STRUCTURAL AND COMPOSITIONAL STUDIES ON SELECTED PHASES OF IRON AND STONY-IRON METEORITES.

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ABSTRACT

On the basis of new data for the frequency of band width distributions in a collection of 63 octahedrites, a revised classification into coarse, medium and fine octahedrites has been proposed. A study of the nickel contents and structures of iron meteorites would suggest that the following relationships hold: hexahedrites and nickel-poor ataxites, 5.5-6.0% nickel; coarse octahedrites, 6.0-7.2% nickel; medium octahedrites, 7.0-10.2% nickel; fine octahedrites 7.7-14% nickel; nickel-rich ataxites, 14-23(?)% nickel.

New data on the metal phase of iron meteorites indicate that the gallium and germanium contents are distributed between three distinct levels, confirming a previous observation by Goldberg, Uchiyama and Brown (1951) with regard to gallium. Cobalt and copper values are shown to vary more or less sympathetically with the nickel content. The distribution of chromium would appear to be complicated by the presence of troilite either close to, or contaminating, the sample analysed. Similar data for the metal phase of nine stony-iron meteorites suggest a similarity in nickel content and trace element content of all the samples analysed.

Semi-quantitative determinations have been made of cobalt, chromium, copper, germanium, manganese, nickel, lead, tin, vanadium and zinc in troilite from fourteen iron and two stony-iron meteorites. Similar determinations have been made on schreibersite from two iron meteorites. Semi-quantitative analyses of barium, cobalt, chromium, copper, gallium, germanium, manganese, nickel, tin, titanium, vanadium, and zirconium in olivine from four pallasites, together with macro-analyses and optical data, suggest that the olivine has a constant composition.

The data have been used to calculate new abundances for these elements in meteorites and new data on the geochemical behavior of these elements.

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PART I : INTRODUCTION

The purpose of this work is to re-investigate the quantitative distribution of gallium in iron meteorites using an entirely different analytical method (i.e. emission spectrography) than the neutron activation technique used by Goldberg, Uchiyama and Brown (1951) in their previous study. Quantitative distributions of cobalt, copper, chromium and germanium in iron meteorites were also studied as well as semi-quantitative trace-element content of the silicate phase of pallasites (stony--iron meteorites) and the troilite and schreibersite phase of both pallasites and iron meteorites.

From the collections of the Australian Museum, Sydney, and the Geochemistry Section of the California Institute of Technology, 78 iron and 9 stony-iron meteorites were made available for study. This is a sample of approximately 14 per cent of all the iron and 15 per cent of all the stony-iron meteorites listed in Prior's catalogue (1953).

This collection of iron meteorites is considered to be a more or less random sampling of all types of iron meteorites, at least insofar as no conscious effort was made to acquire any particular struct -ure types. In Table 1 a comparison has been made of the abundance of the various structure types of iron meteorites in the collection used in this study, with the abundances calculated from all the known finds and falls of iron meteorites recorded in the catalogues (Prior 1953). There is a considerable similarity in both values, suggesting that the present collection is a random sample of iron meteorites.

Table 1

	This Collection		All Iron Meteorites of Known Structure (calculations from data given by Prior 1953).	
	Number	Number Frequency	Number	Number Frequency
Hexahedrites and nickel-poor ataxites	11	14%	66	14%
Coarse octahedrites	15	19%	107	23%
Medium octahedrites	34	43.5%	181	39%
Fine octahedrites	14	18%	81	17%
Nickel-rich ataxites	5	6.5%	33	7%
Total	79		468	

Of the various stony-iron meteorites the pallasites are the most common (67 per cent) followed by the mesosiderites (29 per cent), siderophyres (2 per cent) and lodranites (2 per cent). For this investigation eight pallasites and one mesosiderite were available for study. The one mesosiderite (i.e. Pinnaroo) has pallasitic characteristics since olivine is the dominant silicate mineral present.

PART II : EXPERIMENTAL TECHNIQUES

1. METAL PHASE OF IRON AND STONY-IRON METEORITES.

A. Band Width Studies on Octahedrites.

So that compositional studies on the iron meteorites could be related to their structural featrres, the kamacite band widths of the octahedrites of the collection were measured. The widths of the kamacite bands in octahedrites vary according to the relative orientation of the section plane to the structure octahedron. In the absence of knowledge of the orientation of each section, the apparent mean thickness of band widths for each section was determined by measuring a number of band widths for each particular direction in the Widmanstatton pattern and averaging for each of these directions. The mean apparent band width was then given by the mean of each of these average values. When sections were large enough, band widths for any particular direction were measured until the total traverse was at least 100 times the mean band width.

B. Nickel Analytical Technique:

Three samples (averaging 0.2 g) were drilled from a section of each meteorite using a 1/8" diameter tungsten carbide-tipped drill. Any non-magnetic material was removed and the drillings examined under a binocular microscope for possible remaining contamination. Each sample was dissolved in dilute HCl and, generally, this resulted in complete solution. Occasionally insignificant residues (less than 0.1 mg) remained and were discarded. They were probably schreibersite and/or graphite flakes. Goldberg et al. (1951) have demonstrated that results obtained from complete solution of samples (using aqua regia) were essentially identical with those using partial solution with HCl.

It is assumed that the precisions of nickel contents recorded for the present work are similar to those reported by Goldberg et al. (1951) since the same analytical technique was used and also since a series of determinations made on the Canyon Diablo iron meteorite were within the spread reported by them.

C. Trace-element Analytical Techniques.

Samples were drilled from flat surfaces using a 1/8 inch diameter tungsten carbide tipped drill so that each sample was at least 150 mg. Three such samples were taken from each iron meteorite, and dissolved in 6N redistilled contamination-free nitric acid. Solutions containing the internal standards (see below) were then added and the whole evaporated to dryness. The product, a mixture of metal oxides and nitrates, was then heated at 400°C for 15 minutes to convert it completely to oxides.

Because of the difference in levels of concentrations of the trace elements, two series of standards, and two analytical methods were devised covering (i) gallium and (ii) cobalt, copper, chromium, germanium.

(i) gallium : the gallium spectrographic standards were prepared in a synthetic meteorite base composed of iron (91 per cent) and nickel (9 per cent) dissolved in nitric acid and converted to oxides as described in the preparation of the samples. Ahrens (1951) has suggested the use of indium as an internal standard for gallium. In these standards indium was added to give a constant concentration of 100 ppm.

The detection of gallium down to 1 ppm in a base rich in iron and nickel necessitated a special analytical technique. The problem is to resolve the analytical gallium line used (Ga 4032.98) from the strong lines Fe 4032.62 and Cr 4033.07. This was done by 1) using a small (10 μ) slit; 2) using a low amperage (3 amp) and a sodium carbonate-quartz flux to allow selective volatilization of the gallium relative to the iron and nickel; 3) reducing cyanogen background by sodium carbonate-quartz flux. Because of the low temperature of the arc at the amperage used, the first few seconds of the burn are very erratic and unsteady. To obviate this, the exposure was held up until the temperature of the sample had risen sufficiently to volatilize the sodium into the arc.

The precisions of the gallium analyses in various concentration ranges are given in Table 2. The normal method was to analyse, in duplicate, each of the three samples taken from a particular iron meteorite. The duplicate analyses were divided between two photographic plates, to take into account maximum variation in the analytical method. The spread of analyses of the same samples taken over a period of 18 months is shown in Table 3.

An idea of the accuracy of the analytical technique is given in Table 4 in which a comparison is made of results given by the neutron activation technique of Goldberg _et al_ (1951), the fluorimetric technique used by E.B. Sandell and H. Onishi and the emission spectrographic technique used here. Oxide samples and metal drillings from six iron meteorites were submitted to Sandell and Onishi and gallium was determined using a method described by Onishi (1955). Each value reported by them is the result of a single analysis. The gallium content given for each oxide sample has been multiplied by a factor of 1.43 (representing the oxygen dilution of a metal sample when converted to FeO and NiO) to compare it to the concentration in the metal samples. From this comparison it would appear that there is no significant loss of gallium on conversion of the metal sample to an oxide sample.

From Table 4 it is apparent that the results of Goldberg _et al._ (1951)

Table 2

Statistical data on gallium analyses (ppm)

	Region I		Region II		Region III	
	Canyon Diablo	Mooranoppin	Admire	Delegate	Moonbi	Wedderburn
Sample A	72	86	19	20		
	87	83	19	21.5		2.78
	80	80		20	8.15	3.08
B	77	83	19	20	8.95	2.62
	72	81	20	20	9.10	2.93
	75	79		20	8.50	
C	77	73	17	17	7.70	2.46
	75	83	20	20	8.00	
	72	77		15.5		
Mean	76	80	19	20	8.40	2.78
Standard Deviation	±5	±4	±1.4	±2	±0.55	±0.25
% spread	6.6%	5%	7.4%	10%	6.5%	8.7%

Table 3

Re-analyses of samples

(illustrating reproducibilities with regard to changing conditions)

Meteorite	Samples analyzed	No. of analyses in mean	Ga ppm	Ge ppm	Cu ppm	Cr ppm	Co per cent
Bugaldi	A.B.C.	6	<10	<5	95	44	0.48
	A.B.C.	3	< 3	<5	95	39	0.45
Canyon Diablo	A.B.C.	9	76	280	160	<5	0.49
	A.B.	2	82	290	135	<5	0.49
Henbury	I A.B.C.	9	62	210	190	<5	0.49
	II A.B.C.	6	58	190	165	~15	0.44
Kyancutta	A.B.C.	6	20	<50	230	50	0.59
	A	1	18.5	36	170	27	0.50
Roebourne	A.B.C.	6	17	<50	190	44	0.57
	A	1	18.5	36	200	44	0.56
	B	1	17	31	230	39	0.56
Roper River	A.B.C.	6	17	<50	170	<5	0.59
	B	1	18	32	130	<5	0.47
Wedderburn	A.B.C.	6	2.8	<5	640	<50	0.63
	B	1	2.6	<5	510	14	0.59

Table 4

Comparison of Gallium contents (ppm) of metal phase of meteorites determined by three different methods

	Sandell and Onishi			Goldberg et al. (1951) A	This work B	Factor $x = \frac{A}{B}$
	Oxide sample	Oxide sample recalculated to metal	Metal sample			
Admire	-	-	-	21.4	19	1.13
Altonah	2	2.8	2.6	2.31	2.6	0.885
Arispe	-	-	-	55.6	54	1.03
Bear Creek	-	-	-	17.5	17	1.03
Canyon Diablo	61	86	-	76.3	74	1.03
Carlton	-	-	-	13.0	12	1.08
Coahuila	-	-	-	64.5	54	1.19
Duchesne	-	-	2.6	-	3	-
Goose Lake	-	-	-	75.1	57	1.31
Henbury	50	71	80, 70	17.2	60	0.287
Huizopa	-	-	-	2.49	4.3	0.578
Indian Valley	-	-	-	62.9	57	1.10
Perryville	25	36	43 42	37.9	20	1.90
Pinon	-	-	-	2.39	4.6	0.523
Sacramento Mountains	-	-	-	20.4	20	1.02
Sandia Mountains	-	-	-	56.5	54	1.05
Spearman	17	24	-	21.4	20	1.07
Springwater	-	-	-	17.9	15.5	1.15
Toluca (Xiquipilco)	-	-	-	55.2	62	0.890

fall between the high results of Sandell and Onishi and those of this investigation. Generally, there is good agreement between the three methods. The Henbury iron meteorite is exceptional. From the results it appears likely that the iron meteorite labelled "Henbury" and analysed by Goldberg et al. was not the same as the "Henbury" iron meteorite examined originally in this work. To investigate this point further, two separately obtained iron meteorites labelled "Henbury" were analysed. Henbury I came from a specimen purchased from H.H. Nininger and Henbury II was a specimen which has been for some time in the collection of the Geochemistry Section, California Institute of Technology. Both samples show gallium (and germanium, copper, chromium, cobalt) contents well within the spreads of the analysis methods (see Table 3).

A general description of all spectrographic techniques used, is given in Table 5.

(ii) Germanium, copper, chromium, cobalt : the spectrographic standards were prepared using the synthetic meteorite base in the same manner as the gallium standards. Care was taken to keep the solutions free of Cl^- ion so that volatile chlorides (particularly $Ge\ Cl_4$) would not be lost on conversion to oxides.

Ahrens (1951) suggested palladium as an internal standard for the less volatile elements, so 500 ppm of palladium was added to each standard.

The analytical procedure is quite straightforward and is given in Table 5.

The precisions of the analytical techniques applied to the elements germanium, copper, chromium and cobalt are given in Tables 6,7,8 and 9 respectively.

Table 5

Analytical Methods -- Conditions and Procedures

	Metal phase: Ga	Metal phase: Ge.Co.Cr.Cu	Silicate (Olivine)	Sulfide (Troilite) and Phosphide (Schreibersite)
Excitation	3 amps	5 amps	15 amps	15 amps
Slit width	10 μ	10 μ	25 μ	25 μ
Sensitivity control	No filters, etc.	neutral filters	neutral filters	rotating sector
Exposure	Begin 90 sec. exposure after sodium flame appears strongly in arc.	90 secs.	completion of burn	completion of burn.
Sample Dilution	Ga 10 ppm-1:4 (10 per cent Na_2CO_3 in SiO_2) Ga 10 ppm-2:3 (10 per cent Na_2CO_3 in SiO_2)	1:4 carbon	1:1 (10 per cent Na_2Co_3 in SiO_2)	1:3 carbon
Sample weight, etc.	25 mg. Duplicate analysis for each sample. Three samples from each meteorite (see text)	20 mg. As for Ga	25 mg. Duplicate on single samples	20 mg. Duplicate on single samples

Table 5 (continued)

	Ga	Ge.Co.Cr.Cu	Silicate (Olivine)	Sulfide (Troilite) and Phosphide (Schreibersite)
Analytical lines	Ga 4032.98Å	Co 3044.00	Ba 4554.04	Co 3044.00
(M.I.T. Wave-	In* 3256.09	Cr 4254.35	Co 3453.50	Cr 4254.35
length Tables.		Cu 3273.96	Cr 4254.35	Cu 3273.96
1939)		Ge 3039.06	Cu 3273.96	
			Ga 2943.64	Ge 2651.57
		Pd*3242.70	Mn 2933.44	Mn 2933.44
			Ni 3050.82	Ni 3050.82
			Ti 3349.41	Pb 2833.07
			V 4379.24	Sn 2839.99
			Zr 3391.97	V 4379.24
				Zn 3345.93

* Internal standard

Spectograph: Jarrel-Ash 21 ft. diffraction grating instrument with a dispersion of 5.2Å/mm in the first order. J-A. "Varisource" power source.

Excitation (general): 240v. D.C. arc. Sample as the anode. 4 mm analytical gap magnified 5x and focused on the slit. Central 3 mm used with 10-25μ slit width.

Electrodes: High purity 1/4 inch graphite rods as anode. Shape of anode described by Myers (1951). Pointed 1/8 inch cathode.

Wavelength range: 2300-4800 Å first order. Plates: Eastman Kodak III-O.

Processing: Developed at 20°C for 4 minutes in DK-50.

Densitometer: Jarrell-Ash Model J-A 200 (for 10μ slit) A.R.L. Model No.2250 (for 25 μ slit).

Plate Calibration: Method of Dieke and Crosswhite (1943).

Table 6

Statistical data on germanium analyses (ppm)

	Region I		Region II		Region III	
	Bingara No. 2	Osseo	Yarroweyah	Albin	Gundaring	Weekeroo
Sample A	160	300	134	36	39	60
	170	300	165	27	35	56
B	160	340	155	30	39	67
	170	310	135	27	36	56
C	170	320	160	28	40	54
	190	310	145	27	38	56
Mean	170	313	154	29	38	58
Standard Deviation	±11	±15	±12	±3.5	±2	±4.8
% spread	6.5%	4.8%	7.7%	11%	5.5%	8.3%

Table 7

Statistical data on copper analyses (ppm)

	Delegate	Mt. Edith	Negrillos	Roper River	Wedderburn
Sample A	97	160	115	180	700
	120	145	110	180	670
	83				
Sample B	110	155	115	146	700
	110	145	110	164	590
	79				
Sample C	115	134	125	164	530
	105	145	105	173	
Mean	102	147	110	168	638
Standard Deviation	±15	±9	±8	±14	±79
% spread	15%	6%	7%	8%	12%

Table 8

Statistical data on chromium analyses (ppm)

	Altonah	Bendock	Boxhole	Brenham	Mukerup
Sample A	45 53	40 43	60 62	60 52	185 195
B	45 47 39	39 40	53 60	57 66	210 215
C	45 56 53	49 40	64 73	73 68	205 190
Mean	45	42	62	63	200
Standard Deviation	±6.4	±3.7	±6.6	±7	±12
% spread	13%	9%	11%	9%	6%

Table 9

Statistical data on cobalt analyses (per cent)

	Bingara No. 2	Canyon Diablo	Henbury	Mt. Edith	Wedderburn
Sample A	0.53 0.55	0.47 0.51 0.49	0.49 0.50 0.52	0.57 0.55	0.65 0.61
B	0.50 0.52	0.47 0.51 0.51	0.48 0.49 0.51	0.57 0.51	0.63 0.65
C	0.55 0.58	0.46 0.49 0.46	0.48 0.47	0.57 0.51	0.59 0.65
Mean	0.54	0.49	0.49	0.55	0.63
Standard Deviation	±0.028	±0.022	± 0.017	±0.02	±0.025
% spread	5%	4.5%	3.5%	5.5%	4%

2. TROILITE AND SCHREIBERSITE PHASES OF IRON AND STONY-IRON METEORITES.

(i) Troilite: Samples were drilled under a binocular microscope from sections of meteorites using a laboratory model dental machine fitted with S.S. White No. 2 "carbide" dental burrs. These burrs are approximately 1 mm in diameter and are suitable for sampling small areas of troilite relatively free of phases other than FeS. Burnham (1955) has used the same technique in sampling chalcopyrite and sphalerite and concludes that no systematic contamination effects are introduced by this method.

The analysis method (Table 5) has been adapted from that used by Burnham (1955). The standards were the same as those used by him in his study of trace elements in chalcoprite and sphalerite. The base is a relatively pure natural chalcopyrite from Ajo, Arizona to which oxides of cobalt, germanium, manganese, nickel, tin and vanadium have been added. Not included in these standards were chromium, copper and zinc. Separate standards for these elements were available in a base composed of microcline, quartz and iron oxide. Standards covered the concentration range 0.001, 0.01, 0.1, 1.0 per cent.

The mean of at least two determinations, is given, except in the case of zinc where only one determination was made.

The analyses were made over a period of four days and unfortunately insufficient material was available to permit testing the reproducibility of the method for a longer interval of time. There was sufficient Canyon Diablo troilite to allow testing the reproducibility of the method over the limited time of the analysis period. Some 7 samples were run and the results are shown in Table 10. Standard deviation for most elements are reasonably good. Where percentage spreads of 17 percent or more are found, the values are on the lower end of the sensitivity of the element.

(ii) Schreibersite: Samples were prepared and analysed in the same way as troilite; the assumption is made that substitution of phosphorous for sulphur does not produce significant matrix effects. Insufficient material was available to allow any determination of the reproducibility of the analytical method.

3. OLIVINE PHASE OF STONY-IRON METEORITES.

Olivine samples were prepared for analysis by (i) the rapid-silicate method for macro-elements and (ii) a semi-quantitative spectrographic methods for trace-element content.

(i) Rapid Silicate Method: Samples ($2\frac{1}{2}$ - $3\frac{1}{2}$ g) were prepared by chipping olivine fragments from the mass by means of a dental chisel. Unoxidised and uncontaminated fragments were hand picked under a binocular microscope for crushing and finally analysis.

(ii) Spectrographic Method: Samples were drilled in the same method as troilite sampling. Duplicate analyses were also made on the material used for the macro-analysis. The precision of the method has been determined by previous workers in the spectrographic laboratory of the Division of Geological Sciences in the California Institute of Technology as approximately $\pm$ 25 per cent.

Table 10

Statistical data for troilite analyses (based on Canyon Diablo troilite analyses).

	Co ppm	Cr per cent	Cu ppm	Ge ppm	Mn ppm	Ni per cent	Pb ppm	Sn ppm	V ppm	Zn ppm
Plate A	--		720	12	290			--	11	580
	1200		1000	--	380			--	5	400
Plate B	1000	>1%	1000	10	290	≥1%	<5	44	6	
	940		1000	11	330			30	6	
	980		1000	11	270			34	10	
	1000		1000	8	350			30	12	
	1300		1000	8	--			30	15	
Mean	1080	>1%	960	10	320	≥1%	<5	35	8	490
Standard Deviation	±140		±100	±1.7	±40			±6	±3.8	
Per cent spread	13%		10%	17%[a]	12%			17%[a]	47%[a]	

[a] high per cent spread due to very faint line and variable background.

PART III : EXPERIMENTAL RESULTS

1. IRON METEORITES

A. Structure and Nickel Content of Metal Phase.

Table 11 gives the results of the determination of the nickel content of the metal phase of iron meteorites. The band widths of the octahedrites and the structures of the other iron meteorites are also given.

The following notation is used in the tables with regard to the structure of the iron meteorites:

Hexahedrite (H)

Coarsest octahedrite (Ogg)

Coarse octahedrite (Og)

Medium octahedrite (Om)

Fine octahedrite(Of)

Finest octahedrite (Off)

Brecciated octahedrite (Ob)

Nickel-rich ataxite (D_1)

Nickel-poor ataxite (D_2)

Table 11.

Meteorite	Mean Apparent Band width (mm)	Structure Classification: This Work	Structure Classification: Previous Work and Reference	Nickel Content Per Cent: This Work	Nickel Content Per Cent: Goldberg *et al.* (1951)	Nickel Content Per Cent: Previous work.
1 Altonah	0.36[a]	Of	Of(29)	--	8.45 8.64	b
2 Arispe	3-4[a]	Og	Ogg(29)	--	6.57 6.97	b
3 Arltunga	--	Ataxite (anom.)	D_2(45)	10.08(3)[c]	--	10.22 Chapman (45)[d]
4 Ballinoo	<0.1	Of	Off(37)	10.06(3)	--	8.85 Mariner and Hoskins (78) 9.87 O.Sjostrom (14)
5 Basedow Range	1.0	Om	--	7.42(3)	--	--
6 Beaconsfield (Cranbourne)	>2	Og	Og(77)	7.18(3)	--	7.34 O. Sjostrom (11)
7 Bear Creek	0.50	Om	Of(65) Om(29)	--	10.26 10.02	b
8 Bendego	--	Og	Og(19)	--	--	6.80 Derby (19)
9 Bingara No.2	--	H	H(79)	5.75(2)	--	4.75 White (79)
10 Bingara No.3 (Barraba)	--	H	H(50)	--	--	5.55 5.53 Mingaye (50)

Table 11 (continued)

	Meteorite	Mean Apparent Band Width (mm)	Structure Classification: This Work	Structure Classification: Previous Work and Reference	Nickel Content Per Cent: This Work	Nickel Content Per Cent: Goldberg et al. (1951)	Nickel Content Per Cent: Previous work
11	Bingara No. 4 (Warialda)	--	H	H(54)	5.66(3)	--	5.68 Mingaye (54)
12	Bischtube	--	Og	Og(65)	--	--	6.48 Scherer and Sjostrom (12)
13	Boxhole	0.80	Om	Om(2)	7.72(2)	--	7.80 7.54 Alderman (2)
14	Bugaldi	0.40	Of	Of(37)	8.99(3)	--	8.05 Liversidge (42)
15	Canyon Diablo	2.2[a]	Og	Og(29)	--	7.24 7.11	b
16	Carlton	0.2[a]	Of	Of(29)	--	12.68	b
17	Casas Grandes	--	Om	Om(65)	--	--	7.74 Whitfield (47)
18	Coahuila	--	H	H(29)	--	5.61 5.65	b
19	Coolac	>2(56)[a]	Og	Og(36)	6.95(3)	--	4.72 Hodge-Smith (36) 6.78 Henderson (33)
20	Coopertown	--	Om	Om(65)	--	--	9.12 Smith (72)
21	Cowra	--	D_1	Off(7) D_1(62)	13.72(3)	--	13.18 13.28 Mingaye (50)

Table 11 (continued)

	Meteorite	Mean Apparent Band Width (mm)	Structure Classification: This Work	Structure Classification: Previous Work and Reference	Nickel Content Per Cent: This work	Nickel Content Per Cent: Goldberg et al. (1951)	Nickel Content Per Cent: Previous work
22	Cuernavaca	--	0f	0f(17)	--	--	8.76 Hildebrand (17)
23	Delegate	0.80	0m	0m(51) 0m-0g(37)	9.34(3)	--	9.25 Mingaye (51)
24	Duchesne	0.25	0f	0f(57)	--	--	9.20 Hawley (57)
25	Forsyth Co.	--	D_2	D_2(13)	--	--	4.18 de Schweinitz (67) 5.55 Sjostrom (13)
26	Gibeon (Mukerup, Bethany)	0.40	0f	0f(74)	7.96(3)	--	7.68 7.93 Bennett (74)
27	Gladstone	>2	0g	0g-0gg(37) 0gg (66)	6.74(3)	--	6.4 Connah (66)
28	Glenormiston	--	0b	0b(66)	7.12(3)	--	8.74 Connah(66)
29	Goose Lake	1.6[a]	0m	0m-0g(29)	--	8.44 8.48	b
30	Gundaring	0.80	0m	0g(37) 0g-0gg(71)	8.32(3)	--	8.18 Simpson (71)
31	Henbury	0.90	0m	0m(29)	--	7.73 7.59	b
32	Hex River Mtns.	--	H	H(65)	--	--	5.68 Cohen (17)

Table 11 (continued)

	Meterorite	Mean Apparent Band Width (mm)	Structure Classification: This Work	Structure Classification: Previous Work and Reference	Nickel Content Per Cent: This work	Nickel Content Per Cent: Goldberg et al. (1951)	Nickel Content Per Cent: Previous work
33	Huizopa	0.2[a]	Of	Of(29)	-	7.76 7.87	b
34	Indian Valley	--	H	H(29)	--	5.72 5.56	b
35	Kyancutta	1.0	Om	Om(75)	8.28(3)	--	7.30 Hey (75)
36	Langwarrin (Cranbourne)	Irregular >2	Og	Og(77)	7.05(3)	--	6.24 Walcott (77)
37	Magura	Irregular >2	Og	Og(65)	--	--	7.08 Fahrenhorst (16)
38	Misteca	--	Om	Om(65)	--	--	8.21 Manteuffel (10)
39	Moonbi	0.50	Om-Of (anom.)	Of(7)	7.99(3)	--	7.89 Mingaye (48)
40	Mooranoppin	>2	Og	Ogg(69)	6.91(3)	--	7.21 Bowley (69)
41	Mount Dooling	>2	Og	Om (68)	6.41(2)	--	5.96 Simpson (68)
42	Mount Edith	0.60	Om	Om(27)	9.40(2)	--	9.45 Whitfield (27) 9.18 Simpson (69)
43	Mount Magnet	--	D_1	Off(37)	14.72(3)	--	13.56 Simpson (70)

Table 11 (continued)

	Meteorite	Mean Apparent Band Width (mm)	Structure Classification: This Work	Structure Classification: Previous Work and Reference	Nickel Content Per Cent: This Work	Nickel Content Per Cent: Goldberg et al. (1951)	Nickel Content Per Cent: Previous work
44	Mount Stirling	>2	Og	Og(37)	5.93(3)	--	6.72 Bowley (69)
45	Mungindi No.1	0.30	Of	Off(37)	12.18(3)	--	10.96 Knauer (8)
46	Mungindi No.2	0.30	Of	Off(37)	12.36(3)	--	8.23 Mariner and Hoskins (78)
47	Murnpeowie	>2	Og	Og(73)	6.47(3)	--	6.32 Hey (73)
48	Murphy	--	H	H(65)	--	--	5.52 Fahrenhorst (17)
49	N arraburra	0.50	(Om-Of anom.)	Off(37)	10.22(3)	--	9.74 Liversidge (43)
50	Negrillos	--	H	H(65)	--	--	5.32 Henderson (32)
51	Nocoleche	>2	Og	Om(37) Og(18)	6.42(3)	--	2.91 Cooksey 3.62 (+Co) (18)
52	Osseo	>2(69)[a]	Og	Ogg(44)	--	--	6.51 Marble (44)
53	Perryville	--	Ataxite (anom.)	Ataxite (29)	--	8.12 9.63	b
54	Pinon	--	D_1	D_1(29)	--	16.58	b

Table 11 (continued)

	Meteorite	Mean Apparent Band Width (mm)	Structure Classification: This Work	Structure Classification: Previous Work and Reference	Nickel Content Per Cent.: This Work	Nickel Content Per Cent.: Goldberg et al. (1951)	Nickel Content Per Cent.: Previous work.
55	Providence	1.5	Om	Og(82)	--	--	10.30 McHargue (82)
56	Rio Loa	--	H	H(65)	--	--	5.70 Henderson (32)
57	Roebourne	1.25	Om	Om(78)	8.04(3)	--	8.33 Mariner and Hoskins (78)
58	Roper River	0.75	Om	--	9.91(3)	--	--
59	Sacramento Mtns.	--	Om	Om(29)	--	8.17 8.03	b
60	Sandia Mtns.	--	H	H(65))	--	5.94 5.94	b
61	Santa Rosa	--	Og	D_2(65)	--	--	6.52 Sjostrom (15)
62	Sao Juliao	--	Og	Ogg(65)	--	--	6.02 Cohen (9)
63	Scottsville	--	H	H(65)	--	--	5.33 Knauer (17)
64	Spearman	1.25[a]	Om	Om(29)	--	8.00 8.78	b
65	Tawallah Valley	--	D_1	D_1(38)	18.21(3)	--	16.90 Hodge-Smith (38)
66	Temora	>2	Og	Ogg(7)	6.66(3)	--	4.11- (7)
67	Thunda	1.0	Om	Om(37)	8.27(3)	--	8.49 Fahrenhorst (16)

Table 11 (continued)

	Meteorite	Mean Apparent Band Width (mm)	This Work	Previous Work and Reference	This Work	Goldberg *et al.* (1951)	Previous work
68	Tieraco Creek	0.40	Of	Of(39)	10.55(3)	--	9.66 White (39)
69	Tlacotepec	--	D_1	D_1(58)	--	--	16.23 Hawley (58)
70	Toluca(Xiquipilco)	0.90	Om	Om(29)	--	8.31	b
71	Uwet	--	H	H(63)	--	--	5.78 Prior (63)
72	Wedderburn	--	D_1	D_1(23)	22.24(3)	--	23.95 Edwards (23)
73	Weekeroo	--	Ob	Ob(35)	7.51(2)	--	6.89 Hodge-Smith (3
74	Willamette	--	Om	Om(65) Og(40)	--	--	7.88 Davison (40) 8.30 Whitfield (40)
75	Wonyulgunna	0.80	Om	Om(71) Om-Og(37)	9.05(3)	--	8.26 Simpson (71)
76	Yarroweyah	--	D_2	D_2(77)	5.70(2)	--	4.95 Baley and Hall (77)
77	Yenberrie	2	Og	Og(53)	6.97(3)	--	5.98 Mingaye (53)
78	Youndegin	2	Og	Og-Ogg(71)	6.92(3)	--	6.46 Fletcher (26) 7.01 Bowley (71)

[a] band width not determined in this work. Value given by Goldberg *et al.* (1951) or reference (as indicated

[b] for previous analyses see Goldberg *et al.* (1951).

[c] number of analyses.

[d] analyst and reference

B. Trace-element Content of Metal Phase

The gallium, germanium, copper, chromium and cobalt contents of the metal phase of iron meteorites determined in this study are listed in Table 12.

During a preliminary semi-quantitative study of oxide samples of the Coya Norte (hexahedrite), Canyon Diablo (coarse octahedrite), Henbury (medium octahedrite), Altonah (fine octahedrite) and Cape of Good Hope (nickel rich ataxite) iron meteorites, the following elements were recorded as being present in concentrations less than the sensitivities reported in Table 13:

antimony, arsenic, barium, beryllium,
bismuth, boron, cadmium, gold, indium,
lanthanum, lead, manganese ($\leq$ 1ppm),
molybdenum, niobium, platinum, scandium,
silver, strontium, tantalum, thallium,
thorium, tin, titanium, tungsten, uranium,
vanadium, zinc, zirconium.

Table 12

	METEORITE	STRUCTURE	NICKEL PER CENT	GALLIUM ppm This Work	GALLIUM ppm Previous Work and Reference	GERMANIUM ppm This Work	GERMANIUM ppm Previous Work and Reference	COPPER ppm This Work	COPPER ppm Previous Work and Reference	CHROMIUM ppm This Work	CHROMIUM ppm Previous Work and Reference	COBALT Per Cent This Work	COBALT Per Cent Previous Work and Reference
1	Altonah	Of	8.56	2.6	2.31(29)	<5		130		45		0.42	0.44 (29)
2	Arispe	Og	6.77	54	55.6 (29)	230		110		46		0.48	0.49 (29)
3	Arltunga	Ataxite (anom.)	10.08	32		68		300		73	2600(45)	0.63	1.01 (45)
4	Ballinoo	Of	10.06	45		10		255		60		0.54	0.74 (78) 0.60 (14)
5	Basedow Range	Om	7.92	17		30		190		88		0.48	
6	Beaconsfield	Og	7.18	79		260		120	200 (11)	<5		0.48	0.48 (11)
7	Bear Creek	Om	10.14	17	17.5(29)	25		155		<5		0.51	0.67 (29)
8	Bendego	Og	6.80	48		200	400(19)	175		32		0.44	
9	Bingara No.2	H	5.75	66		170		120	100 (79)	33		0.54	0.79 (79)
10	Bingara No.3 (Barraba)	H	—	48		1 25		100	100 (50)	55		0.45	0.52 (50) 0.50
11	Bingara No.4 (Warialda)	H	5.66	46		140		140		53		0.45	0.78 (54)
12	Bischtube	Og	6.48	51		160		110		23		0.42	
13	Boxhole	Om	7.72	15.5		28		130		62		0.50	0.44 (2)
14	Bugaldi	Of	8.99	<3		<5		95		40		0.47	0.37 0.48 (42)
15	Canyon Diablo	Og	7.18	74	76.3(29)	280		160		<5		0.49	0.50 (29)
16	Carlton	Of	12.68	12	13.0(29)	19		200		<5		0.50	0.63 (29)
17	Casas Grandes	Om	7.74	18.5		30		160	120 (47)	51		0.48	0.60 (47)
18	Coahuila	H	5.63	54	64.5(29)	150		120		45		0.45	0.53 (29)
19	Coolac	Og	6.95	92		340		160		<5		0.52	0.26 (36) 0.87 (33)
20	Coopertown	Om	9.12	18		32		110		50		0.49	0.35 (72)
21	Cowra	D_1	13.72	81		15		190		40		0.70	1.04 (50) 1.00 (50)
22	Cuernavaca	Of	8.76	15		37		120		<5		0.59	
23	Delegate	Om	9.34	20		45		100		<5		0.58	

Table 12 (cont.)

	METEORITE	STRUCTURE	NICKEL PER CENT	GALLIUM ppm This Work	GALLIUM ppm Previous Work and Reference	GERMANIUM ppm This Work	GERMANIUM ppm Previous Work and Reference	COPPER ppm This Work	COPPER ppm Previous Work and Reference	CHROMIUM ppm This Work	CHROMIUM ppm Previous Work and Reference	COBALT Per Cent This Work	COBALT Per Cent Previous Work and Reference
24	Duchesne	Of	9.12	~3		<5		125	800 (57)	<5		0.38	0.41 (57)
25	Forsyth Co.	D_2	5.55	57		160		120		50		0.47	0.33 (67)
26	Gibeon	Of	7.96	2.9		<5		185	60 (116) 80 (116)	200		0.39	0.30 (116) 0.55 (116)
27	Gladstone	Og	6.74	91		410		150		<5		0.51	0.10 (66)
28	Glenormiston	Ob	7.12	15.5		73		190		<5		0.52	0.21 (66)
29	Goose Lake	Om	8.46	57	75.1 (29)	220		390		<5		0.52	0.69 (29)
30	Gundaring	Om	8.32	20		38		155		48		0.61	
31	Henbury	Om	7.66	60	17.2 (29)	210		190		<5		0.49	0.70 (29)
32	Hex River Mtns.	H	5.68	46		145		105		30		0.42	
33	Huizopa	Of	7.81	4.3	2.49(29)	<5		135		230		0.38	0.67 (29)
34	Indian Valley	H	5.64	57	62.9 (29)	160		110		42		0.45	0.50 (29)
35	Kyancutta	Om	8.28	18.5		36		200		27		0.55	0.39 (75)
36	Langwarrin	Og	7.05	80		340		195	600 (77)	<5		0.51	0.58 (77)
37	Magura	Og	7.08	82		345		125		<5		0.46	
38	Misteca	Om	8.21	18.5		40		145		60		0.55	
39	Moonbi	Om-Of (anom.)	7.99	8.3		<5		200		350		0.43	0.56 (48)
40	Mooranoppin	Og	6.91	79		400		175		<5		0.50	0.88 (69)
41	Mount Dooling	Og	6.41	62		190		165	200 (68)	40		0.48	0.64 (68)
42	Mount Edith	Om	9.40	17		33		150	100 (69)	<5		0.55	0.63 (69)
43	Mount Magnet	D_1	14.72	8.9		<5		160		<5		0.54	0.77 (70)
44	Mount Stirling	Og	6.93	63		410		225		<5		0.55	0.81 (69)
45	Mungindi No.1	Of	12.18	13		50		290		<5	300 (18)	0.56	0.88 (8)
46	Mungindi No. 2	Of	12.36	15		30		230		<5		0.51	1.36 (78)
47	Murnpeowie	Og	6.47	44		76	70(73)	160	20(73)	190	<50 (73)	0.47	0.32 (73)
48	Murphy	H	5.52	42		145		115		46		0.45	

Table 12 (cont.)

	METEORITE	STRUCTURE	NICKEL PER CENT	GALLIUM ppm This Work	GALLIUM ppm Previous Work and Reference	GERMANIUM ppm This Work	GERMANIUM ppm Previous Work and Reference	COPPER ppm This Work	COPPER ppm Previous Work and Reference	CHROMIUM ppm This Work	CHROMIUM ppm Previous Work and Reference	COBALT Per Cent This Work	COBALT Per Cent Previous Work and Reference
49	Narraburra	Om-Of (anom)	10.22	11		< 5		155	100 (43)	< 5		0.59	0.47 (43)
50	Negrillos	H	5.32	55		135		110		80		0.46	
51	Nocoleche	Og	6.42	45		135		125	700 (18) 300	100		0.47	0.21 (18)
52	Osseo	Og	6.51	82		310		125	1000 (44)	17		0.47	0.11 (44)
53	Perryville	Ataxite (anom.)	8.88	20	37.9 (29)	77		285		97		0.54	0.68 (29)
54	Pinon	D_1	16.58	4.6	2.39(29)	< 5		40		110		0.59	0.87 (29)
55	Providence	Om	10.30	20		30		120	200 (82)	35		0.50	0.30 (82)
56	Rio Loa	H	5.70	48		230		190		36		0.53	
57	Roebourne	Om	8.04	17		35		200		42		0.56	0.59 (78)
58	Roper River	Om	9.91	17		32		150		< 5		0.53	
59	Sacramento Mtns.	Om	8.10	20	20.4(29)	28		165		22		0.48	0.55 (29)
60	Sandia Mtns.	H	5.94	54	56.5 (29)	140		125		25		0.49	0.53 (29)
61	Santa Rosa	Og	6.52	50		165		120		60		0.48	
62	Sao Juliao	Og	6.02	37		73		80		< 5		0.47	
63	Scottsville	H	5.33	58		130		115		43		0.47	
64	Spearman	Om	8.39	20	21.4 (29)	50		180		< 5		0.58	0.56 (29)
65	Tawallah Valley	D_1	18.21	< 1.5		< 5		< 30		54		0.69	1.09 (38)
66	Temora	Og	6.66	91		350		110		< 5		0.45	
67	Thunda	Om	8.27	15.5		39		145	200 (16)	< 5	100 (16)	0.50	0.56 (16)
68	Tieraco Creek	Of	10.55	16		23		110		< 5		0.60	0.72 (39)
69	Tlacotepec	D_1	16.23	< 3		< 5		< 30	900 (58)	170	300 (58)	0.74	0.68 (58)
70	Toluca (Xiquipilco)	Om	8.31	62		155		125		< 5		0.44	0.53 (29)
71	Uwet	H	5.78	45		165		135	< 100 (63)	28		D.47	0.75 (63)
72	Wedderburn	D_1	22.24	3.4		< 5		580		14		0.61	0.50 (23)

Table 12 (cont.)

	METEORITE	STRUCTURE	NICKEL PER CENT	GALLIUM ppm		GERMANIUM ppm		COPPER ppm		CHROMIUM ppm		COBALT Per Cent	
				This Work	Previous Work and Reference	This Work	Previous Work and Reference	This Work	Previous Work and Reference	This Work	Previous Work and Reference	This Work	Previous Work and Reference
73	Weekeroo	Ob	7.51	34		58		170		<5		0.44	0.46 (35)
74	Willamette	Om	8.30	18.5		29		110		50		0.45	0.21 (40)
75	Wonyulgunna	Om	9.05	15.5		34		120		<5		0.51	
76	Yarroweyah	D_2	5.70	50		155		145	1000 (77)	67		0.48	0.81 (77)
77	Yenberrie	Og	6.97	86		340		130	200 (53)	<5		0.49	1.43 (53)
78	Youndegin	Og	6.92	86		320		155	200 (71)	<5		0.49	0.55 (26) 0.92 (71)

Table 13

Sensitivity of elements in semi-quantitative analytical spectrographic techniques

Element	Sensitivity (ppm)	Element	Sensitivity (ppm)	Element	Sensitivity (ppm)	Element	Sensitivity (ppm)
Ag	0.5	Cs	50	Ni	1	Ti	50
As	200	Cu	1	Pb	10	U	500
Au	20	Ga	1	Pt	50	V	1
B	10	Ge	20	Rb	10	W	100
Ba	1	In	10	Sb	200	Y	10
B e	0.8	K	2000	Sc	5	Yb	1
Bi	10	La	100	Sn	5	Zn	100
Ca	1	Li	30	Sr	1	Zr	2
Cd	20	Mn	1	Ta	200		
Co	1	Mo	2	Th	200		
Cr	10	Nb	20	Ti	1		

C. Trace-element Content of Troilite and Schreibersite Phases.

In Table 14 the cobalt, chromium, copper, germanium, manganese, nickel, lead, tin, vanadium and zinc contents of troilite samples from 13 iron meteorites, and troilite from a terrestial occurrence, are listed.

A similar suite of trace-elements has been determined in schreibersite from two iron meteorites (see Table 15).

Table 14

Troilite from iron and stony-iron meteorites

Number	Meteorite	Properties of the metal phase: Structure Type	Properties of the metal phase: Ni content per cent	Properties of the troilite: Surface area on sample (mm^2)	Properties of the troilite: Abundance in Meteorite	Co ppm	Cr ppm	Cu ppm	Ge ppm	Mn ppm	Ni per cent	Pb ppm	Sn ppm	V ppm	Zn ppm
1	Ballinoo[a]	Of	10.06	>64	rare	4400	>1%	1000	50	5	≫1%	≤5	<30	7	500
2	Beaconsfield[b]	Og	7.18	~400		1.50%	—	—	—	—	4.30%	—	—	—	—
3	Brenham	P	10.88	—	—	130	1400	680	7	270	0.15	<5	<30	12	440
4	Canyon Diablo[a]	Og	7.18	>200	common	1080	>1%	960	10	320	≥1%	<5	35	8	490
5	Cape of Good Hope	D_1	16.48	1.0	rare	<10	>1%	56	8	380	0.08	<5	160	70	440
6	Coolac	Og	6.95	8.0	very common	2600	220	130	17	<5	≫1%	<5	<30	8	580
7	[b]Cranbourne A B	Og	6.38	large	common	— 1900	—	700 400			0.44% 0.52%	—			
8	Henbury A B	Om	7.61	>200 4.0	rather common common	8 15	>1% >1%	690 690	7 6	500 680	0.050 0.060	<5 <5	66 62	130 120	440 440
9	[b]Langwarrin A B	Om	7.05	3400		2400 900	tr tr	500 tr			1.02% 0.18%	—			
10	Moonbi	Om-Of (anom.)	7.99	100	rare	<10	>1%	800	7	150	0.13	<5	390	170	330
11	Mt.Stirling	Og	6.93	80	common	3500	170	280	13	5	≫1%	<5	<30	5	360
12	Narraburra	Om-Of (anom)	10.22	8.0	very common	3200	80	190	7	<5	≫1%	<5	<30	5	470
13	Nocoleche	Og	6.42	4.0	rare	2700	>1%	1000	35	180	≥1%	<5	250	200	500
14	Rio Loa	H	5.70	13	rare	150	>1%	1500	9	400	0.28	<5	750	320	580
15	Roper River	Om	9.91	4.0	rare	2800	100	200	7	<5	≫1%	<5	<30	5	440
16	Sandia Mts.	H	5.94	6.0	rather common	160	>1%	1000	8	350	≥1%	<5	390	130	400
17	Springwater	P	13.16	—	—	180	900	500	6	350	0.27	<5	<30	9	470
18	Toluca	Om	8.31	100	rare	2800	>1%	730	6	480	0.60	<5	30	10	400
19	De Norte Co. Terrestrial troilite					1800	>1%	1000	8	120	0.41	<5	40	33 15	740

[a] Following elements less than sensitivity in Table 13
Ag, As, Au, B, Be, Ca, Cd, In, La, Li, Mo, Na, Nb, Pt, Sb, Sc, U, Y, Zr.

[b] Data from Walcott (1915)

Table 15

Analysis of schreibersite from iron meteorites

	Properties of Metal Phase													
	Structure Type	Ni content per cent	Co per cent	Cr ppm	Cu ppm	Ge ppm	Mn ppm	Ni per cent	Pb ppm	Sn ppm	V ppm	Zn ppm	Fe per cent	P per cent
Beaconsfield[a]	Og	7.18	0.62	-	-	-	-	18.16	-	-	-	-	66.92	14.88
Cranbourne[a]	Og	6.38	0.40	-	1000	-	-	22.35	-	-	-	-	70.05	6.93
Bear Creek	Om	10.14	0.35	90	120	9	<5	$\gg 1$	<5	<30	5	500		
Sandia Mountains	H	5.94	0.19	130	160	8	<5	$\gg 1$	<5	<30	6	500		

[a] Analyses from Walcott (1915)

2. STONY-IRON METEORITES

A. Nickel and Trace-element Content of Metal Phase.

In Table 16 the nickel, gallium, germanium, copper, chromium and cobalt contents of the metal phase of 9 pallasites and 1 mesosiderite are listed.

B. Macro and Trace-element of Olivine Phase.

The new determinations of the macro-element content of olivine from the Admire and Springwater pallasites are given in Table 17 and compared with previously published analyses of olivine from the same and other pallasites.

In Table 18 the barium, cobalt, chromium, copper, gallium, germanium, manganese, nickel, tin, titanium, vanadium and zirconium contents of olivine from the Admire, Albin, Brenham and Springwater pallasites are given.

C. Trace-element Content of Troilite Phase.

The trace-element content of troilite from the Brenham and Springwater pallasites is included in Table 14.

Table 16

NUMBER	NAME	CLASSIFICATION	Apparent Band Width (mm)	METAL PHASE: Nickel Per Cent This Work	Nickel Per Cent Previous Work	Gallium ppm This Work	Gallium ppm Previous Work	Germanium ppm This Work	Germanium ppm Previous Work	Copper ppm This Work	Copper ppm Prev. Work	Chromium ppm This Work	Chromium ppm Prev. Work	Cobalt Per Cent This Work	Cobalt Per Cent Previous Work
79	Admire	Pallasite		12.45 [3][b]	6%(46)[a]	19	21.4(29)[a]	33		230		26[d]		0.50	0.02(46) [a]
80	Albin	P		10.43 [3]		23		30		220		<5		0.57	
81	Bendock	P	0.80	9.20 [3]	7.81 (49)	17		40		140		<5		0.58	0.53 (49)
82	Brenham	P		10.88 [2]	10.35 (41) 8.59 (80)	20		65		170	300(41)[a]	<5		0.60	0.57 (41)
83	Glorieta Mtn.	P	0.4-1.0 (6)[a]	11.79[c]	10.39 (3)	14		18		220	<100 (3)	<5		0.54	0.42 (31) 0.84 (3)
84	Imilac	P		11.32 [3]	11.88 (25)	20		36		190		<5		0.47	
85	Newport	P	0.80	10.83 [2]		19		30		240		<5		0.58	
86	Pinnaroo	Mesosiderite		9.50 [2]	8.94 (2)	19		60		200		70[d]		0.51	0.15 (2)
87	Springwater	P		13.16 [2]	10.72 (59)	16	17.9 (29)	35		170	900(59)	<5	250(59)	0.60	0.53 (59)
	Mean			11.06		19		39		200		<5[e]		0.55	
	Standard Deviation			± 1.29		±2.5		±15		±33				±0.046	
	Per Cent Spread			11%		7%		38%		16%				8%	

[a] Reference.

[b] Number of determinations.

[c] Determination by Henderson (1941a) using same analytical technique.

[d] Sample contaminated by troilite.

[e] Contaminated samples omitted from mean.

Table 17

Analyses of Silicate Phase (Olivine) of Pallasites

	Admire		Alice Springs		Brenham	Molong	Springwater	
	Merrill (Tassin)[a] (1902)	This Work (Blake)	Spencer and Hey (1932)	Winchell (1890)	Eakins (1891)	Mingaye (1891)	This Work (Blake)	Mean
SiO_2	39.14	40.26	37.24	40.50	40.70	40.40	38.54	39.61
TiO_2		0.36					0.03	0.02
Al_2O_3		0.53		–	Tr	0.17	1.26	0.65
FeO	13.185	10.57	16.92	10.51	10.79	9.95	15.35	11.43
Fe_2O_3		0.84		1.77	0.18	0.45	0.76	0.80
CaO		0.00	1.26				0.00	0.00
MgO	47.63	47.21	43.88	47.18	48.02	47.70	43.28	46.21
Na_2O		0.00				0.03	0.00	0.00
K_2O		0.00					0.00	0.00
H_2O-		0.00				0.12	0.04	
H_2O+		0.08				1.52	0.04	
P_2O_5		0.03					0.29	
MnO		0.25			0.14	0.02	0.34	0.19
NiO					0.02			

Table 17 (continued)

	Admire		Alice Springs	Brenham		Molong	Spring-water	
	Merrill (Tassin)[a] (1902)	This Work (Blake)	Spencer and Hey (1932)	Winchell (1890)	Eakins (1891)	Mingaye (1916b)	This Work (Blake)	Mean
CoO						0.06		
Cr_2O_3		0.07					0.12 (0.02)	
S =		0.02					0.01	
Total	99.955	99.91	99.3	99.96	99.85	100.24	100.04	
Less O for S		0.01					0.01	
		99.90					100.03	

a Analyst underlined

Table 18

Trace element content of silicate phase (olivine) of pallasites

	Admire		Albin		Brenham		Springwater	
Element	I	II	I	IA	IB	I	II	Mean
Ba ppm	<1		2	<1	<1	<1		<1
Co ppm	15	8	15	90	75	30	10	35
Cr ppm	250	250	150	100	100	100	100	150
Cu ppm	~1	6	2	4	6	8	10	4
Ga[a] ppm	<2	<2	<2	<2	<2	<2	<2	<2
Ge ppm	<20	<20	<20	<20	<20	<20	<20	<20
Mn ppm	2000	2000	2000	1500	1500	2000	3000	1900
Ni ppm	150	80	150	450	250	350	100	250
Sn ppm	<10	<10	~10	<10	<10	<10	<10	<10
Ti ppm	20	40	60	10	10	10	40	25
V ppm	15	20	15	20	15	10	30	15
Zr ppm	<4		~10	<4	<4	<4		<4
Looked for but not found[b]	Ag, As, Au, Be, Bi, Cd, In, La, Mo, Nb, Pb, Pt, Sb, Sr, Ta, Th, Tl, U, W, Y, Yb, Zn.							

[a] Fe Interference

[b] Sensitivity Table 13.

I: drilled micro-sample

II: macro-sample (Admire and Springwater samples from macro-analysis sample)

PART IV: DISCUSSION

1. IRON METEORITES

A. A Revised Structure-Nickel Content Classification

It is generally recognized that iron meteorites may be classified into the groups hexahedrites, octahedrites and ataxites according to the structures shown by the α and/or γ phases of the iron-metal alloy which constitutes the metal phase. Within the octahedrites, Brezina (1885) suggested a secondary classification based on a number of arbitrary divisions in the range of kamacite band widths in octahedrites (See Table 19). To gain a clearer understanding of the genesis of octahedrites, it is better to base a sub-classification on the distribution frequency band widths within the octahedrites.

Figure 1 is a histogram showing the distribution frequency of band widths in a collection of 63 octahedrites. It should be noted that the band widths are on a logarithmic scale. This scale is used to even out the effects of the changing accuracy of measurement over the large range in band widths observed. Band widths were determined for this study or, in the case of a few octahedrites, were obtained from the literature where the description was adequate.

The histogram shows three well defined peaks suggesting a classification of octahedrites into three groups. To test the level of significance of this observation the chi squared test was applied. Essentially this test consists in fitting a normal (in this case log-normal) distribution curve to the observed distribution and seeing to what extent the population studied differs from this log-normal distribution. The result of this calculation shows that the observed chi^2 (28.31) is larger than the value $(\text{chi})^2_{99.5}$ for 5 degrees of freedom which is derived from tables. We cannot accept, even at the ½% level of significance, the hypothesis that the distribution given in Fig.1 is essentially log-normal.

The size range of band widths is continuous so that break-off points for the three divisions are somewhat arbitrary; the points were chosen close to the centre of the band-width range of lowest frequency. Figure 1 and Table 19 show the relationship of the Brezina classification to this new classification.

Table 19

Comparison of octahedrite structure classifications

Classification	Kamacite Band widths (mm) Brezina (1885)	This work
Coarsest octahedrite (Ogg)	≥ 2.5	-
Coarse octahedrite (Og)	1.5 - 2.5	>2.0
Medium octahedrite (Om)	0.5 - 1.0	0.5 - 2.0
Fine octahedrite (Of)	0.15 - 0.4	0.05-0.5
Finest octahedrite (Off)	0.05 - 0.10	-

The slight minimum in the range 0.2 - 0.28 mm was not considered to be significant so that the finest octahedrite (Off) group of Brezina could not be recognized. The lower boundary (0.05 mm) for the Of group has been arbitrarily chosen to correspond to the lower boundary in Brezina's classification.

These data show that the Om group is the most common, comprising approximately 50 per cent of the octahedrites studied. Coarse and fine groups are equal at 25 per cent.

Increased nickel content of the metal phase is generally related

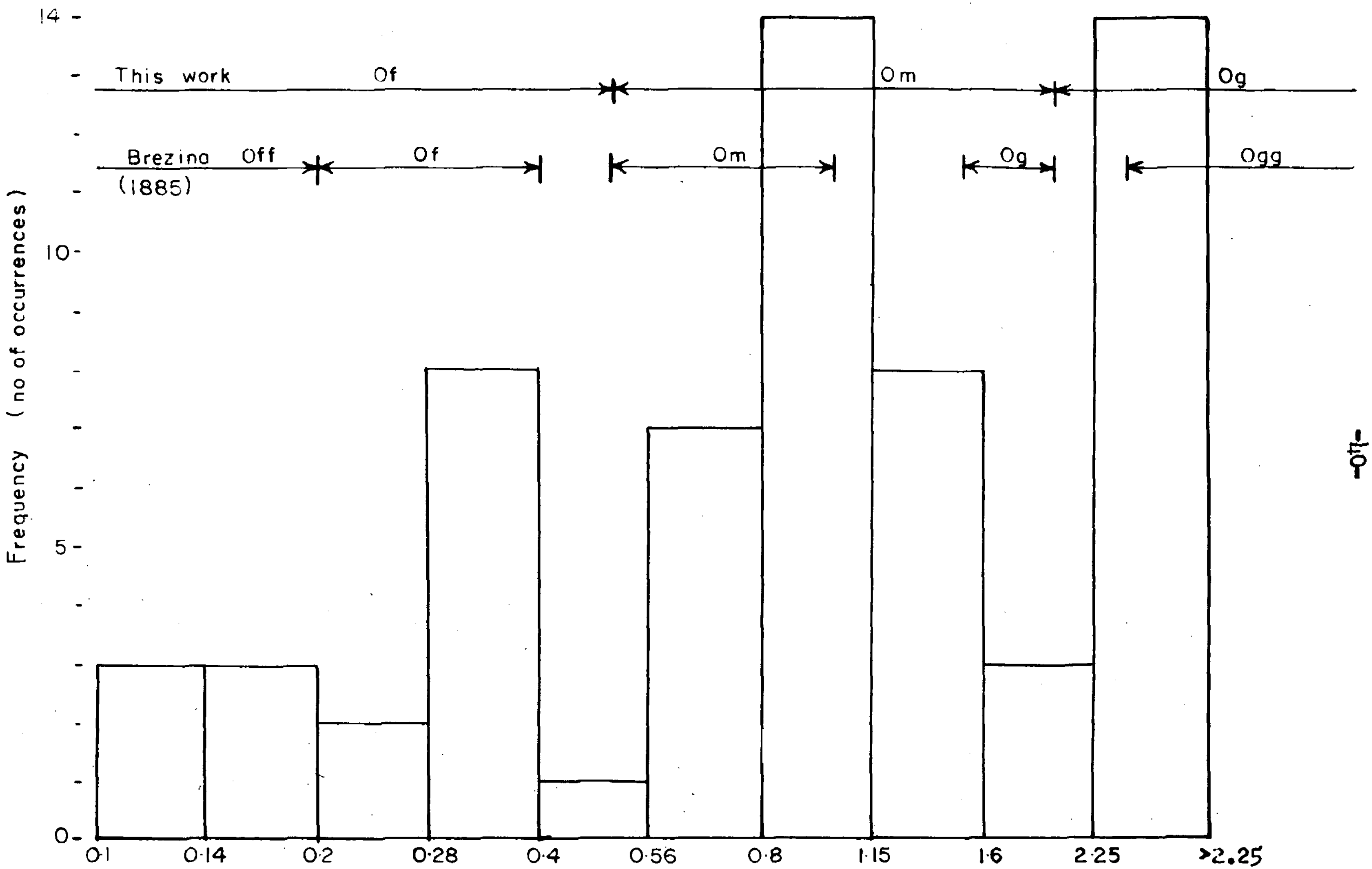


Fig. 1. Distribution of mean apparent band widths (mm) in octahedrites

to a decrease in the completeness of the $\gamma \rightarrow \alpha$ iron-nickel transformation. The nickel contents of 79 iron meteorites (17 per cent of all the iron meteorites for which a structure classification is known) are now known accurately (see Table 11) and it is possible to illustrate the frequency of distribution of nickel in the iron meteorites (See Fig.2).

We can, therefore, derive the following relationships between the structure and the nickel content of the iron meteorites:

(1) Hexahedrites and nickel poor ataxites form the first peak in the frequency of nickel distribution. They have nickel contents within the range 5.5 - 6.0 per cent nickel (mean 5.63 per cent).

(2) The coarse octahedrites start at 6.0 per cent nickel and are most abundant between 6.5 - 7.0 per cent nickel (mean 6.78 per cent). The largest nickel content found was 7.2 per cent nickel.

(3) There is a slight overlap between the end of the coarse octahedrites and the beginning of the medium octahedrites at 7.0 per cent nickel. The medium octahedrites are the most abundant iron meteorites; their maximum abundance lies between 7.5 - 8.5 per cent nickel. The largest nickel content found was 10.2 per cent nickel (mean 8.48 per cent).

(4) The fine octahedrites considerably overlap the Om types, beginning at about 7.7 per cent nickel and continuing up to 14 per cent nickel (mean 10.09 per cent) where the Widmanstatten structure ceases and the nickel-rich ataxites appear.

(5) Nickel-rich ataxites are scattered within the range 14.0 per cent nickel to greater than 22.25 per cent nickel (mean 16.88 per cent).

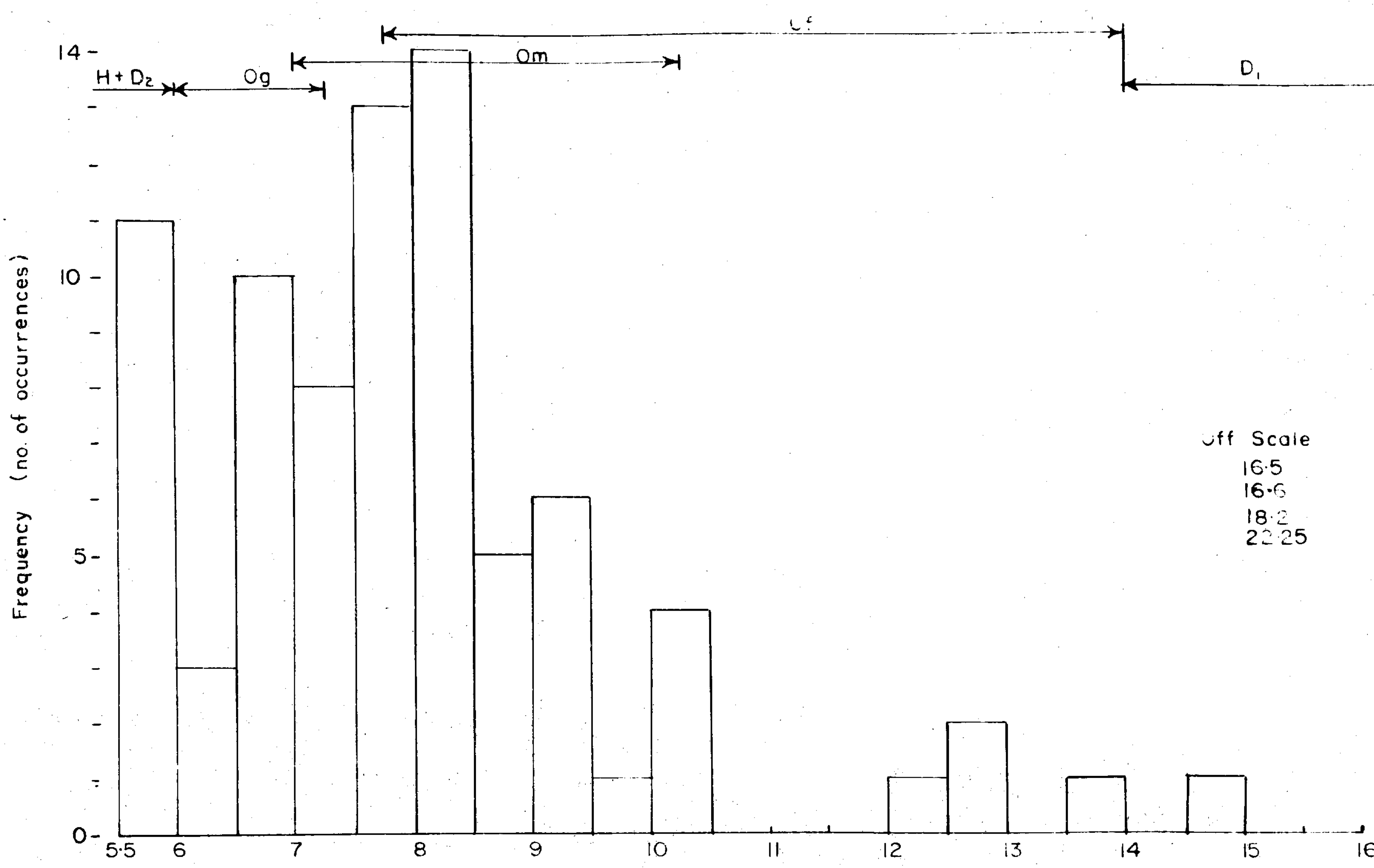


Fig. 2. Distribution of nickel (% in metal phase of iron meteorites

The limits of nickel content in iron meteorites has been in doubt for some time. Farrington (1907) reported the range as 2.10 per cent to 29.99 per cent nickel with one iron meteorite (Oktibbeha nickel-rich ataxite) at 62.01 per cent. With regard to the Oktibbeha ataxite, Farrington (1907) doubted its authenticity entirely on the basis of the unusually high nickel content. In spite of its being the only meteorite greater than 30 per cent nickel, the Oktibehha iron meteorite is most likely a legitimate meteorite. Its reported nickel content is used as the known upper boundary for iron meteorites.

It is of interest to compare the nickel content ranges reported by Berwerth (1914) in his classification of iron meteorites:

Table 20

		Nickel content
I.	Kamacite types (Includes Ogg)	6 per cent
II.	Octahedrite types	
	Og	7-7.5 per cent
	Om	7.5-9 per cent
	Of	9-11 per cent
	Off	11-14 per cent
III.	a) Plessite type	14-18 per cent
	b) Taenite (+ rare plessite) type	26 per cent

On the basis of the present work it is suggested that the structure classification of iron meteorites be revised as shown in Table 21.

The Moonbi and Narraburra iron meteorites are anomalous octahedrites. They both have mean apparent band-widths of 0.50 mm which places them on the border of Om and Of types, and so are classified as anomalous Om-Of iron meteorites.

Table 21

A revised classification of iron meteorites

Type	Characteristic structure and phases present	Band width (mm)	Nickel (per cent)
Hexahedrites H	Normally structurally homogeneous kamacite (α iron-nickel) but occasionally granular. Neumann bands common.	–	5.5–6.0
and Nickel-poor ataxites D_2	Normally kamacite without structure		
Octahedrites: Coarse Og	Widmanstatten pattern coarse to vague—taenite (γ iron-nickel) lamellae thin and rare. Plessite rare and typically coarse or granular.	>2.0	6.0–7.2
Octahedrites: Medium Om	Widmanstatten pattern obvious–taenite conspicuous and plessite (coarse and dense) abundant.	0.5–2.0	7.0–10.2
Octahedrites: Fine Of	Widmanstatten pattern fine to barely visible to the eye–mostly dense plessite with some narrow, widely separated kamacite bands.	0.05–0.5	7.7–14
Nickel-rich ataxites D_1	Normally dense plessite with some scattered kamacite.	—	14—27
	Taenite only	—	27–62

Perryville is another anomalous iron meteorite, but one with somewhat different properties. It was discussed by Goldberg et al (1951) as an ataxite with anomalous nickel values (8.12 and 9.63 per cent determined by different observers.) An iron meteorite with almost identical behavior is the Arltunga. It has a higher nickel content (10.08 per cent) but the structure is similar. Mawson (1934) described it as an ataxite or micro-octahedrite. Both Perryville and Arltunga iron meteorites are much lower than the 14 per cent lower limit of the nickel-rich ataxites.

It may be that these iron meteorites represent altered normal octahedrite types (c.f. the metabolites of Prior 1953) but the process by which any known type of octahedrite might be changed so as to have all the properties of these iron meteorites is not clear.

The so-called "brecciated" octahedrites (or better granular octahedrites Ob) are represented by the Glenormisten and Weekeroo iron meteorites. They bear a close resemblance to the behavior of the anomalous ataxites, the pairs Arltunga-Weekeroo and Perryville-Glenormisten are essentially identical. The nickel contents of the Ob-type iron meteorites would put them on the Og-Om border. The Glenormiston has the lower nickel content (7.12 per cent), with a structure made up of an irregular aggregate of elongated kamacite grains with some taenite and plessite. The Weekeroo has a slightly higher nickel content (7.51 per cent) with a unique structure.

Irregularly oriented areas, each displaying coarse octahedral structures, have been described by Hodge-Smith (1932). Silicate inclusions (less than one per cent) were also observed.

The origin of these anomalous iron meteorites is not obvious.

B. Trace-element Distribution in the Metal Phase.

(i) Distribution of gallium:

Figure 3 shows the trimodal distribution of gallium in the metal phase of iron meteorites, confirming the observations of Goldberg *et al.* (1951). A logarithmic plot of the gallium contents of various structure classes of iron meteorites against nickel concentrations (Fig. 4.) indicates that the gallium levels are concentrated in three distinct regions. The Ga concentration limits of these regions as determined by Goldberg *et al.* agrees well with those found in the present study.

Table 22.

	Ga(ppm)		Ni (Per cent)	
	Goldberg	This Work	Goldberg	This work
Region I	45-100	42-93	5.5-8.7	5.3-8.5
Region II	17-22	15-20	7.5-12.8	7.6-12.4
Region III	1.7-2.5	~1-5	7.7-17	7.8->23

The decreased sensitivity of the spectrographic method at Ga <5 ppm is the cause of the diffuseness of Region III.

Approximately 11 per cent of the 78 iron meteorites studied had Ga values outside these well-defined limits.

Region I: includes all hexahedrites, nickel-poor ataxites and coarse octahedrites within the range 5.3-7.2 per cent Ni. From 7.2-8.5 per cent Ni it includes 14 per cent of the medium octahedrites analyzed (Henbury, Toluca, Goose Lake). Toluca and Goose Lake had both been found to lie in this Region by Goldberg *et al.*

Region II: includes 86 per cent of the medium octahedrites with nickel contents 7.6 - 10.3 per cent. Two fine octahedrites (approximately 18 per cent of type Of iron meteorites analyzed) lie between 10.2 - 12.4 per cent Ni.

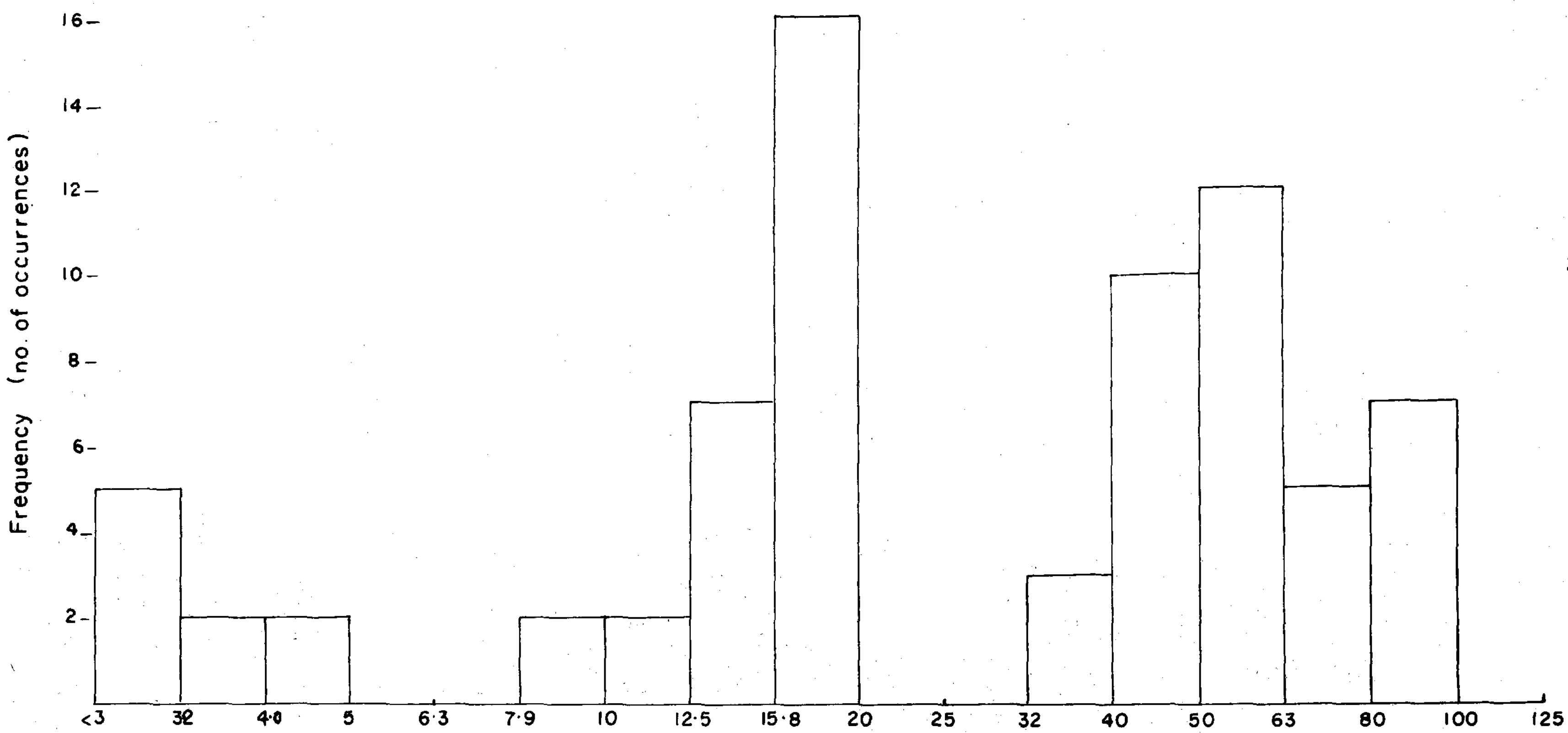


Fig. 3. Distribution of gallium (ppm) in metal phase of iron meteorites

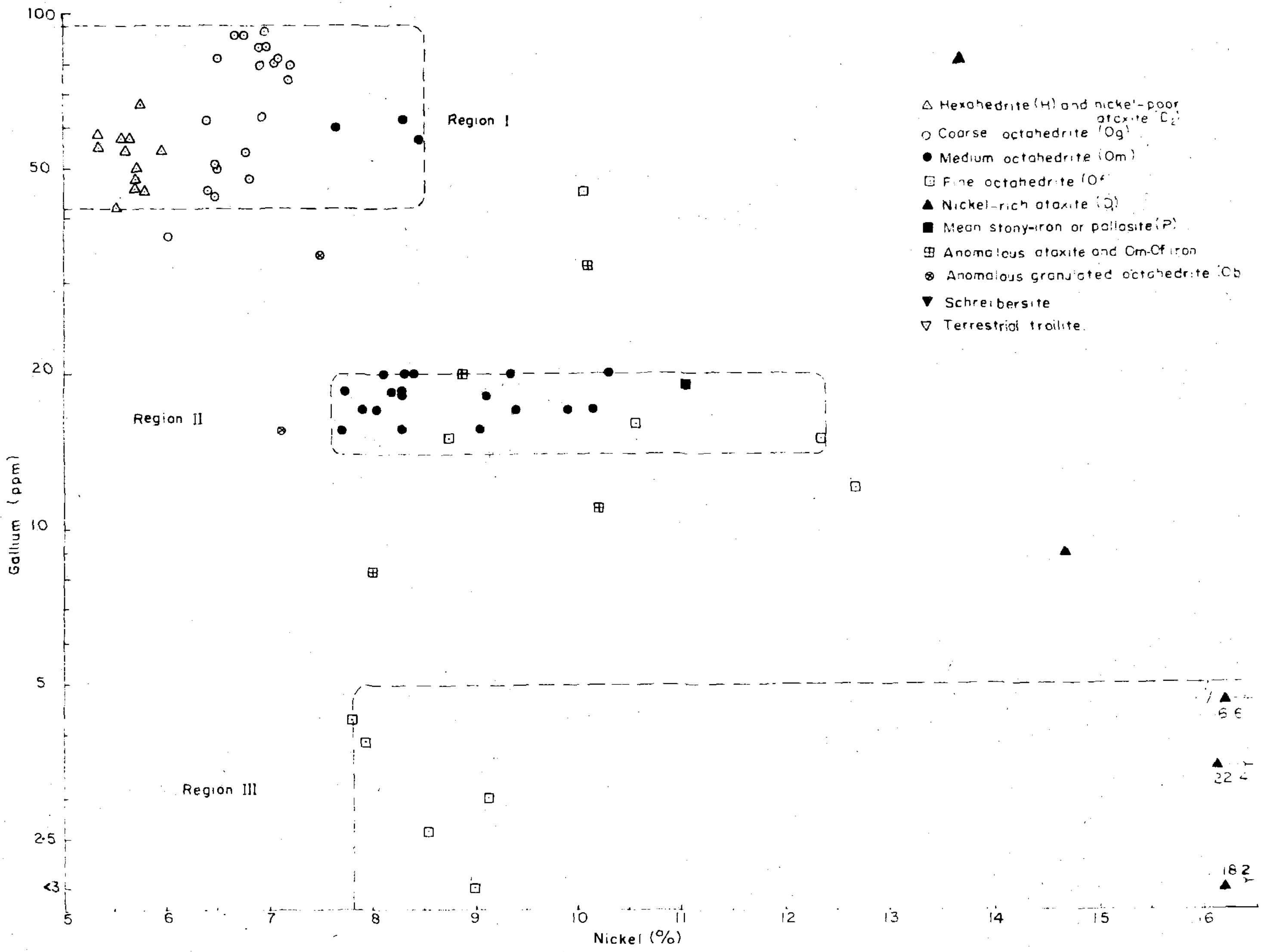


Fig. 4. Gallium - nickel in metal phase of iron meteorites

Region III: includes 25 per cent of all fine octahedrites analyzed, these lie between 7.8 - 9.1 per cent Ni and 67 per cent of the nickel-rich ataxites up to the observed limit of 22.4 per cent Ni.

The Cowra (D_1) and Ballinoo (Of) iron meteorites lie within Region I but have nickel contents greater than 8.5 per cent.

The Sao Juliao (Og), Weekeroo (Ob) and Arltunga (anom. ataxite) iron meteorites lie between Regions I and II.

The Narraburra and Moonbi (Om-Of), Carlton (Of) and Mt. Magnet (D_1) iron meteorites lies between Regions II and III.

Of particular interest is the observation that iron meteorites with nickel contents between 7.6 - 8.5 per cent may lie in either one of the three levels. Of these iron meteorites, those with Om structure may lie in Regions I or II and those with Of structure only in Region III.

There is a general trend for the Ga content to decrease as the nickel content increases.

(ii) Distribution of germanium: Figure 5 suggests a trimodal distribution of germanium in the metal phase or iron meteorites. A logarithmic plot of the germanium contents of various structure classes of iron meteorites against nickel contents (Fig. 6) shows that germanium contents are concentrated in three distinct regions. Only 15 per cent of the iron meteorites studied fall outside these well-defined limits. <u>The iron meteorites lying in each of these regions are the same as those in the corresponding Ga regions</u>.

Thus we may directly compare the gallium and germanium contents of each of the three regions.

Table 23

	Per cent of iron meteorites in Region	Ge ppm	Ga ppm	Ni per cent
Region I	52.3%	123-410	42-93	5.3 - 8.5
Region II	33.5%	23-50	15-20	7.6 -12.4
Region III	14%	<5	~1-5	7.8 ->23

Region I: includes all hexahedrites, nickel-poor ataxites and coarse octahedrites (except the Sao Juliao and Murnpeowie iron meteorites). The medium octahedrites Goose Lake, Henbury and Toluca fall in this Region.

Region II: includes all other medium octahedrites and three fine octahedrites (Cuernavaca, Mungindi, Tieraco Creek).

Region III: includes most of the fine octahedrites and all nickel-rich ataxites (except Cowra). The Sao Juliao (Og) Murnpeowie (Og) Glenormiston (Ob), Weekeroo (Ob), Arltunga (anom ataxite), and Perryville (anom. ataxite) iron meteorites lie between Regions I and II. The Carlton (Of), Ballinoo (Of) and Cowra (D_1) iron meteorites lie between Regions II and III.

As with Ga, iron meteorites with nickel contents in the range 7.6 - 8.5 per cent may lie in Regions I, II or III.

There is an overall tendency for Ge to decrease with increasing Ni content.

Relation between gallium and germanium:

The following general remarks may be made:

(1) The definition of Regions I, II and III are quite distinct. Iron meteorites with Ga contents lying within a Region have Ge contents which correspond to the same Region. Region III is rather diffuse due to

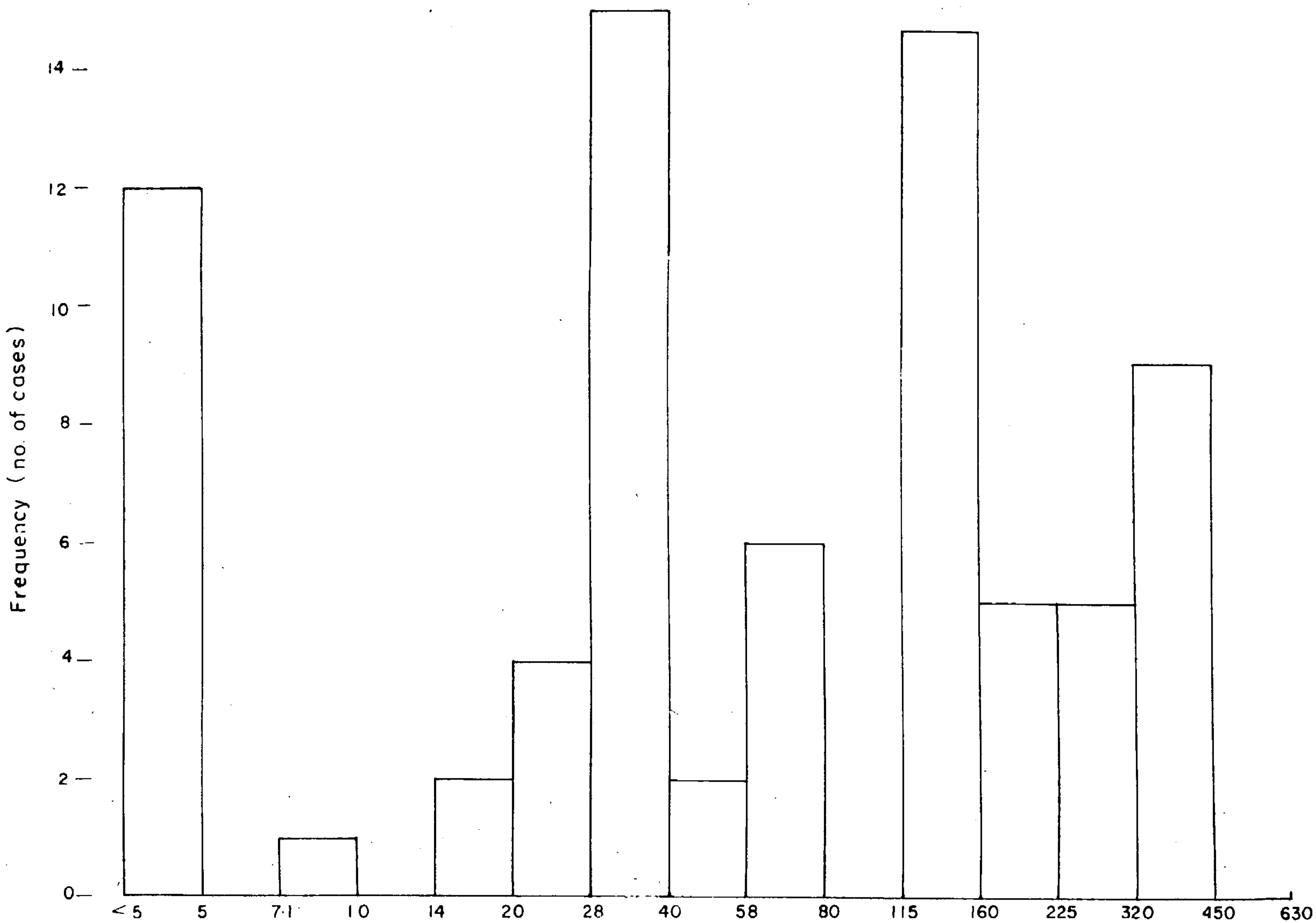


Fig. 5. Distribution of germanium (ppm) in metal phase of irons

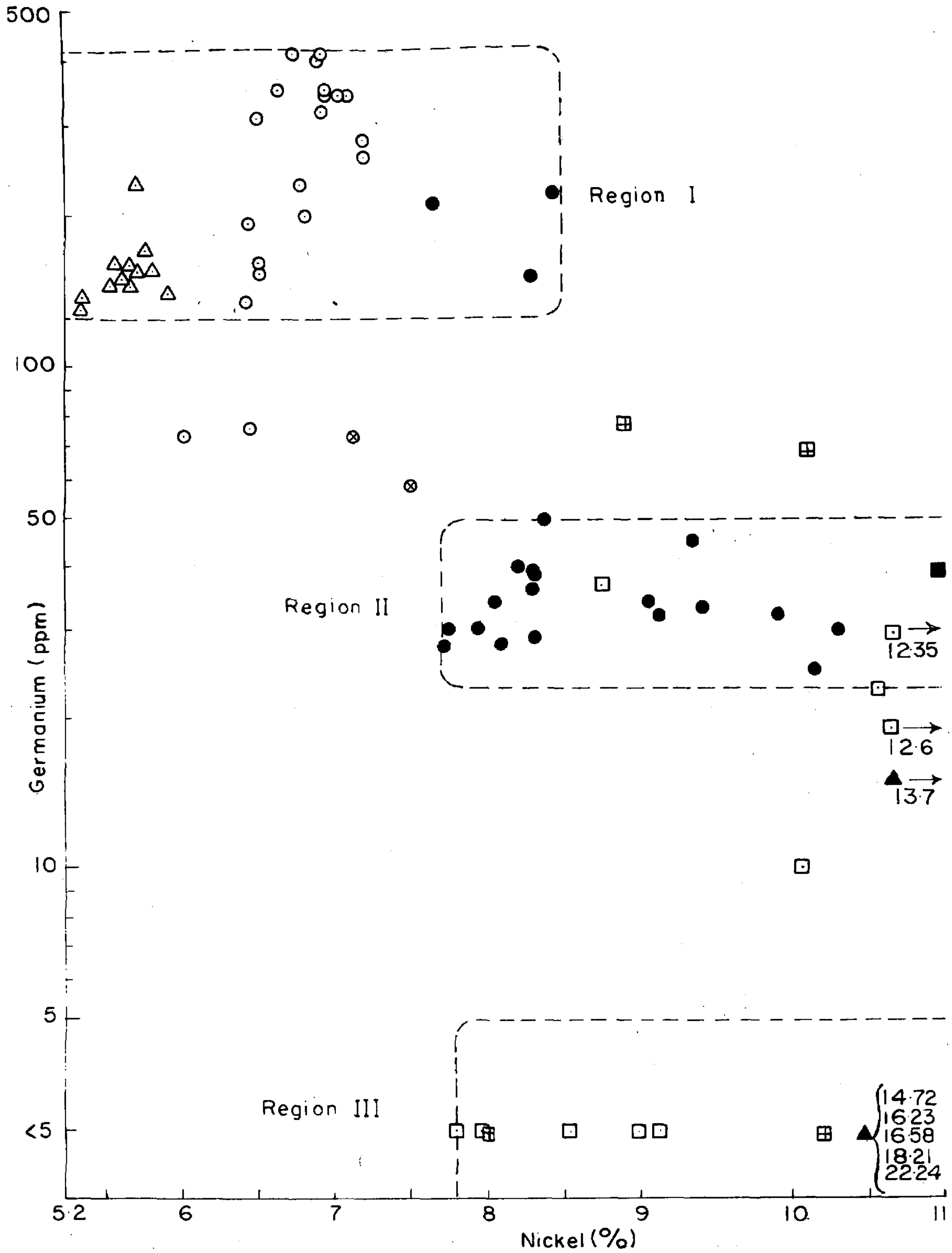


Fig. 6. Germanium–nickel in metal phase of iron meteorites

the poor senstitivity of the analysis method in this concentration range.

(2) In Group III, the hexahedrites, nickel-poor ataxites and medium octahedrites tend to have lower Ga-Ge concentrations than do the coarse octahedrites.

(3) The anomalous Om-Of iron meteorites (Moonbi, Narraburra) have germanium values within Region III but their gallium values are anomalous and lie between Regions II and III.

(4) The anomalous ataxite Perryville was shown by Goldberg et al. (1953) to lie between gallium Regions I and II. In this work it was found to have gallium and germanium values between Regions I and II. The Arltunga iron meteorite has a similar behavior.

(5) The granular octahedrites (Ob) lie between Ga-Ge Regions I and II.

(iii) Distribution of copper: Figure 7 shows the normal Gaussian distribution of copper in the metal phase of iron meteorites which was determined in this work. The arithmetic mean concentration is 160 ppm.

In Figure 8 the copper content has been plotted against the nickel content. The copper values are rather scattered but there is a trend of increasing copper with increasing nickel.

The nickel-rich ataxites have particularly variable copper contents. Pinon, Tlacotepec and Tawallah Valley iron meteorites have greater than 50 ppm Cu while Cowra and Mt. Magnet average 180 ppm. The Wedderburn has the very high value of 580 ppm. It is not clear why this should be so.

(iv) Distribution of chromium: Figure 9 shows the bimodal distribution of chromium in iron meteorites determined in this work; there is a large peak at <5 ppm and a smaller one at 49 ppm. The Cr distribution about this second peak shows a log-normal distribution.

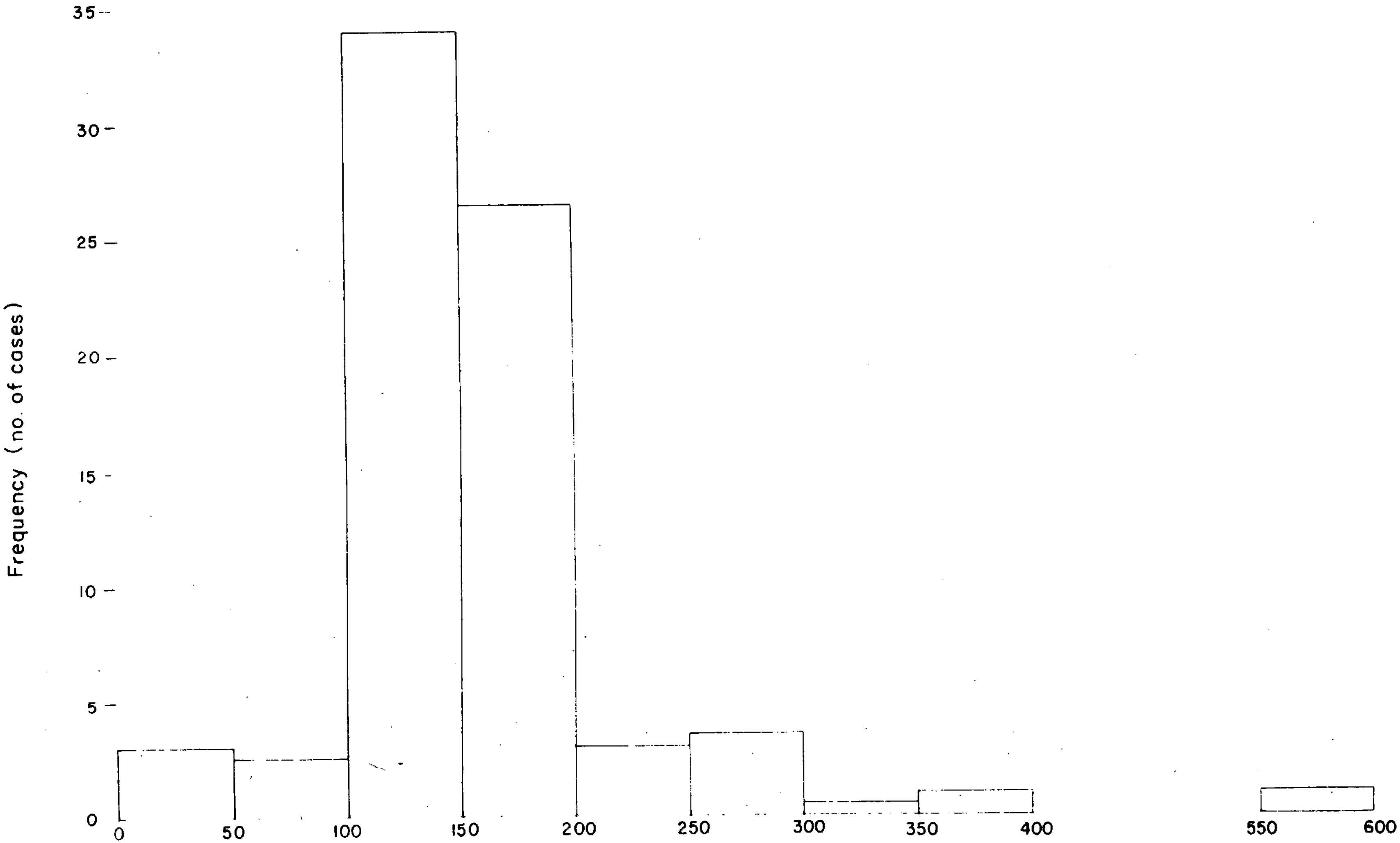


Fig. 7. Distribution of copper (ppm) in metal phase of iron meteorites

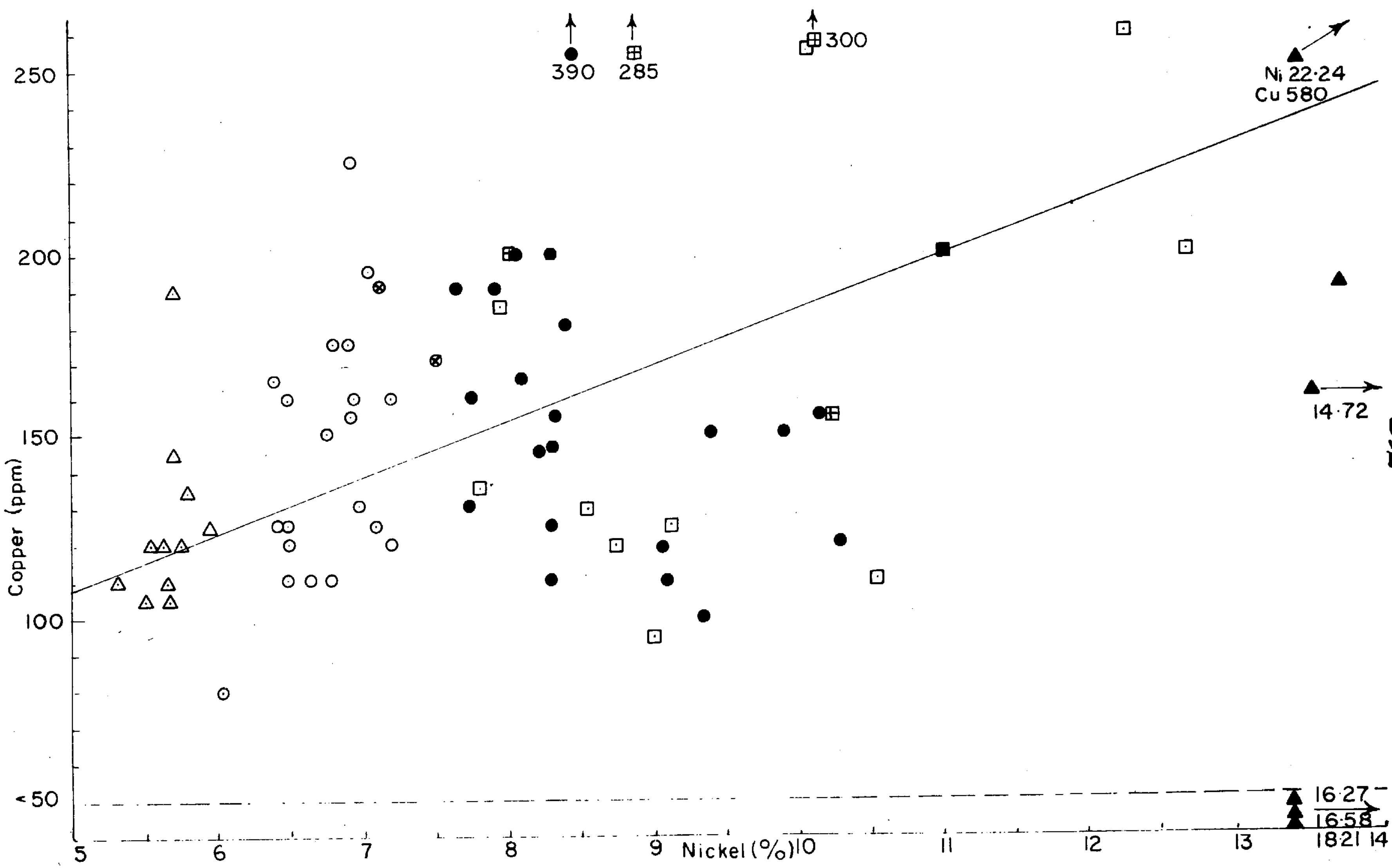


Fig. 8. Copper-nickel in metal phase of iron meteorites

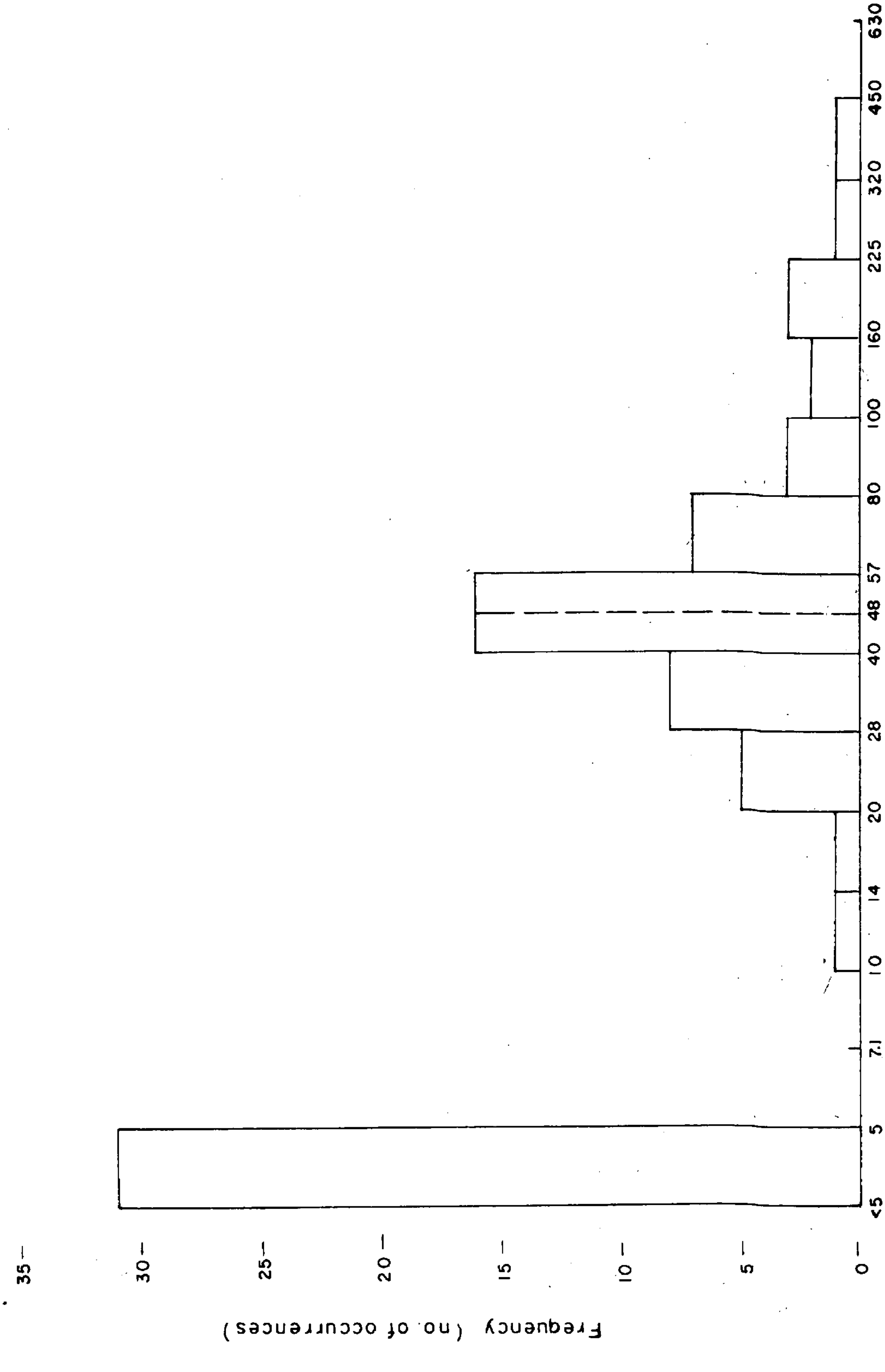


Fig 9. Distribution of chromium (ppm) in metal phase of iron meteorites

The plot of Cr against Ni (Figure 10) shows no relationship between these variables. In this regard Cr is exceptional amongst the elements studied.

It would seem that at least 60 per cent of the iron meteorites with <5 ppm chromium had troilite nodules very close to the samples which were analyzed. Only about 13 per cent of those iron meteorites with Cr >20 ppm contained any troilite nodules. Chromium is an extremely chalcophile element so that the troilite nodules may act as a "sponge" to soak up Cr and thus impoverish the metal phase surrounding the modules. At the same time it is possible that samples with Cr >5 ppm have been contaminated by troilite. (see page 76).

(v) Distribution of cobalt: Figure 11 shows the normal Gaussian distribution of cobalt in the metal phase of iron meteorites. The arithmetic mean value is 0.51 per cent.

A plot of cobalt-nickel contents (Fig. 12) shows a considerable spread but there is a tendency for cobalt and nickel to increase together.

Fine octahedrites with less than 0.49 per cent cobalt have Ga-Ge contents in Region III while those with greater than 0.49 per cent cobalt have Region II.

C. Trace-Element Distribution in the Troilite and Schreibersite Phases.

With regard to troilite, the distribution of the elements will be discussed relative to the nickel content. Nickel is the next most abundant element after iron but is more sensitive to variation. The elements belong to one of two groups:

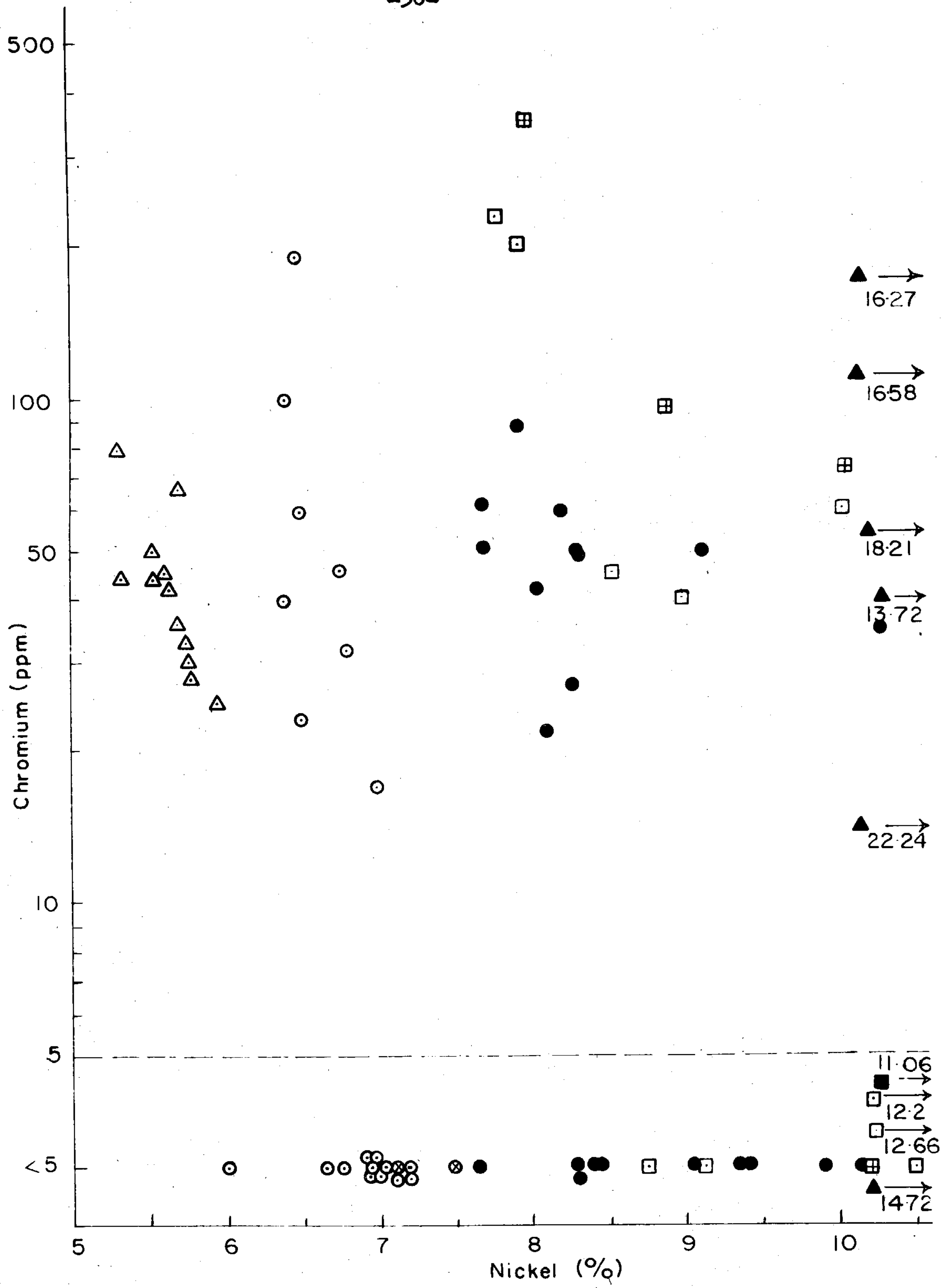


Fig 10. Chromium-nickel (in metal phase of iron meteorites)

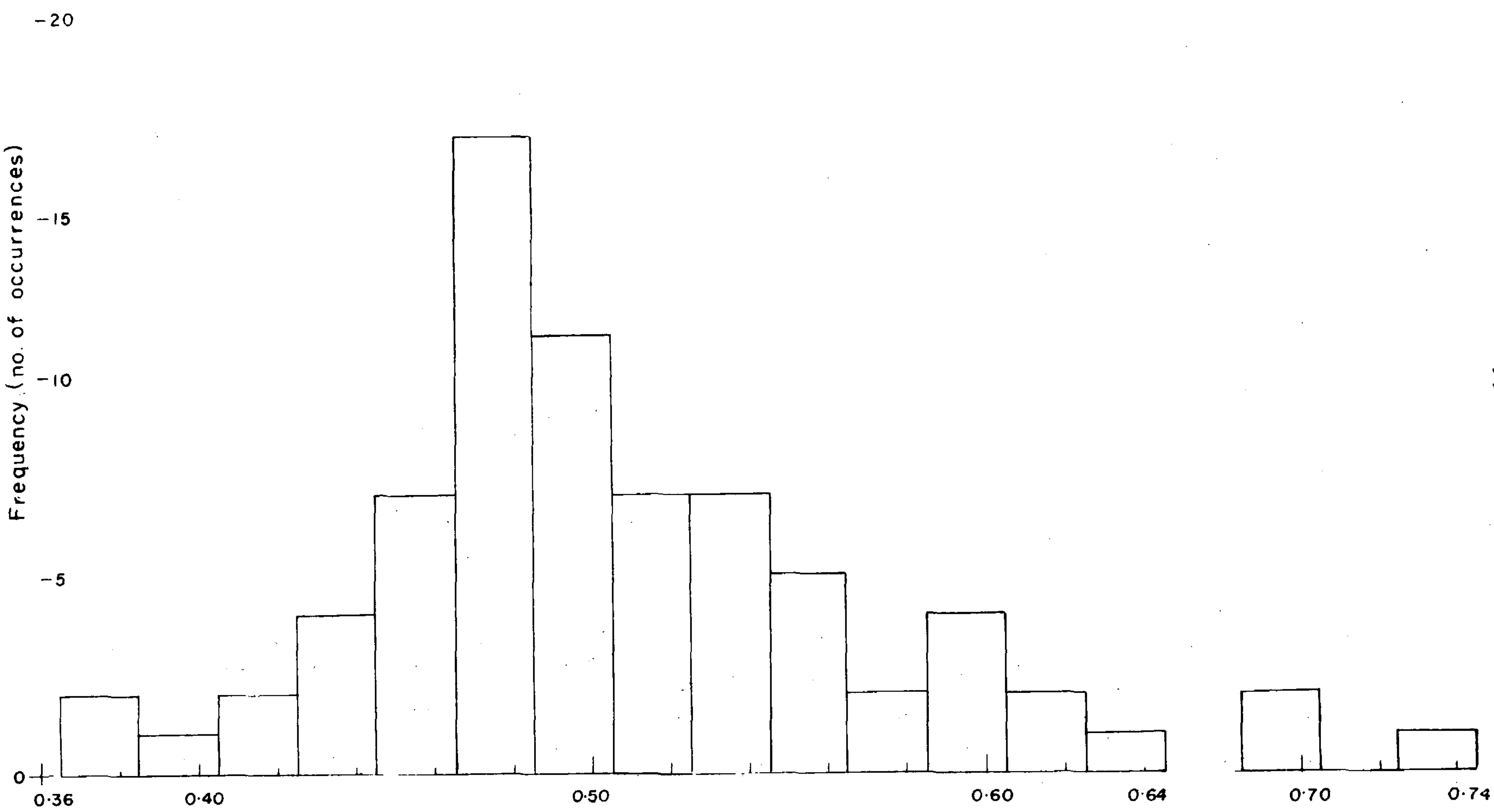


Fig. 11. Distribution of cobalt (%) in metal phase of iron meteorites

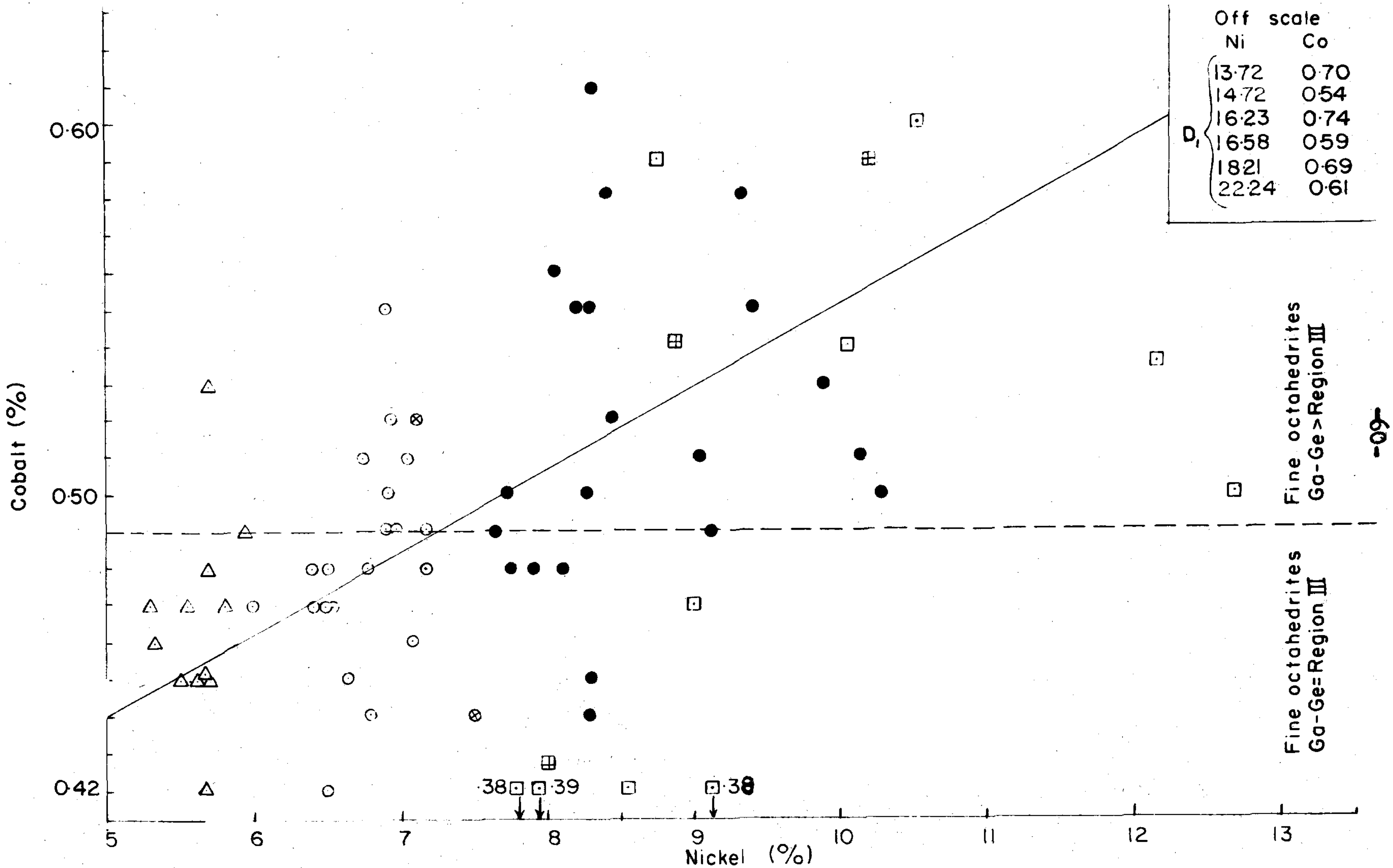


Fig. 12. Cobalt-nickel in metal phase of iron meteorites

(i) those elements which increase as the nickel content increases, and (ii) those elements which decrease as the nickel content increases. Zinc is exceptional and remains more or less constant with respect to increasing nickel content.

(i) Elements increasing with increasing nickel content of troilite.

<u>Cobalt</u>: Figure 13 demonstrates the similar behavior of cobalt and nickel.

<u>Germanium:</u> The behavior of germanium is much less striking (Fig. 14) but there does seem to be a general trend of increasing germanium with increasing nickel.

(ii) Elements decreasing with increasing nickel content of troilite.

<u>Manganese</u>: Manganese shows a definite decrease as the nickel content increases (Fig. 15).

<u>Chromium</u>: The manganese-chromium relationships are shown in Figure 16. The points are rather scattered but there is a definite tendency for the manganese and chromium contents to vary in the same way. Thus chromium decreases as nickel increases.

<u>Vanadium:</u> Figure 17 describes manganese-vanadium relationships. The points are rather scattered but there is a definite tendency for the manganese and vanadium contents to vary in the same way. Vanadium contents decrease as nickel content increases.

<u>Copper:</u> Copper (Fig. 18) displays a less obvious tendency to increase as the nickel content decreases.

<u>Tin:</u> Is similar to copper inasmuch as it shows a poorly marked increase as nickel decreases (Fig. 19).

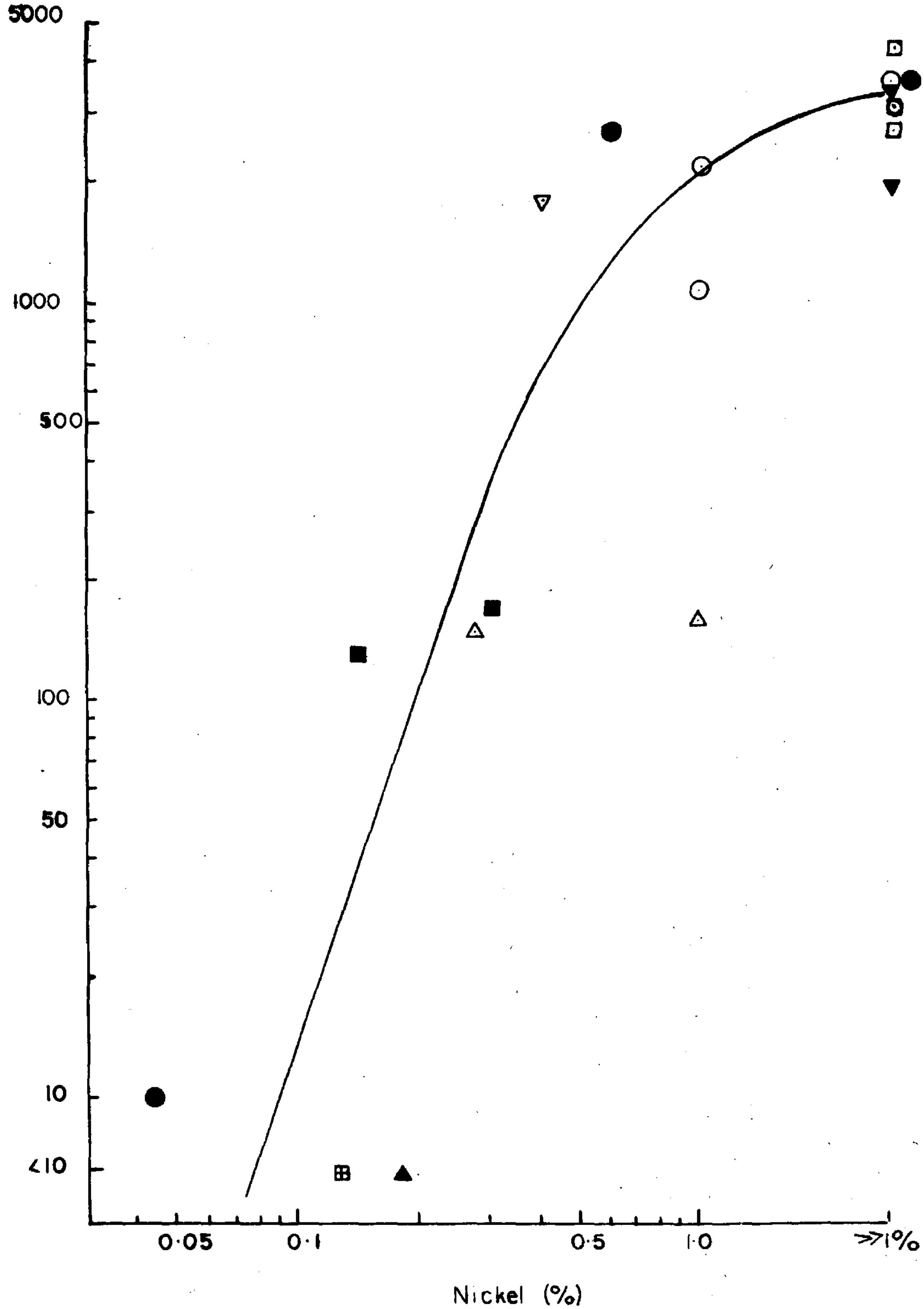


Fig. 13. Nickel – cobalt distribution in troilite of iron meteorites

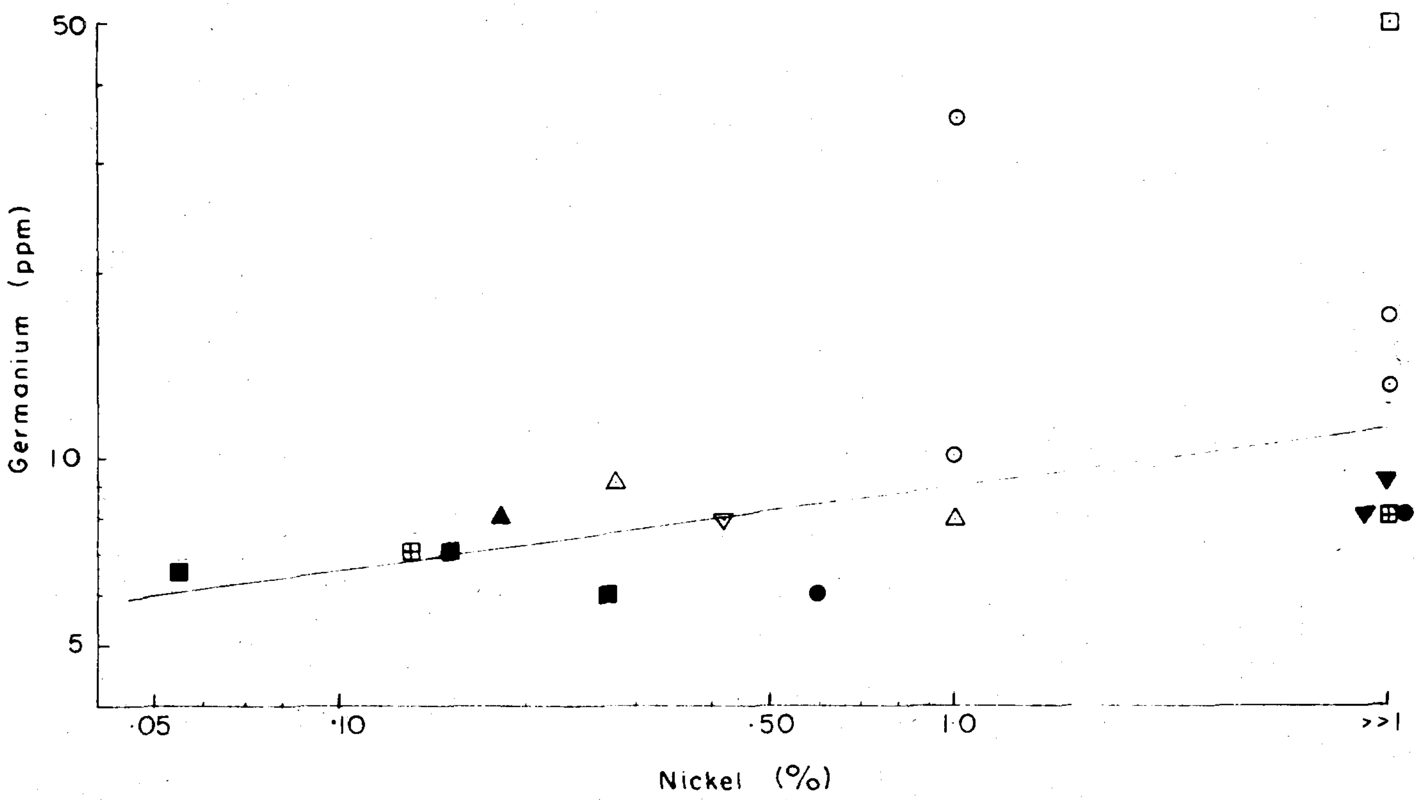


Fig 14. Nickel-germanium in troilite of iron meteorites

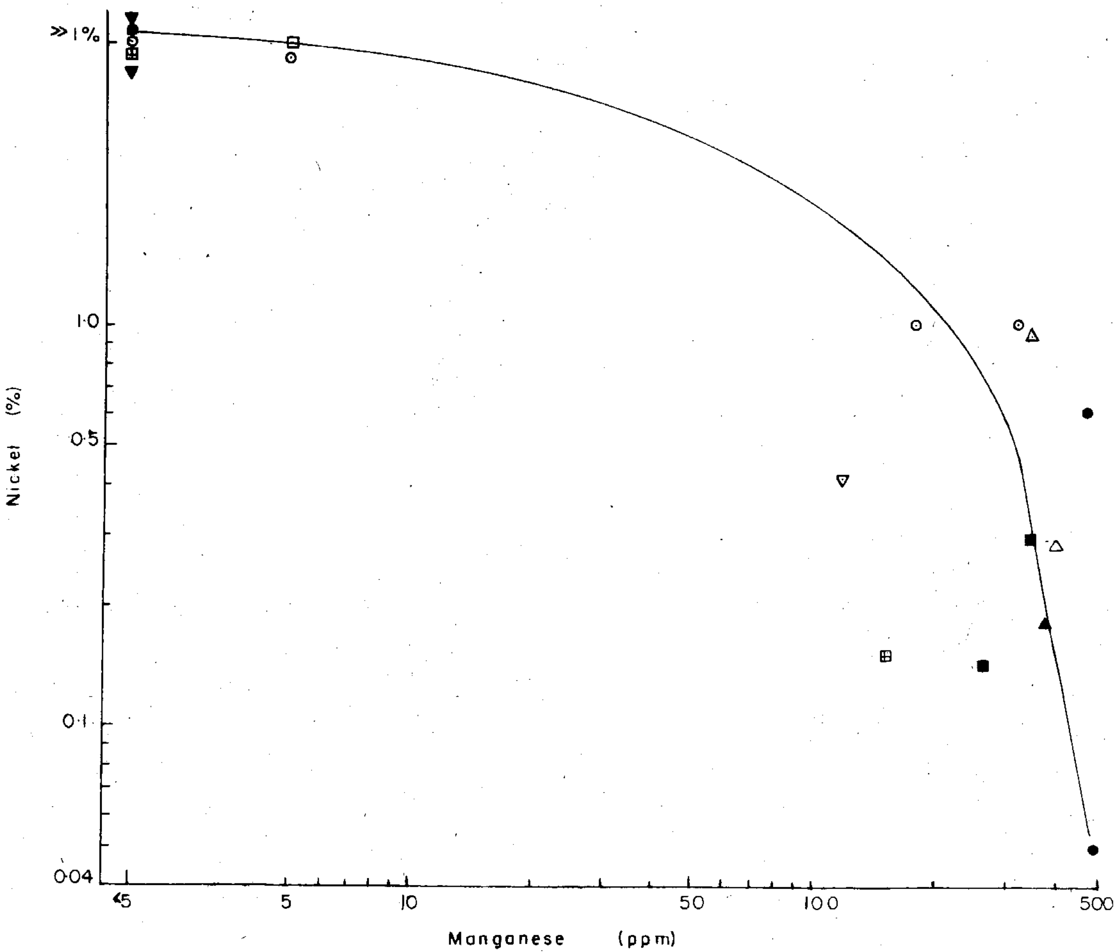


Fig. 15. Nickel - mangese distribution in troilite of iron meteorites

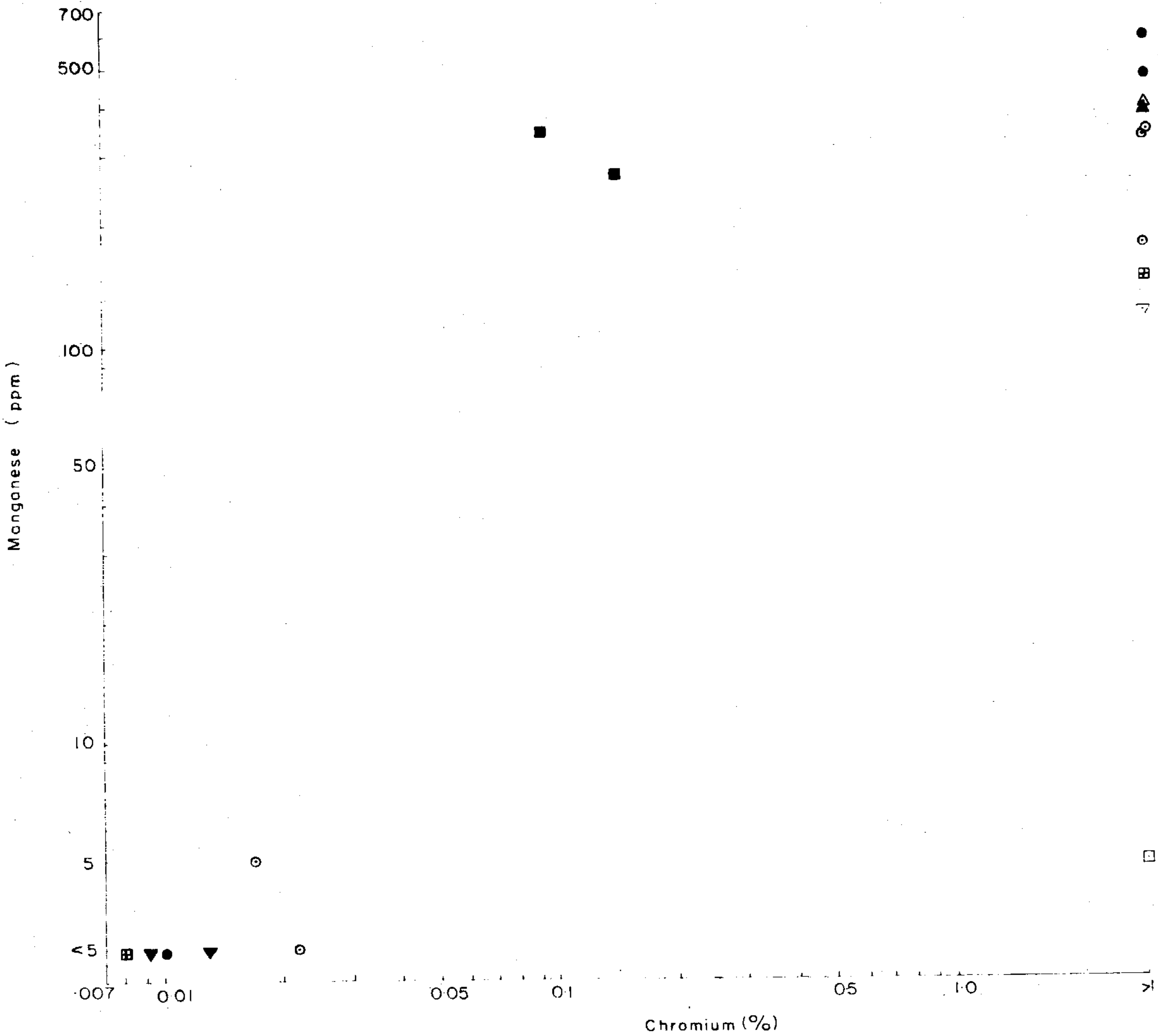


Fig. 16. Manganese - chromium in troilite of iron meteorites

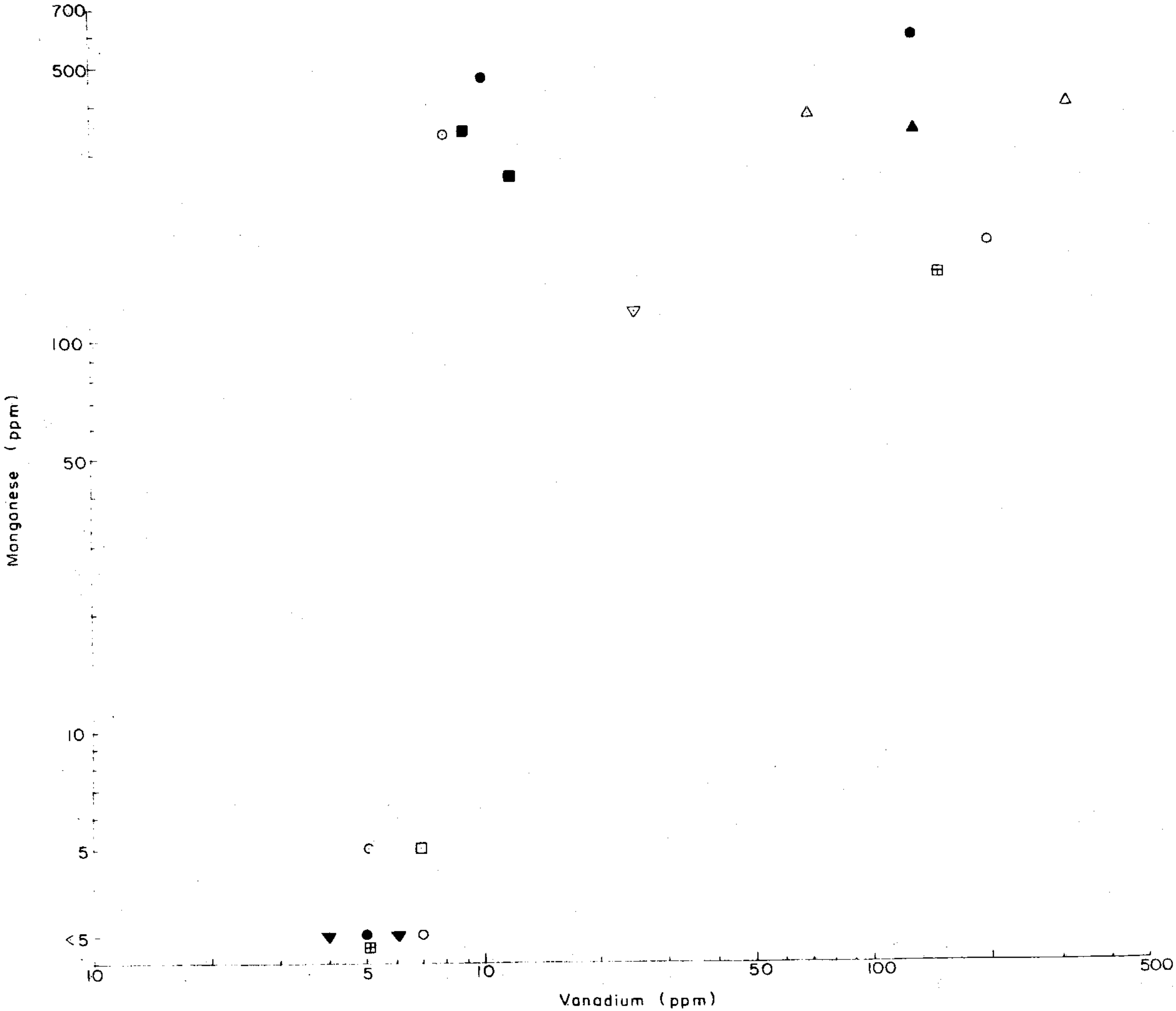


Fig. 17. Manganese-vanadium in troilite of iron meteorites

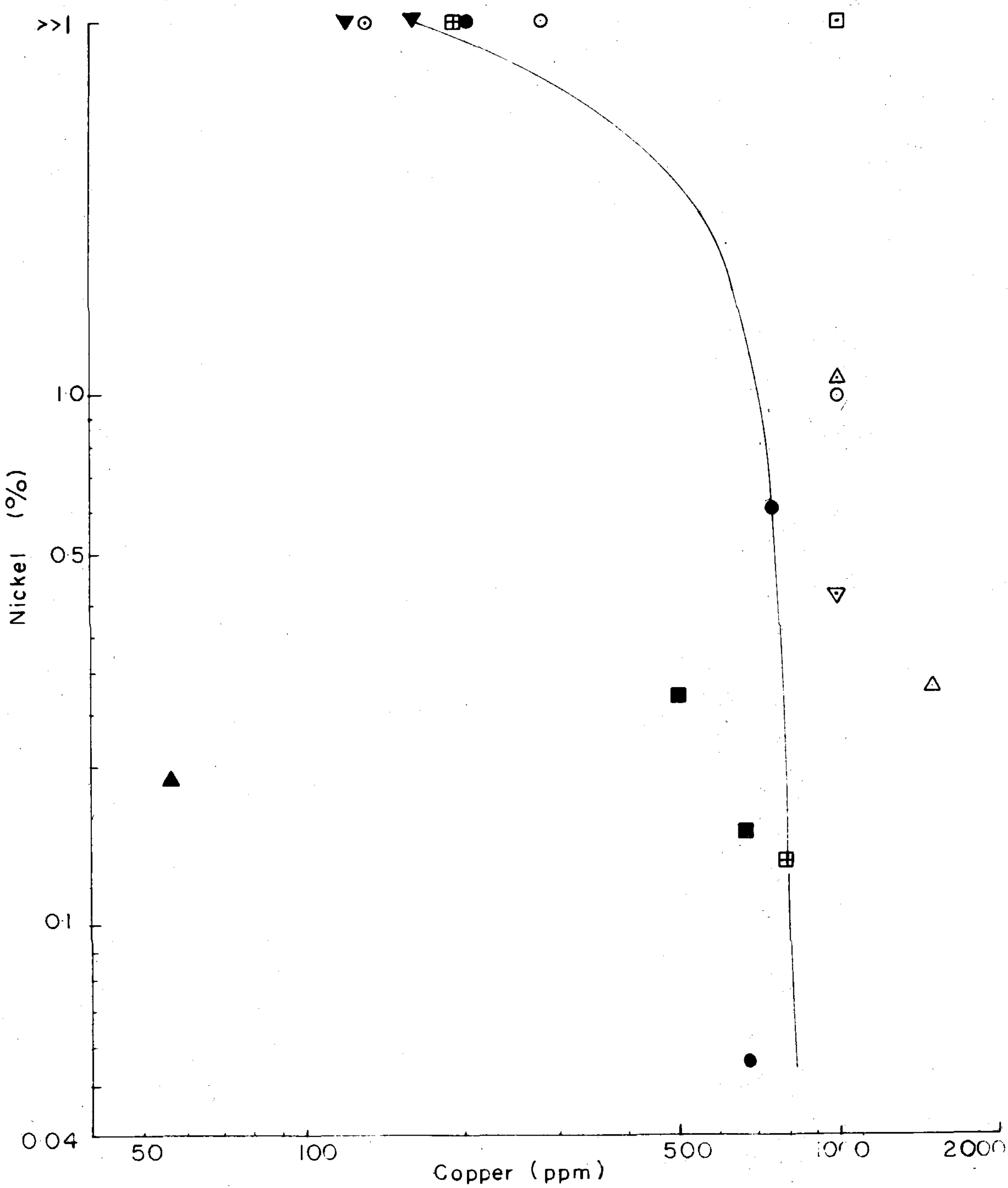


Fig. 18. Nickel-copper in troilite of iron meteorites

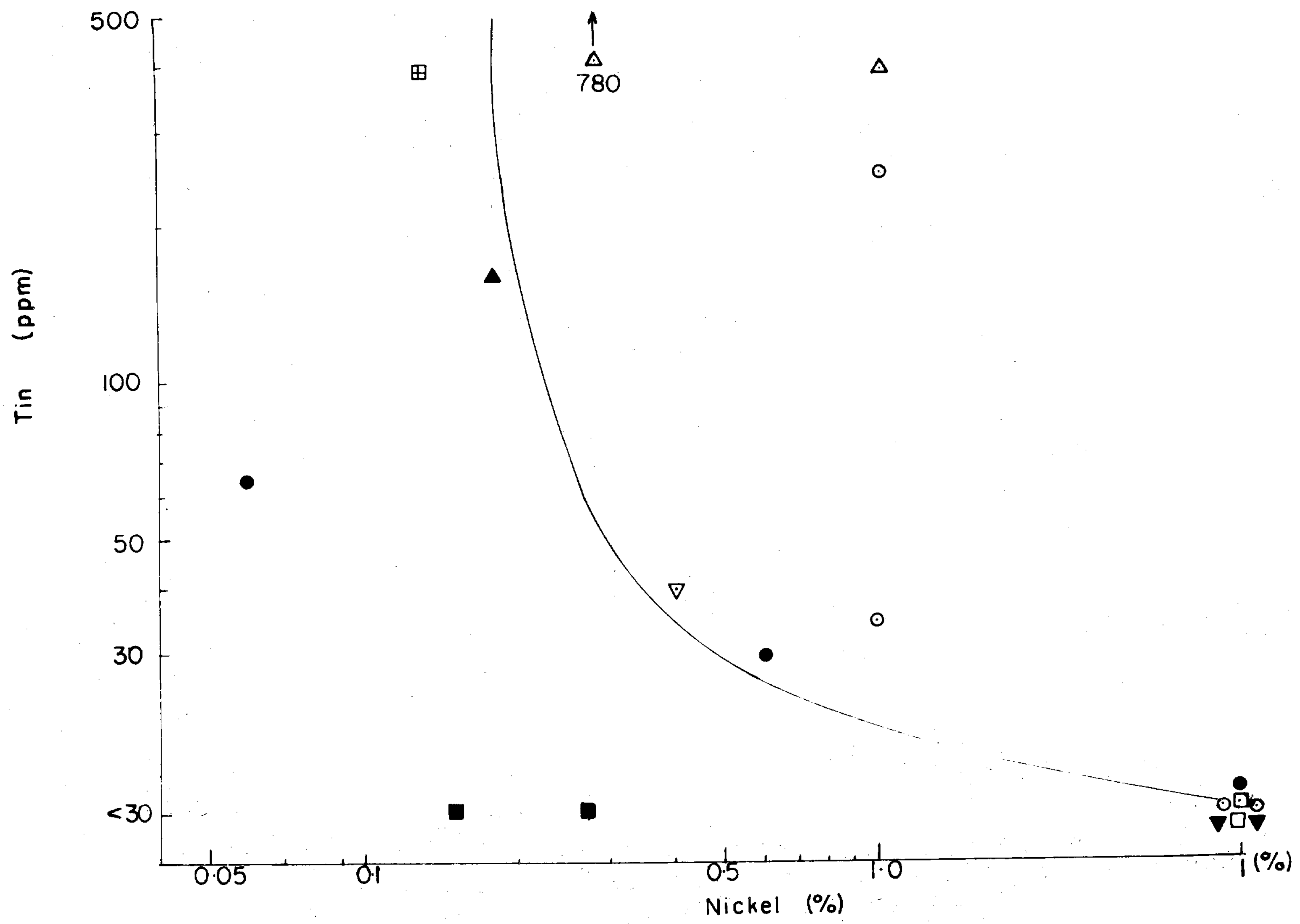


Fig. 19. Nickel – tin in troilite of iron meteorites

(iii) Other elements

Lead: Lead is not present in concentrations greater than the sensitivity of approximately 5 ppm.

Zinc: The zinc content remains remarkably constant with change in nickel content.

(iv) Terrestrial troilite: Eakle (1922) briefly described the only known terrestrial occurrence of troilite which replaces magnetite in a serpentine in Del Norte County, California. The identification was based on the analysis, (Fe: 62.70 per cent, S: 35-40 per cent) which has a Fe/S ratio very similar to that of meteoritic troilite. The sample was non-magnetic and soluble in sulfuric acid whereas pyrrhotite is both magnetic and insoluble in sulfuric acid. In an unpublished work, L.T. Silver and G. Neuerburg have indicated that structure studies using X-ray analysis indicate that the Del Norte material and meteoritic troilite are identical.

The trace element content is very similar to meteoritic troilite and in particular resembles a troilite from a coarse octahedrite.

Fryklund and Harner (1955) have analyzed some terrestrial pyrrhotites and found very much smaller Co, Ni, Cu contents than were found in the Del Norte troilite.

Ni: 26-260 ppm

Co: 10-90 ppm

Cu: 56-340 ppm

With regard to schreibersite, the behavior of the elements in this phase has been included in the graphs describing their behavior in the sulfide phase (see Figs. 13-19). It is observed that similar trends are shown in both phases.

2. STONY-IRON METEORITES

A. Structure, Nickel Distribution, and Trace-element Distribution in the Metal Phase.

(i) Structure: Unlike the iron meteorites, little has been published on the structure of the metal phase of stony-iron meteorites. Perry (1944)did not describe their structure but mentioned that those stony-iron meteorites which he examined showed structures in the metal phase similar to those of iron meteorites of similar nickel composition.

A number of etched, polished surfaces of stony-iron meteorites have shown that depending on the size of the metal areas, the structure varies considerably.

Small areas: It was not possible to determine the critical size when small area structures became large area structures, but there is almost certainly a continuous gradation between them. The small area structures are certainly the most abundant (see Fig. 20a). They are characterized by a zonal arrangement of metal phases:

(1) grey border zone of kamacite

(2) very thin zone of silvery-white taenite

(3) dark grey core of dense plessite. In some of the larger grains, small kamacite bands with taenite borders cross the plessite, occasionally showing an approach to an octahedral orientation.

This is the general arrangement described by Ninninger (1932) in the Springwater pallasite. Merrill (1902) also observed these three zones but identified them as:

(1) broad, white outer band of kamacite

(2) thin schreibersite plates.

(3) inner dark zone probably spongy kamacite with lawrencite or troilite or nearly pure iron.

Large areas: Some stony-iron meteorites contain areas in which the metal phase comprises most of the mass. In some cases (e.g. Brenham and Glorieta Mountain pallasites) they may actually grade into iron meteorites. The characteristic structure of these larger metallic areas is (Fig. 20b):

(1) border zone of kamacite

(2) usually a thin taenite sheet

(3) major central zone showing normal Widmanstatten structure of kamacite bands with thin taenite borders and associated with dark plessite.

Invariably measurements of mean apparent band widths are within the range of Om iron meteorites.

It would appear then, that the structure of the metal phase is at least partly a function of the size of the metal areas. The cooling history of the metal phase may be examined in the light of Uhlig's (1954) studies on the origin of the various phases of iron meteorites.

(1) It is well known that the $\gamma \rightarrow \alpha$ phase transformation begins at the grain boundaries; this accounts for the kamacite border around the metal phase. Untransformed taenite forms the centre of each small grain. Because of the large diffusion distances within the large grains, the transformation was much slower, and sufficient time was available for the transformation of the centre to proceed further and form the Widmanstatten pattern.

(2) Assuming a sudden change to low pressure conditions, the kamacite remains stable but the centre portion of taenite is unstable (being now in $\alpha + \gamma$ region) and transforms to acicular α_2 phase. If

there is an increased nickel gradient from the centre to the margin of the taenite, only the centre portions will transform.

(3) If this transformation takes place at room temperature or above, the metastable acicular α_2 phase will decompose into plessite leaving the untransformed taenite as a rim.

A similar mechanism of preferential $\gamma \rightarrow \alpha$ transformation at grain interfaces may explain some cases of the presence (and absence) of swathing kamacite about troilite inclusions in iron meteorites. Perry (1944) has suggested that swathing kamacite is iron rejected from the FeS structure during cooling and shrinking of the sulfide phase. This does not explain the occasional occurrence of thick kamacite masses swathing thin troilite plates found in some octahedrites. It also does not explain why some small troilite inclusions do not show swathing kamacite rims. It is suggested that the presence of swathing kamacite may be an indication of the α-transformation beginning at interfaces with foreign phases. The absence of this structure around small troilites may be merely a feflection of the insignificant effects of their small surface areas in initiating the transformation.

(ii) Nickel Distribution: The nickel content of the metal phase is essentially constant and does not depart more than $\pm$ 11 per cent from the mean of 11.06 per cent nickel.

(iii) Trace-element Distribution: The concentrations of the various trace-elements are essentially constant from sample to sample. The Ga, Cu, Cr and Co values vary only within the spread of the analysis method. Germanium is more variable but if the Ge contents of three of the more variable pallasites (Brenham, Glorieta

Figure 20; Structure of metal phase of pallasites.

a. Structure of small metal phase areas in Springwater pallasite. x3$\frac{1}{2}$

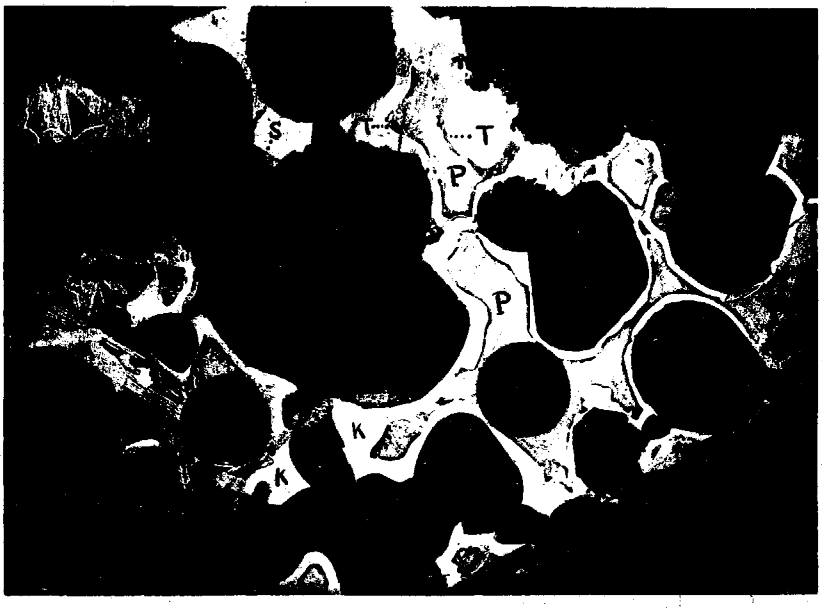
K : kamacite O : olivine

T : taenite Tr: troilite

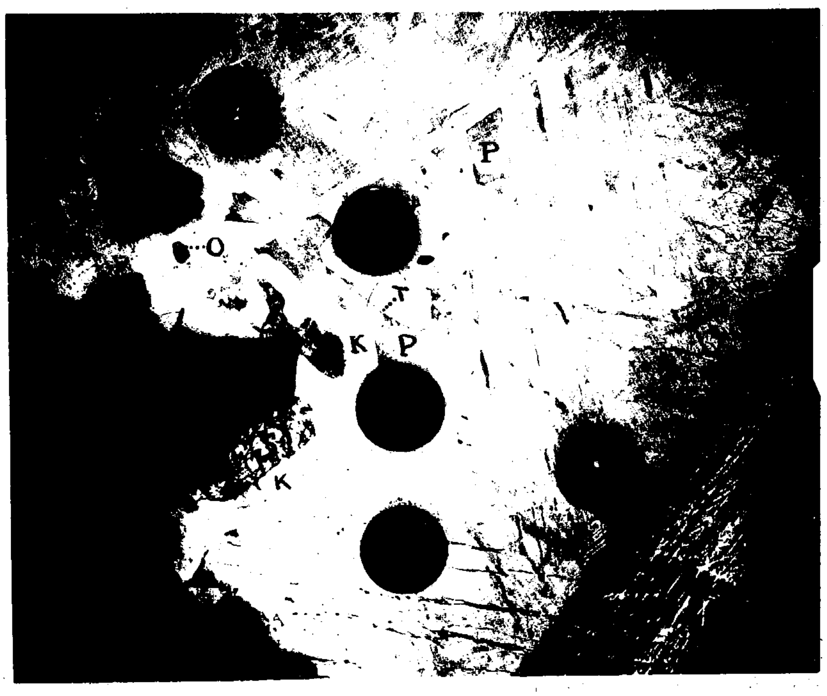
P : dense plessite S : schreibersite

(dark circular areas in metal are sample drill holes)

b. Structure of large metal phase areas in Newport pallasite. x3$\frac{1}{2}$



a.



b.

mountain, and Pinnaroo) are eliminated from the mean, the agreement is complete.

The Ga-Ge concentrations all fall within Region II of the iron meteorites.

B. Macro-and Trace-element Distribution in the Olivine Phase.

Olivine is the only silicate recorded from pallasites. Typically the colorless, pale greenish to pale yellow (often gem quality) olivine occurs as rounded grains set in a metal matrix. Single crystals and aggregates may occur. Some pallasites have euhedral and others somewhat angular grains. Internal fractures are common and are often filled with magnetite. Merrill (1902) reported a well defined and regular pinacoidal cleavage which, on basal sections, resembles the prismatic cleavage of enstatite.

Optical characteristics of olivines from two pallasites have been determined:

Table 24

	X	Y	Z	$2V_x$
Admire olivine	1.652	1.671	1.676	91^o
Springwater olivine	1.654	1.675	1.682	91^o

They are essentially identical and correspond to a chrysotile type olivine with the composition $Fo_{82}Fa_{18}$ from the 2 V_x values (see Winchell 1951).

From both the macro and trace-element analyses it is seen that the olivines from different pallasites are remarkably constant in composition.

C. Trace-element Distribution in the Troilite Phase.

Bronze-coloured troilite, often associated with schreibersite (see Fig. 20a and 20b) and magnetite, generally occurs between the silicate and metal phases.

Trace element analyses of troilite from two pallasites indicate a remarkable similarity in composition. From Figs. 13-19 it is seen that the nickel-trace element relationship in pallasitic troilite is very similar to that in an iron meteorite of the structure of a medium octahedrite. It is probably significant that when the structure of the metal phase of a stony-iron meteorite is sufficiently developed, it is similar to that of a medium octahedrite.

3. NEW MEAN ABUNDANCES OF ELEMENTS IN VARIOUS PHASES OF IRON AND STONY-IRON METEORITES.

A. Abundance Data

From the data accumulated in the present study some general conclusions may be drawn on the mean abundances of certain elements in meteorite phases (Table 25).

Arithmetic means are given except in the following cases:-

Chromium: The derivation of the mean abundance of chromium in the metal phase deserves some comment. Two points of view may be taken:

(1) The distribution histogram (Fig. 9) suggests a bimodal distribution with a large number of iron meteorites (41 per cent) containing <5 ppm and the rest (59 per cent) show a log-normal distribution about 49 ppm. The arithmetic mean of values >5 ppm is 70 ppm, but the mean derived from the distribution histogram is probably more significant, since the increased absolute error in the higher concentrations is compensated by using the logarithmic plot. It is of interest to note

that the arithmetic mean of all analyses (using 5 ppm for all values <5 ppm) is 43 ppm.

It has been observed that about 60 per cent of iron meteorites containing <5 ppm Cr had troilite inclusions in the fragments sampled. The metal phase in the neighborhood of troilite may have been impoverished in Cr due to the scavenging effect of the sulfide. In view of this, the mean of the values >5 ppm is suggested as the mean abundance in the metal phase of iron meteorites.

(2) There is the other point of view, that the mean Cr content of the metal phase is represented by a value <5 ppm and that the values >5 ppm are due to varying amounts of troilite contamination. Such contamination can be extremely difficult to control and in samples containing greater than 100 ppm of chromium was in all likelihood present.

At the present stage of our knowledge it does not seem possible to rule out either one of these cases.

<u>Gallium and germanium:</u> From the trimodal frequency distribution of gallium and germanium, in the metal phase of iron meteorites (Figs. 3 and 5) it can be seen that an arithmetic mean of the concentrations, would give a poor representation of the actual abundance of these elements. As the various levels of gallium and germanium concentration show some relation to the structure type of the meteorite, it seems a fair assumption that a close approximation to the actual abundances of these elements may be given by weighting the mean gallium -germanium concentrations in the various structure types according to the relative abundance of the structure types.

Figures have been given for the observed number frequency abundances of the various structure types (Table 1). Using these figures, with the mean gallium and germanium contents of the various structure types,

Table 25

Abundances of elements in various phases of iron and stony-iron meteorites

	Metal Phase		Sulfide Phase (Troilite)		Phosphide phase (Schreibersite)	Silicate (Olivine) phase
Element	Iron meteorites	Stony-iron meteorites	Iron meteorites	Stony-iron meteorites	Iron meteorites	Stony-iron meteorites
Magnesium (%)	--	--	~0.003	--	--	27.8
Titanium (ppm)	<1	<1	~2	--	--	25
Vanadium (ppm)	<1	<1	90	10	6	15
Chromium (ppm)	48[a] <5[b]	<5	>1%	1100	110	150
Manganese (ppm)	~1	<5	220	310	<5	1900
Iron (%)	90.04	88.5	63.6	63.6	~64.4	9.3
Cobalt (%)	0.51	0.55	0.18	0.0155	0.27	35
Nickel (%)	8.45	11.06	>1%	0.21	~23%	250 ppm
Copper (ppm)	160	200	660	600	140	4
Zinc (ppm)	<100	<100	455	455	500	<<100
Gallium (ppm)	~27[c]	19	0.35[d]	--	--	<2
Germanium (ppm)	~90[c]	40	14	6	9	<20
Tin (ppm)	<5	<5	<170	<30	<30	<10
Lead (ppm)	~0.37[e]	--	~15[e]	--	<5	<10

FOOTNOTES TO Table 25.

[a] Mean derived from second maximum in Figure 9 (see text).

[b] Mean derived from first maximum in Figure 9 (see text).

[c] Mean weighted according to abundances of various structure types of iron meteorites (see text).

[d] Mean derived from data of Goldberg *et al.* (1951).

[e] Mean derived from data of Patterson *et al.* (1955).

a composite value for the mean concentration, over all iron meteorites is given (Table 26).

From Table 25, the similarity, in composition, of the metal phase of both iron and stony-iron meteorites can be generally observed. The nickel (and iron) values vary to a certain degree, but, in determining the mean nickel contents of iron meteorites, no account was taken of the effect of the great variation in nickel concentration of iron meteorites (i.e. for 5.5 to approximately 62 per cent).

The chromium values agree if the mean concentration in iron meteorites is actually <5 ppm.

4. NEW DATA ON THE GEOCHEMICAL BEHAVIOR OF CERTAIN ELEMENTS.

In 1937 Goldschmidt first used the terms siderophile, chalcophile and lithophile to designate the preference shown by an element to enter either the metallic, sulfide or silicate phases. A classification of the elements according to these designations was based on the observed behavior of the elements, in distributing themselves between the molten iron and silicate blast furnace products, and between various phases of meteorites. The data on meteorites mainly consisted of a few analyses of questionable accuracy of iron meteorites, troilite from both stony and iron meteorites and the silicate portion of stony meteorites.

It seems unlikely that the phases in the stony meteorites were in equilibrium with regard to the distribution of the trace elements, since it now appears that the stony (chondritic) meteorites are consolidated aggregates of fragments of the various phases which, have been derived from a number of sources.

On the other hand there does not seem to be any reason to doubt that trace element distributions in the metal, silicate and sulfide

Table 26

Structure Type	Observed Abundances (from Table 1)	Mean Gallium (ppm)	Mean Germanium (ppm)
Hexahedrites and nickel-poor ataxites	14%	50	160
Coarse Octahedrites	23%	70	300
Medium Octahedrites	39%	16	35
Fine Octahedrites	17%	3	~5
Nickel-rich ataxites	7%	2	~2
Weighted Mean value (iron meteorites)		~27	~90
Arithmetic Mean value (stony-iron meteorites)		19	40

phases of the stony-iron meteorites reflect equilibrium conditions. The data in Table 27 indicate the trace-element distributions between these phases in pallasites and present a new interpretation of the geochemical behavior of certain elements. The latest classification given by Goldschmidt (1954) and the new classifications are compared in Table 27. Differences are apparent in the relative classifications of vanadium, manganese, cobalt, nickel, zinc and gallium.

Table 27

Trace elements distribution between metal-sulfide-silicate phases of pallasites and the geochemical character of some elements.

Mass Number	Element	Metal	Troilite	Olivine	Geochemical Character (This Work)	Geochemical Character (Goldschmidt (1954)
12	Magnesium per cent	--	~0.003	27.8	L≫C>S	L
22	T itanium ppm	<1	~2	25	L>C>S	L,(C)
23	Vanadium ppm	<1	10	15	L≥C≫S	C,L,C
24	Chromium ppm	<5	1100	150	C>L≫S	C,L
25	Manganese ppm	<5	310	1900	L>C≫S	C,L
26	Iron per cent	88.5	63.6	9.3	S>C>L	S,C
27	Cobalt per cent	0.55	155	35	S≫C>L	S,((L))
28	Nickel per cent	11.0	0.21	0.025	S≫C>L	S,((L))
29	Copper ppm	200	600	4	C>S≫L	C
30	Zinc ppm	<100	460	≪100	C>S(L)	C,(L)
31	Gallium ppm	19	~0.4	<2	S≫C(L)	C,(L)
32	Germanium ppm	40	6	<20	S>C>L	S
50	Tin ppm	<100	<30	<10	--	S,(L)
83	Lead ppm	~0.37[a]	~15[a]	<10	C≫S(L)	C,(S)

L = lithophile
C = chalcophile
S = siderophile

>: factor <10
≫: factor >10

C > (C) > ((C))

[a] From iron meteorite phases (Patterson *et al.* 1955).

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