been discussed by Walter Nichiporuk (in Mason, 1971), and his summary of the data is presented in table 33, supplemented by additional determinations on enstatite chondrites by Baedecker and Wasson (1975) and on achondrites by Jérome (1970). Vanadium is unusual in showing little fractionation between the different classes of chondrites, and even between chondrites and achondrites, except for the enstatite achondrites, which are considerably depleted in this element. Bunch, Keil, and Snetsinger (1967) showed that in the ordinary chondrites much of the vanadium is concentrated in the chromite, which contains an average of 4,800 ppm V; most of the remainder is probably in the pyroxenes (Mason and Graham, 1970). Meteoritic ilmenite contains little V (<100 ppm, according to Snetsinger and Keil, 1969). In the enstatite chondrites, which contain no chromite, vanadium is probably in a sulfide phase, most likely daubreelite ($FeCr_2S_4$); Allen and Mason (1973) recorded >0.1 percent V in sulfide in the Khairpur enstatite chondrite. The depleted nature of the enstatite achondrites may be ascribed to the small amount of sulfide in these meteorites.

Vanadium has essentially no siderophile affinity; Linn, Moore, and Schmitt (1968) analyzed five iron meteorites and found less than 0.2 ppm in the metal phase; coexisting troilite contained vanadium in concentrations ranging from 0.62 to 44.5 ppm.

CHROMIUM

Chromium is a minor constituent in most stony meteorites and a trace constituent in irons. The analytical data are very extensive. Schmitt, Linn, and Wakita (1972) determined chromium in 120 stony meteorites by instrumental neutron-activation analysis, and their results are summarized in table 34. Bunch and Olsen (1975) provided a comprehensive discussion of the geochemistry of chromium in meteorites.

In most stony meteorites, chromium is present partly as chromite and partly in atomic substitution in pyroxenes. The conditions governing this partition are not well known. In ordinary chrondrites, Mason and Graham (1970) recorded ~800 ppm in orthopyroxene and ~4,000 ppm in clinopyroxene; however, in the Shaw chondrite Fredriksson and Mason (1967) recorded 6,000 ppm in orthopyroxene and 8,000 ppm in clinopyroxene, and orthopyroxene in the Johnstown achondrite contains 5,600 ppm. The high Cr contents in the pyroxenes in Shaw and Johnstown may reflect unusually high temperatures of equilibration. Olivine in meteorites usually contains 300–500 ppm Cr, and troilite about the same amount. The metal phase in chondrites contains less than 100 ppm, except in the C2 and C3 chondrites, in which as much as 1.0 percent has been recorded (Bunch and Olsen, 1975). Chromium is thus lithophile in most stony meteorites, and has little chalcophile or siderophile affinity. However, in the highly reduced enstatite chondrites and enstatite achrondites, chromium is present not as chromite but as the sulfospinel daubreelite, $FeCr_2S_4$, and as heideite, $(Fe,Cr)_{1+x}(Ti,Fe)_2S_4$.

Chromium is generally in trace concentration in the metal phase of iron meteorites. Lovering and others (1957) measured this element in 88 irons and found a range of <1–2,360 ppm and an average of 37 ppm; Smales, Mapper, and Fouché (1967) measured 66 irons and found a range of <5–2,441 ppm, with an average of 115 ppm. The averages tend to be weighted by a few very high values: Tucson, 2,360; Nedagolla, 2,441; and Clark County, 1,565 ppm. Some of this chromium may be present as minute inclusions of daubreelite or carlsbergite (CrN). Scott (1972) plotted Cr versus Ni content for many irons, and found a negative correlation for groups IIAB, IIIAB, and IVA; groups IIC, IIC, and IVB cluster well on the Cr-Ni plot.

MANGANESE

Manganese is a minor element in stony meteorites, and is always determined in a complete analysis. Extensive series of measurements have been made by spectrographic (Moore and Brown, 1962) and neutron-activation analysis (Schmitt and others, 1972); the latter data have been used in the compilation of table 35. Manganese shows a remarkably small degree of variation between the different classes of stony meteorites. Although of comparable abundance to chromium, it differs from this element in not occurring as specific manganese minerals, except as alabandite, (Mn,Fe)S, in enstatite chondrites and enstatite achondrites; in other chondrites most of it is present in solid solution in olivine and pyroxenes, Mason and Graham (1970) recording ~3,000 ppm in olivine, ~3,000 ppm in orthopyroxene, and ~2,000 ppm in diopside. A small amount (~5,000 ppm) is contained in accessory chromite, and trace amounts (~200 ppm) in troilite. The chief feature of the meteorite geochemistry of manganese is the very close coherence with ferrous iron, a consequence of the similarity in ionic radius between Fe^{+2} and Mn^{+2}; this coherence extends to both lunar and ter-

TABLE 34.—*Chromium in stony meteorites*
[From Schmitt and others, 1972]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
C1	3	2,010-2,720	2,430	12,700
C2	7	2,830-3,770	3,070	12,400
C3	9	2,160-3,900	3,530	12,300
H	40	2,240 -4,410	3,430	10,900
L	47	3,000-4,900	3,780	10,900
LL	17	3,230-4,980	3,690	10,600
E4	2	3,050-3,240	3,210	10,100
E5,6	5	2,800-4,160	3,290	9,600
		Calcium-poor achondrites		
Ae	5	180-730	460	1,000
Ah	4	5,000-16,500	10,100	22,000
Ac	1	5,700	---	17,800
Au	2	4,430-5,060	4,890	13,800
		Calcium-rich achondrites		
Aa	1	1,700	---	4,500
An	2	1,580-1,820	1,680	4,000
Aho	7	2,720-5,380	4,470	10,200
Aeu	19	1,350-3,920	2,280	5,400

restrial rocks, as illustrated by Laul and Schmitt (1973).

Few data are available on manganese in the metal phases of meteorites. Bauer and Schaudy (1970) determined the contents of carefully selected metal phases in 21 iron meteorites and found a range of 9.8–22 ppm.

IRON

Iron is a major element in all classes of meteorites except the enstatite achondrites, and as a consequence the abundance data are very extensive. The standard procedures of analytical chemistry, when carefully applied, give reliable results for total iron. Von Michaelis, Ahrens, and Willis (1969) have shown that the older data on chondrites summarized by Urey and Craig (1953) show a greater spread of values than more recent analyses, indicating an improvement in overall quality in recent years. The figures in table 36 are derived as far as possible from recent analyses of observed falls.

As discussed in the introduction to this report, the individual classes of chondrites can be distinguished by their total iron content, and by the relative proportion of iron in oxidic compounds (mainly ferromagnesian silicates) and in nickel-iron and troilite (fig. 2). Urey and Craig (1953) utilized the total iron content to divide the chondrites into H (high-iron) and L (low-iron) groups. Bronzite chondrites are all H, averaging 27.6 percent, whereas hypersthene chondrites are all L, averaging 21 percent; the amphoterites are sometimes considered a

TABLE 35.—*Manganese in stony meteorites*
[From Schmitt and others, 1972]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
C1	3	1,740-2,300	1,880	9,300
C2	7	1,540-1,740	1,630	6,200
C3	9	1,280-1,650	1,490	4,900
H	40	1,860-2,800	2,260	6,700
L	47	2,210-2,780	2,460	6,700
LL	17	2,330-2,830	2,560	7,000
E4	3	1,800-2,500	2,200	6,800
E5,6	5	1,480-2,540	1,790	5,000
		Calcium-rich achondrites		
Ae	5	830-2,550	1,400	2,800
Ah	5	3,570-4,390	3,990	8,300
Ac	1	4,100	---	12,000
Au	2	2,860-2,910	2,890	7,700
		Calcium-rich achondrites		
Aa	1	700	---	1,700
An	2	3,520-3,860	3,700	8,200
Aho	8	3,460-4,000	3,800	8,200
Aeu	20	2,440-5,810	4,000	9,000

subclass of hypersthene chondrites, denoted LL, and averaging 20.0 percent. Carbonaceous chondrites seem to be all H, since on a volatile-free basis they contain 25–27 percent, and their Fe/Si ratio is similar to or somewhat greater than that for the bronzite chondrites. Enstatite chondrites show a wide range of total iron contents, and designation as H or L types is of doubtful utility.

Urey (1961) pointed out the significance of the Fe/Si ratio in chondrites, both for the recognition of different classes and subclasses, and as an indication of chemical fractionations between different classes. The data in table 36 show small but consistent differences between the three types of carbonaceous chondrites, the Fe/Si ratio being 0.901 for C1, 0.841 for C2, and 0.816 for C3. The latter figure is essentially identical with that for the bronzite chondrites (0.812). The lower iron content of the hypersthene chondrites and the amphoterites is reflected in the Fe/Si ratios of 0.577 and 0.536 respectively. Enstatite chondrites show a wide range of Fe/Si ratios, and those that are most iron-rich have ratios slightly exceeding one.

The interpretation of this range of Fe/Si ratios in terms of iron-silicate fractionation in the chondrites has been cogently discussed by Anders (1964). He came to the following conclusions: (1) The metal-silicate fractionation in chondrites involved loss of metal from primordial matter with Fe/Si≈ 0.8–1.0. (2) At the time of fractionation, the material had gone through a high-temperature stage and contained individual metal and silicate grains.

TABLE 36.—*Iron in stony meteorites*

[From Mason, 1971; and additional data]

Class	Number analyzed	Range (weight percent)	Mean (weight percent)	Atoms10^6Si
		Chondrites		
C1	3	17.76-19.01	18.40	901,000
C2	9	20.85-23.78	21.90	841,000
C3	6	24.04-25.94	25.15	816,000
H	36	24.57-30.88	27.61	812,000
L	60	20.15-23.61	21.81	577,000
LL	13	18.56-21.30	20.03	536,000
E4,5	4	30.35-35.02	32.96	975,000
E6	5	22.17-29.03	25.46	657,000
		Calcium-poor achondrites		
Ae	4	.47-1.55	1.02	19,000
Ah	5	11.57-13.48	12.42	254,000
Ac	1	21.34	---	620,000
Au	3	11.31-16.40	14.45	381,000
		Calcium-rich achondrites		
Aa	1	7.45	---	182,000
An	1	16.04	---	359,000
Aho	5	11.92-14.02	13.22	282,000
Aeu	11	12.58-17.74	14.63	322,000

(3) The fractionation probably occurred while the material was in a dispersed state.

At the time Anders wrote, a serious objection to his postulate of primordial matter with $Fe/Si \approx 0.8-1.0$ was the apparent low abundance of iron in the Sun—$Fe/Si=0.12$, according to Goldberg, Müller, and Aller (1960). This seemed to require that primordial matter was low in iron, and that high-iron chondrites must have been enriched in this element. However, this apparent impasse has been resolved by a reevaluation of the spectrographic data for the solar abundance of iron (Garz and Kock, 1969). This reevaluation has led to an increase in the figure for the solar abundance of iron by a factor of ~10 compared to that given by Goldberg, Müller, and Aller, the Fe/Si ratio now being given as 1.0. Thus, it now appears that the high-iron chondrites, specifically the C1 carbonaceous chondrites, are closely akin to original solar matter.

Relative to the chondrites, all the achondrites (except the unique chassignite) show marked depletion in iron and correspondingly lower Fe/Si ratios. To a considerable extent, this is due to marked impoverishment of these meteorites in nickel-iron and troilite, which are present in very small amounts (except in the ureilites). The enstatite achondrites are extremely depleted; they consist essentially of almost iron-free enstatite ($MgSiO_3$).

The iron meteorites consist essentially of nickel-iron, and minor to trace amounts of accessory minerals such as troilite, schreibersite, and graphite. Samples for analysis are generally selected to avoid the accessory minerals as far as possible, and the resulting data thus correspond more closely to the metal phase than to the overall composition of the meteorite. The metal phase is essentially a three-component system Fe-Ni-Co; the cobalt content is uniformly low, ranging from 0.3–1.0 percent, so the iron and nickel contents are inversely related. The range of iron content in iron meteorites can thus be derived directly from a plot of nickel contents (fig. 9).

Buddhue (1946) compiled the analytical data for the different classes of iron meteorites, and calculated average compositions, after eliminating those analyses that appeared unreliable. His results are given in table 37.

In stony and stony-iron meteorites the principal iron-bearing minerals are nickel-iron, troilite, and the ferromagnesian silicates olivine and pyroxene. Small amounts of the accessory minerals chromite ($FeCr_2O_4$) and ilmenite ($FeTiO_3$) are usually present. The C1 and C2 carbonaceous chondrites are unique in having much of their iron present as the hydrated magnesium-iron silicate serpentine (or chlorite), and in having magnetite (Fe_3O_4) and pentlandite ($(Fe,Ni)_9S_8$) as accessory minerals.

TABLE 37.—*Mean iron content of individual classes of iron meteorites*

[From Buddhue, 1946]

Class	Number of meteorites	Weight percent
Hx	34	93.59
Ogg	18	92.33
Og	34	91.22
Om	92	90.67
Of	37	90.53
Off	10	86.75
D	38	79.63
All irons[1]	327	89.70

[1] Including metal in pallasites, mesosiderites, and chondrites; the average for the metal from these groups is very close to the overall average.

COBALT

Cobalt is a ubiquitous element in meteorites, being present in amounts up to 1 percent in irons. Schmitt and others (1972) made extensive measurements by instrumental neutron-activation analysis in most classes of stony meteorites, and their results, along with some additional data, are reported in table 38. The concentration of cobalt shows a close correlation with the amount of metallic nickel-iron in a meteorite; the distinction between H and L (+LL) classes of chondrites is clearly seen, and the low Co contents of the achondrites is related to their low metal contents.

Lovering and others (1957) found cobalt in 88 iron meteorites to range from 0.38 to 0.92 percent with an average of 0.51 percent. Moore, Lewis, and Nava (1969) analyzed 100 irons and found a range of 0.32–1.02 percent. The relationship between cobalt and nickel content of iron meteorites is illustrated in figure 8. In the two metal phases of meteorites, cobalt is concentrated in kamacite, which usually contains two to five times as much Co as the associated taenite.

Cobalt is a strongly siderophile element in meteorites, generally with little or no chalcophile or lithophile affinity. For example, in the Sikhote-Alin iron

TABLE 38.—*Cobalt in stony meteorites*

[From Schmitt and others, 1972; and additional data from Laul and others, 1972; Case and others, 1973; Binz, Kurimoto, and Lipschutz, 1974; Binz and others, 1975, 1976; and Baedecker and Wasson, 1975]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6 Si
		Chondrites		
C1	3	460-550	480	2,200
C2	7	460-700	530	1,900
C3	9	480-740	620	1,900
H	46	440-1,260	820	2,300
L	50	290-870	570	1,450
LL	21	250-870	460	1,200
E4	2	810-870	860	2,400
E5,6	4	680-1,000	820	2,100
		Calcium-poor achondrites		
Ae	5	2.1-57	14	26
Ah	2	18-19	19	37
Ac	1	141	---	390
Au	6	65-172	112	280
		Calcium-rich achondrites		
Aa	1	20.4	---	47
An	2	43-47	45	90
Aho	8	10-34	20	43
Aeu	20	2-22	7	14

Yavnel (1950) found 0.47 percent in the kamacite, 0.03 percent in the schreibersite, 0.01 percent in the troilite, and 0.01 percent in the chromite. Mason and Graham (1970) have shown that in stony meteorites the metal phase contains up to 1 percent Co, whereas the silicates (olivine, pyroxene, plagioclase) contain 1–50 ppm and the troilite 40–60 ppm. The C1 and C2 carbonaceous chondrites contain little or no free metal, and the state of combination of the cobalt is not known; in the C3 chondrites, Fuchs and Olsen (1973) have found up to 6.9 percent in kamacite, up to 2.0 percent in taenite, 0.8 percent in pentlandite, but less than 0.05 percent in troilite.

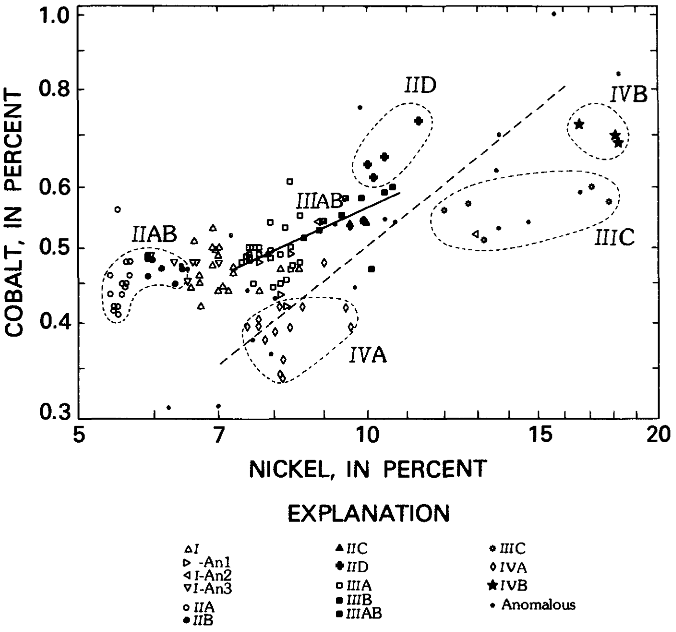

FIGURE 8.—Co-Ni distribution in iron meteorites. Most chemical groups are well resolved (as indicated by short-dashed outlines), but they are scattered on either side of the Co/Ni ratio for C1 chondrites (dashed line). In group IIIAB, Co content correlates positively with Ni content. Reprinted from Scott (1972) and published with permission.

NICKEL

The extensive data on nickel in meteorites were comprehensively reviewed by C.B. Moore, in Mason (1971); the data for stony meteorites are summarized in table 39. Nickel in chondrites shows a fairly constant relationship to total iron, the ratio Fe/Ni (atomic) ranging from 18 to 20. In the ordinary (H, L, LL) chondrites, essentially all the nickel is contained in the metal phase; the mean content of metal in each of these classes, in weight percent, is: H, 18.5; L, 7.4; LL, 2.6, and the nickel concentrations reflect these metal contents. However, the nickel concentration does not diminish proportionally with the metal content. This was noted many years ago by Prior (1916), who established certain chemical and mineralogical regularities within the chondrites, which have been codified as Prior s rules, as follows:

1. The smaller the amount of nickel-iron in a chondrite, the higher the Ni/Fe ratio in the nickel-iron.
2. The smaller the amount of nickel-iron in a chondrite, the higher the FeO/MgO ratio in the ferromagnesian silicate minerals.

The carbonaceous chondrites contain little or no nickel-iron. In the C1 and C2 chondrites most of the nickel is probably contained in the layer-lattice silicates that form the matrix of these meteorites; the C3 chondrites contain a little metal, with up to 66 percent Ni, and pentlandite, with up to 19 percent Ni (Fuchs and Olsen, 1973)—coexisting troilite contains less than 0.05 percent Ni.

Most achondrites are practically metal free, and nickel is then present only in trace amounts. Even in the ureilites, which contain 3–6 percent nickel-iron, the nickel content is only about 0.1 percent, a notable depletion relative to chondritic abundances.

In the pallasites, which consist of approximately equal amounts of nickel-iron and olivine, the nickel content of the metal ranges from 7.9–16.4 percent, with a mean of 10.5 percent, and the coexisting olivine contains 40–70 ppm (Buseck and Goldstein, 1969).

The nickel content of iron meteorites is illustrated in figure 9. The vast majority contain between 5 percent and 11 percent nickel. Those with the very lowest nickel contents are hexahedrites made up primarily of kamacite that has lost nickel to adjacent schreibersite [$(Fe,Ni)_3P$] inclusions.

COPPER

Copper is a trace element in meteorites, being present in irons usually at the 100–200 ppm level, in chondrites at about 100 ppm, and being significantly depleted in achondrites at about 1–20 ppm. The data for the stony meteorites are summarized in table 40. Some fractionation is evident between the chondrite classes, the copper concentration decreasing in the order C1–C2–C3—(H, L, LL).

Smales, Mapper, and Fouché (1967) reported on copper in 67 irons and found a range of 74–360 ppm (mean 172 ppm), with four exceptions (Hoba 1.3, Nedagolla 1.5, Santa Catharina 850, San Cristobal

1,016 ppm). Moore, Lewis, and Nava (1969) obtained similar results in analyses of 70 irons: range 60–360 ppm, mean 170 ppm, with exceptions Dayton (510 ppm), Tlacotepec (10 ppm), and Weaver Mountains (10 ppm).

It is remarkable that, in spite of its low concentration, copper generally occurs in meteorites as minute grains of native copper. Ramdohr (1973) recorded native copper in more than half of the 350 meteorites he examined, and noted that many of his polished sections were so small that one of the rare copper grains would not likely be exposed. He commented: "The occurrence of copper is very surprising, because copper is rather soluble in the structure of γ-(Fe,Ni), and because taenite is always so plentiful that all the copper present ought to be dissolved in it" (p. 26). Ramdohr noted that the native copper is commonly found in taenite-rich plessite, which suggests formation by exsolution at relatively low temperatures during the very slow cooling that most meteorites have undergone.

Hey and Easton (1968) studied the distribution of copper in the different minerals of four chondrites, with the following results in parts per million: kamacite 22–65, taenite 1,610–2,610, troilite <1–114, olivine 17.8–41.5, pyroxene 6.0–22.3; these data show that most of the copper in these meteorites must reside in the taenite.

TABLE 39.—*Nickel in stony meteorites*

[From C. B. Moore in Mason, 1971; and additional data]

Class	Number analyzed	Range	Mean	Atoms/10^6Si
	Chondrites (weight percent)			
C1	3	0.97-1.09	1.03	47,800
C2	10	1.17-1.34	1.23	44,900
C3	7	1.24-1.50	1.33	41,100
H	27	1.38-1.99	1.70	47,600
L	29	.98-1.57	1.27	32,500
LL	12	.68-1.28	.91	23,200
E4	3	1.66-1.95	1.81	52,200
E5	2	1.62-1.81	1.71	47,000
E6	6	1.11-1.96	1.53	37,700
	Calcium-poor achondrites (ppm)			
Ae	3	80-270	190	330
Ah	4	5-90	33	64
Ac	1	475	---	1,310
Au	6	900-2,300	1,300	3,300
	Calcium-rich achondrites (ppm)			
Aa	1	40	---	93
An	1	990	---	2,100
Aho	6	8-88	48	97
Aeu	6	5-12	7	15

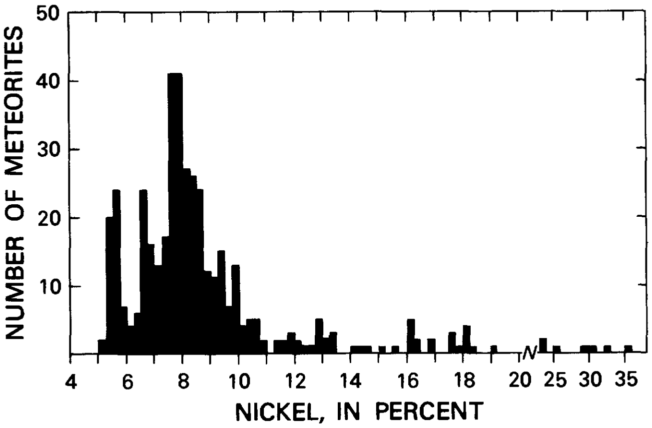

FIGURE 9.—Histogram of the nickel content of analyzed iron meteorites, plotted at 0.25-percent Ni intervals. No analyzed iron meteorite contains less than 5 percent Ni, and only seven contain more than 20 percent; Dermbach (42 percent) and Oktibbeha County (61 percent) lie outside the histogram. Copyright © 1975 by the Regents of the University of California; reprinted from Buchwald (1975) by permission of the University of California Press.

ZINC

The data on zinc in meteorites have been comprehensively reviewed by C.B. Moore, in Mason (1971). Zinc abundances in stony meteorites are summarized in table 41. Zinc in chondrites is a strongly depleted element in terms of the criteria of Anders (1971b); the atomic ratio C1:C2:C3 is 1.00:0.48:0.26, and the ordinary (H, L, LL) chondrites are more depleted than the C3 class. Within the ordinary chondrites, the different types (3, 4, 5, 6) show no significant fractionation of zinc (Binz and others, 1976). Enstatite chondrites show strong fractionation, with E3, 4 meteorites having zinc abundances comparable to C1 chondrites, whereas E5, 6 meteorites average even lower than the ordinary chondrites, although the range is large. The achondrites, except for the ureilites and nakhlites, are notably depleted in zinc relative to the chondrites.

Zinc abundances in stony meteorites are comparable to those of copper. However, in contrast to copper, which is siderophile, zinc is lithophile in most meteorites. Nishimura and Sandell (1964) showed that in the ordinary chondrites very little zinc is contained in the metal or troilite phases; it is distributed in subequal amounts in the acid-soluble (olivine and phosphate) and acid-insoluble (pyroxene, plagioclase, and chromite) fractions. In the enstatite chondrites, on the contrary, most of the zinc is in the sulfide phases. This is consistent with mineralogical observations; enstatite chondrites contain sphalerite and zincian daubreelite, (up to 5.5 percent Zn (Keil, 1968), but these phases have not been recorded from ordinary chondrites. Meteoritic chromite may show considerable concentration of zinc, up to 2.31 percent ZnO (Bunch and others, 1970).

Zinc is present at very low concentration in the metal phase of iron meteorites, except for group I (table 42). The data confirm that zinc has little or no siderophile affinity in meteorites; chromite, sphalerite, and zincian daubreelite have been recorded from irons, and inclusions of these minerals may contribute to the higher zinc values of some iron meteorites.

GALLIUM

Gallium is a trace element in meteorites, seldom exceeding 10 ppm in stony meteorites and 100 ppm in irons. The data were assembled and evaluated by P.A. Baedecker and J.T. Wasson, in Mason (1971), and additional determinations since that time have confirmed the earlier work. The information on stony meteorites is summarized in table 43. Gallium shows moderate depletion in the sequence C1–C2–C3—ordinary chondrites, the relative atomic ratio being 1.00:0.66:0.45:0.29. Enstatite chrondrites have gallium abundances comparable to those in the carbonaceous chondrites, and show moderate depletion in the sequence E4–E5–E6. Ordinary chondrites show no significant variation of gallium content between the different types (Case and others, 1973). Achondrites are notably depleted in gallium relative to the chrondrites.

Fouché and Smales (1967a) studied the distribution of gallium in 27 chondrites belonging to the H, L, and E classes, by separating each into magnetic (that is, metal-phase) and nonmagnetic fractions and analyzing each fraction separately. The average values in parts per million for the H chondrites are: metal 11.3, nonmagnetic 3.8, bulk 5.3; for the L chondrites: metal 11.4, nonmagnetic 5.3, bulk 5.6. They found that in the enstatite chondrites practically all the gallium is in the metal phase. Moss and others (1967) found 2.4–2.8 ppm in the silicate fraction of four ordinary chondrites, and 2–9 ppm in the sulfide fraction. These results were confirmed by Allen and Mason (1973), who also measured this element in separated minerals; in the nonmetallic phases gallium is notably concentrated in plagioclase (up to 18 ppm) and chromite (up to 90 ppm). Gallium is mainly siderophile in the ordinary chondrites, but does show chalcophile and lithophile affinities. Chou, Baedecker, and Wasson (1973) found that metal/silicate concentration ratios for Ga and

Ge were lower in type 3 ordinary chondrites than in types 4–6; they commented: "Apparently appreciable fractions of these elements condensed from the nebula in oxidized form and entered the metal during later thermal events" (p. 2159).

The abundance of gallium in iron meteorites has been extensively studied since Lovering and others (1957) demonstrated a wide range in gallium contents (<2–93 ppm) and a quantization into four groups. This work has been greatly extended by Wasson and his coworkers, and was comprehensively discussed by Scott and Wasson (1975); their results are summarized in table 7 and figure 10. They concluded that each of these discrete groups probably formed in a separate parent body.

GERMANIUM

Germanium is almost exclusively siderophile in meteorites, being present in the metal phases kamacite and taenite. The extensive data have been assembled and discussed by P.A. Baedecker and J.T. Wasson, in Mason (1971). On the whole, the data from different investigators are remarkably consistent. The information on stony meteorites is summarized in table 44, largely from the results of Fouché and Smales (1967a), with some additional data. This table shows that Ge is strongly fraction-between the different chondrite classes, being relatively depleted in the sequence C1–C2–C3–H—(L, LL) in the ratio (atomic) 1.00:0.57:0.39:0.25:0.15. Enstatite chondrites have Ge concentrations com-

TABLE 40.—*Copper in stony meteorites*

[From Schmitt and others, 1972; and additional data from Laul and others, 1972; and Binz and others, 1974]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
C1	3	106–137	127	540
C2	7	90–129	116	390
C3	10	85–138	108	300
H	24	48–137	90	230
L	32	52–132	94	220
LL	15	60–107	80	190
E4	2	172–193	185	430
E5,6	4	87–202	110	260
		Calcium-poor achondrites		
Ae	5	1–24	13	22
Ah	1	7	---	13
Au	2	11–22	11	25
		Calcium-rich achondrites		
Aa	1	10	---	22
An	2	3.7–5.0	4.4	8.6
Aho	5	.8–18.2	6.7	13
Aeu	7	.9–8.5	3.0	5.8

parable to those in C1 and C2 chondrites (Baedecker and Wasson 1975). Data are very sparse for Ge in achondrites, but the figures show extreme depletion, as would be expected from the absence or near absence of nickel-iron in most of these meteorites. (The ureilites analyzed contain as much as ~6 percent nickel-iron, and the mean Ge content is similar to that of the ordinary chondrites.)

Chou and Cohen (1973) and Chou, Baedecker, and Wasson (1973) have studied the distribution of Ge between metal and silicates in the different petrologic types (3, 4, 5, 6) of the ordinary chondrites. They find that, as for Ga, the metal/silicate concentration ratio of Ge is lower in type 3 chondrites than in types 4–6; they ascribe this to a redistribution of the element from oxidized to reduced form during postcondensation thermal events.

Lovering and others (1957) discovered that germanium shows a remarkable variation in iron meteorites, and, like gallium, the values are quantized into discrete groups. This work has been greatly extended by Wasson and his coworkers, and was comprehensively reviewed by Scott and Wasson (1975); their results are summarized in table 7 and figure 11. Table 7 shows a range of Ge content over the different groups of iron meteorites from 0.03 to

TABLE 41.—*Zinc in stony meteorites*

[From C. B. Moore, in Mason, 1971; and additional data from Keays and others, 1971; Laul and others, 1972; Laul and Schmitt, 1973; Case and others, 1973; Krahenbuhl and others, 1973; Binz and others, 1974, 1975; and Rosman and de Laeter, 1974]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
C1	3	295-310	303	1,260
C2	3	175-187	183	600
C3	6	105-130	120	330
H	8	28-89	51	130
L	15	8-102	58	130
LL	11	44-82	68	150
E3,4	4	90-519	400	1,040
E5,6	6	7.5-86	29	64
		Calcium-poor achondrites		
Ae	2	5-25	15	24
Ah	2	3-63	34	60
Au	6	35-280	186	420
		Calcium-rich achondrites		
Aa	1	2.1	---	4.4
An	2	42-71	57	110
Aho	5	.35-30	5.8	11
Aeu	7	.78-20	4.8	9.0

TABLE 42.—*Zinc in iron meteorites*

[Data from Kelly and Moore, 1973, except for group I, which are from Smales, Mapper, and Fouché, 1967]

Group	Number Analyzed	Range	Median
I	10	12-42	27
IIA	5	.34-1.5	.5
IIB	3	.25-.39	.3
IIC	4	.23-2.2	.4
IID	5	2.1-3.7	2.9
IIIA	8	.40-2.8	.6
IIIB	4	1.2-2.1	1.5
IVA	5	.1-12	.5
IVB	4	.45-16	2.5

520 ppm, but some anomalous irons contain even higher concentrations; one exceptional iron, Butler, a finest octahedrite with 16 percent Ni, contains 2,000 ppm.

ARSENIC

Arsenic is a trace element in meteorites, in amounts ranging up to about 30 ppm. The data have been assembled and discussed by M.E. Lipschutz, in Mason (1971), and are summarized in table 45. Arsenic concentrations show relatively small variations between the different chondrite classes. The H, L, LL classes show a consistent relationship between As and metal content, the As content diminishing as the metal content decreases in the sequence H–L–LL. Enstatite chondrites, which usually have higher metal content than ordinary chondrites, also show higher As concentrations; the high content for the E5 chondrite, St. Marks, may be due to an unusually high metal content in the sample analyzed. Data for achondrites are too sparse to be worth tabulating; Wänke and others (1972) recorded 0.092 ppm in the Kapoeta howardite and 0.18 ppm in the Juvinas eucrite, thus showing strong depletion for these meteorites relative to the chondrites.

Onishi and Sandell (1955) claimed As to be both siderophile and chalcophile in chondrites on the basis of their analyses of As contents in separated metal, sulfide, and silicate portions of two composites, each consisting of 7 H and L group meteorites; their results in parts per million were 11, 8, 0.4 and 13, 11, 0.2 espectively. However, Fouché and Smales (1967) found As in chondrites to be contained almost entirely in the metal phase, and this was confirmed by Mason and Graham (1970). The explanation of this discrepancy perhaps lies in incomplete separation of metal from sulfide in the material analyzed by Onishi and Sandell.

Smales, Mapper, and Fouché (1967) determined As in 67 irons and found a range from 0.43 to 30.7 ppm, with a mean of 8.8 ppm. Cobb (1967) analyzed 33 irons and found a range of <1–30 ppm, with a mean of 9 ppm. Scott (1972) correlated these and other data with Ni content (fig. 12).

SELENIUM

The data for selenium in meteorites have been assembled and critically evaluated by I. Pelly and M.E. Lipschutz, in Mason (1971). The information in table 46 has been extracted from their compilation, and additional data taken from other sources. Selenium shows relative depletion in the sequence C1–C2–C3—H, L, LL), the atomic ratio being 1.00:0.48:0.27:0.24; the concentrations in enstatite chondrites are comparable to those in C1 and C2 chondrites. Pelly and Lipschutz pointed out that selenium concentrations in chondrites are independent of petrologic type, and that the Se/S ratio is relatively uniform throughout. (For the different classes of chondrites the atomic ratio Se/S ranges from 14×10^{-5} to 19×10^{-5}.) Mason and Graham (1970) found that selenium is concentrated in meteoritic troilite, and was not detectable in other phases. Thus, selenium is entirely

TABLE 43.—*Gallium in stony meteorites*

[From Baedecker and Wasson, in Mason, 1971; and additional data from Keays and others, 1971; Laul and others, 1972; Baedecker and Wasson, 1975; Case and others, 1973; Binz and others, 1974, 1975, and 1976; Chou, Baedecker, and Wasson, 1973 and 1976a, b; Ikramuddin and Lipschutz, 1975; and Ikramuddin and others, 1976]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
C1	2	9.2-10.0	9.6	38
C2	2	8.1-8.2	8.2	25
C3	6	4.9-8.1	6.4	17
H	7	4.9-5.8	5.3	12
L	26	3.6-6.2	5.2	11
LL	5	2.9-6.0	4.6	10
E4	3	13.5-17.5	16.0	39
E5	1	14.9	---	35
E6	5	8.5-12.0	10.5	22
		Calcium-poor achondrites		
Ae	1	0.056	---	0.08
Au	6	.95-5.0	2.5	5.3
		Calcium-rich achondrites		
Aa	1	0.36	---	0.71
An	1	2.70	---	4.4
Aho	5	.72-1.34	1.08	1.8
Aeu	8	1.26-1.51	1.42	2.5

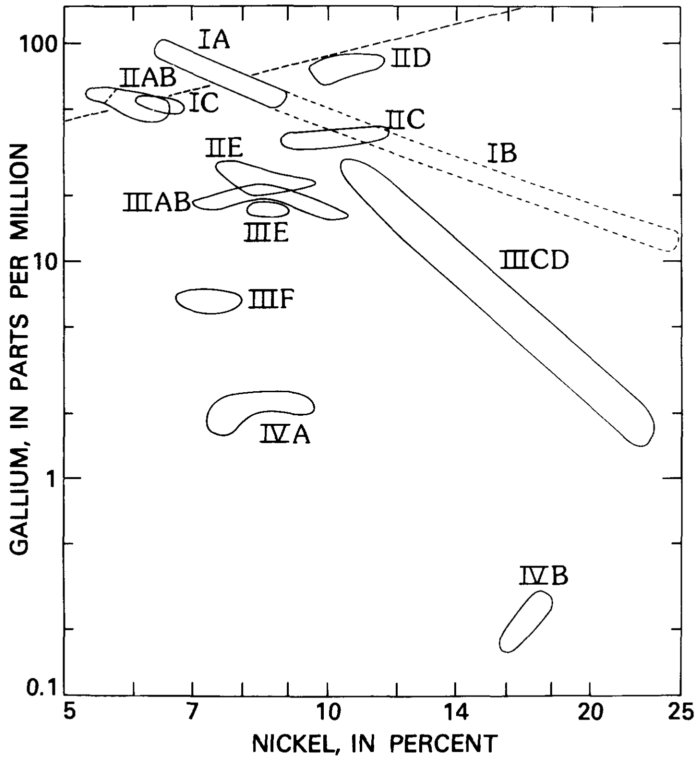

FIGURE 10.—Logarithmic plot of Ga against Ni for iron meteorites, showing quantization into the different groups. Apart from IA and IIICD, the groups show very limited ranges of Ga contents, less than ± 20 percent about the mean. IB is very sparsely populated with only eight meteorites and is shown in short-dashed outline. About 14 percent of known iron meteorites are anomalous and are not shown. The straight dashed line through groups IA, IC, and IIAB shows the Ga/Ni ratio for C1 chondrites. Reprinted from Scott and Wasson (1975); copyrighted by American Geophysical Union.

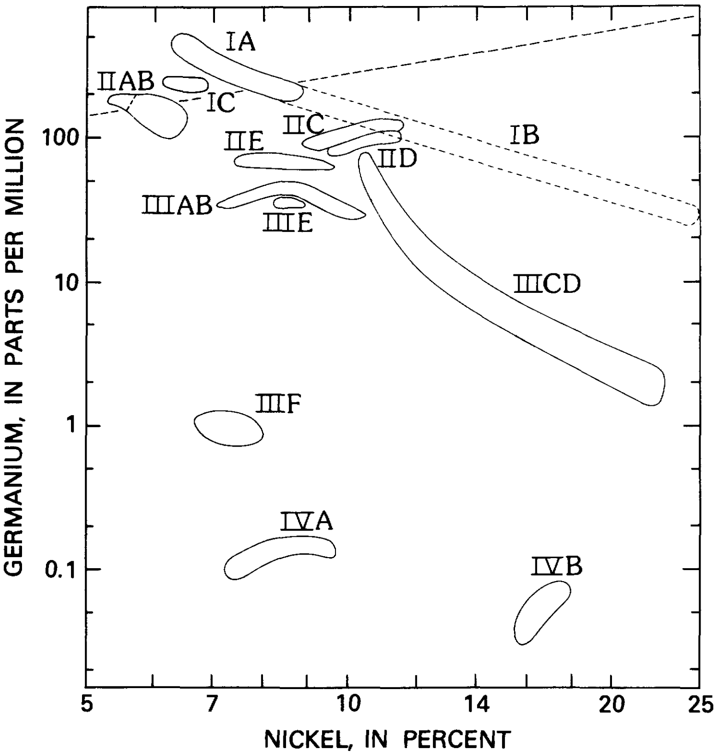

FIGURE 11.—Logarithmic plot of Ge against Ni for iron meteorites; note the similarity to figure 10. Most groups except IAB and IICD show very small Ge variations in comparison with the total range of more than four orders of magnitude. Group IB is very sparsely populated with only eight meteorites and is shown in short-dashed outline. The straight dashed line through groups IIAB and IA is the Ge/Ni ratio for C1 chondrites. Reprinted from Scott and Wasson (1975); copyrighted by American Geophysical Union.

chalcophile in stony meteorites and is camouflaged in troilite and other sulfur-bearing minerals. The extreme depletion of Se in achondrites is due to the paucity of troilite in these meteorites.

Relatively few data exist for Se in iron meteorites. Seitner and others (1971) analyzed 10 irons, and found an upper limit of 0.01 ppm in 6 of them. Kiesl and Hecht (1969) analyzed troilite from three irons, and found Se contents ranging from 128 to 300 ppm. These data confirm the highly chalcophile character of this element.

BROMIME

The abundance of this element has been the subject of several investigations, but the results are confusing and difficult to interpret. For example, the following figures in parts per million have been published for Bruderheim, a hypersthene (L6) chondrite: 0.97, 1.56 (Wyttenbach and others, 1965); 0.05, 0.13, 0.20, 0.23, 0.24 (Reed and Allen, 1966); 0.18, 0.18, 0.15, 0.16, 0.11, 0.12 (Goles and others, 1967); 0.030, 0.026 (Lieberman and Ehmann, 1967). If this spread in figures is not the result of experimental error or of contamination, it indicates that bromine is distributed very inhomogeneously within this meteorite, and that sampling is a major problem. Reed and Allen found that much of the bromine in Bruderheim and other meteorites was leachable in hot water.

The data in table 47 have been selected from the compilation by G.W. Reed, in Mason (1971), and additional information on C3 chondrites from Anders and others (1976), and on the achondrites from Laul and others (1972). Bromine shows strong relative depletion in the sequence C1–C2–C3–(H, L), the atomic abunrdance ratios being 1.00:0.48:0.24:-

TABLE 44.—*Germanium in stony meteorites*

[From Fouché and Smales, 1967; and additional data from Krahenbuhl and others, 1973; Chou and others, 1973 and 1976a, b; Baedecker and Wasson, 1975; and Anders and others, 1976]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
Chondrites				
C1	3	27.8-34.9	31.2	117
C2	3	19.6-24.9	22.8	67
C3	7	18.2-24.0	21.1	52
H	7	11.3-13.4	12.7	29
L	9	4.6-12.4	8.7	18
LL	4	6.9-11.6	8.4	17
E4	3	42-51	47	110
E5	1	45	---	100
E6	4	21-36	30	60
Calcium-poor achondrites				
Ae	1	0.21	---	0.29
Au	5	2.0-29.5	11	22
Calcium-rich achondrites				
An	1	2.6	---	4.5
Aho	1	.31	---	.51
Aeu	1	.06	---	.10

TABLE 45.—*Arsenic in chondritic meteorites*

[From M. E. Lipschutz, in Mason, 1971; and additional data from Case and others, 1973; and Binz and others, 1974 and 1976]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
C1	2	1.6-2.0	1.7	6.2
C2	3	1.9-2.0	2.0	5.7
C3	5	1.5-2.4	1.8	4.4
H	6	2.5-3.3	2.6	5.7
L	10	.92-3.5	1.6	3.2
LL	4	1.1-1.3	1.2	2.4
E4	3	2.3-4.8	3.2	7.2
E5	1	5.5	---	12
E6	5	2.6-5.1	3.4	6.5

TABLE 46.—*Selenium in stony meteorites*

[From I. Z. Pelly and M. E. Lipschutz, in Mason, 1971; and additional data on carbonaceous chondrites from Krähenbühl and others, 1973, and Anders and others, 1976; on enstatite chondrites from Binz and others, 1974; on ureilites from Binz and others, 1975; and on other achondrites from Laul and others, 1972]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
C1	3	19.1-21.1	19.5	67
C2	3	11.3-12.3	11.8	32
C3	7	5.7-10.8	8.0	18
H	6	7.0-9.5	7.9	16
L	6	5.9-12	8.4	16
LL	8	5.6-14	10	19
E4	3	28-41	34	73
E5	1	30	---	62
E6	5	14-24	19	35
		Calcium-poor achondrites		
Ae	1	1.78-2.09	1.9	2.4
Au	4	.68-1.24	.92	1.7
		Calcium-rich achondrites		
An	1	0.088	---	0.14
Aho	3	.118-.603	.42	.63
Aeu	5	.078-.396	.25	.39

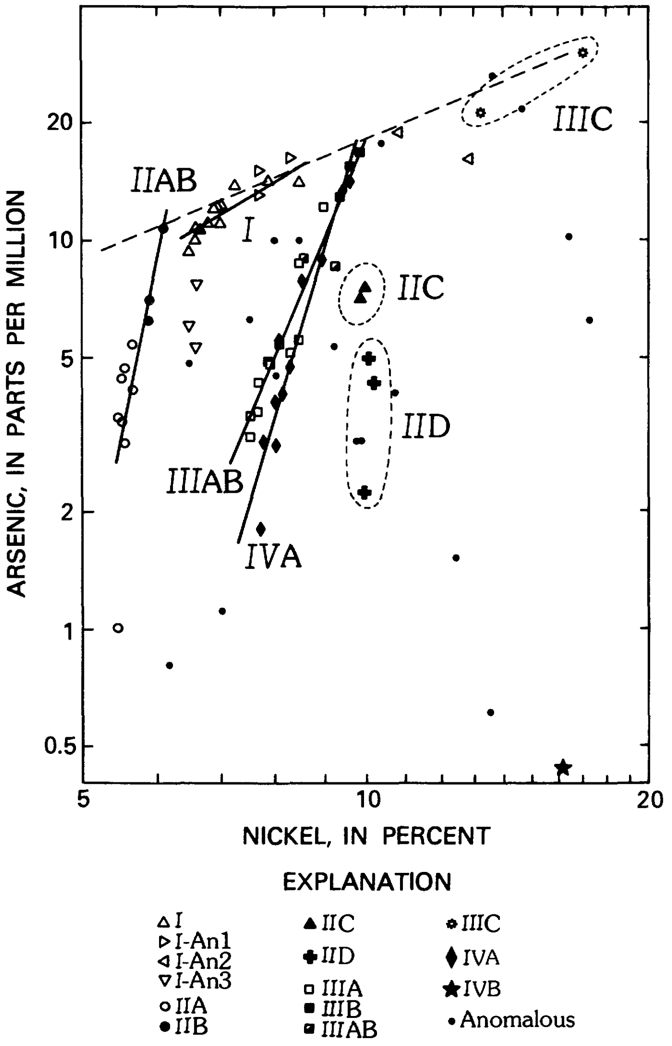

FIGURE 12.—As-Ni distribution in iron meteorites. The dashed line is the As/Ni ratio for C1 chondrites; group I and IIIC meteorites contain these elements in this ratio. In groups I, IIAB, IIIAB, and IVA, As content correlates positively with Ni content. Short-dashed lines enclose well-resolved groups. Reprinted from Scott (1972) and published with permission.

0.24:0.04. Bromine also shows relative depletion with petrologic type in ordinary chondrites; Keays, Ganapathy, and Anders (1971) demonstrated a decrease of average Br concentrations of 3.1, 2.7, 0.50, and 0.40 ppm in the sequence L3–L4–L5–L6. Enstatite chondrites have comparable abundances to the carbonaceous chondrites.

No obvious correlation exists between bromine and any of the major elements in meteorites. However, as shown in table 47, the chondrites show a fairly consistent Cl/Br relationship. Reed and Allen (1966) found 40 ppm Br in chlorapatite from the Mt. Sterling iron meteorite; this suggests that chlorapatite may be the principal host of bromine in meteorites.

RUBIDIUM

A considerable number of rubidium determinations have been made on stony meteorites, many with a view to ^{87}Rb–^{87}Sr dating. The data have been assembled and discussed by G.G. Goles, in Mason (1971), and are summarized in table 48, along with additional determinations. Rubidium shows a rather narrow abundance range in chondrites, with some exceptions, notably among the LL and E classes. Three different samples of Soko-Banja (LL) gave 0.580, 4.880, and 0.515 ppm Rb (Gopalan and Wetherill, 1969); Krähenberg (LL) has light and dark areas, and a light area contained 1.94 ppm and a dark area 50.8 ppm Rb (Kempe and Müller, 1969). The low value of 0.8 ppm Rb in the E5 chondrite St. Marks has been established by two independent analyses (Gopalan and Wetherill, 1970; Laul and others, 1973). For most chondrites, the K/Rb weight ratio is in the range 200–400.

Selective solution experiments on Abee (E4) and Bruderheim (L6) chondrites by Shima and Honda (1967) showed that Rb is contained almost entirely in the HF-soluble fraction, hence probably in plagioclase. This was confirmed by Mason and Graham (1970), who found up to 28 ppm Rb in chondrite plagioclase. El Goresy (1967) identified some grains of potassium feldspar in troilite nodules in the Odessa iron, and found that they have remarkably high Rb contents, 0.2–0.6 percent; the K/Rb ratio is of the order of 30, implying a high degree of fractionation.

Rubidium, unlike lithium, sodium, and potassium, appears to show little or no chalcophile affinity in the enstatite chondrites.

STRONTIUM

The data on strontium in stony meteorites are quite extensive, and have been assembled and discussed by K. Gopalan and G.W. Wetherill, in Mason (1971); a selection of the data is provided in table 49. Strontium abundances show relatively small variations between different chondrite classes; the somewhat higher concentration in C3 chondrites is linked with the higher calcium content of these meteorites, frequently in the form of chondrules and inclusions consisting largely of melilite and calic pyroxene. Strontium in chondrites and many achondrites shows a close coherence with calcium, as can

TABLE 47.—*Bromine in stony meteorites*

[From G. W. Reed, in Mason, 1971; and additional data from Anders and others, 1976; and Laul and others, 1972]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si	Cl/Br (atoms)
Chondrites					
C1	2	3.3-5.1	4.0	14	410
C2	3	.8-4.8	2.5	6.7	310
C3	7	.81-2.24	1.5	3.4	400
H	8	.14-.78	.26	.53	700
L	10	.12-.39	.23	.43	740
LL	3	.18-.87	.57	1.1	480
E4	2	1.8-6.5	3.9	8.3	380
E6	2	1.0-1.5	1.3	2.4	360
Calcium-poor achondrites					
Ae	2	0.01-.28	0.14	0.18	67
Ah	1	.11	---	.16	260
Au	1	.55	---	1.0	150
Calcium-rich achondrites					
Aa	1	0.41	---	0.70	---
An	1	.44	---	.69	---
Aho	5	.04-.37	.13	.19	270
Aeu	6	.03-.29	.11	.17	410

TABLE 48.—*Rubidium in stony meteorites*

[From G. G. Goles in Mason, 1971; and additional data from Keays and others, 1971; Laul and others, 1972 and 1973; Krähenbühl and others, 1973; Anders and others, 1976; and Higuchi and others, 1976]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
C1	3	1.42-2.33	1.88	6.0
C2	3	1.20-1.85	1.25	3.1
C3	7	1.04-1.36	1.21	2.6
H	11	2.0-3.5	2.9	5.6
L	20	1.9-4.0	3.1	5.4
LL	11	.5-5.5	2.3	4.0
E4	4	1.4-2.5	2.2	4.4
E5	1	.8	---	1.5
E6	5	.8-1.9	1.4	2.5
		Calcium-poor achondrites		
Ae	2	1.65-2.00	1.81	2.1
Ah	1	.14	---	.19
Ac	1	.4	---	.76
Au	4	.016-.076	.035	.06
		Calcium-rich achondrites		
Aa	1	0.031	---	0.05
An	2	2.4-2.8	2.6	3.4
Aeu	9	.05-.70	.28	.40

TABLE 49.—*Strontium in stony meteorites*

[From K. Gopalan and G. W. Wetherill in Mason, 1971; and additional data from McCarthy and others, 1972 and 1973; Tera and others, 1970; Gale and others, 1975; and Mittlefehldt and Wetherill, 1977]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si	Ca/Sr atoms
		Chondrites			
C1	2	7.1-7.6	7.4	23	2,300
C2	5	8.6-10.6	9.9	24	3,000
C3	4	12-17	14	29	2,600
H	15	9.3-11.1	10.0	19	2,600
L	15	10.1-11.9	11.1	19	2,500
LL	12	10.5-11.9	11.1	19	2,400
E4	3	6.5-7.6	7.2	14	2,600
E5,6	5	7.5-8.5	8.2	14	2,800
		Calcium-poor achondrites			
Ae	1	1.4	---	1.6	13,000
Ah	1	2.1	---	2.7	8,100
Ac	1	7.2	---	13	1,700
Au	1	.7	---	1.2	19,000
		Calcium-rich achondrites			
Aa	1	133	---	208	2,900
An	1	58	---	83	4,000
Aho	4	27-59	40	54	2,300
Aeu	10	51-92	76	107	2,100

be seen from the relative constancy of the Ca/Sr ratios in table 49; a few achondrites, notably the aubrites, diogenites, and ureilites are strongly depleted in strontium relative to calcium.

As might be expected, most of the strontium in meteorites resides in the calcium minerals—plagioclase, clinopyroxene, and phosphates (chlorapatite and merrillite). The data of Mason and Graham (1970) and Allen and Mason (1973) on separated minerals demonstrated that Sr shows a marked preference for plagioclase over clinopyroxene. Gray, Papanastassiou, and Wasserburg (1973) recorded the following Sr contents in parts per million in the Peace River (L6) chondrite: total meteorite 11.18, plagioclase 92.86, phosphate 75.49. Shima and Honda (1967) in in selective solution experiments showed that in Bruderheim, in L6 chondrite, practically all the Sr was contained in the HF-soluble fraction (plagioclase and pyroxene), whereas in Abee, an E4 chondrite, about half was in the sulfide fraction, which dissolved in bromine water. Thus, strontium resembles calcium and magnesium in showing chalcophile affinity in enstatite chondrites.

The calcium-rich achondrite Angra dos Reis is notable for having the highest Sr content and the most primitive $^{87}Sr/^{86}Sr$ ratio (0.69884); this primitive ratio is due to this meteorite's extremely low Rb content, which has thus contributed essentially no radiogenic Sr. Slightly lower $^{87}Sr/^{86}Sr$ ratios, down to 0.69877, have been recorded in melilite-clinopyroxene chondrules from the Allende (C3) meteorite (Gray, Papanastassiou, and Wasserburg, 1973). In chondrites this ratio ranges up to 1.001 (Gopalan and Wetherill, 1970).

YTTRIUM

The data on the abundance of yttrium in meteorites are comparatively sparse. However, Haskin and others (1966) have provided figures for meteorites representing all the chondrite classes, and for the principal classes of achondrites; their data are summarized in table 50, along with additional data on the howardites and the eucrites.

The figures show that yttrium is relatively unfractionated between the different classes of chondrites. In terms of the Y/Si atomic ratio, there is a small but systematic decrease from the carbonaceous chondrites through the ordinary (H, L, LL) chondrites to the enstatite chondrites. The Ca/Y atomic ratio is relatively uniform at 13,000–17,000.

Among the calcium-poor achondrites, the single enstatite achondrite analyzed (Norton County) is comparable in Y/Si ratio to the enstatite chondrites, and the two hypersthene achondrites give rather divergent figures, but appear significantly lower in yttrium than the chondrites. The calcium-rich achondrites are enriched in this element, moderately for the nakhlites, and quite markedly for the howardites and eucrites. Angra dos Reis, a unique calcium-rich achondrite, has the highest Y/Si ratio so far found for meteorites, and also has the highest calcium content of any meteorite.

Yttrium is essentially lithophilic in meteorites. Mason and Graham (1970) analyzed mineral separates of two chondrites (Modoc and St. Severin) and found yttrium to be highly enriched in the calcium phosphate minerals, being present in them at concentrations about 200 ppm; it was not detected in metal or olivine, and was present at about 1 ppm in plagioclase, pyroxene, and troilite. The only mineral besides the phosphates enriched in yttrium was calcic clinopyroxene (diopside and pigeonite), which contained about 20 ppm. Yttrium is very similar to calcium in ionic radius, and this evidently conditions its tendency to concentrate in calcium-rich minerals.

ZIRCONIUM

Zirconium (and hafnium) were determined by neutron-activation analysis in 28 chondrites and 7 achondrites by Ehmann and Rebagay (1970), who also reviewed earlier meteorite analysis for these elements; the data for achondrites were revised and extended by Ehmann and others (1976). Their results are summarized in table 51, together with additional data on the calcium-rich achondrites and on chondrites by Palme (1974) Ehmann and Chyi (1974), and Ganapathy, Papia, and Grossman, (1976). Zirconium shows a rather uniform concentration in all classes of chondrites. The calcium-poor achondrites are depleted in Zr relative to the chondrites, whereas the calcium-rich achondrites are notably enriched.

The location of the zirconium within the meteorite phases is not revealed by the chemical analyses. However, Marvin and Klein (1964) discovered zircon as an accessory mineral in the Vaca Muerta mesosiderite and in troilite nodules of the Toluca iron (the latter confirming a report by Laspeyres and Kaiser as long ago as 1895). They recovered about 2 mg of zircon from 125 g of the mesosiderite. P. Ramdohr (written commun., 1965) has identified a crystal of zircon in a section of the Muizenberg chondrite. In stony meteorites, zirconium (and hafnium) are probably contained largely in small, sporadically distributed crystals of zircon; 10 ppm zirconium corresponds to 20 ppm (0.002 percent zircon. In Angra dos Reis, the achondrite with the highest Zr content, Keil and others (1976) identified baddeleyite, ZrO_2.

NIOBIUM

Information on the abundance and distribution of niobium in meteorites is extremely sparse. Graham and Mason (1972) analyzed 6 chondrites and 6 achondrites for this element by spark-source mass spectrometry, and Erlank and others (1972) analyzed 10 achondrites by X-ray fluorescence. These data are summarized in table 52; they show niobium at a fairly uniform concentration in all the chondrites analyzed, and a relative enrichment in the calcium-rich achondrites.

Niobium is remarkably concentrated in meteoritic rutile; El Goresy (1971) determined Nb in rutile from three irons and one mesosiderite, and reported NoO_2 1.63–2.93 percent in rutile from the irons and 0.04–0.38 percent in rutile from the mesosiderite. Graham and Mason (1972) noted a remarkably linear covariance of Nb and Zr both in the meteorites and in lunar rocks, and this was also established by Erlank and others (1972). Marvin (1975) noted that the marked coherence of Nb and Zr in lunar rocks does not extend to the constituent minerals; niobium is concentrated in titanium minerals, especially rutile, not in zirconium minerals. It is, therefore,

TABLE 50.—*Yttrium in stony meteorites*

[From Haskin and others, 1966; and additional data on howardites from McCarthy and others, 1972; and on eucrites from McCarthy and others, 1973]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6
		Chondrites		
C1	2	1.4–1.7	1.6	4.8
C2	2	1.8–2.1	2.0	4.6
C3	3	2.4	2.4	4.9
H	2	2.1–2.2	2.2	3.9
L	2	2.0–2.1	2.1	3.4
LL	2	1.9–2.0	2.0	3.2
E4	2	1.0–1.5	1.3	2.1
E5	1	1.74	---	3.2
		Calcium-poor achondrites		
Ae	1	2.09	---	2.6
Ah	2	.22–1.22	.7	.9
Ac	1	.64	---	1.2
		Calcium-rich achondrites		
Aa	1	35	---	54
An	2	3.2–4.4	3.8	5.2
Aho	4	4.4–12	7.6	10
Aeu	8	14–26	17	24

somewhat paradoxical that the Ti/Nb ratio in the rocks is much more variable than the Zr/Nb ratio.

MOLYBDENUM

Information on the abundance and distribution of molybdenum in meteorites is rather limited. For stony meteorites, no data are available for achondrites; Case and others (1973) analyzed 26 chondrites for this element, and their data are summarized in table 53. They are in agreement with the earlier work of Kuroda and Sadwell (1954). Molybdenum shows a somewhat higher concentration (in terms of atoms/10^6Si) in the carbonaceous chondrites than in the ordinary chondrites; among the latter, the concentration decreases in the sequence H-L-LL, which is also the sequence of decreasing metal content. This is to be expected in view of the siderophile nature of molybdenum. In composites of the chondrites they analyzed, Kuroda and Sanwell (1954) found the metal to contain an average of 8.0 ppm, the troilite 5.7 ppm, and the silicate 0.6 ppm. Mason and Graham (1970) analyzed metal and troilite separates from two chondrites, and found that the metal contained 7–10 ppm, the troilite 3 ppm Mo. The siderophile nature of molybdenum in chondrites has been strikingly confirmed by the discovery by Wark and Lovering (1976) of minute grains of Mo-rich alloy (Mo as high as 26 percent) in the Allende (C3) chondrite.

TABLE 51.—*Zirconium in stony meteorites*

[From Enmann and Rebagay, 1970, and Ehmann and others, 1976; and additional data on calcium-rich achondrites from McCarthy and others, 1972 and 1973; on chondrites by Palme, 1974, Ehmann and Chyi, 1974, and Ganapthy and others, 1976]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
C1	1	4.1	---	12
C2	3	4.6-5.8	5.2	11
C3	1	5.9	---	12
H	5	4.8-7.5	6.3	11
L	9	3.9-8.9	5.9	9.7
LL	2	5.2-6.5	5.9	9.7
E4	2	3.8-6	4.9	9.1
E5	1	7	---	13
E6	2	3.6-7.7	5.2	8.4
		Calcium-poor achondrites		
Ae	2	0.64-1.2	0.9	1.0
Ah	2	1.0-2.2	1.5	1.9
Ac	1	1.5	---	2.7
Au	1	3.9	---	6.4
		Calcium-rich achondrites		
Aa	1	100	---	150
An	1	8.1	---	11
Aho	4	15-36	24	31
Aeu	8	36-87	52	70

Smales, Mapper and Fouché (1967) determined molybdenum in 67 irons, and found a narrow range, 2.2–24.5 ppm, with a mean of 7.2 ppm. Fifty-eight of these meteorites were in the restricted range 4.1–8.6 ppm, and there appear to be no systematic differences between the different classes. These results are in agreement with the more limited data of Murthy (1963) and Wetherill (1964); however, Wetherill found one iron, Weaver Mountains (an ataxite with 18 percent Ni), with 30.1 ppm.

RUTHENIUM

The data on the abundance of ruthenium in chondrites have been assembled and discussed by W. Nichiporuk, in Mason (1971), and are summarized in table 54. They show a relatively small range over the different chondrite classes, and a notable correlation between diminishing metal content and diminishing Ru concentration in the sequence H-L-LL. Hara and Sandell (1960) prepared two composite samples of six and nine chondrites (H and L), and separated and analyzed the metal and the troilite phases; the metal contained 4.3 and 5.3 ppm, the troilite 6.3 and 5.2 ppm Ru. This indicates that Ru is about equally siderophile and chalcophile in ordinary chondrites. However, Mason and Graham (1970) found Ru to be concentrated in the metal phase of chondrites, and did not detect this element in troilite, which suggests that Ru may be completely siderophile in these meteorites.

The only analysis for Ru in an achondrite is for the diogenite Johnstown, for which a concentration of 0.0029 ppm has been recorded (Bate and Huizenga, 1963).

The most extensive data in Ru in iron meteorites are those of Crocket (1972), who analyzed for this element in 46 irons. He found a range of 0.16–36 ppm, and an average of 7.32 ppm. Scott and Wasson (1975) have plotted the data on a Ru-Ni diagram (fig. 13); negative correlations are present within the major groups, excluding IA. They noted many similarities to the Ir-Ni plot, although the total

TABLE 52.—*Niobium in meteorites*

[From Graham and Mason, 1972; Erlank and others, 1972]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
C1	1	0.3	---	0.9
C2	2	.5-.6	0.6	1.2
C3	1	.7	---	1.3
H	1	.4	---	.7
L	1	.4	---	.7
		Calcium-poor achondrites		
Ac	1	0.3	---	0.6
		Calcium-rich achondrites		
Aa	1	5	---	6.5
Aho	5	1.0-2.9	1.9	2.4
Aeu	8	2.1-6.3	3.5	4.6

TABLE 53.—*Molybdenum in stony meteorites*
[From Case and others, 1973]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
C1	2	1.2-1.5	1.4	4.0
C2	3	1.2-1.8	1.5	3.4
C3	6	1.7-2.4	2.0	3.8
H	7	1.3-2.0	1.7	2.9
L	3	1.1-1.6	1.3	2.0
LL	5	.8-1.4	1.1	1.7

TABLE 54.—*Ruthenium in stony meteorites*
[From Walter Nichiporuk, in Mason, 1971]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
C1	3	0.58-0.78	0.69	1.9
C2	3	.69-.88	.83	1.8
C3	1	1.0-1.1	1.0	1.8
H	14	.82-1.4	1.1	1.8
L	11	.60-.82	.75	1.1
LL	1	.50	---	.74
E4	2	.92-1.1	1.0	1.6

variation of Ru is only 10^2, in contrast to 10^4 for Ir.

Wark and Lovering (1976) have identified micron-sized metallic grains containing as much as 49 percent Ru in Ca, Al-rich inclusions in the Allende (C3) chondrite.

RHODIUM

The data on rhodium in meteorites have been assembled and discussed by W. Nichiporuk, in Mason (1971). They indicate that this element is the least abundant of the platinum group. The sparse data for the stony meteorites are presented in table 55. No analyses are available for the carbonaceous chondrites. For the other classes of chondrites Rh concencentrations do not range widely; however, it may be significant that the single LL meteorite (Benton) has the largest Rh concentration and the smallest content of metallic nickel-iron of any of the analyzed chondrites. Nichiporuk and Brown (1965) separated the metal phase from five chondrites and found this metal to contain 0.9–1.1 ppm Rh and to account for the total rhodium content of these meteorites. This

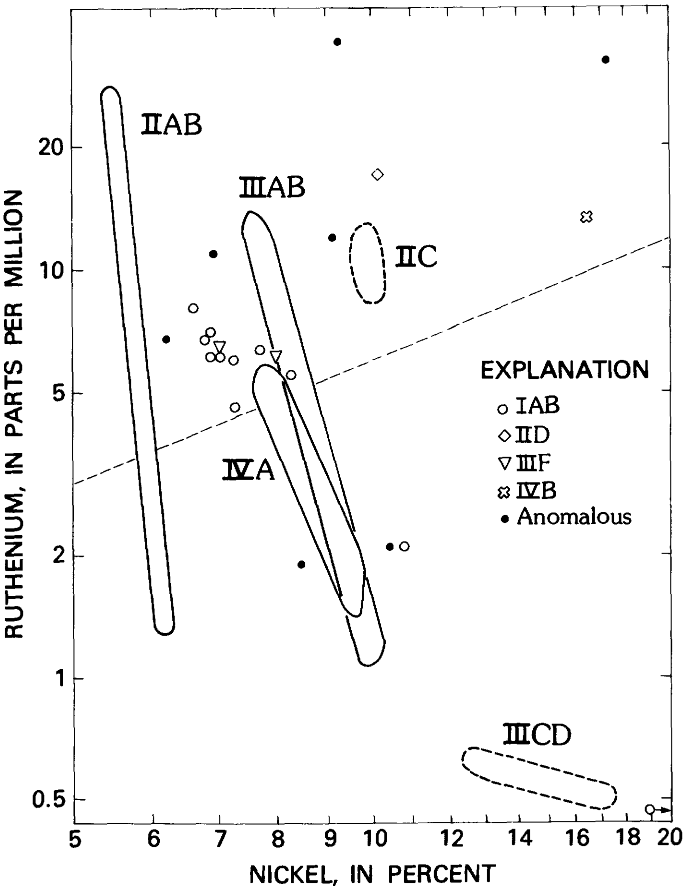

FIGURE 13.—Logarithmic plot of Ru against Ni for iron meteorites. Most groups are shown only in outline; this is short dashed when only a few data points define a group. The straight dashed line shows the Ru/Ni ratio for C1 chondrites. Reprinted from Scott and Wasson (1975), copyrighted by American Geophysical Union.

indicates that the rhodium is probably entirely siderophile in chondrites.

The data on Rh in iron meteorites indicate a range of 0.14–5.5 ppm. Rhodium concentration shows a generally inverse relationship to nickel concentration, although there are some exceptions.

PALLADIUM

The date on palladium in meteorites have been assembled and discussed by W. Nichiporuk, in Mason (1971). The information on stony meteorites is given in table 56; this table includes data from Keays, Ganapathy, and Anders (1971) on L and LL chondrites, and omits the data of Greenland (1967), which are inconsistently high for this element. Palladium concentrations are comparable with and a little lower than those for ruthenium. Fouché and Smales (1967b) analyzed separated magnetic (nickel-iron) and nonmagnetic fractions of 20 chondrites and found Pd to be concentrated in the magnetic fraction at 28 to 360 times that in the nonmagnetic fraction; thus palladium is siderophile with little or no chalcophile or lithophile affinity.

Nichiporuk and Brown (1965) measured palladium in 24 irons, Smales, Mapper, and Fouché (1967) in 67, and their results are in good agreement. Smales and his coworkers found a range from 1.6 to 19.7 ppm with a mean of 4.3 ppm; only two irons contained more than 10 ppm, San Cristobal (13.8) and Santa Catharina (19.7), both of these being ataxites having more than 20 percent Ni. Scott (1972) correlated the Pd-Ni relationship in iron meteorites with

TABLE 55.—*Rhodium in stony meteorites*

[From Walter Nichiporuk, in Mason, 1971]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
H	4	0.20-0.40	0.25	0.40
L	4	.15-.31	.22	.31
LL	1	.48	---	.70
E	1	.25	---	.36

the chemical groupings (fig. 14); he pointed out that Pd, unlike the other platinum metals, shows positive correlations with Ni in several groups, specifically I, IIAB, IIIAB, and IVA.

SILVER

Silver is an element of notably low abundance in meteorites, seldom as high as 1 ppm and usually much less. P. R. Buseck, in Mason (1971), assembled and reviewed the data available at that time, but since then several papers have been published on the abundance of silver in different classes of stony meteorites, and these data are summarized in table 57. Individual values within the different classes are notably variable, and this variation is sometimes seen in different samples of the same meteorite. However, the mean values show some significant trends, notably a depletion in the sequence C1–C2–C3–(H, L, LL) and in the sequence E4–E5–E6. The achondrites are depleted in silver relative to the chondrites. Silver shows a fairly good correlation with sulfur in the chondrites, the S/Ag ratio (atomic, × 10^{-6}) showing a relatively small range, from 0.45 to 1.24, suggesting that this element is chalcophile in behavior. Greenland (1967) found fairly uniform Se/Ag ratios in the chondrites he analyzed, which supports this hypothesis. Little direct information is available on the distribution of

TABLE 56.—*Palladium in stony meteorites*

[From Walter Nichiporuk, in Mason, 1971; and additional data from Keays and others, 1971]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
C1	3	0.33-0.62	0.49	1.3
C2	4	.59-.79	.68	1.3
C3	3	.66-1.0	.77	1.3
H	6	.52-1.4	.91	1.4
L	11	.38-.78	.56	.78
LL	3	.48-.60	.54	.76
E4	2	.44-1.08	.80	1.3
E6	2	.67-.69	.68	.93

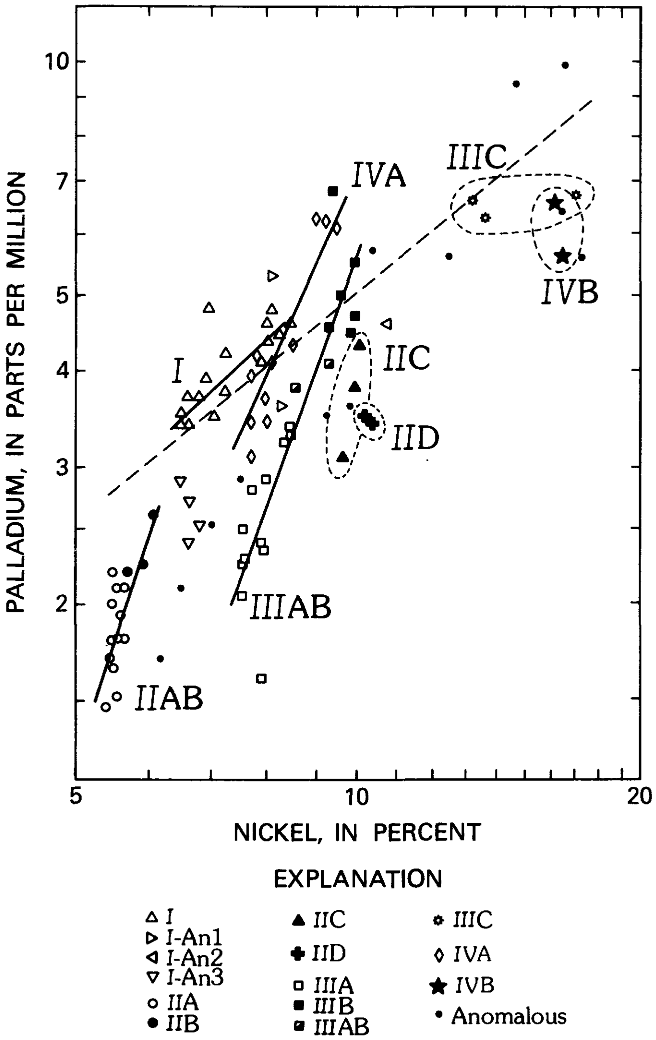

FIGURE 14.—Pd-Ni distribution in iron meteorites; the dashed line is the Pd/Ni ratio for C1 chondrites. Solid lines indicate positive Pd-Ni correlation within groups; short-dashed lines enclose well-resolved groups. Reprinted from Scott (1972) and published with permission.

silver in meteorites. Mason and Graham (1970) noted that this element was detected in troilite separated from chondrites, but not in other minerals. Anders and others (1975) found 1.48 and 1.66 ppm Ag in HCl, HF-insoluble fractions (largely chromite and spinel) of the Allende meteorite, and 0.090 ppm in the buk meteorite; however, treatment of these fractions with nitric acid reduced the silver content to 0.08 and 0.03 ppm, which suggests that the silver was probably contained in pentlandite rather than the chromite and spinel.

Several investigations have been made of silver in iron meteorites, the most extensive being that of Smales, Mapper, and Fouché (1967). In 67 irons they found 28 having less than 0.01 ppm, and the concentration in the remainder ranged up to 0.1 ppm. Thus, the concentrations in the irons is notably lower than in the chondrites, indicating that silver has relatively little siderophile affinity.

CADMIUM

The data on cadmium abundances in meteorites were assembled and discussed by P. R. Buseck, in Mason (1971). However, since then a considerable number of papers with data on cadmium in stony meteorites have been published and table 58 is compiled from these sources. The data are extensive, but where the same meteorite has been analyzed by different investigators the agreement is frequently poor. Different samples of the same meteorite may give markedly different results (Keays and others, 1971), suggesting that Cd is inhomogeneously distributed, and sampling may be a problem. The data in table 58 show that Cd concentrations may be extremely variable within a single class. However, significant trends can be distinguished in the means. Carbonaceous and E4 chondrites have much higher Cd concentrations than other classes of stony meteorites. Cadmium is clearly a strongly depleted element as defined by Anders (1971b), the relative depletion in the sequence C1-C2-C3-(H, L, LL) being 1.00:0.58:0.16:0.03. The Zn/Cd ratio (atomic) is fairly constant for the carbonaceous and enstatite chondrites at 700–1,100, whereas in the ordinary (H, L, LL) chondrites this ratio is 2,600–3,300, indicating a considerable depletion in Cd relative to Zn in the (H, L, LL) classes. In general, the achondrites are depleted in Cd relative to the chondrites.

Iron meteorites have even lower Cd abundances than stones. Rossman and de Laeter (1974) analyzed 19 irons, and found Cd contents ranging from 0.1 to 22.3 ppb, the mean being 5.2 ppb. They note a strikingly different abundance pattern of Cd and Zn in irons; for example, Zn abundances in group I irons are tightly clustered, whereas Cd abundances range widely.

Cadmium is chalcophile in terrestrial rocks and presumably also in meteorites, although no analyses for cadmium on separated minerals have been found in the literature.

INDIUM

The abundance data for indium in meteorites were assembled and discussed by P. A. Baedecker, in Mason (1971), but since then a large number of publications dealing with this element has appeared and table 59 has been compiled from these sources. The data for chondrites show that indium is a strongly depleted element, the relative depletion in the sequence C1–C2–C3–(H, L) being 1.00:0.48:0.25:0.04; a similar depletion is evident in the sequence E4–E5–E6. Table 59 shows the extreme variability in indium concentrations within the H, L, and LL groups. This was first established by Tandon and Wasson (1968) in a suite of L chondrites, and they found a significant correlation with petrological type, indium concentrations diminishing in the sequence L3–L4–L5–L6; they also establshed a strong correlation between indium concentrations, total C, and concentrations of primordial ^{36}Ar and ^{132}Xe. These findings stimulated a great interest in the abundance and distribution of indium in meteorites, hence the large number of recent publications. Other investigators have confirmed Tandon and Wasson's findings, and extended them to the other chondrite classes. The geochemical behavior of indium is evidently linked with its volatility; along with Bi and Tl, it has the lowest condensation temperature of any of the metallic elements (~460°K from a solar gas at 10^{-5} atmosphere, according to Laul and others, 1973). Accordingly, it is also an element likely to be volatilized and lost from a meteorite undergoing mild thermal metamorphism; Ikramuddin and Lipschutz (1975) and Ikramuddin, Binz, and Lipschutz (1976) demonstrated this experimentally in the Allende (C3) and Abee (E4) meteorites.

TABLE 57.—*Silver in stony meteorites*

[From P. R. Buseck, in Mason, 1971; and additional data from Keays and others, 1971; Laul and others, 1972 and 1973; Krähenbühl and others, 1973; Binz and others, 1975; Anders and others, 1976; and Higuchi and others, 1976]

Class	Number analyzed	Range (ppb)	Mean (ppb)	Atoms/10^6Si
Chondrites				
C1	3	118-238	182	0.46
C2	3	33-172	115	.23
C3	7	81-158	111	.19
H	22	22-240	91	.14
L	11	36-1,350	163	.23
LL	11	29-554	137	.19
E4	4	220-377	304	.48
E5	1	189	---	.29
E6	5	14-167	91	.12
Calcium-poor achondrites				
Ae	1	13-74	44	0.04
Au	6	4.4-89	32	.04
Calcium-rich achondrites				
Aa	1	18	---	0.02
An	2	40-58	49	.06
Aho	5	3.1-214	44	.05
Aeu	7	[1]3.3-98	34	0.04

[1] Omitting one value of 2,100 ppb.

TABLE 58.—*Cadmium in stony meteorites*

[From P. R. Buseck, in Mason, 1971; and additional data from Laul and others, 1972 and 1973; Krähenbühl and others, 1973; Binz and others, 1974, 1975 and 1976; Rosman and de Laeter, 1974; Chou and others, 1976a; and Anders and others, 1976]

Class	Number analyzed	Range (ppb)	Mean (ppb)	Atoms/10^6Si
		Chondrites		
C1	3	434-686	639	1.55
C2	3	379-610	470	.90
C3	7	4-485	155	.25
H	11	1-152	30	.04
L	12	7-129	41	.05
LL	11	3-96	37	.05
E4	4	85-918	640	.96
E5	1	42	---	.06
E6	5	4-220	72	.09
		Calcium-poor achondrites		
Ae	2	2-14	8	0.007
Ah	1	14	---	.014
Au	4	12-85	38	.050
		Calcium-rich achondrites		
An	2	71-92	82	0.091
Aho	5	1.6-88	23	.024
Aeu	5	1.7-8.7	4.4	.005

Indium is evidently strongly chalcophile in chondrites. Fouché and Smales (1967a) separated six H and L chondrites into magnetic (metal phase) and nonmagnetic fractions and analyzed each fraction separately; an upper limit of 0.0005 ppm was found in the metal phase, whereas in the nonmagnetic fractions the In concentration ranged up to 0.10 ppm. They also found that 90 percent of the indium in the nonmagnetic fractions of the Abee (E4), Daniel's Kuil (E6), and Bruderheim (L6) meteorites could be leached out with bromine water, which dissolves troilite and other sulfides.

Smales, Mapper, and Fouché (1967) measured indium in 67 iron meteorites; for 38 they recorded <0.01 ppm, and for the remainder the range is 0.0003–0.041 ppm.

TIN

The rather sparse data on tin in meteorites were assembled and discussed by P. R. Buseck, in Mason (1971). He noted the variability of the results obtained on the same meteorite by different analysts, and sometimes in replicates of the same meteorite by a single analyst, and remarked, "It is unclear whether the spread is a reflection of the difficulties of the analyses or whether it indicates a lack of tin homogeneity in these meteorites" (p. 377). De Laeter, McCulloch, and Rosman (1974) analyzed 18 chondrites and 2 achondrites; their results are summarized in table 60. They pointed out that Sn is a strongly depleted element in chondrites, the ratio (atomic) in the sequence C1–C2–C3–(H, L) being

TABLE 59.—*Indium in stony meteorites*

[From P. A. Baedecker, in Mason, 1971; and additional data from Keays and others, 1971; Laul and others, 1972 and 1973; Krähenbühl and others, 1973; Binz and others, 1974, 1975, and 1976; Baedecker and Wasson, 1975; Ikramuddin and Lipschutz, 1975; Ikramuddin and others, 1976; Chow and others, 1976a, b; Wasson and others, 1976; and Anders and others, 1976]

Class	Number analyzed	Range (ppb)	Mean (ppb)	Atoms/10^6Si
		Chondrites		
C1	3	72-88	80	0.19
C2	3	46-51	49	.091
C3	7	23-45	30	.047
H	22	.054-103	5.5	.008
L	10	.06-25.5	5.7	.007
LL	11	.59-81	11	.014
E4	4	13-87	68	.10
E5	1	22	---	.031
E6	5	.39-5.7	3.2	.004
		Calcium-poor achondrites		
Ae	2	0.22-0.29	0.26	0.0002
Ah	1	.50	---	.0005
Au	5	1.2-2.5	1.7	.002
		Calcium-rich achondrites		
An	2	20.3-24.4	22.4	0.024
Aho	5	1.67-13.8	5.2	.005
Aeu	7	.52-4.04	1.5	.002

1.00:0.46:0.24:0.12; the limited data for the enstatite chondrites shows a comparable depletion from E4 to E6.

Tin appears to be siderophile in chondrites. Onishi and Sandell (1957) and Shima (1964) found this element to be essentially confined to the magnetic (nickel-iron) fraction of these meteorites. Its concentration in the metal phase may account for the variable analytical results, owing to sampling problems.

De Laeter and Jeffery (1967) analyzed 14 irons for Sn, and compared their results with those of previous investigators. They found a range from 0.1 to 7.6 ppm, in good agreement with prior results; however, Winchester and Aten (1957) recorded two irons with higher values, Tocopilla (20.2 ppm) and Muonionalusta (10.7 ppm). De Laeter and Jeffery's mean is 1.9 ppm; they observed that this mean is raised by a high mean (5.8 ppm) for the coarse octahedrites, and that the other classes of iron meteorites appear to be relatively impoverished in tin. Scott (1972) correlated Sn contents with the Ga-Ge groups; he noted that the highest abundances (4–8 ppm) are found in group I.

ANTIMONY

The data on antimony in meteorites were assembled and discussed by W. D. Ehmann, in Mason (1971). Since then, however, a considerable amount of new data has been published, and this has been used in the preparation of table 61; in general these new data are in good agreement with earlier work. Antimony shows moderate depletion in the sequence C1–C2–(H, L, LL), the ratio (atomic) being 1.00:0.61:0.32 (the mean figure for C3 chondrites seems anomalously high). Among the enstatite chondrites the E6 class is significantly depleted with respect to E4 and E5. The limited data on achondrites show that most of them are depleted relative to the chondrites.

Antimony appears to be siderophile in stony meteorites. Fouché and Smales (1967b) analyzed separately the metallic phase and the nonmagnetic

TABLE 60.—*Tin in stony meteorites*

[From de Laeter and others, 1974]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
C1	1	1.64	---	3.7
C2	2	.88-1.02	0.95	1.7
C3	2	.42-.78	.58	.89
H	8	.08-.57	.31	.43
L	3	.27-.37	.34	.43
E4	1	1.65	---	2.2
E6	1	.67	---	.82
		Calcium-poor achondrites		
Ae	1	0.04-0.12	0.08	0.07
		Calcium-rich achondrites		
Aeu	1	0.37-0.42	0.39	0.41

material in 20 chondrites, and found that most of the antimony was in the metal phase. For the H chondrites, the metal contained an average of 0.39 ppm and nonmagnetic fraction 0.034 ppm; for the L chondrites, 0.81 ppm and 0.031 ppm; for the E chondrites, 0.67 ppm and 0.055 ppm. The antimony not in the metal phase is probably in troilite rather than silicates, since this element is strongly chalcophile in terrestrial environments.

Smales, Mapper, and Fouché (1967) measured antimony in 67 irons, finding a range from 0.003 to 2.2 ppm, with a mean of 0.21 ppm. Except for San Cristobal (2.2) and Santa Catharina (1.56), all figures were less than 0.7 ppm, and they suggested that the two high values may be due to the presence of troilite inclusions in the samples of these meteorites. Scott (1972) correlated these data with Ni content and Ga-Ge grouping (fig. 15); groups I, IIIAB, and IVA are clearly resolved, with a positive correlation plainly visible in IIIAB.

TELLURIUM

Fairly extensive data exist for the abundance of tellurium in stony meteorites, but very little for tellurium in iron meteorites. The data available to 1970 were assembled and discussed by I. Pelly and M. E. Lipschutz, in Mason (1971). However, since then, extensive new data have been published on

TABLE 61.—*Antimony in stony meteorites*

[Data for chondrites from Krähenbühl and others, 1973; Binz and others, 1974 and 1976; Anders and others, 1976; for achondrites from Tanner and Ehmann, 1967, and Higuchi and others, 1976]

Class	Number analyzed	Range (ppb)	Mean (ppb)	Atoms/10^6Si
		Chondrites		
C1	3	124-184	138	0.31
C2	2	103-107	105	.19
C3	7	41-203	126	.19
H	7	59-130	79	.11
L	5	58-110	82	.10
LL	3	64-88	74	.091
E4	3	138-241	215	.30
E5	2	232-345	289	.38
E6	4	87-301	156	.19
		Calcium-poor achondrites		
Ae	2	15-38	27	0.022
Ah	2	6-36	21	.020
Au	4	8-28	14	.017
		Calcium-rich achondrites		
Aho	2	62-230	146	0.14
Aeu	1	24	---	.024

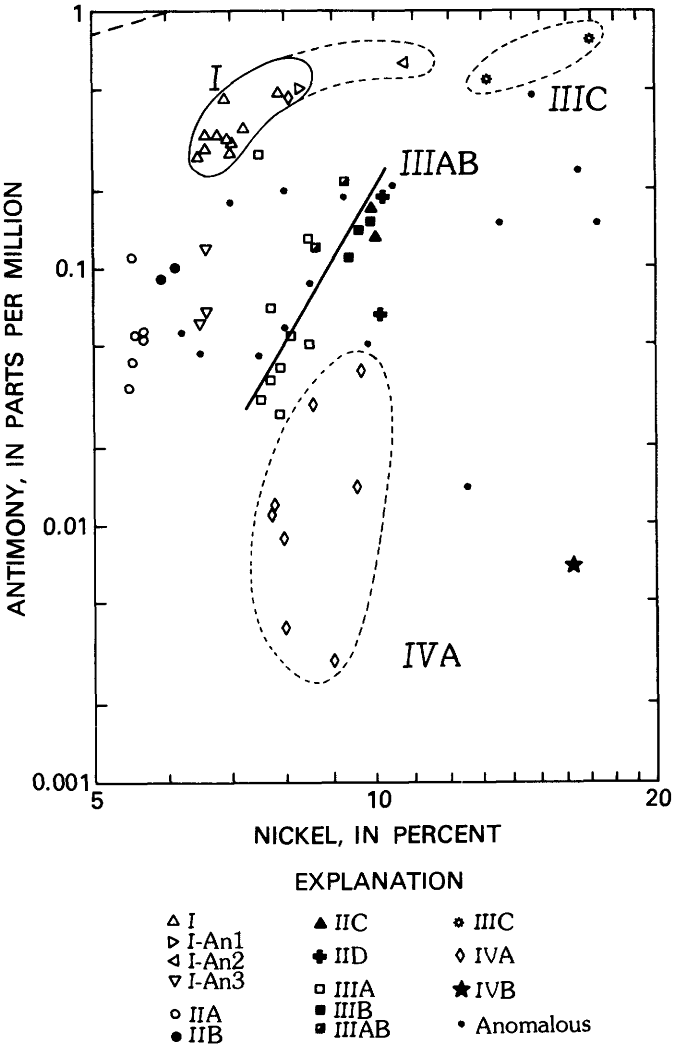

Figure 15.—Sb-Ni distribution in iron meteorites; all iron meteorites fall below the Sb/Ni ratio for C1 chondrites, dashed in upper left corner. Solid line indicates positive Sb-Ni correlation within group IIIAB; short-dashed lines enclose well-resolved groups. Reprinted from Scott (1972) and published with permission.

chondrites, and these have been used in the preparation of table 62. Tellurium is a normally depleted element in chondrites, according to Case and others (1973) and Krähenbühl and others (1973); in the sequence C1–C2–C3–H the relative concentration (atomic) of tellurium decreases in the proportion 1.00:048:0.20:0.06, and a similar depletion is evident in the sequence E4–E5–E6.

Little is known about the distribution of tellurium among different phases of meteorites. Mason and Graham (1970) recorded that this element shows approximately equal concentration in metal and troilite of chondrites and is absent from the other phases; this indicates that tellurium is both siderophile and chalcophile in these meteorities. In iron meteorites, however, tellurium appears to be almost exclusively chalcophile, according to Goles and Anders (1962); they recorded 5 ppm in Canyon Diablo troilite, 0.09 ppm in the metal, and 1.7 ppm in Toluca troilite, 0.05 ppm in the metal. The equilibrium conditions in iron meteorites, however, may have been considerably different from those in the chondrites.

IODINE

The data on iodine in meteorites were assembled and discussed by G. W. Reed, in Mason (1971). Since then, no additional data have been published. The information for chondrites are summarized in table 63. The data are rather sparse, and are frequently variable for the same meteorite analyzed by different investigators, and for different samples of the same meteorite analyzed by the same investigator. Thus, for Bruderheim (L6) the following values (ppb) have been recorded: 16, 27, 5 (Goles and Anders, 1962); 450, ≤74 (Reed and Allen, 1966); 6, 7 (Goles and others, 1967); 18, 27 (Clark and others, 1967). The figures for C1 carbonaceous chondrites are somewhat more consistent: Orgueil 400 (Goles and others), 230 (Reed and Allen); Ivuna 500, 1040, 1210 (Reed and Allen). Goles and Anders (1962) and Reed and Allen (1966) have shown that a significant amount of the iodine in chondrites is water leachable, which may account for much of the variability shown by different samples of the same meteorite. Iodine behaves as a strongly depleted element in the sequence C1–C2–C3–(H, L), the ratio (atomic) being 1.00:0.57:0.26:0.08; a similar depletion is evident in the sequence E4–E5–E6.

Clark and others (1967) determined iodine in a considerable number of achondrites, the results ranging from 14 to 1,000 ppb, and most were less than 100 ppb. Goles and Anders (1962) and Goles and others (1967) measured iodine in troilite and metal from several iron meteorites, with the following results (in ppb, the first figure for metal, the second for troilite): Grant 11, 24; Toluca 250, 1,030; Canyon Diablo 28, 62; Sardis 99, 3,590. The higher figure for iodine in some of the troilites suggests that this element is chalcophile; however, both Toluca and Sardis are finds, and the latter is strongly weathered, so the high iodine contents may be a terrestrial effect. Reed and Allen (1966) found 1,700 ppb I in chlorapatite from the Mt. Stirling iron.

CESIUM

Cesium is an element of low abundance in meteorites. The only record greater than 1 ppm is 2.8 ppm in the dark part of the Krähenberg (LL5) chondrite; the light part contained 0.08 ppm. The data available to 1970 were assembled and discussed by G. G. Goles, in Mason (1971). However, since then, many additional determinations have been made, and these have been used in the compilation of table 64. Cesium is a depleted element in chondrites; in the sequence C1–C2–C3–(HL5, 6) the atomic ratio is 1.00:0.54:0.28:0.12, and a similar depletion is seen in the sequence E4–E5, 6. However, the figures for the ordinary (H, L, LL) chondrites show a high degree of variability. The H3,4 and L3,4 chondrites are notably enriched in Cs relative to the (5,6) types of these classes. This trend is not evident in the data for the LL class (Laul and others, 1973), in which Jelica (LL6) has the highest Cs content, except for the light part of Krähenberg mentioned above. Since Cs is the most volatile of the alkali metals, the erratic behavior of this element in chondrites can be ascribed, at least in part, to this factor (Goles, 1971).

The only information on the distribution of Cs over the different minerals of meteorites has been provided by Mason and Graham (1970), who found 0..3–0.4 ppm Cs in plagioclase from the Modoc (L6),

TABLE 62.—*Tellurium in stony meteorites*

[Data on chondrites from Keays and others, 1971; Krähenbühl and others, 1973; and Binz and others, 1974, 1976; on achondrites, from Clark and others, 1967, and Binz and others, 1975]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
C1	3	2.89-3.14	3.04	6.5
C2	3	1.75-2.02	1.86	3.1
C3	6	.15-1.4	.90	1.3
H	3	.22-.43	.30	.39
L	10	.14-.97	.48	.57
LL	2	.41-.61	.55	.64
E4	3	1.5-3.0	2.4	3.2
E5	2	.25-1.3	.78	.99
E6	4	.25-.52	.41	.46
		Calcium-poor achondrites		
Ae	3	0.22-2.3	0.93	0.74
Ah	1	.12	---	.11
Au	5	.023-.093	.050	.059
		Calcium-rich achondrites		
An	1	0.15	---	0.15
Aho	1	.16	---	.15
Aeu	6	.16-.36	.25	.24

St. Severin (LL6), and Winona (E?) meteorites. This would account for the major part of the Cs in these meteorites.

The achondrites are generally depleted in Cs relative to the chondrites, with the notable exception of the nakhlites; it should be noted that the nakhlites are also notably rich in Rb relative to the other achondrites.

BARIUM

The data on barium in meteorites were assembled and discussed by C. C. Schnetzler, in Mason (1971). Since then, additional information has been published and has been incorporated in table 65. Although the data on stony meteorites are quite extensive, for many of them, especially finds, values tend to be high and erratic, probably the result of terrestrial contamination; for example, Moore and Brown (1963) found a range from 3 to 290 ppm in 45 chondrite finds. On this account, considerable selectivity has been used in assembling the data for table 65, finds being omitted; where different figures are available for the same meteorite, the lowest value has generally been taken. The table shows that the abundance of barium is fairly uniform over the different chondrite classes, and ranges from 2 to 6 ppm, with no significant fractionation between the different classes. Hubbard and Gast (1971) analyzed a chondrite composite and found 3.8 ppm. The calcium-poor achondrites have Ba abundances comparable with those in the chondrites, whereas the calcium-rich achondrites are relatively enriched in this element. Mason and Graham (1970) found that most of the Ba in stony meteorites is contained in plagioclase (40–72 ppm), and minor amounts in calcium phosphate minerals (11–16 ppm). In a melilite-clinopyroxene chondrule from the Allende meteorite, Mason and Martin (1974) found 66 ppm in the melilite and 18 ppm in the pyroxene. In the angrite Angra dos Reis, the 21.5 ppm Ba probably resides in the accessory mineral celsian, $BaAl_2Si_2O_8$.

THE LANTHANIDES

Prior to 1960, our knowledge of the abundance of the lanthanides in meteorites was limited to a single determination by Noddack (1935), using X-ray spectroscopy, of these elements in a composite mixture (12 parts chondrite, 1 part achondrite). Beginning in 1960, however (Schmitt and others, 1960), a large amount of data has been accumulated, mainly by the techniques of neutron activation, isotope dilution, and spark-source mass spectrographic analysis. An extensive account was provided by Haskin and others (1966), and their data are summarized in table 66, together with additional information from table 84 on a chassignite, a ureilite, an angrite, and two howardites.

The lanthanides are a unique group of elements, strongly coherent geochemically because of the filling of the 4-*f* electron shell. The ionic radius decreases gradually from 1.14A (La^{+3}) to 0.85A (Lu^{+3})—the lanthanide contraction—and chemical fractionation of the individual elements is thereby inhibited (as was demonstrated by the century-long struggle to separate and characterize the individual

TABLE 63.—*Iodine in chondrites*
[From G. W. Reed, in Mason, 1971]

Class	Number analyzed	Range (ppb)	Mean (ppb)	Atoms/10^6Si
C1	2	230-1,210	580	1.16
C2	2	300-480	390	.66
C3	2	170-260	215	.30
H	2	67-120	68	.09
L	3	30-76	53	.07
E4	2	140-300	220	.29
E5	1	64-100	82	.10
E6	1	17-89	53	.06

elements). This geochemical coherence may be somewhat modified for Ce by its having a stable Ce^{+4} ion, and for Eu by its existence as Eu^{+2} under reducing conditions.

Table 66 shows that the abundances of the individual elements vary little over the different classes of chondrites, especially when the figures for atoms/10^6Si are compared (which eliminates the effect of the combined water content of C1 and C2 chondrites). Cerium shows greater variability than the other lanthanides; Masuda, Nakamura, and Tanaka (1973) noted anomalous Ce abundances in some chondrites. Among the chondrite classes, lanthanide abundances are consistently highest in the C3 chondrites. This has been investigated intensively in the Allende meteorite, and shown to be due to the presence therein of Ca,Al-rich chondrules and aggregates containing concentrations of lanthanides up to 20 and more times the chondritic average (for example, Gast and others, 1970; Tanaka and Masuda, 1973; Martin and Mason, 1974). Enstatite chondrites show consistently lower lanthanide abun-

TABLE 64.—*Cesium in stony meteorites*

[From Keays and others, 1971; Laul and others, 1972 and 1973; Krähenbühl and others, 1973; Binz and others, 1975; Anders and others, 1976; and Higuchi and others, 1976]

Class	Number analyzed	Range (ppb)	Mean (ppb)	Atoms/10^6Si
		Chondrites		
C1	3	178-211	192	0.39
C2	3	121-137	131	.21
C3	7	59-98	81	.11
H3,4	7	22-188	101	.12
H5,6	15	53-110	38	.046
L3,4	8	110-619	307	.35
L5,6	4	4.0-72	40	.045
LL	11	36-590	202	.23
E4	4	110-241	202	.26
E5	1	35	---	.043
E6	5	36-147	90	.098
		Calcium-poor achondrites		
Ae	1	60	---	0.046
Ah	1	7.6	---	.0064
Au	4	1.9-6.3	3.5	.0039
		Calcium-rich achondrites		
Aa	1	1.9	---	0.0020
An	2	287-288	288	.27
Aho	5	2.3-28	9.6	.0086
Aeu	7	2.1-43.5	14	.013

dances than the other chondrite classes. The calcium-poor achondrites have abundances similar to those in chondrites, except for the ureilite, which is strongly depleted in these elements. The calcium-rich achondrites show strong enrichment in the lanthanides, the highest concentrations being in Angra dos Reis (Aa), a unique meteorite which also has the highest Ca concentration of any meteorite. It can be predicted that calcium would be the only major element for which the lanthanides could be expected to proxy, since its ionic radius falls within the lanthanide series, being close to that of Nd.

Although the lanthanides proxy for calcium, they are quite selective in the phases that they enter. Mason and Graham (1970) have shown that in the Modoc (L6) and St. Severin (LL6) chondrites practically all the lanthanides are contained in the accessory phosphate minerals, and very little in other calcium minerals (except Eu, which is enriched in plagioclase as Eu^{+2}). In the calcium-rich achondrites, which contain little or no phosphate, the lanthanides are distributed between the calcium-rich pyroxene and the calcium-rich plagioclase in a complementary fashion, the pyroxene being relatively enriched in the heavier elements and strongly depleted in Eu, whereas the plagioclase is enriched in the lighter elements and shows a strong positive Eu anomaly (Schnetzler and Philpotts, 1969). A similar distribution pattern between calcium-rich pyroxene and melilite in a chondrule from the Allende (C3) meteorite has been established by Mason and Martin (1974).

TABLE 65.—*Barium in stony meteorites*

[From C. C. Schnetzler, in Mason, 1971; and additional data from McCarthy and others, 1972 and 1973; Nakamura and Masuda, 1973; and Nakamura, 1974]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
C1	1	2.4	---	4.8
C2	2	2.5-3.1	2.8	4.4
C3	1	4.4	---	5.8
H	4	3.2-5.3	4.1	4.9
L	4	3.3-3.9	3.7	4.0
LL	2	3.5-6	4.8	5.2
E4	2	2.3-2.8	2.6	3.2
E6	1	2.8	---	3.0
		Calcium-poor achondrites		
Ae	1	2	---	1.5
Ah	2	2.5-4	3.3	2.7
Ac	1	7.1	---	8.4
		Calcium-rich achondrites		
Aa	1	21.5	---	21
An	1	32.5	---	30
Aho	4	10-22	15	13
Aeu	8	18.6-53.0	30.7	28

TABLE 66.—*Lanthanides in stony meteorites*

[Figures in parentheses are number of meteorites analyzed in each class. From Haskin and others, 1966, and additional data from table 84]

Absolute abundances, in ppm

	C1(2)	C2(3)	C3(3)	H(4)	L(3)	LL(2)	E(3)	Ae(1)	Ah(1)	Ac(1)	Au(1)	Aa(1)	An(2)	Aho(2)	Aeu(4)
La	0.19	0.31	0.39	0.32	0.36	0.28	0.20	0.21	0.44	0.39	0.070	8.3	1.7	0.99	3.7
Ce	.63	.91	1.15	.63	1.5	.88	.58	.81	.4	1.12	---	19	5.8	2.7	9.7
Pr	.094	.12	.14	.12	.14	.10	.10	.11	---	.13	.019	3.7	.74	.33	1.4
Nd	.42	.60	.82	.60	.67	.65	.32	.63	---	.54	---	17	3.3	1.7	7.0
Sm	.133	.20	.29	.22	.23	.22	.13	.22	.080	.11	.014	5.5	.79	.55	2.3
Eu	.053	.074	.100	.080	.083	.073	.046	.022	.0089	.038	.0041	1.6	.22	.20	.72
Gd	.24	.31	.42	.34	.36	.29	.20	.38	---	.11	.025	7.6	.93	.69	3.1
Tb	.044	.046	.064	.053	.053	.053	.031	.061	---	.02	---	1.1	.115	.13	.57
Dy	.22	.34	.41	.33	.33	.34	.18	.40	.14	.12	.022	8.7	.89	.87	3.8
Ho	.056	.072	.093	.074	.085	.078	.046	.100	.036	.03	.0054	2.0	.143	.21	.80
Er	.14	.23	.26	.23	.25	.21	.14	.25	.14	.09	.018	4.6	.39	.62	2.3
Tm	.022	.033	.041	.039	.035	.034	.020	.036	.021	---	---	.56	.052	.11	.38
Yb	.13	.18	.22	.19	.20	.18	.12	.22	.15	.10	.025	4.2	.27	.64	2.0
Lu	.023	.030	.036	.034	.036	.031	.023	.039	.033	---	.0085	.7	.048	.10	.35

Atoms/10^6Si

	C1(2)	C2(3)	C3(3)	H(4)	L(3)	LL(2)	E(3)	Ae(1)	Ah(1)	Ac(1)	Au(1)	Aa(1)	An(2)	Aho(2)	Aeu(4)
La	0.37	0.48	0.51	0.38	0.33	0.30	0.22	0.17	0.35	0.45	0.075	8.2	1.5	0.85	3.3
Ce	1.2	1.4	1.5	.74	1.6	.94	.65	.64	.32	1.3	---	19	5.2	2.3	8.5
Pr	.18	.18	.18	.14	.15	.11	.11	.086	---	.15	.020	3.6	.66	.28	1.2
Nd	.79	.89	1.0	.68	.70	.67	.35	.48	---	.61	---	16	2.9	1.4	6.0
Sm	.24	.29	.35	.24	.23	.22	.13	.16	.060	.12	.014	5.0	.66	.44	1.9
Eu	.094	.10	.12	.087	.081	.072	.048	.016	.0067	.041	.0041	1.4	.18	.16	.58
Gd	.42	.42	.48	.36	.34	.28	.20	.27	---	.11	.023	6.6	.74	.52	2.4
Tb	.076	.062	.072	.055	.049	.049	.030	.042	---	.021	---	.95	.090	.097	.44
Dy	.37	.45	.46	.33	.30	.31	.17	.27	.097	.12	.021	7.3	.68	.64	2.9
Ho	.092	.094	.10	.073	.077	.070	.044	.066	.024	.030	.0048	1.7	.11	.15	.60
Er	.23	.30	.28	.23	.22	.19	.13	.16	.094	.087	.016	3.8	.29	.44	1.7
Tm	.035	.042	.043	.038	.032	.030	.018	.023	.014	---	---	.45	.038	.078	.28
Yb	.20	.22	.23	.18	.17	.16	.11	.14	.097	.094	.021	3.3	.19	.44	1.4
Lu	.035	.037	.037	.030	.030	.026	.021	.024	.021	---	.0072	.55	.034	.067	.25

TABLE 67.—*Lanthanide abundances in chondrite composites*

[In parts per million. A. Haskin and others, 1966; B. Haskin and others, 1968; C. Hubbard and Gast, 1971; D. Nakamura, 1974; E. Osborn and others, 1974. Number in parentheses, number of chondrites analyzed; leaders indicate no data]

Composite	A(20)	B(9)	C	D(10)	E(12)
La	0.30	0.330	0.325	0.329	0.34
Ce	.84	.88	.798	.865	.91
Pr	.12	.112	---	---	.121
Nd	.58	.60	.567	.630	.58
Sm	.21	.181	.186	.203	.195
Eu	.074	.069	.0692	.0770	.0732
Gd	.32	.249	.255	.276	.255
Tb	.049	.047	---	---	.0475
Dy	.31	---	.305	.343	.285
Ho	.073	.070	---	---	.078
Er	.21	.200	.209	.225	.195
Tm	.033	.030	---	---	.032
Yb	.17	.200	.231	.220	.20
Lu	.031	.034	.0349	.0339	.034

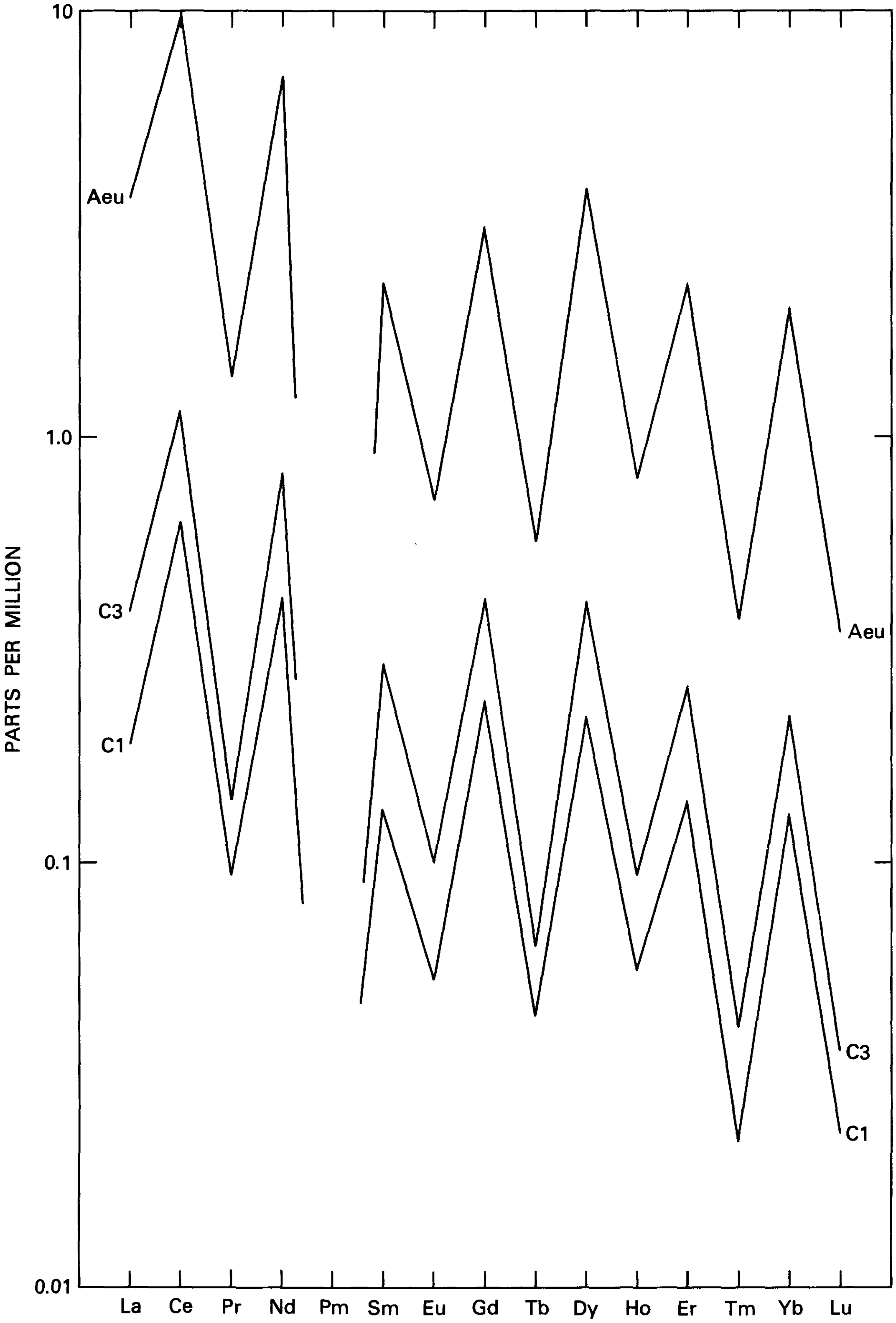

FIGURE 16.—Lanthanide abundances in C1 chondrites, C3 chondrites, and the eucrites (calcium-rich achondrites); note the regularity of the even-odd elemental pattern and the gradual decrease in abundance with increasing atomic number.

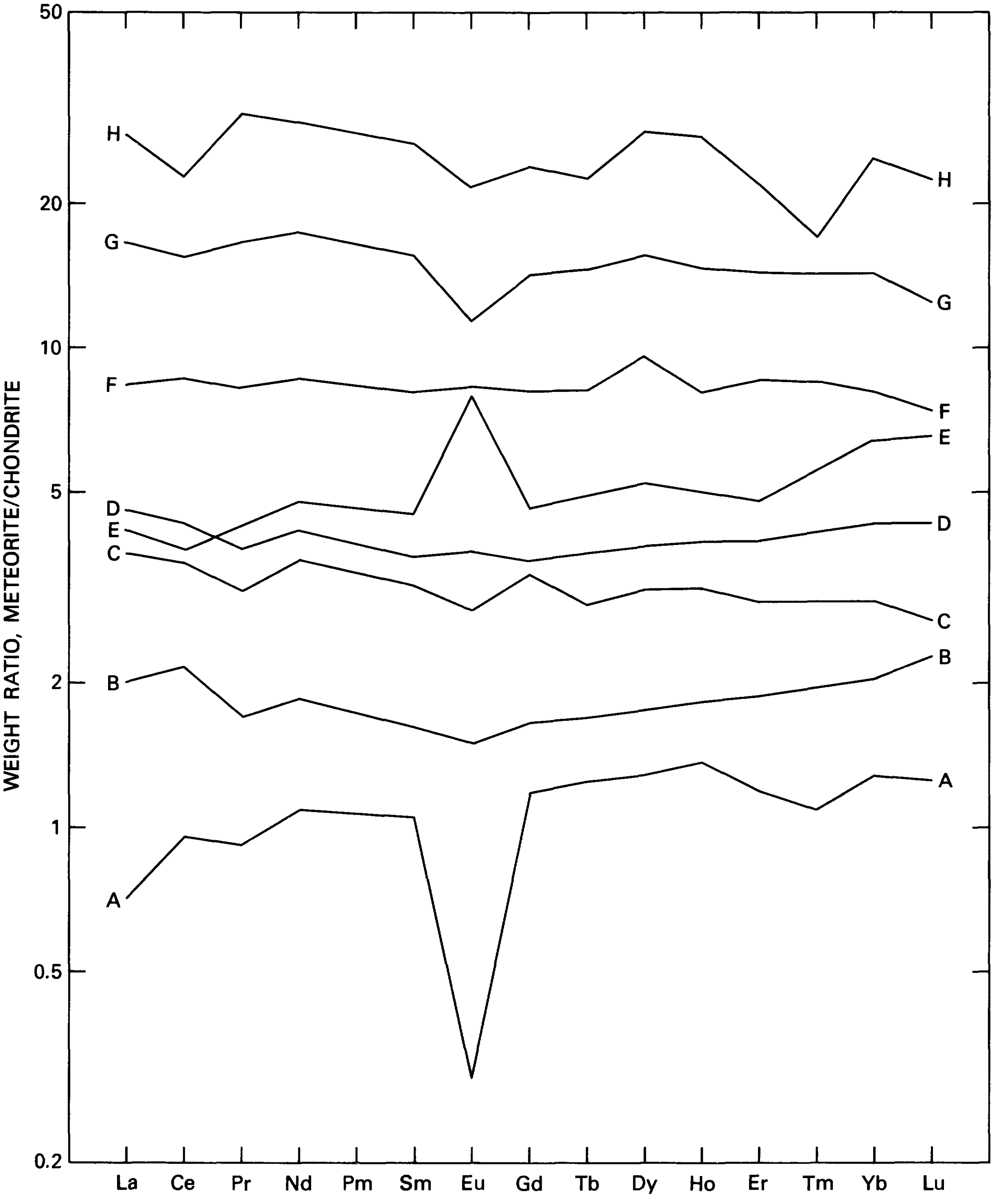

FIGURE 17.—Chondrite-normalized lanthanide abundances in achondrites. *A*, Norton County (Ae); *B*, Zmenj (Aho); *C*, Estherville silicates (M); *D*, Bununu (Aho); *E*, Moore County (Aeu); *F*, Juvinas (Aeu); *G*, Stannern (Aeu); *H*, Angra dos Reis (Aa).

The lanthanide distribution in meteorites provides the clearest example of the validity of the Oddo-Harkins rule, which states that elements of even atomic number are more abundant than those of odd atomic number on either side. This is illustrated in figure 16, which compares the lanthanide abundances in the C1, C3, and Aeu meteorites (from table 66). The close parallelism of these patterns, covering practically the full range of anthanide abundances in stony meteorites, is quite remarkable.

The figure also illustrates the gradual decrease in abundance with increasing atomic number, although Sm shows a somewhat lower abundance than would be predicted from a smooth curve.

To aid in the comparison of lanthanide distribution paterns not only in meteorites, but also in lunar and terrestrial rocks, the convention of normalization to mean chondritic abundances has been widely adopted. This procedure, in which the abundance of each element is divided by the mean chondritic abundance of that element and the quotient then plotted (usually on a logarithmic scale, as in fig. 17), eliminates the sawtooth pattern of figure 16 and facilitates the interpretation of lanthanide distributions. A number of chondrite composites have been analyzed by different researchers to provide the normalizing abundances; these are given in table 67. As can be seen, good agreement exists between the different sets of figures, especially when the figures for Gd and Yb in set A are eliminated.

Figure 17 presents normalized lanthanide distributions for a variety of achondrites. (The numerical data for these meteorites are given in table 84.) A notable feature is the relative flatness and parallelism of most of the curves, indicating a lack of fractionation between individual elements. The lanthanide abundances increase in the sequence Norton County (Ae), Zmenj (Aho), Estherville (silicates from a mesosiderite), Bununu (Aho), Moore County, Juvinas, Stannern (Aeu), Angra dos Reis (Aa). The anomalous behavior of Eu is clearly seen in Moore County and Norton County, and to a lesser extent in Stannern. The positive Eu anomaly in Moore County has been plausibly ascribed to the presence of cumulus plagioclase enriched in this element (Schnetzler and Philpotts, 1969). The negative Eu anomalies in Norton County and Stannern can correspondingly be considered evidence for the possible removal of plagioclase from the parent material of these meteorites.

The Eu anomalies in meteorites were for a long time considered unique to this element among the lanthanides. However, Tanaka and Masuda (1973) discovered Yb anomalies (both positive and negative) in components of the Allende meteorite, and these have been confirmed by Martin and Mason (1974) and others. Conrad, Schmitt, and Boynton (1975) and Mason and Martin (1977) found strong positive Tm anomalies in Ca,Al-rich aggregates from the Allende meteorite. Therefore, although in general the lanthanides behave as a very coherent group in meteorites, individual components in these meteorites may show marked fractionations between adjacent elements.

Haskin and others (1966) reported that partial analyses of two irons for lanthanides show these elements to be present in very low concentrations of the order of 10^{-4}–10^{-5} ppm, confirming their lithophile character.

HAFNIUM

Hafnium (and zirconium) were determined by neutron activation analysis in 28 chondrites and 7 achondrites by Ehmann and Rebagay (1970); the data for achondrites were revised and extended by Ehmann and others (1976). Additional data have been provided by Jérome (1970), Ehmann and Chyi (1974), and Ganapathy, Papia, and Grossman (1976). The more recent data have tended to revise earlier determinations for both elements downwards, and to lower the Zr/Hf weight ratio; Ehmann and Rebagay (1970) gave an average value of approximately 38 for this ratio in 28 chondrites, and Ganapathy, Papia, and Grossman (1976) gave 31.3± 2.2 (on the basis of analyses of 4 chondrites). The information summarized in table 68 indicates that a weight ratio in the 30–35 range is reasonable; it is probably significant that this ratio is shown by the calcium-rich achondrites, in which both Zr and Hf are strongly enriched relative to the chondrites. Values deviating from the 30–35 range are based on few data points and very low values for Hf in the calcium-poor achondrites. The evidence favors close geochemical coherence of Zr and Hf in stony meteorites, and no fractionation between these elements in different classes.

TANTALUM

The data on tantalum abundance in meteorites are rather sparse, being essentially those of Atkins and Smales (1960) and Ehmann (1965), with two determinations by Wänke, Baddenhausen, Balacescu, and others (1972)—Kapoeta (Aho), 0.10 ppm; Juvinas (Aeu), 0.12 ppm. The data are summarized in table 69. They indicate a rather uniform abundance in the different chondrite classes, and relative depletion in the calcium-poor achondrites and enrichment in the calcium-rich achondrites—a pattern characteristic of many nonvolatile lithophile elements. Graham and Mason (1972) noted that the Nb/Ta weight ratio in stony meteorites ranged from 14 to 30, but in view of the paucity of data for both these elements, no significance can be deduced from the range of this ratio; for the calcium-rich achondrites, in which both Nb and Ta have been determined in the same meteorites, this ratio is 29 (Kapoeta), 23 (Juvinas), and 30 (Pasamonte).

The few determinations of Ta in iron meteorites give concentrations of the order of 1 ppb, confirming the lack of siderophile affinity of this element.

TUNGSTEN

The most extensive data on tungsten in meteorites have been provided by Atkins and Smales (1960) and Amiruddin and Ehmann (1962), and their results are in excellent agreement. Rieder and Wänke (1969) measured this element in 10 chondrites, but their results are approximately 50 percent higher than those reported by the other two groups, and have not been used in compiling table 70. Wänke, Baddenhausen, Balacescu, and others (1972) provided data on two calcium-rich achondrites: Kapoeta (Aho), 36 ppb; Juvinas (Aeu), 41 ppb. Hintenberger, Jochum, and Seufert (1973) analyzed 11 stony meteorites; their results for comparable meteorites are somewhat higher than those of Amiruddin and Ehmann, but have been used in table 70 for the C1 and E chondrites.

Amiruddin and Ehmann noted a correlation between tungsten abundances and metal-phase content in stony meteorites. This is reflected in the high abundance in the E chondrites, which are relatively enriched in metal phase, and in the low abundances in the LL chondrite and the achondrites, which contain little or no metal (except the ureilite). Tungsten is evidently a strongly siderophile element; Mason and Graham (1970) noted the presence of this element in metal separates from chondrites, and were unable to detect it in other phases. Iron meteorites are notably enriched in this element relative to

TABLE 68.—*Hafnium in meteorites*

[From Ehmann and Rebagay, 1970; and additional data from Ehmann and others, 1976; Jérome, 1970; Ehmann and Chyi, 1974; and Ganapathy and others, 1976]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si	Zr/Hf (weight)
		Chondrites			
C1	1	0.11	---	0.17	28
C2	1	.14	---	.17	33
C3	1	.19	---	.19	31
H	5	.09-.38	0.18	.17	35
L	8	.07-.32	.17	.14	35
LL	2	.14-.15	.15	.13	48
E	3	.07-.21	.14	.12	36
		Calcium-poor achondrites			
Ae	2	0.01-0.03	0.02	0.01	45
Ah	2	.01-.05	.03	.02	50
Au	1	.055	---	.05	71
		Calcium-rich achondrites			
Aa	1	3	---	2.30	33
An	1	.25	---	.17	32
Aho	5	.50-.92	.70	.47	34
Aeu	9	.61-2.88	1.50	1.04	35

chondrites. In five irons, Amiruddin and Ehmann (1962) recorded 0.78–1.45 ppm; in a sample of troilite from the Canyon Diablo iron they recorded 0.020, 0.013 ppm, and remarked that these figures were upper limits because of the possibility of inclusions of metal.

Wänke and others (1974) noted the remarkably high concentration of 1.84 ppm W in a Ca, Al-rich chondrule from the Allende (C3) meteorite, approximately 20 times the concentration in the bulk meteorite. Similar enrichment was noted for many other refractory elements, and this is consistent with the interpretation of these chondrules as high-temperature condensates. Wark and Lovering (1976) have found up to 2 percent tungsten in metal grains included in these Allende chondrules. Scott (1972) pointed out that tungsten has the highest condensation temperature of the elements, 1,960K at 10^{-4} atm.

RHENIUM

The data on rhenium in meteorites have been assembled and discussed by J.W. Morgan, in Mason (1971). Additional information has been provided by Case and others (1973), Krähenbühl and others (1973), Hintenberger, Jochum, and Seufert (1973), Herman and Wichtl (1974), Anders and others (1976), and Higuchi and others (1976). These additional figures are in good agreement with earlier determinations, except for the data of Hintenberger, Jochum, and Seufert (1973), which tend to be considerably higher than other measurements on the same meteorites; the discrepancy may lie in the technique used, since Hintenberger and coworkers utilized spark-source mass spectrometry, whereas all other determinations were made by neutron-activation analysis. The results are summarized in table 71. Rhenium is a strongly siderophile element, and the data in table 71 reflect this. Atomic abundances

TABLE 69.—*Tantalum in stony meteorites*

[Data from Atkins and Smales, 1960; Ehmann, 1965; Wänke, Baddenhausen, Balacescu, and others, 1972; and Ma and others, 1977]

Class	Number analyzed	Range (ppb)	Mean (ppb)	Atoms/10^6Si
		Chondrites		
C2	1	17	---	0.020
H	4	18-29	23	.021
L	8	17-31	23	.019
		Calcium-poor achondrites		
Ae	2	<10,~4	---	---
Ah	1	8	---	.005
		Calcium-rich achondrites		
Aa	1	370	---	0.28
Aho	1	100	---	.066
Aeu	2	120	---	.082

in the C1, C2, C3, H, and E chondrites are essentially the same, but the L and LL classes are depleted relative to the H chondrites, which correlates with their lower metal contents. The achondrites (essentially metal free except the ureilites) are strongly depleted relative to the chondrites. Fouché and Smales (1967b) analyzed magnetic (metal) and nonmagnetic fractions of a number of chondrites, and found the metal phase to contain 36–360 times the Re concentration of the nonmagnetic fraction. Wänke and others (1974) have recorded a notable enrichment (0.73 ppm) of Re in a Ca,Al-rich chondrule from the Allende (C3) meteorite, about 20 times the concentration in the bulk meteorite.

Most iron meteorites are notably enriched in Re relative to the chondrites, although the concentration range is large, 0.002–4.8 ppm. Scott (1972) plotted Re against Ni and demonstrated a correlation with the chemical groups (fig. 18). Group IIAB spans the total range of Re concentrations, and groups IIIAB and IVA are fractionated by factors of at least 100 and 50. Group I forms a tight cluster lying on the cosmic Re/Ni ratio line. The limited data show a clustering for groups IIC, IID, and IVB.

OSMIUM

The data on osmium in meteorites were assembled and discussed by J. W. Morgan, in Mason (1971), and table 72 provides a summary. Additional information has been provided by Vinogradov and others (1972, 1973), Hintenberger, Jochum, and Seufert (1973), and Herman and Wichtl (1974). The results of these more recent investigations are generally in good agreement with previous determinations, although the figures given by Hintenberger and coworkers for chondrites are consistently higher

TABLE 70.—*Tungsten in stony meteorites*

[From Atkins and Smales, 1960; Amiruddin and Ehmann, 1962; and additional data]

Class	Number analyzed	Range (ppb)	Mean (ppb)	Atoms/10^6Si
		Chondrites		
C1	1	200	---	0.30
C2	2	130-150	140	.16
C3	1	150	---	.15
H	7	100-170	140	.13
L	13	70-190	120	.10
LL	1	80	---	.065
E	2	320-370	350	.32
		Calcium-poor achondrites		
Ae	3	20-120	80	0.044
Ah	1	50-80	65	.040
Au	1	180	---	.14
		Calcium-rich achondrites		
Aho	1	36	---	0.023
Aeu	1	41	---	.028

than those for the same meteorites analyzed by other investigators. The pattern of Os abundances in chondrites shows marked depletion in the sequence H–L–LL, paralleling a decrease in the metal content; achondrites are strongly depleted in Os relative to the chondrites. This pattern is typical of a siderophile element. Wark and Lovering (1976) found microscopic metallic grains in the Allende (C3) chondrite that contain 38 percent Os, although the meteorite contains the normal concentration of Os (~0.9 ppm) for a C3 meteorite. In the ordinary chondrites one would expect to find most of the osmium in the metal phase; however, the data of Vinogradov and others (1972, 1973) on separated phases of chondrites indicate that appreciable amounts may be present in the troilite.

Osmium is present in iron meteorites in concentrations ranging from 0.009 to 58 ppm, with an average of 5.36 ppm (Crocket, 1972). Figure 19 shows the relationship between Os, Ni, and the chemical groupings of iron meteorites; the distribution pattern is similar to that for Re and Ir. Crocket (1972) discussed the high degree of correlation between Os, Ir, and Ru in iron meteorites.

IRIDIUM

The data on iridium abundances in meteorites were assembled and discussed by P. A. Baedecker, in Mason (1971). Since then, however, a large number of new analyses have been made on stony meteorites, and these have been used in the compilation of table 73. Iridium abundances in specific classes are closely similar to those for osmium (table

TABLE 71.—*Rhenium in stony meteorites*

[From J. W. Morgan, in Mason, 1971; and additional data from Case and others, 1973; Krähenbühl and others, 1973; Hintenberger and others, 1973; Herman and Wichtl, 1974; Anders and others, 1976; and Higuchi and others, 1976]

Class	Number analyzed	Range (ppb)	Mean (ppb)	Atoms/10^6Si
		Chondrites		
C1	3	25-43	35	0.051
C2	3	43-49	46	.053
C3	7	50-59	55	.052
H	12	60-100	67	.059
L	16	23-67	37	.030
LL	4	16-25	22	.018
E	7	51-68	60	.050
		Calcium-poor achondrites		
Ae	1	0.25	---	0.00014
Ah	2	.06-1.3	.4	.00024
Au	4	6.8-38.6	20	.016
		Calcium-rich achondrites		
Aa	1	0.07	---	0.000051
An	1	.08	---	.000054
Aho	1	.07	---	.000045
Aeu	1	.06	---	.000039

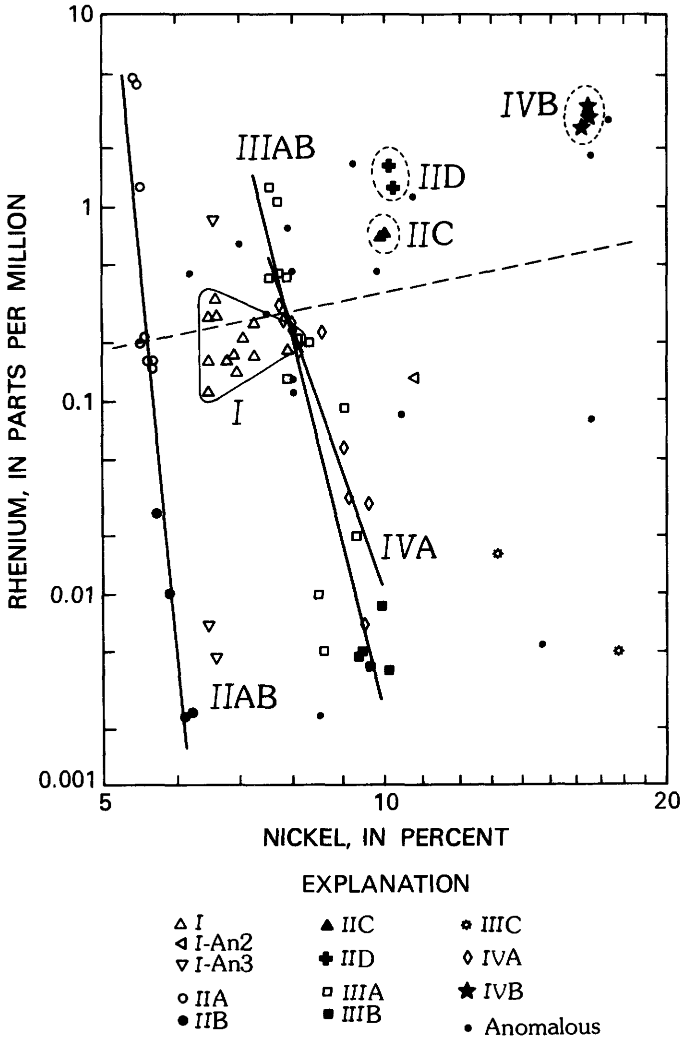

FIGURE 18.—Re-Ni distribution in iron meteorites; the dashed line represents the Re/Ni ratio in C1 chondrites. Solid lines indicate correlations within groups; short-dashed lines enclose well-resolved groups. Reprinted from Scott (1972) and published with permission.

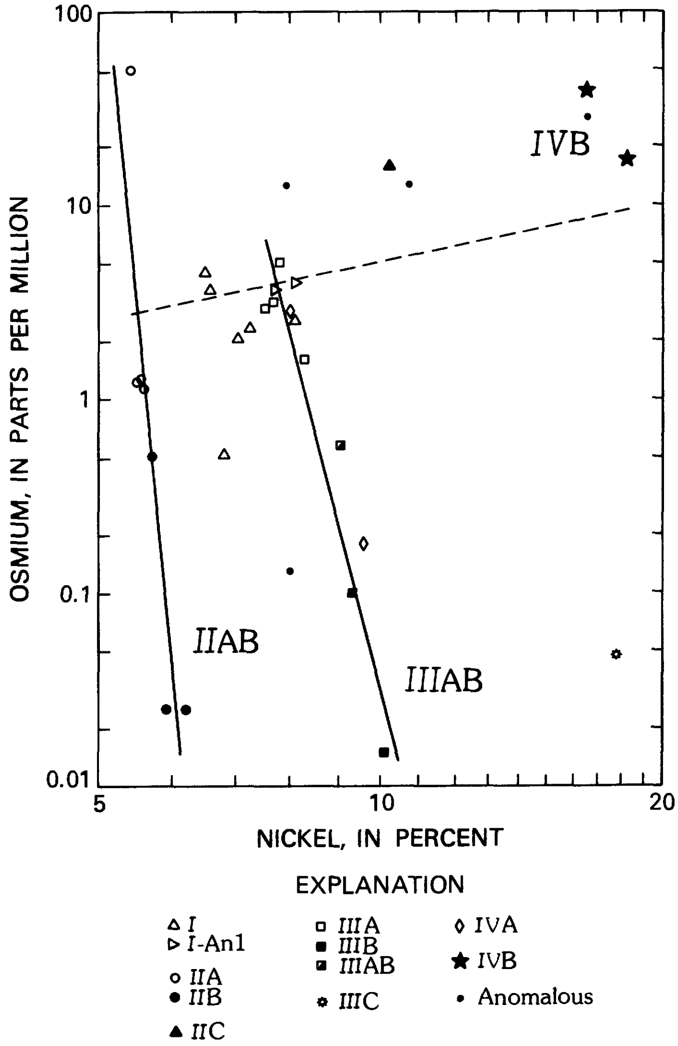

FIGURE 19.—Os-Ni distribution in iron meteorites; the dashed line represents the Os/Ni ratio in C1 chondrites. Solid lines indicate correlations within groups. Reprinted from Scott (1972) and published with permission.

72), which is perhaps surprising, in view of the usually lower abundance of an odd-numbered element than its even-numbered neighbors (the Oddo-Harkins rule). Like Os, Ir abundances in chondrites show a marked depletion in the sequence H-L-LL, paralleling a decrease in metal content; achondrites are strongly depleted in Ir relative to the chondrites. This pattern is typical of a siderophile element. Wark and Lovering (1976) found microscopic metallic grains in the Allende (C3) chondrite containing up to 21 percent Ir.

Chou, Baedecker, and Wasson (1973) magnetically separated metal from 15 chondrites (H) and analyzed the metal and silicate fraction (leached with bromine water to remove troilite) separately. They found 1.4–4.6 ppm Ir in the metal, 0.03–0.12 ppm Ir in the silicates. This confirms the siderophile nature of Ir; the small amount of Ir in the silicate fraction could be present as minute metal inclusions. Vinogradov and others (1972, 1973) analyzed metal, troilite, and silicate fractions from several chondrites, and found Ir concentrated in the metal and greatly depleted in the silicates, but the troilite showed Ir values up to those in the associated metal. However, Ehmann, Baedecker, and McKown (1970) found 10 to 30 times more Ir in meteoritic nickel-iron than in coexisting troilite.

A large number of Ir determinations in iron meteorites have been made, most of them by J. T. Wasson and his coworkers. The data are summarized in figure 20, from Scott and Wasson (1975). Iridium concentrations range over 4 orders of magnitude, from 0.01 to nearly 100 ppm, with an average of 3.96 ppm (Crocket, 1972), and show a marked quantization within the individual chemical groups.

The geochemical behavior of Ir in meteorites is evidently conditioned largely by its high condensation temperature. Scott (1972) listed the following elements having the highest condensation temperatures (in K at 10^{-4} atm): W, 1,960; Os, 1,840; Re, 1,775; Mo, 1,620; Ir, 1,550; Ru, 1,540. This group of elements shows a remarkable degree of geochemical coherence in meteorites, typified by similar distribution patterns in iron meteorites (Scott, 1972), and their concentration in the Ca,Al-rich inclusions in the Allende meteorite as microscopic alloy grains (Wark and Lovering, 1976).

PLATINUM

The rather sparse data on platinum abundances in meteorites were assembled and discussed by W. D. Ehmann, in Mason (1971). For stony meteorites these data have been superseded by the work of Ehmann and Gillum (1972) and Hintenberger, Jochum, and Seufert (1973). Their results are generally in good agreement, and since Ehmann and Gillum analyzed a larger number of meteorites, their data have been used in compiling table 74. Platinum shows a distribution pattern similar to those of Os and Ir, at about twice the absolute abundance level, and the discussion of the geochemical behavior of these elements applies equally to Pt. Wark and Lovering (1976) recorded up to 35 percent Pt in microscopic metallic grains in the Allende (C3) meteorite. Vinogradov and others (1972, 1973) analyzed separated metal, troilite, and silicate fractions for several chondrites and found Pt concentrated in the metal, although in some meteorites

TABLE 72.—*Osmium in stony meteorites*

[From J. W. Morgan, in Mason, 1971]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
C1	3	0.34-0.61	0.48	0.69
C2	5	.54-.75	.67	.75
C3	3	.69-.85	.78	.74
H	8	.66-.92	.82	.71
L	8	.43-.63	.51	.40
LL	4	.32-.50	.38	.30
E	6	.63-.85	.70	.57
		Calcium-poor achondrites		
Ae	1	0.005	---	0.002
Ah	2	.0006-.008	.004	.002
		Calcium-rich achondrites		
Aa	1	0.00078	---	0.0006
An	1	.00070	---	.0005
Aho	1	<.00017	---	---
Aeu	2	.00044-.0074	.004	.003

TABLE 73.—*Iridium in stony meteorites*

[Data as follows: C1, C2, Krähenbühl and others, 1973; C3, Anders and others, 1976; H, L, LL, Müller, Baedecker, and Wasson, 1971; E, Baedecker and Wasson, 1975; Ae, Ah, Aho, Aeu, Chou, Baedecker, and Wasson, 1976; Au, Wasson and others, 1976; Aa, An, Laul and others, 1972; Ac, Boynton, Starzyk, and Schmitt, 1976]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
C1	3	0.49-0.56	0.51	0.72
C2	3	.61-.66	.63	.70
C3	7	.65-.74	.69	.65
H	18	.51-.83	.73	.62
L	17	.31-.59	.46	.36
LL	10	.18-.44	.33	.26
E	8	.40-.70	.56	.45
		Calcium-poor achondrites		
Ae	2	0.00034-0.00059	0.00047	0.00025
Ah	1	.0065	---	.0038
Ac	1	.006	---	.005
Au	5	.055-.76	.33	.25
		Calcium-rich achondrites		
Aa	1	0.0026	---	0.0019
An	2	.00013-.017	.009	.0054
Aho	6	.0005-.018	.015	.0094
Aeu	3	.00013-.00065	.00032	.00020

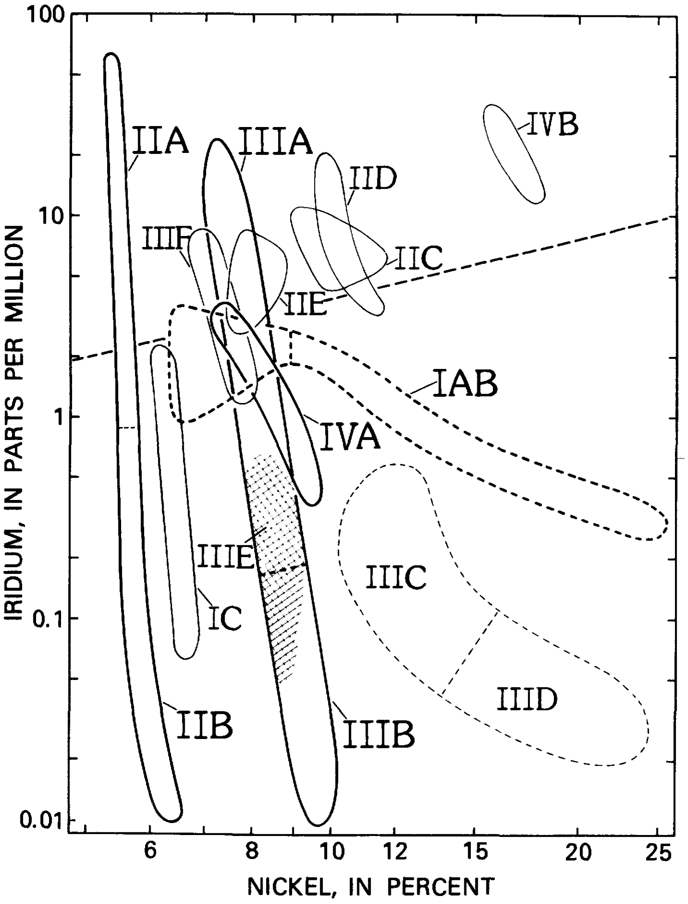

FIGURE 20.—Ir-Ni distribution in iron meteorites; the dashed line represents the Ir/Ni ratio in C1 chondrites. The major groups, IIAB, IIIAB, and IVA are shown in heavier outline; groups IAB and IIICD are drawn with short-dashed lines to contrast them with the other groups. Reprinted from Scott and Wasson (1975), copyrighted by American Geophysical Union.

the troilite fraction contained approximately he same amounts as the metal.

The only determinations of Pt in achondrites are: Haverö (Au), 0.41 ppm (Wänke, Baddenhausen, Spettel, and others, 1972); Yamato(b) (Ah), 0.005 ppm; Johnstown (Ah), 0.019 ppm (Hintenberger, Jochum, and Seufert, 1973).

The data on Pt abundances in iron meteorites are summarized in figure 21. This shows a range of Pt values about 0.5 to 29 ppm, with an average of 9.42 ppm (Crocket, 1972). Crocket pointed out that Pt is more strongly correlated with Ru than with the other platinum-group elements.

GOLD

The data on gold in meteorites available to 1969 were assembled and discussed by W. D. Ehmann, in Mason (1971). Since then, however, a large amount of additional data has been published, by Keays, Ganapathy, and Anders (1971); Crocket (1972); Ehmann and Gillum (1972); Laul and others (1972); Case and others (1973); Krähenbühl and others (1973); Hintenberger, Jochum, and Seufert (1973); Hermann and Wichtl (1974); Binz, Kurimoto, and Lipschutz (1974); Binz, Ikramudden, and Lipschutz (1975); Binz and others (1976); Baedecker and Wasson (1975), Chou, Baedecker, and Wasson (1976b), Wasson and others (1976), Anders and others (1976), and Higuchi and others (1976). The results of different analysts on the same meteorites are usually in good agreement. Table 75 is compiled from a selection of these data. Gold is

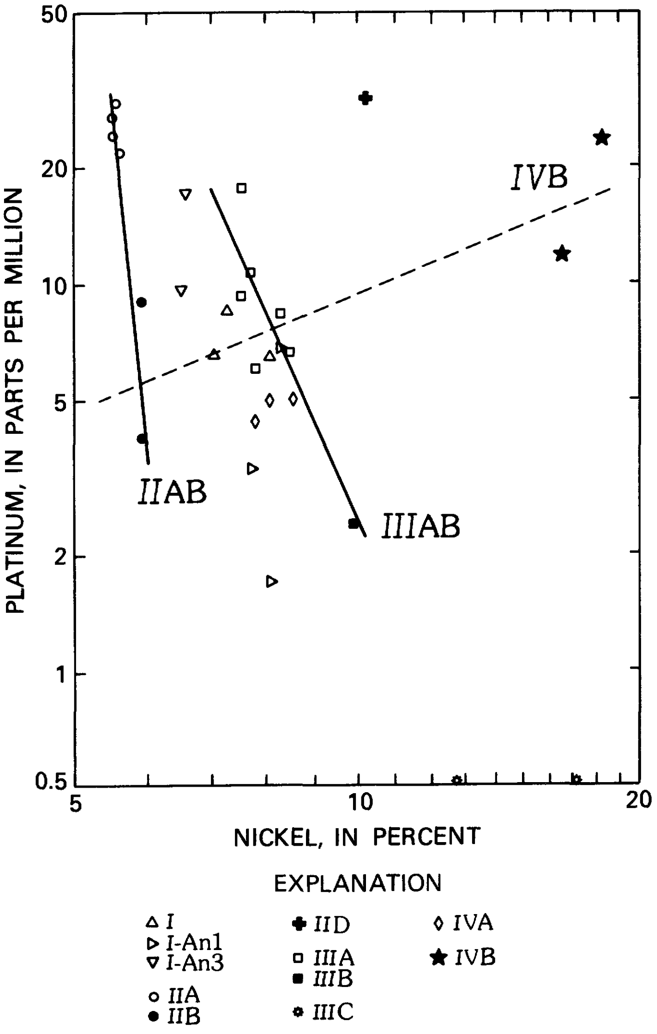

FIGURE 21.—Pt-Ni distribution in iron meteorites; the dashed line represents the cosmic Pt/Ni ratio in C1 chondrites. Solid lines indicate correlations within groups. Reprinted from Scott (1972) and published with permission.

TABLE 74.—*Platinum in chondrites*
[From Ehmann and Gillum, 1972]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
Chondrites				
C1	2	0.94-1.06	1.01	1.41
C2	4	1.05-1.66	1.28	1.41
C3	2	1.22-2.03	1.55	1.44
H	10	.91-2.36	1.49	1.25
L	14	0.70-1.61	1.05	.81
LL	3	.63-1.09	.85	.65
E	6	1.18-2.39	1.71	1.37

considerably less abundant than any of the neighboring platinum metals, but shows the same distribution pattern, evidently because of a similar siderophile character. Fouché and Smales (1967b) separated a number of chondrites into magnetic (metal) and nonmagnetic (silicate+sulfide) fractions, and found that Au was present in metal fractions at 27–290 times the concentration in the nonmagnetic fractions, demonstrating the strong partition of this element into the metal phase. Vinogradov and others (1972, 1973) reported Au determinations on separated metal, troilite, and silicate fractions of several chondrites, and some of their analyses show more Au (up to 1.5 ppm) in troilite than in coexisting metal. This is inconsistent with the results of other investigators, who have found much lower values for Au in troilite; Herman and others (1971) found an average of 0.0046 ppm Au for six troilite samples. Ehmann, Baedecker, and McKown (1970) recorded 30–620 times as much Au in magnetic (metal) fractions of chondrites as in nonmagnetic (troilite plus silicate) fractions.

The numerous determinations of Au in iron meteorites have been assembled and discussed by Scott and Wasson (1975), and are presented in figure 22. The total range of Au values is about 0.05–5 ppm, or approximately 2 orders of magnitude; Crocket (1972) gave an average of 1.32 ppm for iron meteorites. Strong positive correlations between Au and Ni are visible within all chemical groups for which there are sufficient data, with the exception of IAB and IICD. Scott (1972) noted that the distribution of Au is almost identical with that of As.

MERCURY

The data on mercury in meteorites were assembled and discussed by G. W. Reed, in Mason (1971), who commented: "The extremely large range observed within a given class of meteorites makes averaging meaningless. Even for a given meteorite large variations are obtained in the same laboratory. . . . These variations have nothing to do with the laboratory or the method used for analysis" (p. 488). Although many additional analyses for mercury in meteorites have since been reported, this situation has not changed. For example, the following values (in ppm) have been reported for the Orgueil (C1) meteorite: 0.48, 40 (Case and others, 1973); 2.40, 14.0, 213 (Reed and Jovanovic, 1967); 7.80 (Hintenberger, Jochum, and Seufert, 1973); 12.8 (Hermann and Wichtl, 1974); 17.3, 20.1, 20.8. 22.2, 114 (Ehmann and Lovering, 1967); 500 (Ozerova and others, 1973). This is an extreme example, and may be unique to the Orgueil meteorite. However, other meteorites show similar, but less extreme variations; for example, the data for the Holbrook (L6) meteorite: 0.022 (Case and others, 1973); 0.17 (Ehmann and Lovering, 1967); 0.44 (Reed and Jovanovic, 1967); 1.80 (Kiesl and others, 1967). On this account no attempt has been made to average the data in table 76, nor to calculate the mean atoms/10^6Si for the different classes. If one were to assume

TABLE 75.—*Gold in stony meteorites*

[Data as follows: C1, C2, C3, H, L, LL, Ehmann and Gillum, 1972; E4, E5, E6, Baedecker and Wasson, 1975; Ae, Ah, Chou, Baedecker, and Wasson, 1976b; Au, Wasson and others, 1976; Aa, An, Laul and others, 1972; Aho, Aeu, Laul and others, 1972, and Chou, Baedecker, and Wasson, 1976b; Ac, Boynton and others, 1976]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
C1	2	0.12-0.17	0.15	0.21
C2	5	.15-.28	.19	.21
C3	2	.18-.22	.21	.19
H	10	.13-.38	.21	.18
L	13	.10-.24	.16	.12
LL	3	.12-.19	.15	.11
E4	3	.32-.44	.36	.31
E5	1	.34	---	.28
E6	4	.18-.29	.23	.17
		Calcium-poor achondrites		
Ae	2	0.0005-0.0017	0.0011	0.00057
Ah	1	.0019	---	.0011
Ac	1	.006	---	.005
Au	5	.014-.045	.029	.021
		Calcium-rich achondrites		
Aa	1	0.0072	---	0.0050
An	1	.00055	---	.00034
Aho	10	.0029-.019	.0065	.0040
Aeu	7	.0003-.0067	.0025	.0016

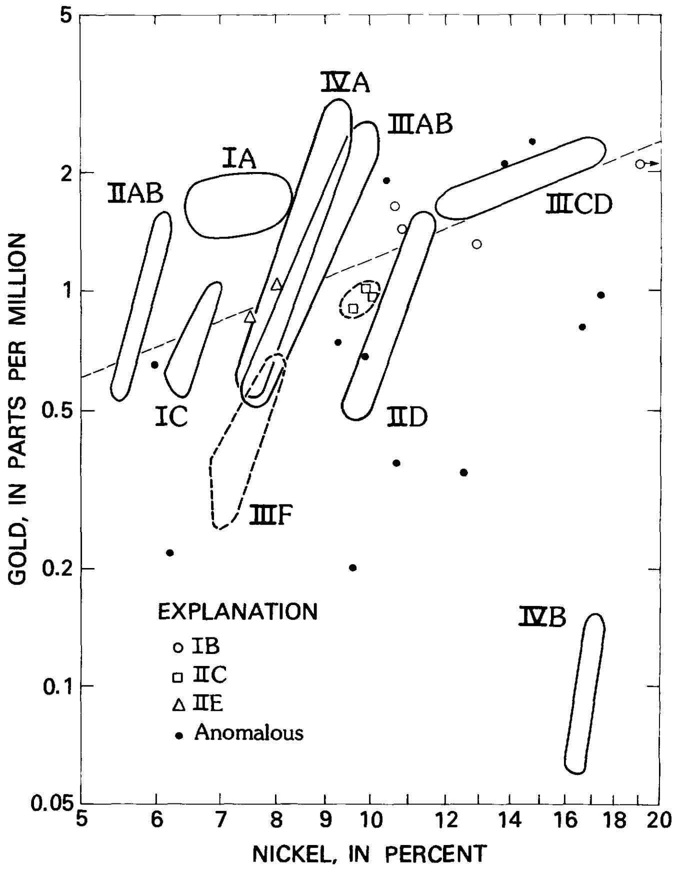

Figure 22.—Au-Ni distribution in iron meteorites; the dashed line represents the Au/Ni ratio in C1 chondrites. Most groups are shown only in outline; this is short dashed when only a few data points define a group. Reprinted from Scott and Wasson (1975), copyrighted by American Geophysical Union.

similar abundance for Hg as for the neighboring even-numbered elements Pt and Pb, a mean abundance in C1 chondrites of ~1 ppm (equivalent to ~1.4 atoms/10^6Si) would be reasonable.

Reed and Jovanovic (1967) investigated the progressive release of Hg from chondrites on heating, and found in many of them that a large part of the Hg was given off below 450°C. They interpreted the Hg released above 450°C as trapped in crystal lattices or present in solid solution, and released after diffusion to surfaces in a manner analogous to the escape of trapped gases. The most likely phase to contain Hg in solid solution is troilite, and Ozerova and others (1973) noted that troilite appears to be a good mercury concentrator in several meteorite classes, having a consistently higher mercury content than the meteorite as a whole. Thus, mercury in combination in meteorites is a chalcophile element, but much of it is in a labile form which is readily released and transported by gentle heating. This ready release and transportation is probably responsible, at least in part, for the extreme variability in the Hg content of stony meteorites.

The limited data on Hg in iron meteorites show low concentrations and hence a lack of siderophile character. Ozerova and others (1973) reported analyses of 10 iron meteorites, the range of Hg concentration being 0.01–0.12 ppm, with a mean of 0.04 ppm. Tanner (1968) analyzed 19 irons, and found a range from 0.03 to 1.25 ppm (all but three less than 0.4 ppm); he found troilite to be considerably enriched in Hg relative to the metal phase.

THALLIUM

The abundance data for thallium in meteorites were assembled and discussed by M. E. Lipschutz, in Mason (1971), but since then a considerable number of publications dealing with this element have appeared, and table 77 has been compiled from these sources. The data for chondrites show that Tl is a strongly depleted element, the relative depletion in the sequence C1–C2–C3–(H, L, LL) being 1.00:-0.51:0.24:~0.02; a similar depletion is evident in the sequence E4–E5, 6. In some chondrite classes Tl abundances are extremely variable, particularly noteworthy in the H chondrites: if, out of the 22 meteorites analyzed, Sharps (220 ppb), Tieschitz (53 ppb), and Supuhee (361 ppb) are omitted, the range is much less, 0.11–5.64 ppb. (Sharps and Tieschitz are type 3 chondrites, Supuhee a type 6.) The geochemical behavior of thallium in meteorites is very similar to that of indium, and a comparison of table 77 with table 59 shows that the atomic abundances of these two elements are remarkably similar in most meteorite classes. The geochemistry of Tl in meteorites is evidently related to its volatility; along with In and Bi, it has the lowest condensation temperature of any of the metallic elements (~430K from a solar gas at 10^{-6} atm, according to Laul and others, 1973). Accordingly, it is also an element likely to be volatilized and lost from a meteorite undergoing mild thermal metamorphism; Ikramuddin and Lipschutz (1975) and Ikramuddin, Binz, and Lipschutz (1976) demonstrated this experimentally in the Allende (C3) and Abee (E4) meteorites.

Tandon (1967) has shown that in iron meteorites the metal phase contains 0.1–10 ppb Tl, the troilite 2–200 ppb, demonstrating that Tl is distinctly chalcophile in these meteorites. The same is probably true for the stony meteorites; indeed, the C1 and E4 meteorites, which show the highest mean Tl contents, are also those with the highest sulfur contents.

LEAD

Many studies have been made on lead in meteorites, but most of these have been concerned with its isotopic composition, and the abundance data are rather sparse. These data are summarized in table 78; they are taken from Virginia Oversby, in Mason (1971) and additional later sources. Lead is a relatively volatile element, and it condenses in the same temperature range as Bi, In, and Tl, as shown by Larimer and Anders (1967). Like these elements, it is a strongly depleted element in chondrites, the relative depletion in the sequence C1–C2–C3–(H, L) being 1.00:0.62:0.34:0.09. Abundance of Pb in achondrites are similar to those in ordinary chondrites; the one determination on the diogenite Johnstown (Ah) is anomalously high, and suggests terrestrial contamination, always a possible complication with Pb at the low levels in stony meteorites.

Most lead concentrations in the metal phase of iron meteorites range from 0.01 to 0.1 ppm; the coexisting troilite contains 2–10 ppm. Lead is thus a strongly chalcophile element. Because the troilite of iron meteorites contains a substantial amount of Pb but essentially no U and Th (which would add radiogenic Pb), the Pb in the troilite is considered to be the "primordial" Pb existing when the parent bodies of meteorites (and the Earth) accreted. The troilite from the Canyon Diablo iron has been in-

TABLE 76.—*Mercury in stony meteorites*

[From G. W. Reed, in Mason, 1971; and additional data from Case and others, 1973; Reed and Jovanovic, 1967; Hintenberger and others, 1973; Hermann and Wichtl, 1974; Ehmann and Lovering, 1967; Ozerova and others, 1973; and Kiesl and others, 1976]

Class	Number analyzed	Range (ppm)
	Chondrites	
C1	2	0.18-500
C2	4	.01-20
C3	5	.06-7.3
H	13	.26-13.90
L	16	.015-5.99
LL	2	.24-.84
E	3	.16-1.4
	Calcium-poor achondrites	
Ae	2	0.014-0.14
Ah	1	0.12
Au	1	0.09
	Calcium-rich achondrites	
Aa	1	2.51
An	1	0.23
Aho	2	0.015-0.66
Aeu	5	0.078-9.12

TABLE 77.—*Thallium in stony meteorites*

[Data as follows: C1, C2, Krähenbühl and others, 1973; C3, Anders and others, 1976; H, LL, E, Laul and others, 1973; L, Ganapathy and Anders, 1971; Ah, Hintenberger and others, 1973; Au, Binz and others, 1975, Aa, An, Aho, Aeu, Laul and others, 1972]

Class	Number analyzed	Range (ppb)	Mean (ppb)	Atoms/10^6Si
		Chondrites		
C1	3	124-188	145	0.19
C2	3	84-97	92	.096
C3	7	15-84	52	.046
H	22	.11-361	[1]3.7	.0030
L	10	.05-6.6	1.9	.0014
LL	11	.75-31	7.2	.0053
E4	4	85-115	103	.085
E5	1	3.7	---	.0029
E6	5	1.2-8.6	5.0	.0035
		Calcium-poor achondrites		
Ah	1	5.8	---	0.0032
Au	4	.31-5.31	1.6	.0011
		Calcium-rich achondrites		
Aa	1	.86	---	0.00058
An	2	3.1-7.2	5.2	.0030
Aho	4	.51-4.3	1.8	.0010
Aeu	7	.12-1.97	.73	.00044

[1] Omitting high value of 221 and 361.

tensively investigated by several research teams, and its Pb is the least radiogenic yet discovered. Tatsumoto, Knight, and Allegre (1973) gave the following isotope ratios for this Pb: 206/204, 9.307; 207/204, 10.294; 208/204, 29.476. These ratios have been modified in stony meteorites by the addition of radiogenic isotopes (206, 207, 208); the most radiogenic lead is that from the Nuevo Laredo achondrite (Aeu), which has the following isotopic ratios: 206/204, 222.38; 207/204, 140.05; 208/204, 233.64 (Tatsumoto and others, 1973).

BISMUTH

Since 1970, a large amount of data on the abundance of Bi in stony meteorites has been published, and is summarized in table 79. Bismuth abundances are closely comparable with those of thallium for the same meteorite classes, and this geochemical coherence has been noted and discussed by several investigators (for example, Laul and others, 1973); it is evidently related to similar condensation histories. Bismuth is a strongly depleted element, the relative depletion in the sequence C1–C2–C3–(H, L, LL) being 1.00:0.55:0.31:~0.08; similar depletion is seen in the sequence E4–E6, with the two E5 meteorites showing anomalously low abundances. Within the H, L, and LL classes, the abundance range is very great; high abundances are characteristic of, but not exclusive to, the type 3 meteorites. Achondrites are strongly depleted in Bi relative to the chondrites.

Because of its low condensation temperature (~460K from a solar gas at 10^{-5} atm, according to Laul and others, 1973), Bi is an element likely to be volatilized and lost from a meteorite undergoing mild thermal metamorphism. Ikramuddin and Lip-

TABLE 78.—*Lead in stony meteorites*

[From Virginia Oversby, in Mason, 1971; and additional data from Gale and others, 1972; Tatsumoto and others, 1973; Tilton, 1973; Hintenberger and others, 1973; Huey and Kohman, 1973; and Hutchison and others, 1975]

Class	Number analyzed	Range (ppm)	Mean (ppm)	Atoms/10^6Si
		Chondrites		
C1	1	1.94	---	2.6
C2	3	1.51-1.60	1.54	1.6
C3	2	.93-1.10	1.02	.89
H	6	.08-.46	.24	.19
L	7	.06-.51	.37	.27
E4	2	1.98-2.17	1.08	.88
		Calcium-poor achondrites		
Ae	2	0.36-0.57	0.47	0.23
Ah	1	4.37	---	2.4
		Calcium-rich achondrites		
Aa	1	0.55	---	0.36
An	1	.352-.553	.48	.29
Aeu	2	.193-.324	.26	.15

schutz (1975) and Ikramuddin, Binz, and Lipschutz (1976) demonstrated this experimentally for the Allende (C3) and Abee (E4) meteorites.

Few data exist on Bi in iron meteorites. Tanner (1968) analyzed 19 irons and found a range from 0.5 to 7.9 ppb; 3 samples of troilite from these irons contained 61–68 ppb. Santoliquido and Ehmann (1972) found 1.6 ppb Bi in Canyon Diablo metal and 125 ppb in troilite from this meteorite. Bismuth is thus a strongly chalcophile element in these meteorites.

THORIUM

Most of the information on thorium abundances in meteorites has resulted from the analyses of J. W. Morgan and J. F. Lovering. Morgan, in Mason (1971), assembled and discussed the data available at that time. Additional information has since been published and the data are summarized in table 80. Thorium shows a distribution pattern characteristic of refractory lithophile elements: relatively uniform abundances in the different chondrite classes, marked depletion in calcium-poor achondrites

TABLE 79.—*Bismuth in stony meteorites*

[Data as follows: C1, C2, Krähenbühl and others, 1973; C3, Anders and others, 1976; H, LL, Laul and others, 1973; L, Keays and others, 1971; E, Binz and others, 1974; Ee, Santoliquido and Ehmann, 1972; Ah, Ehmann and Huisenga, 1959; Au, Binz and others, 1975; Aa, An, Aho, Aeu, Laul and others, 1972]

Class	Number analyzed	Range (ppb)	Mean (ppb)	Atoms/10^6Si
		Chondrites		
C1	3	103-188	110	0.14
C2	3	64-96	75	.077
C3	7	43-59	49	.043
H	22	.17-100	17	.013
L	10	.14-80	14	.010
LL	11	1.30-67	16	.011
E4	2	86-177	133	.11
E5	2	2.5-2.6	2.6	.0020
E6	4	15.0-28.9	18	.012
		Calcium-poor achondrites		
Ae	3	0.74-5.5	2.8	0.0013
Ah	1	1.2-5.6	2.8	.0015
Au	6	.96-10	3.3	.0023
		Calcium-rich achondrites		
Aa	1	2.4	---	0.0016
An	2	.50-5.64	3.1	.0019
Aho	4	.59-4.56	2.6	.0015
Aeu	7	.37-7.0	3.9	.0023

(except for the chassignite), and marked enrichment in the calcium-rich achondrites; Angra dos Reis (Aa) has the highest concentration of any meteorite. This distribution pattern parallels those of the lanthanides.

Crozaz (1974) separated the phosphate mineral merrillite from the St. Severin (LL6) chondrite and analyzed it for Th and U. The Th value, 3.21 ppm, indicates strong concentration of the element in this mineral; the meteorite contains approximately 0.5 percent merrillite, which accounts for 16 ppb Th, about one-third of the total Th in the meteorite.

Bate, Potratz, and Huizenga (1958) analyzed two iron meteorites for Th, and found extremely low values, of the order of 10^{-11} g/g.

URANIUM

The data on uranium abundances in meteorites were assembled and discussed by J. W. Morgan, in Mason (1971), and additional information has since been published, and a summary is presented in table 81. The distribution pattern is similar to that for thorium. The Th/U ratio for chondrites is usually between 3 and 4, although Morgan and Lovering (1968) recorded Th/U ratios ranging from 2.2 to 7.1. Morgan and Lovering (1973) recorded Th/U ratios ranging from 1.0 to 10.0 for achondrites. In the chondrites, uranium is concentrated in the phosphate minerals merrillite and apatite. Pellas and Storzer (1975) found a range from 0.05 to 0.77 ppm U in merrillite from 16 chondrites, with a mean of about 0.3 ppm, and a range from 1 to 5 ppm in

TABLE 80.—*Thorium in stony meteorites*

[From J. W. Morgan, in Mason, 1971; and additional data from Morgan and Lovering, 1973; Hintenberger and others, 1973; and Tatsumoto, 1973]

Class	Number analyzed	Range (ppb)	Mean (ppb)	Atoms/10^6Si
		Chondrites		
C1	4	26-38	32	0.038
C2	6	38-46	42	.039
C3	3	61-79	67	.052
H	8	34-42	40	.028
L	8	38-49	42	.027
LL	5	43-50	46	.029
E	6	29-42	34	.023
		Calcium-poor achondrites		
Ae	2	4-47	28	0.012
Ah	3	4-30	15	.0074
Ac	1	57	---	.040
Au	1	3	---	.0019
		Calcium-rich achondrites		
Aa	1	885	---	0.52
An	1	191	---	.10
Aho	3	63-312	167	.086
Aeu	7	340-680	450	.24

apatite; compared to merrillite, uranium in apatite is always enriched by a factor between 6 and 13. Zircon, an extremely rare mineral in meteorites, acts as a sink for uranium; Fleischer and others (1965) found up to 4,000 ppm in this mineral from the Vaca Muerta mesosiderite, and the only coexisting mineral having more than 1 ppm U was merrillite (≤90 ppm).

Tatsumoto, Unruh, and Desborough (1976) found the Ca,Al-rich inclusions in the Allende (C3) meteorite to be strongly enriched in U and Th, with up to 0.112 ppm U and 0.546 ppm Th; the Th/U ratio in these inclusions ranges from 3.5 to 10.6.

The metal phase of iron meteorites contains uranium at levels of 10^{-10} g/g or less (Reed and others, 1958). Goles and Anders (1962) found a range from 3.5 to 17 ppb U in troilites from five iron meteorites, indicating that U has distinct chalcophile affinity in these meteorites.

CONCLUSIONS

As discussed in the introduction, agreement is now widespread that elemental abundances in chondrites, specifically the C1 carbonaceous chondrites, approximate those of the unfractionated nonvolatile matter of the solar system. In order to provide a compact summary, the data for the C1 chondrites are assembled in table 82, in ppm and as atoms/10^6Si.

TABLE 81.—*Uranium in stony meteorites*

[From J. W. Morgan, in Mason, 1971; and additional data from Gale and others, 1972; Fisher, 1972 and 1973; Hintenberger and others, 1973; Morgan and Lovering, 1973; Tatsumoto and others, 1973; Tilton, 1973; Krähenbühl and others, 1973; Anders and others, 1976; and Higuchi and others, 1976]

Class	Number analyzed	Range (ppb)	Mean (ppb)	Atoms/10^6Si	Th/U
Chondrites					
C1	4	7.4-11.5	9.1	0.011	3.5
C2	5	10.2-11.9	11.7	.010	3.6
C3	7	12.9-18.8	16.1	.012	4.2
H	11	11-25	13	.0090	3.1
L	13	8-24	15	.0095	2.8
LL	5	11-14	13	.0082	3.5
E	6	6-16	10	.0066	3.4
Calcium-poor achondrites					
Ae	2	3.7-5.2	4.5	0.0019	6.2
Ah	3	1.5-11.6	8.2	.0039	1.8
Ac	1	21	---	.014	2.7
Au	4	≤.9-6.9	~4	~.003	~1
Calcium-rich achondrites					
Aa	1	207	---	0.12	4.3
An	1	49	---	.026	3.9
Aho	3	23-89	53	.026	3.2
Aeu	7	16-214	101	.052	4.5

This table brings out some well-established features of the elemental abundances. All the abundant elements (>10,000 atoms/10^6Si) have low atomic numbers, 28 (Ni) or less. The abundances of elements of higher atomic number are uniformly low (only Cu, Zn, Ga, Ge, Se, Br, and Se have abundances greater than 10 atoms/10^6Si) and relatively constant; the odd-even relationship is well marked, elements of odd atomic number being generally about 10 times less abundant than those of even atomic number on either side. Elements of low atomic number (<28) show much greater variability in relative abundances than those of higher atomic number. The very low abundances of the lightest elements, Li, Be, and B, can be ascribed to the relative instability of their nuclei; Sc is also an element of unusually low abundance. The most abundant nonvolatile elements, Mg, Si, and Fe, have almost identical atomic abundances, and hence when completely oxidized will form olivine, $(Mg,Fe)_2SiO_4$, whereas if the iron is partly reduced to metal and/or sulfide, olivine will be partly replaced by pyroxene, $(Mg,Fe)SiO_3$, and if all the iron is reduced the silicate will be pure $MgSiO_3$. This is the sequence we observe in the chondrites, from C3–L–H–E chondrites, although the sequence is not a continuous one and does not imply direct production of one class from another.

Also included in table 82 are the current solar abundances (Ross and Aller, 1976). Ross and Aller commented (p. 1228): "Except for lithium, beryllium, and boron, the non-volatile component of the solar atmosphere fits well with data from carbonaceous chondrites. There are a few exceptions, such as indium, but one can be skeptical of the abundance of an otherwise unremarkable metal whose solar abundance is alleged to differ markedly from the meteoritic value. The difference is almost certainly to be attributed to bad *f*-values or to blending or confusion with other lines, or both. Lithium, beryllium, and boron can be destroyed at the bottom of the solar convection zone."

TABLE 82.—*Chondritic and solar abundances*

[For C1 chondrites, except as noted. Solar abundances from Ross and Aller, 1976]

Element	C1 ppm	C1 atoms/10^6Si	Sun atoms/10^6Si
Li	1.6	60	0.22
Be[1]	.035	.81	.32
B	5.7	144	<4
F	72	1,000	810
Na	5,100	60,000	43,000
Mg	95,600	1,060,000	890,000
Al	8,500	85,000	74,000
Si	103,000	10^6	10^6
P	800	7,000	7,100
S	59,000	502,000	320,000
Cl	773	5,700	6,300
K	500	3,500	3,200
Ca	10,600	72,000	50,000
Sc	5.1	31	25
Ti	430	2,400	2,500
V	49	254	230
Cr	2,430	12,700	11,000
Mn	1,880	9,300	5,900
Fe	184,000	901,000	710,000
Co	480	2,200	1,800
Ni	10,300	47,000	43,000
Cu	127	540	260
Zn	303	1,260	630
Ga	9.6	14	38
Ge	31.2	117	71
As	1.7	6.2	--
Se	19.5	67	--
Br	4.0	14	--
Rb	1.88	6.0	8.9
Sr	8.6	27	18
Y	1.6	4.8	2.8
Zr	3.1	9.1	13
Nb	.3	.9	1.6
Mo	1.4	4.0	3.2
Ru	.69	1.9	1.5
Rh[2]	.25	.40	.56
Pd	.49	1.3	.6
Ag	.18	.46	.16
Cd	.64	1.55	1.6
In	.080	.19	1.0
Sn	1.64	3.7	2.0
Sb	.14	.31	.22

TABLE 82.—*Chondritic and solar abundances*—Continued

Element	C1	C1	Sun
	ppm	atoms/10^6Si	atoms/10^6Si
Te	3.04	6.5	--
I	.58	1.16	--
Cs	.19	.39	<.6
Ba	2.4	4.8	2.8
La	.19	.37	.30
Ce	.63	1.2	.79
Pr	.094	.18	.10
Nd	.42	.79	.38
Sm	.133	.24	.12
Eu	.053	.094	.1
Gd	.24	.42	.30
Tb	.044	.076	--
Dy	.22	.37	--
Ho	.056	.092	--
Er	.14	.23	.13
Tm	.022	.035	.041
Yb	.13	.20	.16
Lu	.023	.035	.13
Hf	.11	.17	.1
Ta[1]	.017	.020	--
W	.20	.30	1.0
Re	.035	.051	~.01
Os	.48	.69	.1
Ir	.51	.72	.16
Pt	1.01	1.4	1.3
Au	.15	.21	.13
Hg	~1?	~1.4?	.3
Tl	.145	.19	.18
Pb	1.94	2.6	1.9
Bi	.11	.14	<1.6
Th	.038	.045	.03
U	.0086	.010	<.1

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[1] Abundances for C2 chondrites.

[2] Abundances for H chondrites.

TABLE 83.—*The minerals of meteorites*

Name	Formula	Occurrence
Alabandite[1]	(Mn,Fe)S	Accessory in some enstatite chondrites and enstatite achondrites.
Andradite	$Ca_3Fe_2Si_3O_{12}$	Accessory in Allende (C3).
Awaruite	Ni_3Fe	Accessory in Odessa iron and Allende (C3).
Baddeleyite	ZrO_2	Accessory in Chassigny (Ac).
*Barringerite	$(Fe,Ni)_2P$	Accessory in Ollague pallasite.
Bloedite	$Na_2Mg(SO_4)_2 \cdot 4H_2O$	Accessory in Ivuna (C1).
*Brezinaite	Cr_3S_4	Accessory in Tucson iron.
*Brianite	$CaNa_2Mg(PO_4)_2$	Accessory in some irons.
*Buchwaldite	$CaNaPO_4$	Accessory in Cape York iron.
Calcite	$CaCO_3$	Accessory in C1 and C2.
*Carlsbergite	CrN	Accessory in many irons.
Celsian	$BaAl_2Si_2O_8$	Accessory in Angra dos Reis (Aa).
Chalcopyrite	$CuFeS_2$	Accessory in Karoonda (C3).
Chaoite	C	Rare, in ureilites.
Chlorite	See serpentine	----------
Chlorapatite	$Ca_5(PO_4)_3Cl$	Accessory in many meteorites.
Chromite	$FeCr_2O_4$	Accessory in most meteorites.
Clinopyroxene	$(Ca,Mg,Fe)SiO_3$	Common in stones and stony-irons.
Cohenite	$(Fe,Ni)_3C$	Accessory in many irons and in E chondrites.
Copper	Cu	Common as an accessory.
Cordierite	$Mg_2Al_4Si_5O_{18}$	Accessory in Allende (C3).
Cristobalite	SiO_2	Accessory, mainly in E chondrites.
*Daubreelite	$FeCr_2S_4$	Accessory in E, Ae, and many irons.
Diamond	C	Present in ureilites.

TABLE 83.—*The minerals of meteorites*—Continued

Name	Formula	Occurrence
Djerfisherite	$K_3CuFe_{12}S_{14}$	Accessory in some E, Ae, and Toluca iron.
Dolomite	$CaMg(CO_3)_2$	Accessory in C1.
Epsomite	$MgSO_4 \cdot 7H_2O$	Prominent in C1.
*Farringtonite	$Mg_3(PO_4)_2$	Accessory in some pallasites.
*Gentnerite[2]	$Cu_8Fe_3Cr_{11}S_{18}$	Accessory in Odessa iron.
Graftonite	$(Fe,Mn)_3(PO_4)_2$	Rare accessory in some irons.
Graphite	C	Common accessory in irons and some stones.
Grossular	$Ca_3Al_2Si_3O_{12}$	Accessory in Allende (C3).
Gypsum	$CaSO_4 \cdot 2H_2O$	Accessory in C1 and C2.
*Haxonite	$Fe_{23}C_6$	Accessory in many irons.
Heazlewoodite	Ni_3S_2	Accessory in Odessa iron.
*Heideite	$(Fe,Cr)_{1+x}(Ti,Fe)_2S_4$	Accessory in Bustee (Ae).
Hercynite	$(Fe,Mg)Al_2O_4$	Accessory in some C3.
Hibonite	$CaAl_{12}O_{19}$	Accessory in some C2 and C3.
Ilmenite	$FeTiO_3$	Accessory in many stones and stony-irons.
Kaersutite	$NaCa_2Fe_4TiAl_2Si_6(O,OH)_{24}$	Accessory in Chassigny (Ac).
Kamacite	α-(Fe,Ni)	In irons, stony-irons, and most chondrites.
Kirschsteinite	$CaFeSiO_4$	Accessory in Angra dos Reis (Aa).
*Krinovite	$NaMg_2CrSi_3O_{10}$	Rare accessory in a few irons.
*Lawrencite	$(Fe,Ni)Cl_2$	Accessory in some meteorites.
*Lonsdaleite	C	Rare in ureilites.
Mackinawite	FeS_{1-x}	Common as an accessory.
Magnesite	$(Mg,Fe)CO_3$	Accessory in C1.
Magnetite	Fe_3O_4	Accessory in carbonaceous chondrites.
*Majorite	$Mg_3(MgSi)Si_3O_{12}$	In Coorara and Tenham chondrites.

TABLE 83.—*The minerals of meteorites*—Continued

Name	Formula	Occurrence
Melilite	$Ca_2(Mg,Al)(Si,Al)_2O_7$	In chondrules in C3.
*Merrihueite	$(K,Na)_2Fe_5Si_{12}O_{30}$	Rare accessory in Mezo-Madaras chondrite.
Merrillite	$Ca_9MgNa(PO_4)_7$	Accessory in many meteorites.
Molybdenite	MoS_2	Inclusion in metal grain in Allende (C3).
Monticellite	$Ca(Mg,Fe)SiO_4$	Accessory in Sharps chondrite (H3).
Nepheline	$NaAlSiO_4$	Accessory in a few chondrites.
*Niningerite	$(Mg,Fe)S$	Accessory in some E chondrites.
*Oldhamite	CaS	Accessory in E and Ae.
Olivine	$(Mg,Fe)_2SiO_4$	Common in stones and stony-irons.
Orthopyroxene	$(Mg,Fe)SiO_3$	Common in stones and stony-irons.
*Osbornite	TiN	Accessory in Ae.
*Panethite	$(Ca,Na)_2(Mg,Fe)_2(PO_4)_2$	Accessory in Dayton iron.
Pentlandite	$(Fe,Ni)_9S_8$	Accessory, mainly in C2 and C3.
Perovskite	$CaTiO_3$	Accessory in C3.
*Perryite	$(Ni,Fe)_5(Si,P)_2$	Accessory in Ae and E chondrites.
Plagioclase	$(Na,Ca)(Al,Si)_4O_8$	Common in stones and stony-irons.
Potash feldspar	$(K,Na)AlSi_3O_8$	Rare accessory in a few irons.
Pyrite	FeS_2	Accessory in Karoonda (C3).
Ouartz	Si_2O	Accessory in some eucrites and E chondrites.
Rhönite	$CaMg_2TiAl_2SiO_{10}$	Accessory in Allende (C3).
Richterite	$Na_2CaMg_5Si_8O_{22}F_2$	Rare accessory in a few irons, and in Abee (E4).
*Ringwoodite	$(Mg,Fe)_2SiO_4$	In Coorara and Tenham chondrites.
*Roedderite	$(K,Na)_2Mg_5Si_{12}O_{30}$	Rare accessory in irons and E chondrites.
Rutile	TiO_2	Rare accessory.
Sarcopside	$(Fe,Mn)_3(PO_4)_2$	Rare accessory in some irons.

TABLE 83.—*The minerals of meteorites*—Continued

Name	Formula	Occurrence
Schreibersite	$(Fe,Ni)_3P$	Accessory in irons, stony-irons, and some chondrites.
Serpentine (or chlorite)	$(Mg,Fe)_6Si_4O_{10}(OH)_8$	Matrix of C1 and C2.
*Sinoite	Si_2N_2O	Rare in some E chondrites.
Sodalite	$Na_8Al_6Si_6O_{24}Cl_2$	Accessory in some C3.
Sphalerite	$(Zn,Fe)S$	Accessory in E chondrites and some irons.
Spinel	$MgAl_2O_4$	Accessory mainly in C chondrites
*Stanfieldite	$Ca_4(Mg,Fe)_5(PO_4)_6$	Accessory in some stony-irons.
Sulfur	S	Accessory in C1.
Taenite	$-(Fe,Ni)$	As for kamacite.
Tridymite	SiO_2	Accessory in some stones, stony-irons, and irons.
Troilite	FeS	Present in most meteorites.
*Ureyite	$NaCrSi_2O_6$	Rare accessory in some irons.
Whewellite	$CaC_2O_4 \cdot H_2O$	Accessory in Murchison (C2).
Whitlockite	See Merrillite	
Wollastonite	$CaSiO_3$	Accessory in Allende (C_3).
*Yagiite	$(K,Na)_2(Mg,Al)_5(Si,Al)_{12}O_{30}$	Rare accessory in Colomera iron
Zircon	$ZrSiO_4$	Rare accessory.

1. Originally reported in the Abee meteorite by Dawson, Maxwell and Parsons (1960), but later identified as the closely related niningerite.

2. Disapproved by Commission on New Minerals and Mineral Names, IMA, because of inadequate characterization.

* Not known to occur in terrestrial rocks.

TABLE 84.—*Analytical data for a selection of stony meteorites*

[Results in parts per million, except as indicated]

Element	Ivuna (C1)		Orgueil (C1)		Mighei (C2)		Murray (C2)		Murchison (C2)		Felix (C3)	
	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.
Li	1.52	3	1.59	3	1.62	3	1.73	3	1.71	3	1.82	3
Be	-	-	-	-	-	-	.035	82	.041	125	-	-
B	7.1	86	5.2	86	-	-	9.40	40	-	-	-	-
C (percent)	4.83	1	3.10	1	2.48	1	2.78	1	2.18	5	0.45	1
N	-	-	3,185	69	1,299	69	1,905	69	1,550	69	86	69
O (percent)	42.5	1	46.8	1	41.8	1	41.9	1	41.1	1	35.7	1
F	70	68	74	68	66	68	-	-	65	68	-	-
Na (percent)	.46	3	.53	3	.46	3	.36	3	.27	3	.46	3
Mg (percent)	9.70	1	9.53	1	11.73	1	11.92	1	12.03	5	14.32	1
Al (percent)	.85	16	.87	16	1.07	16	.98	16	1.14	5	1.33	16
Si (percent)	10.60	1	10.53	1	12.98	1	13.39	1	13.59	5	15.85	1
P	1,800	1	1,200	1	1,300	1	1,400	1	1,000	5	1,500	1
S (percent)	6.70	1	5.49	1	3.66	1	2.80	1	3.00	5	2.00	1
Cl	750	93	770	93	470	93	200	93	-	-	270	93
K	462	3	589	3	426	3	373	3	374	3	360	3
Ca (percent)	1.34	1	.87	1	1.18	1	1.36	1	1.35	5	1.56	1
Sc	5.0	74	5.2	74	7.3	74	9.1	74	8.4	6	12.3	74
Ti	400	1	400	1	500	1	540	1	800	5	600	1
V	-	-	41	92	-	-	71	92	59	39	79	92
Cr (percent)	.22	1	.24	1	.24	1	.30	1	.33	5	.30	1
Mn (percent)	.18	1	.15	1	.16	1	.16	1	.15	5	.16	1
Fe (percent)	19.01	1	18.42	1	21.24	1	21.25	1	22.13	1	25.94	1
Co	450	23	370	23	550	23	490	23	600	5	570	23
Ni (percent)	1.05	1	1.02	1	1.20	1	1.18	1	1.38	5	1.36	1
Cu	132	74	106	74	120	74	119	74	140	39	128	74
Zn	304	20	303	20	187	20	187	20	175	20	111	4
Ga	8.8	23	9.9	23	7.7	23	6.4	23	7.6	39	6.3	23
Ge	31.3	20	31.3	20	19.6	20	24.9	20	23.8	20	21.1	138
As	1.8	23	1.6	23	1.9	83	2.0	23	-	-	1.5	23
Se	19.5	20	19.2	20	11.8	20	12.3	20	11.3	20	7.63	138
Br	5.1	93	3.5	93	3.3	93	.53	20	.42	20	1.33	138
Rb	2.13	142	2.29	142	1.20	20	1.22	20	1.32	20	1.23	138
Sr	7.1	142	7.6	142	8.6	103	9	77	10.5	39	12	77
Y	1.7	2	1.4	2	1.8	2	-	-	1.9	6	2.4	2
Zr	8.6	29	3.1	67	5.8	29	5.2	29	4.6	67	9	77
Nb	.3	33	-	-	-	-	-	-	.6	33	-	-
Mo	1.3	23	1.4	23	1.8	23	1.4	23	-	-	2.2	23
Ru	.74	104	.75	104	.85	104	-	-	-	-	-	-

TABLE 84.—*Analytical data for a selection of stony meteorites*—Continued

Element	Ivuna (C1)		Orgueil (C1)		Mighei (C2)		Murray (C2)		Murchison (C2)		Felix (C3)	
	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.
Rh	-	-	-	-	-	-	-	-	-	-	-	-
Pd	.54	97	.56	97	.59	97	0.79	108	-	-	2.2	109
Ag (ppb)	150	20	200	20	33	20	141	20	172	20	111	138
Cd (ppb)	677	20	661	20	610	20	417	20	379	20	240	4
In (ppb)	82	20	76	20	50	20	51	20	46	20	23	111
Sn	-	-	1.64	124	.7	83	.89	124	1.0	124	-	-
Sb (ppb)	134	20	130	20	231	20	103	20	107	20	67	23
Te	3.08	20	2.99	20	1.75	20	2.02	20	1.80	20	.847	138
I	.9	99	.40	93	.48	93	.30	93	-	-	.26	93
Cs (ppb)	194	20	191	20	137	20	121	20	135	20	76	138
Ba	-	-	2.4	116	2.5	116	-	-	3.1	7	-	-
La	.19	2	.19	2	.29	2	.39	2	.32	6	.34	2
Ce	.58	2	.66	2	.73	2	1.04	2	.88	6	1.08	2
Pr	.090	2	.097	2	.13	2	.15	2	.13	6	.14	2
Nd	.40	2	.44	2	.61	2	.62	2	.56	6	.81	2
Sm	.134	2	.131	2	.20	2	.21	2	.205	6	.28	2
Eu	.055	2	.050	2	.077	2	.072	2	.079	6	.101	2
Gd	.24	2	-	-	.38	2	.27	2	.29	6	.40	2
Tb	.066	2	.022	2	.047	2	.049	2	.056	6	.061	2
Dy	-	-	.22	2	.36	2	.32	2	.33	6	-	-
Ho	.058	2	.054	2	.076	2	.079	2	.084	6	.096	2
Er	.15	2	.13	2	.20	2	.22	2	.23	6	.28	2
Tm	.022	2	.022	2	.030	2	.037	2	.039	6	.037	2
Yb	.11	2	.15	2	.17	2	.18	2	.22	6	.19	2
Lu	.024	2	.022	2	.032	2	.030	2	.037	6	.037	2
Hf	.34	29	.11	67	.14	29	.21	29	.14	67	-	-
Ta (ppb)	-	-	-	-	-	-	17	117	-	-	-	-
W	-	-	.20	127	-	-	.14	119	.14	8	-	-
Re (ppb)	31	20	38	20	47	20	49	20	43	20	65	23
Os (ppb)	560	104	610	104	730	104	685	120	-	-	-	-
Ir (ppb)	521	20	515	20	657	20	633	20	607	20	679	138
Pt (ppb)	1,060	30	980	30	1,070	30	1,050	30	1,320	30	-	-
Au (ppb)	170	30	130	30	170	30	150	30	190	30	200	23
Hg (ppb)	180	23	480	23	200	44	550	23	-	-	1,600	23
Tl (ppb)	160	20	134	20	97	20	94	20	84	20	51	138
Pb	-	-	2.43	140	1.5	116	1.51	37	1.60	38	-	-
Bi (ppb)	112	20	107	20	96	20	66	20	64	20	41	28
Th (ppb)	29	123	28.6	140	46	123	45	123	-	-	-	-
U (ppb)	10.3	20	8.2	140	17	123	12.8	20	14.5	20	14	138

TABLE 84.—*Analytical data for a selection of stony meteorites*—Continued

Element	Mokoia (C3) Amt.	Mokoia (C3) Ref.	Allende (C3) Amt.	Allende (C3) Ref.	Abee (E4) Amt.	Abee (E4) Ref.	Indarch (E4) Amt.	Indarch (E4) Ref.	St. Marks (E5) Amt.	St. Marks (E5) Ref.	Allegan (H5) Amt.	Allegan (H5) Ref.
Li	2.00	3	1.88	3	2.1	84	1.8	84	0.81	84	1.2	84
Be	-	-	.050	125	.020	82	-	-	-	-	-	-
B	-	-	1.0	9	.77	40	-	-	-	-	.50	40
C (percent)	0.47	1	.26	9	.39	10	.43	1	.36	1	.016	87
N	103	69	62	69	270	88	204	69	180	88	30	88
O (percent)	37.1	1	37.0	9	28.8	10	29.0	1	28.9	1	32.8	11
F	170	89	59	68	280	89	220	89	140	89	32	139
Na (percent)	.38	3	.34	9	.75	10	.75	1	.64	1	.63	11
Mg (percent)	14.46	1	14.9	9	11.48	10	10.54	1	11.64	1	13.90	11
Al (percent)	1.55	16	1.74	9	.84	16	.77	16	.76	16	1.03	11
Si (percent)	15.59	1	16.0	9	17.66	10	16.47	1	17.14	1	17.15	11
P	1,600	1	1,100	9	2,600	10	2,200	1	390	1	1,200	11
S (percent)	2.46	1	2.10	9	6.12	10	5.18	1	5.50	1	2.02	11
Cl	370	89	220	9	750	93	570	93	210	89	7	40
K	282	3	268	3	822	15	905	15	960	1	700	11
Ca (percent)	1.82	1	1.85	9	.74	10	.89	1	.87	1	1.18	11
Sc	10.0	74	12.7	17	7.5	74	6.3	74	5.5	74	8.1	74
Ti	600	1	900	9	500	10	400	1	870	1	600	11
V	75	92	93	17	58	17	57	17	55	17	75	92
Cr (percent)	.35	1	.36	9	.35	17	.31	17	.34	1	.37	11
Mn (percent)	.15	1	.15	9	.20	10	.19	1	.29	1	.23	11
Fe (percent)	24.04	1	23.6	9	30.35	10	33.15	1	32.43	1	28.54	11
Co	600	1	610	9	920	17	910	17	880	17	900	74
Ni (percent)	1.29	1	1.42	9	1.66	10	1.83	1	1.81	1	1.76	11
Cu	96	74	130	9	200	18	225	18	215	18	92	74
Zn	64	89	120	9	320	18	430	18	53	18	43	89
Ga	-	-	5.9	131	17.7	17	16.3	17	16.8	17	-	-
Ge	19.7	138	17	9	48	17	51	17	45	17	13	89
As	-	-	3	9	4.74	97	4.31	97	5.5	18	2.26	70
Se	9.39	138	7.4	54	34	18	23	21	30	18	9.1	21
Br	1.94	138	1.48	54	3.3	93	4.8	93	-	-	.16	99
Rb	1.10	138	1.1	140	2.4	21	2.4	21	.8	21	1.87	70
Sr	15	77	13	140	6.9	53	8	77	6	77	8	77
Y	2.4	2	3.1	9	1.0	2	1.5	2	1.7	77	-	-
Zr	10	77	5.9	67	3.8	29	6	77	7	77	9	77
Nb	-	-	.7	9	-	-	-	-	-	-	-	-
Mo	-	-	.2	9	-	-	-	-	-	-	1.70	70
Ru	-	-	.9	9	.97	104	1.01	104	-	-	.93	106

TABLE 84.—*Analytical data for a selection of stony meteorites*—Continued

Element	Mokoia (C3)		Allende (C3)		Abee (E4)		Indarch (E4)		St. Marks (E5)		Allegan (H5)	
	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.
Rh	-	-	-	-	.25	105	-	-	-	-	-	-
Pd	1.3	109	.69	54	1.08	97	.86	97	-	-	1.5	105
Ag (ppb)	158	138	90	54	316	21	377	21	189	21	22	21
Cd (ppb)	315	138	460	54	460	4	800	18	9.7	18	15	110
In (ppb)	32	111	41	54	57	17	78	17	22	17	.20	21
Sn	-	-	68	124	1.65	124	1.5	83	-	-	-	-
Sb (ppb)	41	138	80	54	230	18	240	18	230	18	80	112
Te	1.02	138	.995	54	2.7	18	2.9	18	1.3	18	.3	99
I	-	-	.5	9	-	-	.31	93	-	-	.07	99
Cs (ppb)	82	138	82	54	216	21	240	21	35	21	10	21
Ba	-	-	4.8	7	2.83	32	2.30	32	-	-	4.6	89
La	.46	2	.44	43	.15	2	.21	2	.25	2	.33	2
Ce	1.06	2	1.25	43	.48	2	.59	2	.66	2	.54	2
Pr	.16	2	.20	43	.054	2	.11	2	.13	2	.12	2
Nd	.84	2	.91	43	.24	2	.37	2	.36	2	.65	2
Sm	.31	2	.29	43	.095	2	.14	2	.14	2	.24	2
Eu	.102	2	.107	43	.049	2	.042	2	.045	2	.087	2
Gd	.40	2	.43	43	.16	2	.21	2	.20	2	.34	2
Tb	.073	2	.074	43	.025	2	.031	2	.036	2	.049	2
Dy	.42	2	.42	43	.16	2	.18	2	.21	2	.39	2
Ho	.098	2	.12	43	.040	2	.053	2	.046	2	.082	2
Er	.26	2	.31	43	.131	2	.15	2	.14	2	.22	2
Tm	.047	2	.049	43	.014	2	.023	2	.024	2	.043	2
Yb	.24	2	.32	43	.094	2	.122	2	.134	2	.19	2
Lu	.038	2	.058	43	.019	2	.023	2	.027	2	.038	2
Hf	-	-	.19	67	.10	29	-	-	-	-	-	-
Ta (ppb)	-	-	-	-	-	-	-	-	-	-	-	-
W	-	-	.15	8	.37	127	-	-	-	-	.23	127
Re (ppb)	58	120	69	54	62	97	54	97	68	120	77	120
Os (ppb)	691	120	930	54	780	104	740	104	671	120	870	106
Ir (ppb)	651	138	810	131	500	17	560	17	610	17	750	31
Pt (ppb)	-	-	1,800	30	1,450	30	1,710	30	-	-	1,980	30
Au (ppb)	180	31	160	131	440	17	320	17	340	17	250	30
Hg (ppb)	-	-	60	44	200	122	160	122	430	121	190	70
Tl (ppb)	50	138	58	54	88	18	177	18	2.6	18	3.3	127
Pb	.93	62	1.10	37	1.98	127	2.17	116	-	-	.165	127
Bi (ppb)	44	138	43	54	71	24	81	24	9.7	24	.31	21
Th (ppb)	61	123	62	37	30	123	29	123	30	123	39	123
U (ppb)	18	138	15	37	9	123	11	123	7	123	11	123

TABLE 84.—*Analytical data for a selection of stony meteorites*—Continued

Element	Forest City (H5) Amt.	Forest City (H5) Ref.	Richardton (H5) Amt.	Richardton (H5) Ref.	Guarena (H6) Amt.	Guarena (H6) Ref.	Leedey (L6) Amt.	Leedey (L6) Ref.	Bruderheim (L6) Amt.	Bruderheim (L6) Ref.	Holbrook (L6) Amt.	Holbrook (L6) Ref.
Li	2.0	84	1.7	84	1.6	84	1.7	84	2.6	84	2.1	84
Be	-	-	-	-	-	-	-	-	.034	82	-	-
B	-	-	.37	40	.26	40	1.37	40	.14	40	-	-
C (percent)	.072	87	.032	87	.024	87	.054	87	.040	87	.060	1
N	48	88	51	88	41	88	33	88	32	88	48	88
O (percent)	33.5	1	32.5	1	32.5	11	36.2	1	35.5	12	36.5	1
F	29	139	122	90	-	-	-	-	32	139	43	139
Na (percent)	.73	1	.71	1	.67	11	.85	1	.75	12	.69	1
Mg (percent)	14.24	1	13.38	1	14.14	11	15.00	1	15.05	12	15.18	1
Al (percent)	1.11	1	1.40	1	1.08	11	1.14	16	1.19	16	1.09	16
Si (percent)	17.31	1	16.01	1	17.18	11	18.45	1	18.67	12	18.74	1
P	1,500	1	2,300	1	1,200	11	1,400	1	1,300	12	1,700	1
S (percent)	1.90	1	2.19	1	2.00	11	2.04	1	2.32	12	2.90	1
Cl	-	-	140	40	78	40	-	-	80	93	41	93
K	841	15	812	15	700	11	600	1	667	78	800	1
Ca (percent)	1.24	1	1.00	1	1.14	11	1.42	1	1.24	12	1.24	1
Sc	6.0	74	6.3	74	-	-	10.1	74	8.9	74	8.2	74
Ti	900	1	600	1	700	11	700	1	700	12	800	1
V	57	92	61	92	-	-	54	92	62	92	59	92
Cr (percent)	.37	1	.38	1	.38	11	.37	1	.41	12	.35	14
Mn (percent)	.22	1	.28	1	.25	11	.24	1	.26	12	.29	1
Fe (percent)	27.20	1	29.79	1	28.54	11	22.60	1	22.75	12	21.56	1
Co	800	74	980	74	900	11	360	74	422	78	520	1
Ni (percent)	1.65	1	1.57	1	1.74	11	1.05	1	1.30	12	1.09	1
Cu	91	74	97	74	-	-	108	74	74	26	96	1
Zn	39	1	72	1	-	-	58	1	35	4	49	1
Ga	4.6	95	-	-	-	-	-	-	4.0	23	4.6	23
Ge	4.45	96	6.95	96	-	-	8.71	96	10.1	94	10.1	94
As	2.48	97	-	-	-	-	-	-	1.52	97	1.1	23
Se	5.5	98	7.7	21	-	-	-	-	5.9	23	7.9	23
Br	-	-	-	-	-	-	-	-	.11	26	.7	93
Rb	3.5	77	1.2	21	-	-	3.2	77	3.7	78	2.8	77
Sr	10.1	53	9	77	-	-	11.3	53	10.8	53	9	77
Y	2.2	2	-	-	-	-	-	-	-	-	2.3	14
Zr	5.6	29	6.1	29	-	-	10	77	6.6	67	9	77
Nb	-	-	-	-	.4	33	-	-	-	-	-	-
Mo	-	-	-	-	-	-	-	-	1.1	23	4.6	23
Ru	.94	106	.82	106	-	-	-	-	.71	106	.75	106

TABLE 84.—*Analytical data for a selection of stony meteorites*—Continued

Element	Forest City (H5)		Richardton (H5)		Guarena (H6)		Leedey (L6)		Bruderheim (L6)		Holbrook (L6)	
	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.
Rh	.21	107	-	-	-	-	-	-	.25	105	.15	107
Pd	1.14	97	-	-	-	-	-	-	.68	26	.44	14
Ag (ppb)	130	107	5.1	21	-	-	-	-	60	26	40	107
Cd (ppb)	-	-	20	110	-	-	-	-	13	4	47	110
In (ppb)	1.0	107	.25	21	-	-	.3	111	.07	26	.5	94
Sn	.24	83	.46	96	-	-	.78	96	.30	124	<.07	96
Sb (ppb)	140	83	93	112	-	-	-	-	58	23	67	23
Te	1.63	98	2.31	98	-	-	-	-	.9	79	-	-
I	-	-	-	-	-	-	-	-	.022	79	.03	99
Cs (ppb)	99	53	79	21	-	-	-	-	8	26	146	14
Ba	3.5	116	3.2	115	5.32	7	3.85	114	3.37	114	3.5	116
La	.33	2	.32	2	.541	7	.378	22	.378	22	.45	2
Ce	-	-	.48	2	1.440	7	.976	22	1.031	22	2.1	2
Pr	.12	2	.12	2	-	-	-	-	-	-	.16	2
Nd	.62	2	.61	2	1.045	7	.716	22	.765	22	.79	2
Sm	.22	2	.20	2	.336	7	.230	22	.247	22	.28	2
Eu	.088	2	.080	2	.1065	7	.087	22	.084	22	.092	2
Gd	.40	2	.34	2	.457	7	.311	22	.335	22	.39	2
Tb	.057	2	.053	2	-	-	-	-	.076	78	.068	2
Dy	-	-	.34	2	.568	7	.390	22	.418	22	.42	2
Ho	.068	2	.068	2	-	-	-	-	.107	78	.103	2
Er	.25	2	.20	2	.357	7	.255	22	.271	22	.31	2
Tm	.053	2	.033	2	-	-	-	-	-	-	.043	2
Yb	.19	2	.19	2	.345	7	.249	22	.28	78	.23	2
Lu	-	-	.033	2	.0507	7	.039	22	.039	22	.037	2
Hf	.12	29	.16	29	-	-	-	-	.20	67	-	-
Ta (ppb)	27	117	-	-	-	-	-	-	17	117	25	118
W	.17	119	.13	119	-	-	-	-	.13	119	.19	119
Re (ppb)	99	97	81	120	-	-	-	-	37	23	50	120
Os (ppb)	850	106	814	120	-	-	-	-	530	104	500	120
Ir (ppb)	780	31	730	31	-	-	-	-	490	136	420	136
Pt (ppb)	1,280	30	2,020	30	-	-	-	-	1,390	30	-	-
Au (ppb)	170	30	270	30	-	-	-	-	220	30	190	23
Hg (ppb)	45	44	360	121	-	-	-	-	44	122	22	23
Tl (ppb)	4.7	129	2.5	21	-	-	-	-	.03	129	-	-
Pb	.14	116	.075	37	-	-	-	-	.061	38	.35	116
Bi (ppb)	8.4	24	1.4	21	-	-	-	-	.3	26	2.3	28
Th(ppb)	-	-	34	123	-	-	-	-	-	-	43	123
U (ppb)	13	73	11	123	17	73	11	73	12	38	14	123

TABLE 84.—*Analytical data for a selection of stony meteorites*—Continued

Element	Modoc (L6)		Manbhoom (LL6)		St. Severin (LL6)		Norton Co. (Ae)		Johnstown (Ah)		Chassigny (Ac)	
	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.
Li	-	-	-	-	1.42	40	.33	85	2.20	40	-	-
Be	-	-	-	-	.043	125	.008	82	.013	125	-	-
B	-	-	-	-	-	-	-	-	.34	40	-	-
C (percent)	.17	87	.26	1	-	-	.040	72	.040	72	-	-
N	40	88	-	-	14	42	44	72	31	72	-	-
O (percent)	36.3	1	39.0	1	38.9	11	46.3	1	43.1	45	39.1	46
F	-	-	-	-	-	-	11	91	3.5	91	-	-
Na (percent)	.69	1	.79	1	.74	11	.067	130	.030	45	.11	46
Mg (percent)	14.94	1	15.47	1	15.22	11	24.55	1	15.6	45	19.80	46
Al (percent)	1.32	1	1.19	16	1.25	11	.097	16	.76	45	.19	46
Si (percent)	18.37	1	18.93	1	18.19	11	25.40	1	25.0	45	17.30	46
P	1,300	1	1,500	1	1,000	11	80	77	50	77	180	46
S (percent)	2.36	1	1.89	1	2.12	11	.70	1	.43	45	-	-
Cl	-	-	-	-	121	40	-	-	13	40	-	-
K	900	1	1,100	1	900	11	70	15	9.9	45	270	46
Ca (percent)	1.16	1	1.08	1	1.37	11	.69	1	1.00	45	.54	47
Sc	8.2	74	8.4	74	8.2	74	9.6	74	14.0	2	5.6	47
Ti	700	1	500	1	660	11	340	77	720	45	400	46
V	69	92	65	92	54	36	-	-	147	47	50	47
Cr (percent)	.38	1	.44	1	.40	11	.05	1	.57	45	.57	46
Mn (percent)	.26	1	.25	1	.25	11	.12	1	.42	45	.41	46
Fe (percent)	22.42	1	19.11	1	20.17	11	1.60	1	12.9	45	21.34	46
Co	440	74	250	74	430	74	10	130	19	47	141	47
Ni (percent)	1.30	1	.81	1	1.05	11	.036	130	.006	47	.048	47
Cu	80	26	67	74	71	36	-	-	7	45	-	-
Zn	46	1	65	21	-	-	1.5	4	.86	134	-	-
Ga	6.3	26	-	-	5	36	.066	134	.23	134	-	-
Ge	11.0	94	-	-	-	-	.087	134	.15	134	-	-
As	.92	97	-	-	-	-	-	-	-	-	-	-
Se	12.9	98	6.4	21	-	-	-	-	-	-	-	-
Br	.7	26	-	-	-	-	.08	133	.11	133	-	-
Rb	3.7	77	1.4	21	.62	101	.20	102	.139	45	.4	35
Sr	11	77	-	-	10	36	1.4	77	2.07	45	7.2	35
Y	2.1	2	2.0	2	2	36	2.09	2	1.22	2	.64	35
Zr	8	77	-	-	6	36	.32	141	1.27	141	1.5	35
Nb	.4	33	-	-	-	-	-	-	-	-	.32	35
Mo	-	-	-	-	-	-	-	-	-	-	-	-
Ru	-	-	-	-	-	-	-	-	-	-	-	-

TABLE 84.—*Analytical data for a selection of stony meteorites*—Continued

Element	Modoc (L6)		Manbhoom (LL6)		St. Severin (LL6)		Norton Co. (Ae)		Johnstown (Ah)		Chassigny (Ac)	
	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.
Rh	.16	107	-	-	-	-	-	-	-	-	-	-
Pd	.57	26	-	-	-	-	-	-	-	-	-	-
Ag (ppb)	110	26	85	21	-	-	-	-	-	-	-	-
Cd (ppb)	10	26	63	21	-	-	27	4	14	134	-	-
In (ppb)	.2	26	69	21	-	-	.4	110	.5	134	-	-
Sn	.28	83	-	-	-	-	.08	124	-	-	-	-
Sb (ppb)	63	83	-	-	-	-	15	112	36	112	-	-
Te	.45	26	-	-	-	-	.5	79	.12	79	-	-
I	-	-	-	-	-	-	.10	79	.025	79	-	-
Cs (ppb)	62	26	128	21	-	-	-	-	7.6	45	-	-
Ba	3.3	116	-	-	6	36	-	-	2.5	45	7.1	35
La	.34	2	.31	2	.391	22	.21	2	.044	2	.39	35
Ce	1.5	2	.90	2	.940	22	.81	2	.4	45	1.12	35
Pr	.13	2	.12	2	-	-	.11	2	-	-	.13	35
Nd	.63	2	.65	2	.662	22	.63	2	-	-	.54	35
Sm	.20	2	.24	2	.217	22	.22	2	.080	2	.11	35
Eu	.080	2	.079	2	.085	22	.022	2	.0089	2	.038	35
Gd	.33	2	.26	2	.295	22	.38	2	-	-	.11	35
Tb	.048	2	.059	2	-	-	.061	2	-	-	.02	35
Dy	.30	2	.35	2	.374	22	.40	2	.14	2	.12	35
Ho	.084	2	.089	2	-	-	.100	2	.036	2	.03	35
Er	.23	2	.24	2	.246	22	.25	2	.14	2	.09	35
Tm	.033	2	.036	2	-	-	.036	2	.021	2	-	-
Yb	.15	2	.19	2	.247	22	.22	2	.15	2	.10	35
Lu	.036	2	.033	2	.039	22	.039	2	.033	2	-	-
Hf	-	-	-	-	-	-	.0036	141	.05	141	-	-
Ta (ppb)	-	-	-	-	-	-	4	117	8	45	-	-
W	-	-	-	-	-	-	.05	119	.006	119	-	-
Re (ppb)	23	97	-	-	-	-	-	-	.77	65	-	-
Os (ppb)	-	-	-	-	-	-	-	-	4	106	-	-
Ir (ppb)	520	94	270	136	-	-	.59	134	6.5	134	6	71
Pt (ppb)	-	-	-	-	-	-	-	-	19	127	-	-
Au (ppb)	120	26	-	-	-	-	1.7	134	1.9	134	6	71
Hg (ppb)	-	-	-	-	-	-	14	44	120	121	-	-
Tl (ppb)	-	-	.88	21	-	-	.020	129	5.8	127	-	-
Pb	.079	37	-	-	-	-	.0218	27	4.37	127	1.0	35
Bi (ppb)	.3	26	8.7	21	-	-	.74	24	2.8	61	-	-
Th (ppb)	59	37	-	-	-	-	3.9	19	30	19	57	35
U (ppb)	19	37	18	73	16	73	3.7	19	11.6	19	21	35

TABLE 84.—*Analytical data for a selection of stony meteorites*—Continued

Element	Havero (Au)		Nakhla (An)		Zmenj (Aho)		Bununu (Aho)		Moore Co (Aeu)		Juvinas (Aeu)	
	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.
Li	1.84	48	-	-	-	-	-	-	2.95	53	5.07	40
Be	-	-	-	-	-	-	-	-	-	-	-	-
B	.5	49	-	-	-	-	-	-	-	-	.63	40
C (percent)	1.81	48	-	-	-	-	-	-	-	-	-	-
N	27	42	-	-	-	-	-	-	-	-	-	-
O (percent)	39.5	48	40.9	46	42.7	1	43.5	51	42.9	52	42.8	126
F	1.6	49	120	80	-	-	-	-	79	80	19	126
Na (percent)	.029	48	.31	46	.21	1	.25	51	.33	52	.31	13
Mg (percent)	23.49	48	7.52	46	10.41	76	8.57	51	5.07	52	4.12	13
Al (percent)	.14	48	.77	46	3.43	76	4.69	51	8.24	52	6.69	13
Si (percent)	18.80	48	22.5	46	23.40	76	22.75	51	22.51	52	23.06	13
P	340	48	540	46	200	76	-	-	160	75	400	13
S (percent)	.19	48	.06	46	.31	1	.35	51	-	-	.19	13
Cl	35	49	80	128	-	-	-	-	20	91	18	40
K	97	48	810	46	160	76	300	51	159	53	235	15
Ca (percent)	.08	48	10.78	46	3.89	76	4.84	51	7.92	52	7.38	13
Sc	4.9	49	50	74	-	-	-	-	24	74	29	74
Ti	400	48	1,700	46	1,920	76	700	51	1,900	52	4,100	13
V	78	48	210	80	-	-	-	-	114	47	96	47
Cr (percent)	.526	48	.29	46	.55	76	.38	51	.30	52	.21	13
Mn (percent)	.29	48	.42	46	.405	76	.41	51	.24	52	.41	13
Fe (percent)	14.94	48	16.04	46	13.39	76	14.08	51	12.20	52	14.73	13
Co	140	48	81	25	-	-	-	-	3	74	6.5	25
Ni (percent)	.12	48	.099	80	.007	1	.06	51	-	-	-	-
Cu	14	48	5.03	25	-	-	-	-	4	47	1.65	126
Zn	165	45	42	25	-	-	1.3	134	1.2	144	2.5	144
Ga	1.13	49	2.70	25	-	-	1.2	134	2	55	1.8	145
Ge	7.9	49	2.6	80	-	-	.29	134	.007	144	.044	145
As	1.5	49	-	-	-	-	-	-	-	-	.18	126
Se	.618	137	-	-	-	-	-	-	.5	144	.077	144
Br	.046	137	4.37	25	-	-	-	-	.014	144	.146	25
Rb	.017	137	2.8	25	-	-	-	-	.050	53	.167	53
Sr	.7	49	58	81	-	-	-	-	64	53	77	53
Y	-	-	4.4	2	5.0	132	12.2	132	9	55	17	2
Zr	3.9	49	8.1	141	10.7	132	28	132	22	55	45.6	34
Nb	-	-	-	-	1.2	132	-	-	-	-	2.7	33
Mo	-	-	-	-	-	-	-	-	-	-	.11	70
Ru	-	-	-	-	-	-	-	-	-	-	-	-

TABLE 84.—*Analytical data for a selection of stony meteorites*—Continued

Element	Havero (Au)		Nakhla (An)		Zmenj (Aho)		Bununu (Aho)		Moore Co (Aeu)		Juvinas (Aeu)	
	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.
Rh	-	-	-	-	-	-	-	-	-	-	-	-
Pd	.06	49	-	-	-	-	-	-	-	-	-	-
Ag (ppb)	27	137	40	25	-	-	-	-	3.17	144	21	25
Cd (ppb)	85	50	71	25	-	-	38	134	7.1	144	29	144
In (ppb)	1.5	49	24	25	-	-	6	134	6.52	144	1.6	25
Sn	-	-	-	-	-	-	-	-	-	-	-	-
Sb (ppb)	8.6	137	-	-	-	-	-	-	1.09	144	42	144
Te	.051	50	.15	79	-	-	-	-	.15	79	.29	79
I	-	-	.18	79	-	-	-	-	.14	79	.039	79
Cs (ppb)	1.4	50	287	25	-	-	-	-	.7	53	5.7	53
Ba	-	-	32.5	32	11.4	56	18.5	41	18.6	53	30.2	53
La	.070	49	2.24	32	.71	132	1.59	132	1.24	47	2.5	2
Ce	-	-	5.97	32	2.12	132	4.18	132	3.08	56	7.2	2
Pr	.019	49	.67	2	.23	132	.53	132	-	-	.98	2
Nd	-	-	3.11	32	1.23	132	2.77	132	2.81	56	5.0	2
Sm	.014	49	.815	32	.39	132	.89	132	.938	56	1.7	2
Eu	.0041	49	.249	32	.13	132	.32	132	.591	56	.62	2
Gd	.025	49	.796	32	.50	132	1.09	132	1.22	56	2.6	2
Tb	-	-	.109	2	.09	132	.21	132	-	-	.40	2
Dy	.022	49	.723	32	.64	132	1.38	132	1.62	56	3.0	2
Ho	.0054	49	.140	2	.15	132	.34	132	-	-	.59	2
Er	.018	49	.404	32	.46	132	.97	132	1.01	56	1.8	2
Tm	-	-	.057	2	.085	132	.16	132	-	-	.28	2
Yb	.025	49	.358	32	.49	132	1.00	132	1.08	56	1.37	2
Lu	.0085	49	.0535	32	.080	132	.15	132	.20	47	.23	2
Hf	.055	49	.25	141	.34	132	.85	132	.61	47	1.3	126
Ta (ppb)	-	-	-	-	-	-	-	-	-	-	120	126
W	.18	49	-	-	-	-	-	-	-	-	.041	126
Re (ppb)	30	49	.08	65	-	-	-	-	.06	65	.01	144
Os (ppb)	-	-	.7	66	-	-	-	-	.44	66	.018	144
Ir (ppb)	240	49	17	25	-	-	17	134	-	-	.028	144
Pt (ppb)	410	49	-	-	-	-	-	-	-	-	-	-
Au (ppb)	24	49	.55	25	-	-	4.8	134	.225	144	7.12	144
Hg (ppb)	-	-	230	121	-	-	-	-	2,740	121	700	70
Tl (ppb)	2.6	137	3.1	25	-	-	-	-	.08	144	.75	25
Pb	-	-	.476	63	-	-	-	-	-	-	-	-
Bi (ppb)	.9	137	.50	25	-	-	-	-	-	-	5.0	25
Th (ppb)	-	-	191	19	100	132	240	132	62	19	373	19
U (ppb)	6	49	49	19	-	-	420	132	19.6	19	99	19

TABLE 84.—*Analytical data for a selection of stony meteorites*—Continued

Element	Pasamonte (Aeu)		Nuevo Laredo (Aeu)		Stannern (Aeu)		Angra dos Reis (Aa)		Estherville silicates (M)	
	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.
Li	6.00	40	-	-	7.27	40	2.02	53	-	-
Be	.039	82	-	-	-	-	-	-	-	-
B	1.08	40	-	-	.78	40	-	-	-	-
C (percent)	.069	72	-	-	-	-	-	-	-	-
N	40	72	-	-	-	-	-	-	19	42
O (percent)	42.3	13	42.4	13	42.6	13	41.6	57	42.4	59
F	43	139	51	91	76	139	-	-	-	-
Na (percent)	.33	13	.42	13	.45	13	.026	53	.16	59
Mg (percent)	4.08	13	3.29	13	3.84	13	6.06	57	11.39	59
Al (percent)	6.72	13	6.24	13	6.53	13	4.62	57	3.30	59
Si (percent)	22.72	13	23.12	13	23.06	13	20.54	57	23.39	59
P	400	13	500	13	600	13	570	57	1,400	59
S (percent)	.02	13	.08	13	.26	13	.46	57	1.05	59
Cl	8	40	-	-	34.5	40	-	-	-	-
K	335	75	400	13	550	75	12.9	53	200	59
Ca (percent)	7.33	13	7.43	13	7.56	13	17.52	57	3.70	59
Sc	26	74	38	74	32	74	57	58	18	2
Ti	4,000	13	5,700	13	5,800	13	14,300	53	1,700	59
V	90	47	-	-	86	47	150	58	165	47
Cr (percent)	.23	13	.20	13	.19	13	.17	58	.52	59
Mn (percent)	.43	13	.43	13	.39	13	.07	58	.40	59
Fe (percent)	15.26	13	15.75	13	14.41	13	7.45	58	12.82	59
Co	5.5	25	-	-	7.3	25	20.4	25	-	-
Ni (percent)	-	-	-	-	-	-	.004	58	-	-
Cu	-	-	-	-	1.04	25	10	58	20	47
Zn	3.2	134	-	-	1.2	25	2.1	25	-	-
Ga	1.8	134	-	-	1.7	145	.36	25	-	-
Ge	.040	145	-	-	.08	135	-	-	-	-
As	-	-	-	-	.30	64	-	-	-	-
Se	-	-	-	-	.287	25	-	-	-	-
Br	-	-	-	-	.061	25	.413	25	-	-
Rb	.230	53	.324	53	.696	53	.031	53	.17	100
Sr	80	47	84	47	97	47	133	53	22	100
Y	17	75	-	-	28	2	35	58	5.6	2
Zr	52	141	-	-	95	141	100	58	-	-
Nb	3.6	33	-	-	4.7	33	5	58	-	-
Mo	-	-	-	-	-	-	-	-	-	-
Ru	-	-	-	-	-	-	-	-	-	-

TABLE 84.—*Analytical data for a selection of stony meteorites*—Continued

Element	Pasamonte (Aeu)		Nuevo Laredo (Aeu)		Stannern (Aeu)		Angra dos Reis (Aa)		Estherville silicates (M)	
	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.	Amt.	Ref.
Rh	-	-	-	-	-	-	-	-	-	-
Pd	-	-	-	-	-	-	-	-	-	-
Ag (ppb)	-	-	-	-	40	25	18	25	-	-
Cd (ppb)	61	134	-	-	1.7	25	-	-	<4	110
In (ppb)	3.3	134	-	-	1.2	25	1.4	25	-	-
Sn	-	-	-	-	-	-	-	-	-	-
Sb (ppb)	24	112	-	-	-	-	-	-	-	-
Te	.3	79	-	-	.25	79	-	-	.36	79
I	.11	79	-	-	.88	79	-	-	.030	79
Cs (ppb)	9.5	53	13.8	53	14.2	53	0.4	53	32	113
Ba	29.5	53	39.3	53	53.0	53	21.5	53	15	47
La	3.2	2	4.0	2	4.9	2	8.3	36	1.12	2
Ce	8.1	2	10.7	2	12.9	2	19	36	3.0	2
Pr	1.26	2	1.47	2	2.0	2	3.7	36	.37	2
Nd	5.7	2	8.0	2	10.0	2	17	36	2.1	2
Sm	1.9	2	2.2	2	3.2	2	5.5	36	.68	2
Eu	.68	2	.74	2	.83	2	1.6	36	.21	2
Gd	2.7	2	2.4	2	4.5	2	7.6	36	1.10	2
Tb	-	-	.59	2	.71	2	1.1	36	.14	2
Dy	3.1	2	4.1	2	4.9	2	8.7	36	.97	2
Ho	.69	2	.84	2	1.07	2	2.0	36	.23	2
Er	1.7	2	2.8	2	3.0	2	4.6	36	.62	2
Tm	.30	2	.48	2	.47	2	.56	36	.096	2
Yb	1.7	2	2.3	2	2.4	2	4.2	36	.50	2
Lu	.40	2	.30	2	.38	2	.7	58	.083	2
Hf	1.01	141	-	-	1.26	141	2.6	143	.43	47
Ta (ppb)	120	117	-	-	-	-	370	143	-	-
W	-	-	-	-	-	-	-	-	-	-
Re (ppb)	-	-	-	-	-	-	.07	65	-	-
Os (ppb)	-	-	7.5	106	-	-	.78	66	-	-
Ir (ppb)	.65	134	-	-	.13	134	2.6	25	-	-
Pt (ppb)	-	-	-	-	-	-	-	-	-	-
Au (ppb)	.52	134	-	-	1.9	134	7.2	25	-	-
Hg (ppb)	-	-	78	116	300	64	2,510	121	-	-
Tl (ppb)	-	-	.75	116	.58	25	.86	25	-	-
Pb	-	-	.324	37	-	-	.546	37	-	-
Bi (ppb)	1.1	24	-	-	.37	25	2.4	25	-	-
Th (ppb)	-	-	480	37	679	19	885	37	-	-
U (ppb)	120	60	130	37	214	19	207	37	31	79

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