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THE MINERALOGY AND CHEMISTRY OF THE CARALUE, MUNDRABILLA AND WITCHELINA METEORITES

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ABSTRACT

Three Meteorites have been analysed, petrologically and mineragraphically described. Two, Caralue and Mundrabilla, are medium octahedrites; Caralue is a genuinely low sulphur meteorite, while Mundrabilla is exceptionally high in sulphur, phosphorus, chlorine, carbon and contains accessory silicates. Eight primary minerals have been found in Caralue and eleven in Mundrabilla. Mineragraphic investigations show interesting crystallisation and deformation events in the two irons. The third meteorite, Witchelina, is a highly-weathered Olivine-Bronzite-Chondrite with a high content of ferric oxide. Nine primary minerals were found in Witchelina, while all three meteorites contain pentlandite, goethite and magnetite formed by weathering.

Sampling and analytical methods are discussed, as are the relationship between composition and mineralogy for the siderites and aerolite. It is concluded that X-ray Fluorescence is a suitable analytical method for S, P and Cl in irons, and for the determination of Si, Ti, Al, Cr, total Fe, Mn, Ca, P, Mg, S and Cl in aerolites. Atomic Absorption Spectroscopy is a valuable technique for determining Ni, Co, Cu, Zn, Cr and Mn in siderites and aerolites.

FIGURE 1 LOCATION MAP

INTRODUCTION

The aim of the project was to describe three previously unstudied Australian Meteorites, one aerolite and two siderites.

The aerolite "Witchelina" was found in sandhill country on Witchelina Station, apparently in the 1920's, by Mr. T. P. Gourlay, in whose family's possession it remained until 1967, when it was donated to the University collection by a grandson of the finder. The location of the find is unknown except for the vague description "from Witchelina Station," which is approximately 15 miles west of Farina in the north of South Australia (location about lat. 30°S, long. 138°E). It is a well-orientated stone with "thumbprints" on the rear surface and an anterior aerothermal ablation surface. The stone weighed 3,637 gms., and was complete except for a few grams removed from one end. The specific gravity of 3.27 reflects its highly weathered state; unweathered chondrites of this class are in the range 3.6 to 3.8. (A.U. 21604)

The siderite "Caralue" is another poorly located meteorite, its location being known only as 11 miles N.W. of Darke Peak (location about 136°E, 33°15'S). This places it about 8 miles west of Caralue, a small railway station in central Eyre Peninsula, South Australia. This meteorite has previously been known as "Cowell," a town over 50 miles distant. This name is considered inappropriate in view of the meteorite's proximity to Caralue, and it is suggested that the name "Cowell" should no longer be used. The meteorite was purchased from R. J. McDonald, apparently the finder, by the University in 1955, and weighed 5.70 Kgms. (A.U. 18295)

The siderite "Mundrabilla" is easily the largest recovered meteorite from Australia, having a total mass of over 16 tons. Two masses of about 11 and 5 tons, plus several hundred smaller fragments were recovered.

The meteorite was located in March 1966 by accident after earlier searches based on reports by a rabbit-trapper had failed. The location is on the Nullarbor Plain in Western Australia (Latitude 30°47'S, Longitude 127°33'E). The samples studied comprising some of the small fragments, were obtained on loan from Mr. R. B. Wilson who, with Mr. A. M. Cooney, located the meteorite. (A.U. 20475)

A. A N A L Y S I S

1. SAMPLING

The aerolite was sampled by crushing a 20-gram block from which a polished, thin section had been made. This allowed a close comparison of the mineralogical and chemical compositions.

Cuttings obtained in sectioning the siderites were used for analysis, and represent a better average than that obtained by the usual methods. Contamination calculated from weight loss of the blade is only .04%, thus contamination of only 4 ppm occurs from a one per cent. componant in the blade. The blade contained no elements capable of causing significant contamination of the samples. Problems arise through oxidation of troilite causing sulphur loss, and also due to the hardness of the troilite and schreibersite causing cutting difficulties. Sampling of siderites is usually done by selecting an area free from inclusions, and either cutting out a block or using drill cuttings from the area. This must then be an unrepresentative sample as has been shown by Henderson and Perry (1958). As a test of the representativeness of the samples, two cuts were made in Caralue and the analyses compared.

2. SOLUTIONS

Three solutions were made of each siderite: the first, dissolved in hydrochloric acid, was used for Atomic Absorption Spectrographic Analysis; the second, in sulphuric acid, for determination of iron by oxidation of the ferrous ion; the third solution, in nitric acid, was evaporated and decomposed to the oxides and used for the X-ray Fluorescence Analysis of sulphur, phosphorus, chlorine and iron. A sample of Mundrabilla troilite was dissolved in hydrochloric acid for a partial analysis of minor elements. A sample of Witchelina was dissolved in hydrofluoric acid and perchloric acid for determination of K_2O, Na_2O and some trace elements.

3. STANDARDS

For Atomic Absorption Spectroscopy, two standards were made containing mixtures of iron, nickel, cobalt, copper and chromium in the range found for siderites of the same type as Caralue and Mundrabilla. For all other Atomic Absorption Spectroscopy, already-prepared standards were used.

For the X-ray Fluorescence analysis of the siderites, two standards were made up: one consisted of a mixture of iron, nickel and cobalt oxides of a similar composition to the siderites, and was used in the determination of iron; the other was made by adding known amounts of sulphur, phosphorus and chlorine to a sample of Caralue. A pressed mount containing an added known amount of chlorine was used to determine chlorine in Witchelina.

Owing to the desirability of having the standard and unknown with similar compositions, it was decided to use a meteorite as a standard for the bulk analysis of Witchelina by X-ray Fluorescence Analysis. As a meteorite suitable for use as a standard could not be found in the Tate Museum Collection, it was decided to use the recently-fallen meteorite Pueblito de Allende (Type 111 Carbonaceous Chondrite), (fell Feb. 8th, 1969) Chihuahua, Mexico (A.U. 20539). As it is an unusual type, it will be well analysed in the future; however, a suitable preliminary analysis was obtained from Dr. Brian Mason.

4 ANALYTICAL METHODS

For the siderites, nickel, cobalt, copper, zinc, manganese and chromium were determined by Atomic Absorption Spectroscopy; iron, sulphur, phosphorus and chlorine by X-ray Fluorescence Analysis, and carbon by combustion. A second determination of iron by a Ferrous Titration was made.

For the aerolite, X-ray Fluorescence analysis on a fused button was used to determine SiO_2, TiO_2, Al_2O_3, Fe_2O_3, CaO, MnO and MgO. A pressed mount was used to determine P_2O_5, S and Cl, while K_2O and Na_2O were determined by Flame Photometry, and Co, Cu, Cr, Zn, Mn and Ni by Atomic Absorption Spectroscopy.

5. COMPOSITION

The results of the analyses of the siderites are shown in Table 1, as is a partial analysis of the Mundrabilla troilite.

It is obvious from the Table that, for the major metals Fe, Ni and Co, the meteorites Caralue and Mundrabilla are very similar. They both fall on a peak for a plot of the frequency distribution for nickel in meteorites, at the value of Medium Octahedrites (normally 7-9% Ni).

TABLE 1 ANALYSES of CARALUE, MUNDRABILLA and MUNDRABILLA TROILITE

N.B. All as percentages except where indicated "ppm" (parts per million)

	Caralue (Cut 1)	Caralue (Cut 2)	Mundrabilla	Mundrabilla (Troilite)
Fe (XRF)	90.79	90.81 91.69 (1)	89.94	n.d.
Ni	8.02	8.02	7.99 – 7.98	0.757
Co	0.397	0.404	0.400	750 ppm
Cu	110 ppm	119 ppm	156 ppm	660 ppm
Zn	32 ppm	31 ppm	45 ppm	124 ppm
Cr	27 ppm	12 ppm	47 ppm	1,912 ppm
Mn	8 ppm	n.d.	47 ppm	812 ppm
S	0.035	0.017	0.682	n.d.
P	0.156	0.165	0.401	n.d.
Cl.	n.d.	0.021	0.033	n.d.
C	0.03	0.04	0.24	n.d.
TOTAL	99.44	99.48	99.72	

cf Reimann GCA 36 801 15.5

(1) Ferrous titration total 100.36%

n.d. Not determined

The minor metals are all somewhat higher in the Mundrabilla iron; this is a reflection of its much higher troilite content, the troilite tending to scavange these elements (Cu, Zn, Cr and Mn).

Sulphur, phosphorus, chlorine and carbon are higher in Mundrabilla, and are amongst the highest recorded. The sulphur content of Mundrabilla is much higher than the value shown, due to selective oxidation of much of the troilite in the small fragments analysed.

The two Caralue cuts are very similar, the only two real differences being for sulphur and chromium. This is not surprising in view of the fact that most of the chromium is present in exsolution lamellae of daubreelite in the troilite, resulting in a lower chromium content for the second cut. To check the rather low sulphur values of Caralue, the sulphur percentage was checked by determining the area of troilite, and the total area of four cut surfaces totalling 165 sq. cms.

TABLE 2 COMPARISON OF ANALYTICAL AND AREA SULPHUR

	Caralue Cut 1	Caralue Cut 2	Witchelina
Analytical	0.035%	0.017%	2.06%
Area	0.048%	0.009%	2.14%

The analytical and area percentages are similar, and, when it is considered that the four cut faces ranged from 0.009% to 0.085% sulphur, and that the size of the inclusions is similar to the width of the saw-cut, then the method and values are very satisfactory.

A comparison of the bulk and troilite compositions of Mundrabilla shows various concentration factors in the troilite for some of the trace elements. Zinc has been concentrated three times, copper four times, manganese sixteen times, chromium fifty times, while cobalt shows a five-fold decrease and nickel a tenfold decrease.

The nickel content of unweathered troilite is usually very low, nickel being strongly siderophilic; however, in this case, weathering has caused the formation of a few percent pentlandite containing most of the nickel present. The bulk values for Mundrabilla are low as most of the troilite has been removed by weathering, causing the loss of the minor elements. The effect of weathering was studied by determining the Cu, Zn, Cr, Mn, Ni and Co content of the metal, knowing that the meteorite contained 2% sulphide.

TABLE 3 The Cu, Zn, Cr, Mn, Co and Ni contents of Sulphide, Metal and Totals for 2% (weathered) and 10% (unweathered) Sulphide.

	Troilite	Metal	2% Sulphide Total	10% Sulphide Total
Cu	660 ppm	143 ppm	156 ppm	190 ppm
Zn	124	43	45	50
Cr	1,912	38	47	205
Mn	810	31	47	102
Co	750	4,150	4,000	3,705
Ni	7,570	79,915	79,9●0	72,720

The total contents were then determined using the values of the metal and sulphide (Table 4), assuming 10% sulphide for the unweathered meteorite. It is believed that 10% Sulphide is not an unreasonable estimate of the true sulphide content. Most elements increase with increasing sulphide, while nickel and cobalt decrease in the over-all analysis.

Witchelina and the standard have very similar compositions, differing virtually only in the relative amounts of the various oxidation states of iron present (Table 4). Witchelina is a more highly reduced chondrite than Pueblito de Allende, and contains more metallic iron, but is als● highly-weathered, and contains a considerable amount of ferric oxide. Ferric oxide is absent, or almost absent, from unweathered ordinary chondrites.

The amounts of the various oxides of iron were determined by a combination of methods; point counting for metal and sulphide iron, a ferrous iron titration, and a total iron determination by X-ray Fluorescence Analysis. From the point counting, the metallic and sulphide iron was determined, and a value for the nickel content of the metal estimated

TABLE 4. Weight Percent Analyses for Pueblito de Allende (Standard). Witchelina, the average for Olivine-Bronzite Chrondites, and the Mole Percent Analysisfor Witchelina.

	Standard	Witchelina	Average (1)	Witchelina Mole %
SiO_2	34.23	34.01	36.17	34.16
TiO_2	0.15	0.14	0.11	0.10
Al_2O_3	3.27	3.35	2.36	1.98
Cr_2O_3	0.52	0.20	0.27	0.23
Fe_2O_3	0.00	12.96	0.00	4.90
FeO	27.15	7.15	9.26	6.01
MnO	0.18	0.22	0.23	0.19
CaO	2.61	2.65	1.95	2.85
Na_2O	0.45	0.95	0.90	0.92
K_2O	0.03	0.18	0.17	0.11
P_2O_5	0.23	0.20	0.17	0.08
MgO	24.62	24.15	22.93	36.16
FeS	4.03	4.27	5.69	2.93
NiS	1.68	1.54	0.00	1.02
Fe	0.17	7.10	17.76	7.67
Ni	0.31	0.57	1.68	0.60
Co	0.06	0.07	0.10	0.07
Cl	0.05	0.05		0.07
Cu		84 ppm		
Zn		79 ppm		
Total Fe	23.83	24.44	28.58	
Total Ni	1.39	1.59	1.68	
Total S	2.05	2.01	2.07	
TOTAL	99.74	99.77	99.75	100.05

(1) Urey and Cragi (1953) Superior Analysis of 94 Chondrites - II Type Av.

(0.57% Ni). It is assumed that the remaining nickel (1.02%) occurs in pentlandite, although some probably occurs as oxides. This allows a value to be found for the ferrous iron content due to troilite. The ferrous iron determination includes metallic iron as well as ferrous iron in troilite and silicate. Knowing the amount of metallic and sulphide iron, a value for the ferrous iron in silicate can be found. The remaining iron is ferric oxide formed by the terrestrial weathering of metal, sulphide and silicate.

Comparing Witchelina with the average for the class, it is found to be significantly low in silica and total iron, the latter probably due to weathering loss, at least in part. It is significantly higher than average for Al_2O_3, CaO and MgO, while, for the remaining elements, it is very similar. The effects of this on the mineralogy will be discussed later.

B. M I N E R A G R A P H Y

A total of eighteen minerals, of which three were formed by terrestrial weathering, were recognised in the three meteorites. The minerals were identified by optical and other physical properties, X-ray diffraction, or by electron probe analysis, or a combination of these methods.

1. SIDERITES

a. Structure

(1) Gross Structure

Caralue shows the typical Widmanstatten structure of octahedrite meteorites, and consists of about 60-90% kamacite-taenite lamellae, with about 10-40% various interlamellar plessite structures, and contains no noteworthy inclusions. The Widmanstatten pattern has only the one orientation, and the meteorite crystalised from a single crystal of γ-iron. Several large cracks are present, and have been accentuated by weathering. The coarse grain-size of the lamellar kamacite is noteworthy. Kamacite lamellae are from 0.8-1.5 mm wide, which places Caralue in the medium Octahedrite Class.

TABLE 5 Minerals present in the Meteorites Caralue, Mundrabilla and Witchelina.

	Caralue	Mundrabilla	Witchelina
Kamacite	Abundant (XRD)	Abundant (XRD)	Abundant (P)
Taenite	Abundant (P)	Abundant (P)	Common (P)
Copper	Very rare (P)	-	-
Graphite	-	Common (XRD,P)	-
Troilite	Rare (XRD,EP)	Abundant (XRD)	Abundant (P)
Pentlandite	Very rare (EP)	Common (P)	Common (P)
Daubreelite	Rare (XRD,EP)	Common (XRD,P)	-
Sphalerite	-	Very rare (P)	-
Schreibersite	Common (XRD,EP)	Very common (XRD,P)	Very rare (P)
Chromite	Very rare (EP)	Very rare (P)	Very rare (P)
Lawrencite	Rare (P)	Common (XRD)	-
Magnetite	Rare (XRD)	Rare (XRD)	Rare (P)
Goethite	Common (XRD)	Common (XRD)	Abundant (P)
Diopside	-	Rare (XRD)	Common (P)
Cristobalite	-	Very rare (XRD)	-
Bronzite	-	-	Abundant (P)
Olivine	-	-	Abundant (P)
Plagioclase-glass	-	-	Common (P)

Identified by XRD, X-ray Diffraction; P, Physical (optical, hardness etc.); EP, Electron Probe.

Mundrabilla shows the Widmanstatten pattern. However, in this case, many orientations exist as the meteorite crystalised from polcrystalline γ-iron. This is also shown in the kamacite grain-size where, in contrast to Caralue, few grains are larger than a few millimetres, even in the apparently coarse lamellae. Mundrabilla has approximately equal amounts of kamacite-taenite lamellae and interlamellar plessites, and contains coarse troilite, graphite and schreibersite inclusions, often with swarthing kamacite. Kamacite lamellae are from 0.5-1.0 mms wide, which places Mundrabilla in the Medium Octahedrite Class.

(2) White or interlamellar Plessites

The two types are common to both Meteorites, and may be described as Granular and Microwidmanstatten types.

Granular plessites consist of angular kamacite (0.02-0.4 mm) with almost 10% angular taenite. Triple points are common with taenite tending to be in these areas. Schreibersite is common, and is much more irregular in grain-size than the nickel-iron, and, in contrast to taenite, tends to be concentrated at grain interfaces. The edges of these areas are more regular, and often have an outer boundary of taenite and schreibersite (Plate 1a). A variation of this texture is found in Mundrabilla with rounded taenite, taenite-schreibersite or schreibersite in a matrix of non-granular kamacite; this may be in contact with the normal granular type, and some taenite grains are shared by both (Plate 1b).

Microwidmanstatten structures resemble the normal structure but on a much finer scale, with kamacite grains only about 0.1 mm thick. Taenites are not as long but may be very variable in shape, from straight to very sinuous. Schreibersite often occurs in this structure as rhabdites (within kamacite grains) or irregular grains between kamacite grains (Plate 1c).

(3) Dark or Lamellar Plessites

Dark etching plessites again consist of two types often occurring together, and it is only then that the two types can be distinguished with any degree of certainty. The Duplex type is apparently the more abundant, and, where it occurs with the Martensitic type, it is central. It is lighter etching, generally coarser with kamacite more abundant, and often has a recognisable Widmanstatten orientation, and formed from the lower nickel portion of the parent taenite grain (Plate 1 d,e,f).

Martensitic plessite may border the duplex structure or, especially in finer taenites, be the only form present. It etches darker, with a less distinct Widmanstatten orientation. It is richer in taenite, and formed by the breakdown of higher nickel taenites than did the duplex.

A third type of lamellar plessite is very common but light etching. It appears to be an early stage of dark plessite formation which, due to its higher nickel content, has been arrested and preserved. The inner boundary of the taenite is very ragged, and the ground mass contains a few ragged unorientated taenite grains. The nature of the ground mass is unknown, but may be a submicroscopic mixture of kamacite and taenite. This plessite often passes laterally into martensite where the parent taenite broadens.

b. Mineralogy

(1) KAMACITE-TAENITE makesup the bulk of the meteorites, and kamacite normally has a Vickers Hardness in the range 260-280, but, in Caralue, the heat-affected outer zone is partly preserved with values down to 160

in the outer 5 mm (Fig. 2a). In Caralue, the grains may be up to 4cm larg but, in Mundrabilla, they are generally much smaller.

Taenite is distinctly creamish compared with kamacite, and has a Vickers Hardness range from 370-420 across a lamellae reflecting the variation in nickel content. The highest values are from the centre of the grain where taenite may be strained (Fig. 2b). Neumann lines are common in the kamacite, and are often refracted at grain boundaries and distorted near inclusions, and only rarely pass through taenite grains.

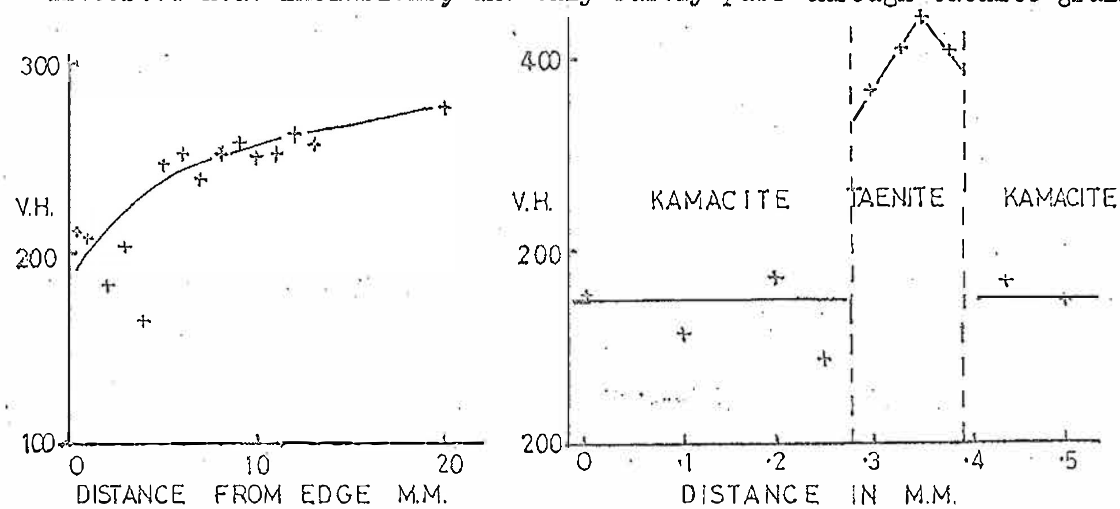

FIG 2a FIG 2b

(2) SCHREIBERSITE is largely restricted to grain boundaries where it occurs in a variety of situations.

(a) Associated with troilite which it partly rims (Caralue) or forms large bordering masses up to 1 cm or more (Mundrabilla). Rare euhedral crystals may also be found around the borders (Plate 2a).

(b) At kamacite-kamacite grain boundaries where it varies from .05 to 1 mm or so in length, particularly in the Widmanstatten Pattern where it alternates with the taenite lamellae.

(c) At kamacite-taenite boundaries where it has grown at the expense of the taenite producing "corrosion" pits in the taenite (Plate 2 b, c). The schreibersite grains are usually isolated in taenite, but Mundrabilla has examples of schreibersite in contact with taenite.

(d) At kamacite-kamacite boundaries showing no relationship to taenite, it is often coarser in these situations. This type of occurrence is common in the white plessites.

(e) As euhedral crystals usually isolated in kamacite grains, this is the so-called rhabdite; very commonly as small crystals along grain boundaries in both meteorites (Plate 2d).

From textual evidence, it can be seen that schreibersite has crystallised over quite a range of time and temperature. It is believed that the schreibersite (a) crystallised much earlier than (b) or (c), which possibly formed at quite low temperature by diffusion of nickel and phosphorus. In the latter two types, the schreibersite has drawn the requisite nickel from earlier-formed taenite by local diffusion of the order of .05 mm or less. That the schreibersite is late forming is shown by the way it has corroded the dark plessite in some places. If it is accepted that this plessite formation took place at a late stage, then the schreibersite formed very late.

(3) LAWRENCITE is quite common, especially in Mundrabilla where drops ooze out of the metal interfaces in a matter of hours. It is greenish-yellow, and is irregularly distributed along kamacite-taenite boundaries and around troilite nodules. As a result of the method of polished section preparation, the very unstable lawrencite was not seen in the sections, although the corrosive effects of its presence were soon

evident. In spite of its instability in the presence of water and oxygen, lawrencite has survived in some apparently highly weathered areas of the meteorites.

(4) TROILITE is rare in Caralue but very common in Mundrabilla, and is the hexagonal form in both cases. The troilite in Caralue consists of single subhedral crystals with a few rounded grains which are strongly pressure twinned. One grain shows two deformation events; the first caused micro-faulting along a few well-defined planes shown by the dislocation of daubreelite exsolution lamellae; the second (?) deformation caused the formation of pressure twinning which crosses over the fractures (plate 3a). Also present in Caralue are thin planar troilites which are probably the so-called Reichenbach lamellae. They are parallel to (110), of the original γ-iron, and are up to 3 cm long; some have a surrounding layer of swarthing kamacite.

Troilite is common in Mundrabilla as rounded polycrystalline nodules, frequently with a series of concentric marginal grains with graphite content decreasing inwards. A zone of subhedral-euhedral graphite grains up to 0.1 mm or more occurs at the margin with some graphite in the metal. The outer troilite band is about 1 mm thick and contains up to 30% graphite, generally very fine, but some coarser elongate grains occur normal to the boundary. One or two more concentric bands inside this contain progressively less graphite with different preferred orientations, probably reflecting the different crystallographic orientations of the troilite. These bands have the same crystallographic orientation around the nodule a distance of several centimetres. The core is polycrystalline, and contains traces of graphite at the margins (plate 2 e,f).

A second type of occurrence in both meteorites is as composite grains with daubreelite and chromite, and is usually associated with large schreibersite grains. The grains are in the range 0.001 to 0.01 mm and are fairly rare. In Caralue, troilite-daubreelite has exsolved from a grain of bulk composition 12.6% Cr, 48.6% Fe and 37.8% S. As the exsolution lamellae (plate 4e) are only 1 to 0.3 microns wide, the electron probe gave a bulk analysis of the grains, two giving the same composition of $Cr_2Fe_7S_{10}$ which falls in the $(Fe,Cr)_{1-x}S$ solid solution field for the Fe-Cr-S system. The grains were at higher temperatures a chromium-pyrrhotite, but at lower temperatures have broken down to the end members FeS and $FeCr_2S_4$. Two electron Microprobe analyses of Caralue troilite gave FeS, as did a measurement of cell parameters by X-ray Diffraction using the calibration graph of Arnold and Reichen
The association chromite-daubreelite-troilite may be of use in defining conditions of formation.

(5) DAUBREELITE is common as light bluish-grey exsolution lamellae in troilite or in the small composite grains described with troilite. It is readily recognised with a Vickers Hardness of 350, a reflectivity of 36 and one poor cleavage parallel to the length of the grain. It contains occasional, apparently later, exsolution lamellae of troilite. It is more resistant to weathering than troilite. A microprobe analysis of Caralue daubreelite gave Fe 19.3%, Cr 37.1%, S 46.0%, corresponding to the theoretical formula of $FeCr_2S_4$. In Mundrabilla, daubreelite lamellae are continuous across boundaries in the concentrically banded troilite.

(6) CHROMITE is very rare, although several macroscopic grains occur in Caralue and are earlier than the daubreelite and may be earlier than the troilite (plate 3a). Very small grains occur with daubreelite and troilite in both meteorites.

(7) COPPER was found as a single grain (.01 mm) marginal to troilite associated with daubreelite and schreibersite in Caralue (Plate 3b).

(8) GRAPHITE is common in Mundrabilla, occurring in several ways. The occurrence with troilite has been described, and it also is very common as euhedral grains in the large marginal schreibersite grains (Plate 3c). Also, in essentially graphite nodules with euhedral graphite and kamacite, taenite, schreibersite and accessory troilite. Isolated graphite euhedra occur in the metal near graphite-bearing troilite nodules. Graphite crystallised early, certainly before the daubreelite.

(9) SPHALERITE is very rare, only two grains being found in Mundrabilla in a troilite nodule associated with daubreelite (Plate 3d).

(10) DIOPSIDE is a common constituent of one troilite nodule with graphite, daubreelite and sphalerite, with some silicate in a large associated schreibersite mass, and in the kamacite. Cristobalite has been tentatively identified as a minor associate with the diopside. Cristobalite indicates crystallisation at a high temperature. The silicates are veined by later troilites, and are up to 2 mm in diameter (Plate 3e).

(11) PENTLANDITE is a rare mineral in Caralue because of the scarcity of troilite, but common in Mundrabilla where it is replacing troilite, particularly near the margins of the nodules. Where seen pentlandite always appears to be a weathering product. (Plate 3f)

(12) GOETHITE is a product of weathering, particularly near the margins of the meteorite and in the troilite nodules. Goethite always rims troilite nodules in Mundrabilla, and forms largely by the weathering of nickel-iron rather than troilite. Magnetite is intimately associated with goethite and only identified by X-ray Diffraction.

C. DISCUSSION

It is generally believed that the sulphides formed from a melt, and this is in agreement with the textural and structural evidence seen. Features such as the concentric banding in the Mundrabilla troilites are difficult to explain except by cooling a melt. There is some evidence for local reheating in Mundrabilla, perhaps by shock. It is not unusual to find among the White Plessites local areas where the grains have become rounded by a later diffusion, and the polycrystalline kamacite has become a single grain. This is the round plessite. Dark plessites sometimes partially break down to the same rounded grains (Plate 1f).

In contrast, Caralue shows a history with at least two deformations of the troilite as discussed before. The sequence of events in Caralue is crystallisation of chromite-troilite, exsolution of daubreelite, fracturing and development of pressure twinning.

It is not known whether the fracturing and pressure twinning were related or two separate events. Caralue shows no evidence of later heating as does Mundrabilla.

The resistance to weathering of the major phases is schreibersite > daubreelite > troilite > Ni-Fe.

Earlier electron probe work by the B.H.P. Co. on some silicate inclusions associated with graphite in Mundrabilla has demonstrated the presence of forsterite, plagioclase and unknown aluminium and calcium-rich phases (R. B. Wilson, personal communication).

TABLE 6 ELECTRON PROBE ANALYSES OF MUNDRABILLA SILICATES

	(a)	(b)	(c)	(d)
Fe	1.6%	0.5%	0.5%	1.0%
Na_2O	5.9	tr	5.4	4.6
Al_2O_3	40.5	tr	28.3	11.4
SiO_2	47.8	39.0	47.1	55.0
CaO	4.1	1.2	14.0	1.2
MgO	tr	56.9	tr	28.0

These analyses correspond to

(a) $(Ca,Fe)\ Na_2\ Al_8\ Si_8\ O_{30}$

(b) Forsterite $Mg_2\ SiO_4$

(c) $Na_2\ (Ca,Fe)_5\ Al_5\ Si_{10}\ O_{33}$

(d) Oligoclase + Forsterite

The forsterite is noteworthy for its very low iron content, a fact noted in other irons. The analysis (a) contains too much Al_2O_3 and too little SiO_2 to be a plagioclase, but may be a mixture of plagioclase and a high alumina-low silica phase. Similarly, the analysis (c) is too high in (Ca,Fe) and too low in alumina and silica to be a pure plagioclase, but may be a mixture of plagioclase and a calcium-iron silicate.

Only the plagioclase and forsterite can be identified with certainty, and more work is necessary to elucidate the true nature of the silicates present. It would appear that a fairly complex silicate assemblage is present. When the sample was digested, some silicate grains were found in the residue, but in insufficient quantities to identify. They included one bright green grain, a few yellowish-green and some colourless grains. At least two silicates could be recognised in the polished section and have been identified as diopside and cristobalite. Two silicates were identified by electron probe analysis and the presence of at least two others suggested.

Caralue is a fairly normal medium octahedrite with evidence of deformation in the sulphides. Metallurgical investigation may be able to define the nature and intensity of the deforming forces.

Mundrabilla is a remarkable, perhaps unique, meteorite with its high sulphur, phosphorus, carbon and chlorine content and variety of silicates present. Very fruitful lines of research are possible in the mineralogy, bulk and trace element composition, isotopic composition, structural and metallurgical aspects, such as heat effects in the atmosphere and in space. However, as yet, only small ablated and weathered fragments are available, and these are not suitable as they are unrepresentative of the true composition (low in S etc.) and metallurgy. It is hoped that some agreement will soon be reached, and the smaller of the two masses sectioned to reveal the true nature of this remarkable meteorite.

2. AEROLITE

a. Mineralogy

(1) NICKEL-IRON is the most abundant opaque with the kamacite the most abundant phase. Taenite, although common, is relatively minor compared to kamacite. Several types of associations are found:

(a) Kamacite in isolated grains is the most common metal phase.

(b) Kamacite, with minor taenite generally around the margins, is not uncommon. This may not be an exsolution feature.

(c) Taenite grains with exsolved kamacite are less common (Plate 6b)

(d) Plessitic kamacite-taenite is very rare, only one grain being positively identified. This is an exsolution texture.

(e) Kamacite-taenite-troilite eutectoids are not uncommon (Plate 5 e, f), but tend to be in smaller grains. The metal is commonly associated with more or less troilite, and the textures suggest they formed from a melt. The metal is later than the silicate, partly or completely surrounding silicate grains or corroding chondrules (Plate 6c). It has been highly weathered and about half of the metal has been oxidised to goethite. The metal phase contains both exsolution textures and eutectoid mixtures, the exsolution textures apparently being later. Heat effects are shown by the softness of the metal (V.H. 160). Schreibersite was very doubtfully identified as a few very small pinkish grains in the metal phase. Chromite is a fairly rare phase occurring as subhedral or euhedral grains up to 0.1 mm with troilite. It may have corroded edges where in contact with the silicates, and is sometimes fractured and infilled with sulphide.

(2) TROILITE is very common, and is usually associated with pentlandite. Like the nickel-iron, it is later than the silicate, but, unlike the metal, it shows evidence of remobilisation. Sulphide occurs in silicates showing evidence of some degree of recrystalisation. It has several modes of occurrence.

(a) As irregular rims around the chondrules (Plate 5 c, d).

(b) As a troilite-silicate shell around chondrules to a depth of about 0.1 mm (Plate 5 a, b). To this depth, the chondrules appear to be recrystallised.

(c) As elongate grains in the bars of some olivine chondrules (Plate 6a)

(d) As very fine grains scattered through completely recrystallised chondrules.

(e) The commonest occurrence is as interstitial grains scattered throughout the silicate matrix in grains from 1-2 mm down to less than the resolving power of the microscope. It is often associated with metal either as host or as inclusions.

(3) PENTLANDITE is very common replacing troilite in varying amounts. No evidence of primary pentlandite was seen.

(4) GOETHITE is very common as veins, veinlets or banded masses replacing nickel-iron in particular. A comparison of the sulphur percentage with the average for the H-type chondrites suggests that there has been little oxidation of troilite to goethite, but that nickel has replaced the iron with no sulphur loss.

(5) OLIVINE is the most abundant mineral occurring as chondrules or in the ground-mass. Colourless, unless goethite-stained, it displays a distinctive fracture pattern, and is optically -ve with a 2V of 92^{o}, giving a composition of Fa_{18}. Olivine occurs in several distinct ways:

(a) Chondrules which vary from single crystals to polycrystalline aggregates with indistinct chondrule shape are most prominent. As a general rule, the most rounded chondrules contain the least number of grains, and almost all show some shock features. Shock invariably produces a turbid glass in the chondrules, either as bars in the less disaggregated chondrules (Plate 6f) or as an irregular ground-mass in the more highly fractured (Plate 5c). The barred chondrules frequently have a preferred orientation showing melting in situ. In some of the granular chondrules, the fragments are almost all euhedral, perhaps indicating recrystallisation. In some chondrules, the glass is limited to an outer shell.

(b) Aggregates of angular fragments with a poorly-defined shape grading imperceptibly into chondrules, are perhaps deformed chondrules.

(c) The ground-mass consists largely of fine angular olivine which may pass into aggregates or crushed chondrules.

(d) As granules which are too angular to be chondrules, but too large to be considered as part of the ground-mass.

X-ray Diffractometer determinations of the olivine composition by the British Museum gave:

(a) 19% Fa using the method of Yoder and Sahama (1957), and

(b) 21% Fa using the method of Louisnatham and Smith (1968).

(6) ORTHOPYROXENE is common as prismatic chondrules (Plate 6c), often fibrous and radiating (Plate 5a). The chondrules are often broken, but are never disaggregated grains, although single angular fragments are found. Partial recrystallisation to coarser grains occurs, and these are almost colourless (chondrules always appear grey because of the fine grain-size) with straight extinction, a 2V of 95^{o}, and are optically -ve. It is therefore a bronzite, Fs_{18}. Recrystallisation of the outer margins of the chondrules is not uncommon (Plate 5a), resulting in a clear coarser rim. Overgrowths of pyroxene occur (Plate 6d), and suggest

chondrule formation occurred by precipitation from a melt or vapour.

(7) CLINOPYROXENE is particularly common in monomineralic chondrules or with olivine. It is finer and apparently less common in the ground-mass. It is colourless and readily identified by its multiple twinning. Grainsize is generally less than 1 mm, and mostly too fine to obtain an optical figure (it is +ve) or 2V. It is believed to be a member of the diopside-hedenbergite series.

(8) GLASS is not uncommon, particularly in the olivine chondrules and scattered through the ground-mass. Some chondrules contain as much as two-thirds glass. Much of the glass is devitrifying and forming groups of radiating crystals of a clear mineral which may be plagioclase.

b. Norm Calculation

The only significant variations from the average for Witchelina are for aluminium, calcium and magnesium, which are high, and silica and iron which are low. Assuming the analyses to be correct, then this results in a higher olivine and lower pyroxene content (less silica) with more feldspar (higher lime and alumina) than average from the norm calculation. It is likely that some of the alumina is in the pyroxene, thus reducing the total amount and lime content of the feldspar. The average composition of H-type chondrites is $Ab_{82}An_{12}Or_6$, and the normative value is too calcic.

Similarly, some of the titania and chrome is probably present in pyroxene, reducing the amounts of ilmenite and chromite. The calculated values for the olivine and orthopyroxene compositions are in good agreement with the values obtained by 2V measurement and X-ray Diffraction.

c. Classification

Witchelina is an Olivine-Bronzite Chondrite in the modified Prior classification system, and belongs to the H-type of Urey and Craig. An attempt was made to place Witchelina in the chemical-petrologic

TABLE 7 C.I.P.W. NORM FOR WITCHELINA

	Witchelina	Average
Feldspar	13.31	5 - 10
Diopside	5.83	)
		)20 - 35
Hypersthene	9.65	)
Olivine	43.18	25-40
Chromite	0.28	
Ilmenite	0.27	
Apatite	0.46	
Halite	0.07	
	73.05	
Fe-Ni-Co	7.76	16 - 21
(Fe,Ni)S	5.81	approx. 5
Fe_2O_3	12.96	0.00
	99.58%	

Feldspar		Hypersthene (Bronzite)	
Orthoclase	7.99	Enstatite	82.45
Albite	51.18	Ferrosilite	17.55
Anorthite	33.83	Diopside	
Olivine		Wollastonite	52.57
Forsterite	81.00	Enstatite	39.10
Fayalite	19.00	Ferrosilite	8.33

classification of Van Schmus and Wood, but, owing to the limited number of their parameters studied, this proved somewhat difficult. The olivine composition is apparently homogenous; clinopyroxene common;

turbid glass present; secondary feldspar absent or very fine; with well-defined chondrules, and it has a clear crystalline matrix. This, plus comparison with some meteorites of known chemical-petrologic type, places Witchelina in the H4 Group.

d. Discussion

Witchelina is a highly weathered stone, this tending to make analytical data doubtful and obscuring the petrology. Work could be done on the composition of the ortho- and clinopyroxene; the glass and its devitrification product, and the metal phases. However, because of the fine size and weathered nature of the material, practical mineral separations are impossible, and the only method available is the electron probe. Better analytical data for the various oxidation states of iron may be obtained by using the chlorine distillation method of Moss, Hey and Bothwell (1961).

C. CONCLUSION

X-ray Fluorescence analysis appears to be a suitable method for the determination of sulphur, phosphorus and chlorine in siderites by converting the sample to oxide via nitrate under strongly oxidising conditions to prevent the loss of SO_2, but at not too high a temperature to drive off volatile ferric chlorides. The method is not really suitable for iron because, with the high percentage present, the relative error becomes quite a significant absolute error. Atomic Absorption Spectroscopy is suitable for determining most other minor and some trace elements.

The composition of aerolites can be quite rapidly determined by X-ray Fluorescence analysis supplemented by Atomic Absorption Spectroscopy, rather than by the more laborious methods usually used. Sulphur and chlorine can be determined accurately on pressed mounts. As the ordinary chondrites have a fairly constant composition, then the use of a meteorite as a standard reduces corrections to a minimum. It is to be hoped that some chondrite will be agreed on as an international standard as are G1 and W1 in terrestrial petrology.

ACKNOWLEDGEMENTS

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APPENDIX 1

NON-TERRESTRIAL MINERALS.

KAMACITE	α-Iron	Fe,Ni	approx. 6.5% Ni
TAENITE	γ-Iron	Fe,Ni	15-35% Ni
TROILITE	Stoichiometric FeS		
DAUBREELITE	$FeCr_2S_4$	(thio-chromite)	
SCHREIBERSITE	$(Fe,Ni)_3P$		
LAWRENCITE	$FeCl_2$		

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P L A T E 1

			Photo-micrograph
(a)	GRANULAR PLESSITE		
	Angular taenite (tn) in a matrix of granular kamacite (km)	CARALUE	(X 110)
(b)	ROUND PLESSITE		
	Round taenite grains in a single kamacite grain. Has an almost complete rim of taenite (tn) and schreibersite (sb)	MUNDRABILLA	(X 40)
(c)	MICROWIDMANSTATTEN PLESSITE	CARALUE	(X 110)
(d)	DARK PLESSITE		
	Showing undecomposed outer taenite (tn), an intermediate zone of martensitic plessite (mt) and a core of coarser duplex plessite (dp)	MUNDRABILLA	(X 110)
(e)	DARK PLESSITE		
	Large kamacite (km) grain cutting earlier martensite (mt)	CARALUE	(X 290)
(f)	DARK PLESSITE		
	Local diffusion of Ni causing breakdown of dark plessite into rounded taenite grains (tn)	MUNDRABILLA	(X 110)

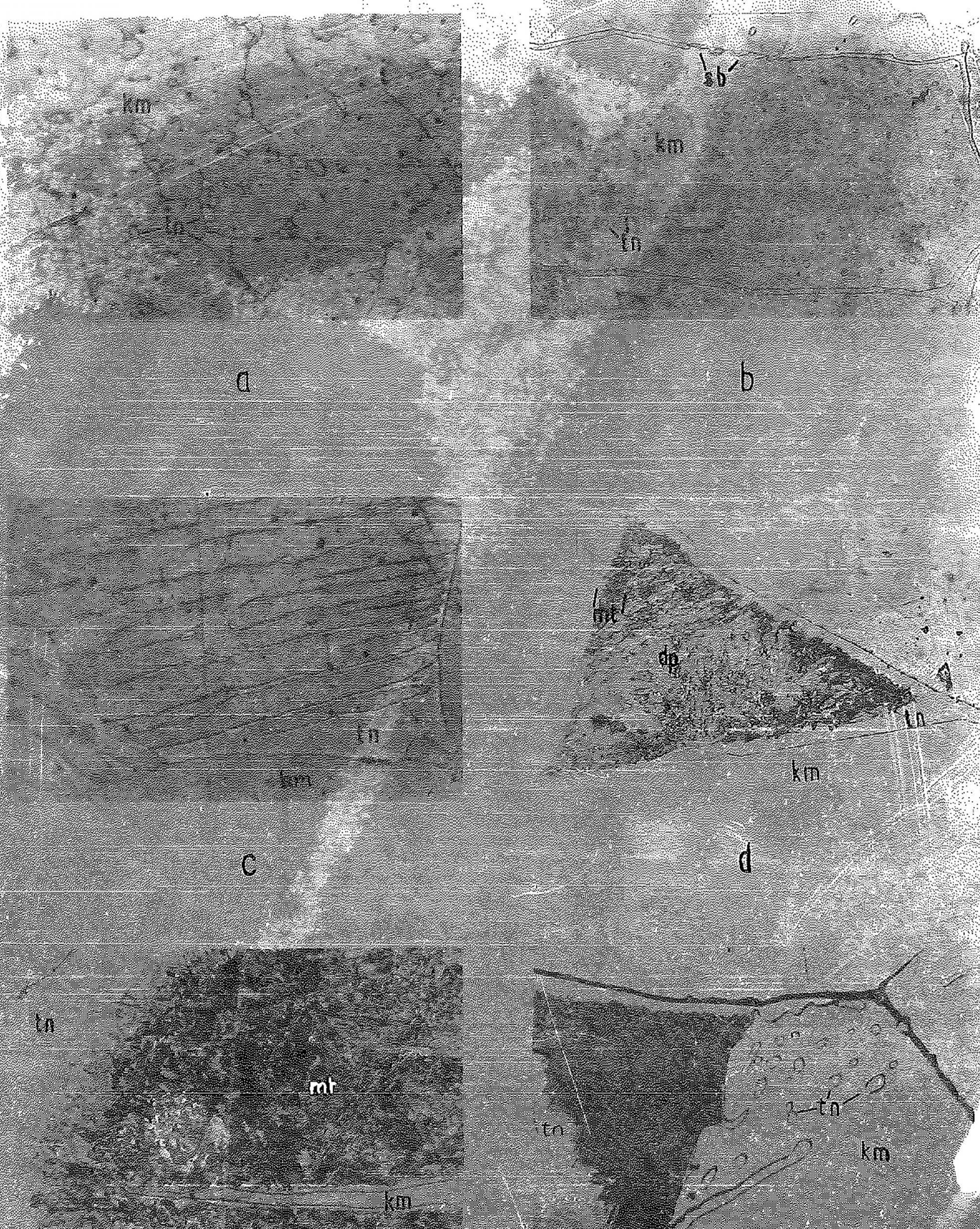


PLATE I

P L A T E   2

(a) SCHREIBERSITE

A troilite (tr) nodule partly rimmed by schreibersite (sb)

A daubreelite exsolution lamellae (dr) and kamacite (km) CARALUE (X 290)

(b) SCHREIBERSITE

Growth of schreibersite (sb) along kamacite-taenite boundary producing a corrosion pit in the taenite (tn) CARALUE (X 290)

(c) SCHREIBERSITE

Diffusion of Ni from taenite (tn) producing ragged edges in the taenite CARALUE (X 110)

(d) SCHREIBERSITE

Small euhedral rhabdites along kamacite grain boundaries MUNDRABILLA (X 700)

(e) GRAPHITE-TROILITE

An outer band of graphite-rich troilite (tr-gr); troilite with basal cleavage (cl) and kamacite

Plane polarised light MUNDRABILLA (X 40)

(f) GRAPHITE-TROILITE

Crossed polars show three bands of troilite-graphite. A band of euhedral graphite (white) forms the outer margin of the nodule MUNDRABILLA (X 40)

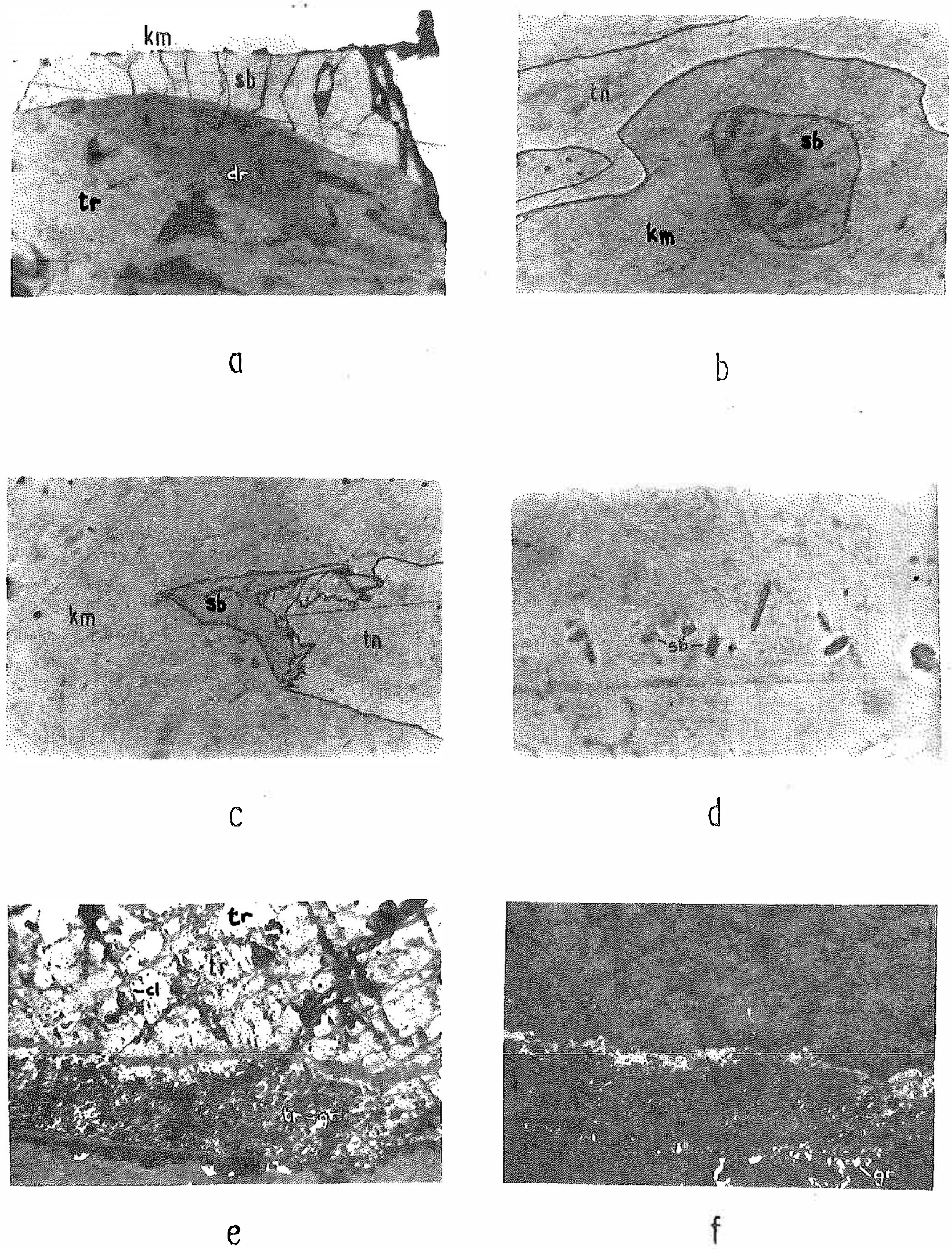


PLATE 2

P L A T E 3

(a) CHROMITE (Cr) Lamellae in troilite (tr).
Fracture offsetting daubreelite (dr) CARALUE (X 40)

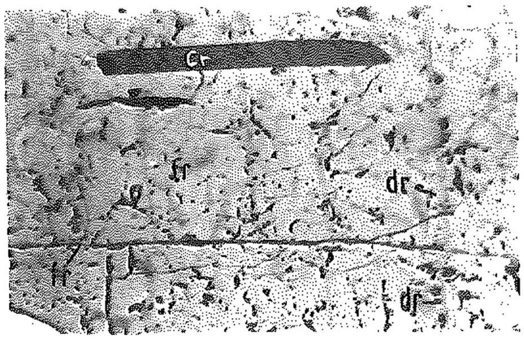
(b) COPPER (Cu)
At margin of troilite (tr) associated
with daubreelite (dr) and schreibersite (sb) CARALUE (X 290)

(c) GRAPHITE (gr) EUHEDRA IN
SCHREIBERSITE (sb) MUNDRABILLA (X 700)

(d) SPHALERITE (sp)
With daubreelite (dr)
graphite (gr) and
silicate (si) in troilite (tr) MUNDRABILLA (X 290)

(e) SILICATE (si) IN TROILITE (tr) MUNDRABILLA (X 40)

(f) PENTLANDITE (Pe) REPLACING TROILITE (tr)
in goethite (ge) with graphite (gr) MUNDRABILLA (X 700)



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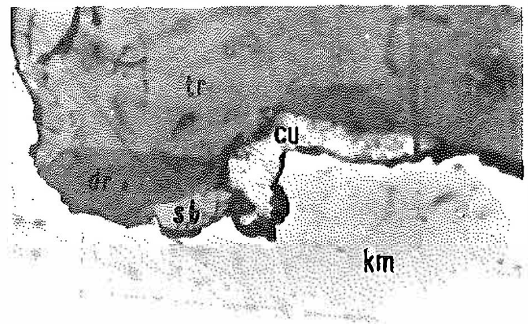

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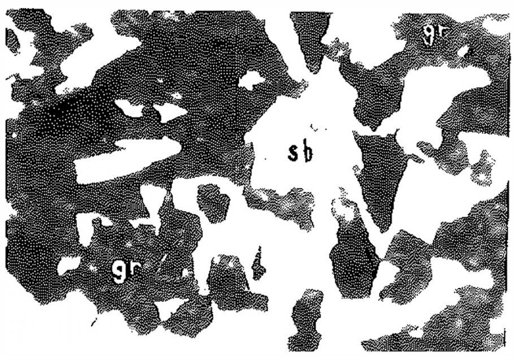

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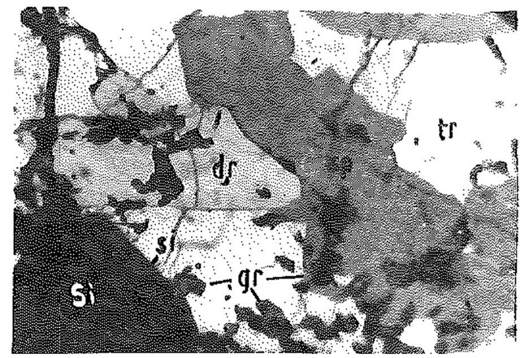

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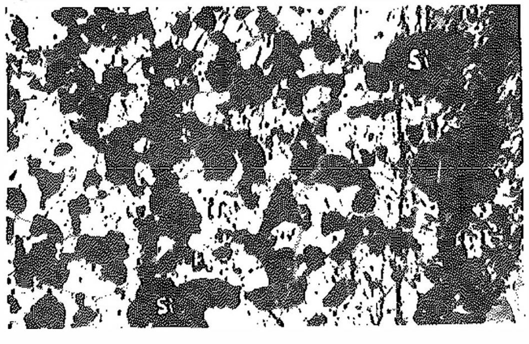

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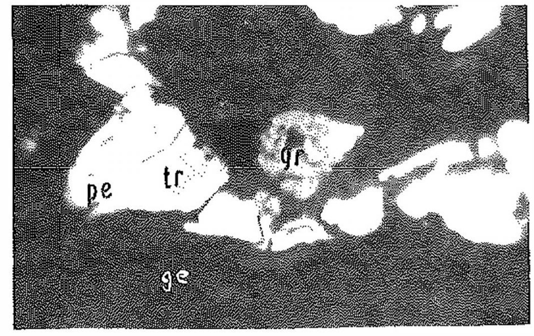

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PLATE 3

P L A T E 4

(a) DAUBREELITE-TROILITE GRAINS

Formed by breakdown of chromium-pyrrhotite CARALUE (X 700)

(b) ETCHED FACE OF CARALUE

Showing Widmanstatten Pattern and

Reichenbach Lamellae (X ½)

E.B.S.

Electron Backscatter Image of daubreelite-

troilite grain in schreibersite (sb)

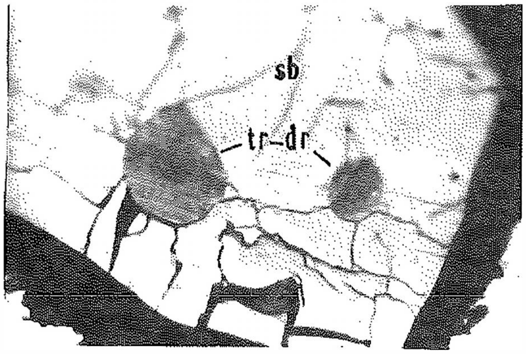
SCANS OF IRON (Fe), NICKEL (Ni),

PHOSPHORUS (P), SULPHUR (S) and

CHROMIUM (Cr) (All X 590)

Concentration of element indicated by

lighter tone



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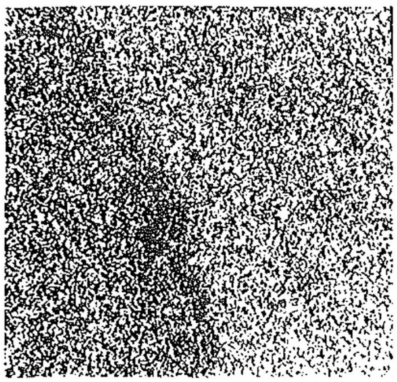
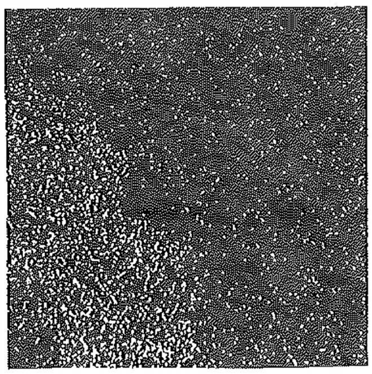
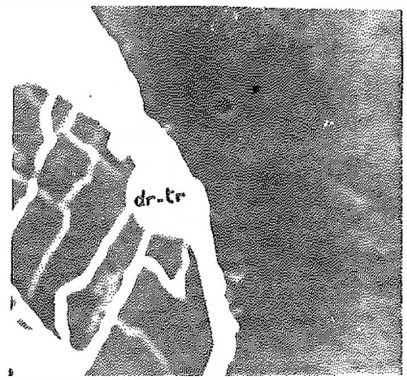
b



Fe



Ni



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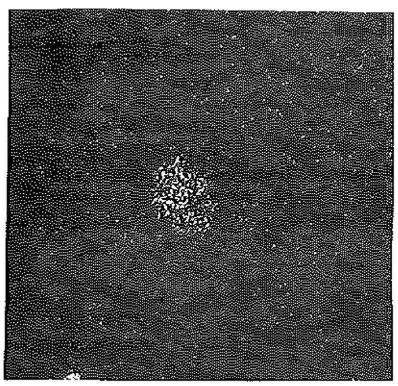
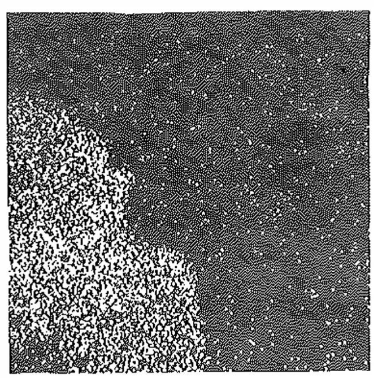


Cr



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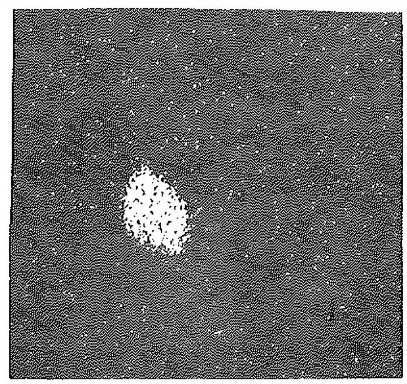


S

PLATE 4

PLATE 5

WITCHELINA

(a) ORTHOPYROXENE with troilite in a recrystallised outer shell. Transmitted light (X 40)

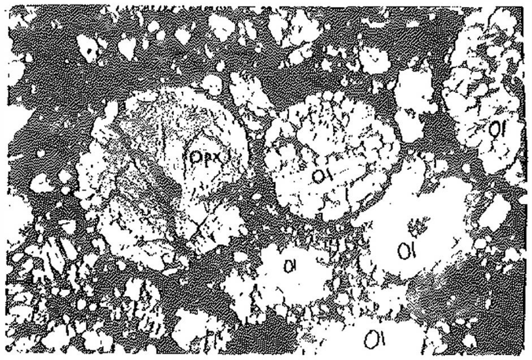
(b) (a) in reflected light (X 40)

(c) TROILITE rimming a granular olivine grain. Transmitted light (X 40)

(d) (c) in reflected light (X 40)

(e) KAMACITE-TAENITE-TROILITE EUTECTOID Reflected light (X 170)

(f) Enlargement of part of (e) (X 700)
kamacite (km), taenite (tn), troilite (tr)



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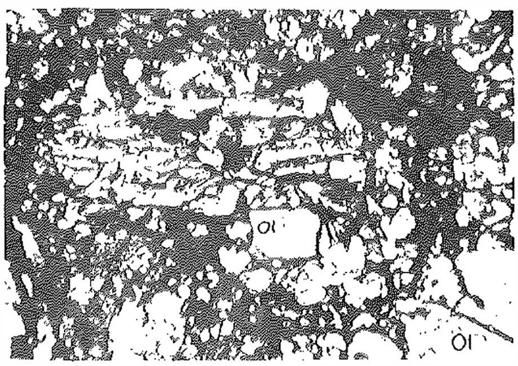

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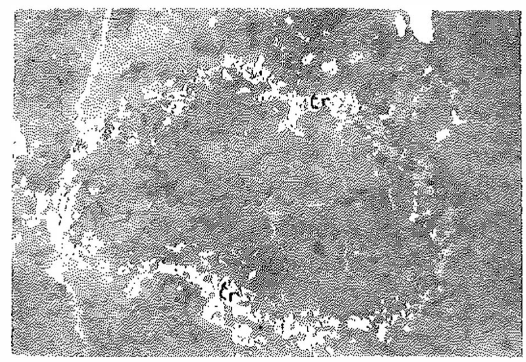

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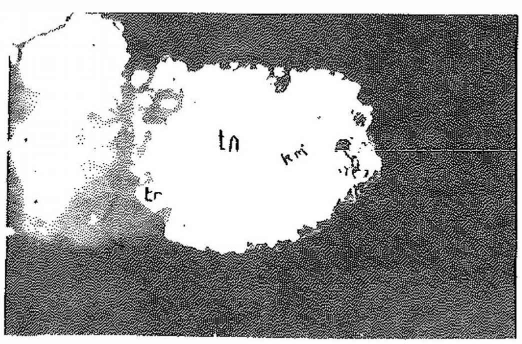

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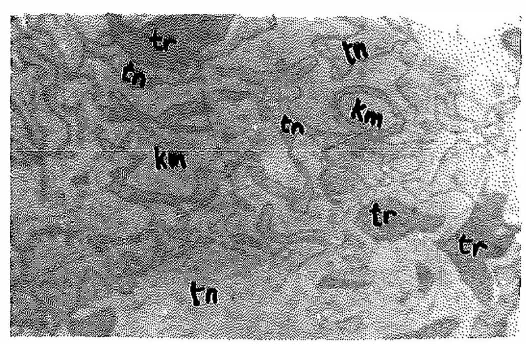

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PLATE 5

P L A T E 6

WITCHELINA

(a) TROILITE in bars of Olivine Chondrule (reflected light) (X 110)

(b) KAMACITE (km) EXSOLVING FROM TAENITE (tn)
with troilite (tr) (reflected light) (X 700)

(c) ORTHOPYROXENE CHONDRULE corroded by kamacite
(transmitted light) (X 40)

(d) ORTHOPYROXENE CHONDRULE OVERGROWTHS
(transmitted light) (X 40)

(e) OLIVINE CHONDRULE with areas of dark
turbid glass (transmitted light)(X 40)

(f) OLIVINE CHONDRULE with a barred
structure containing glass (transmitted light) (X 40)

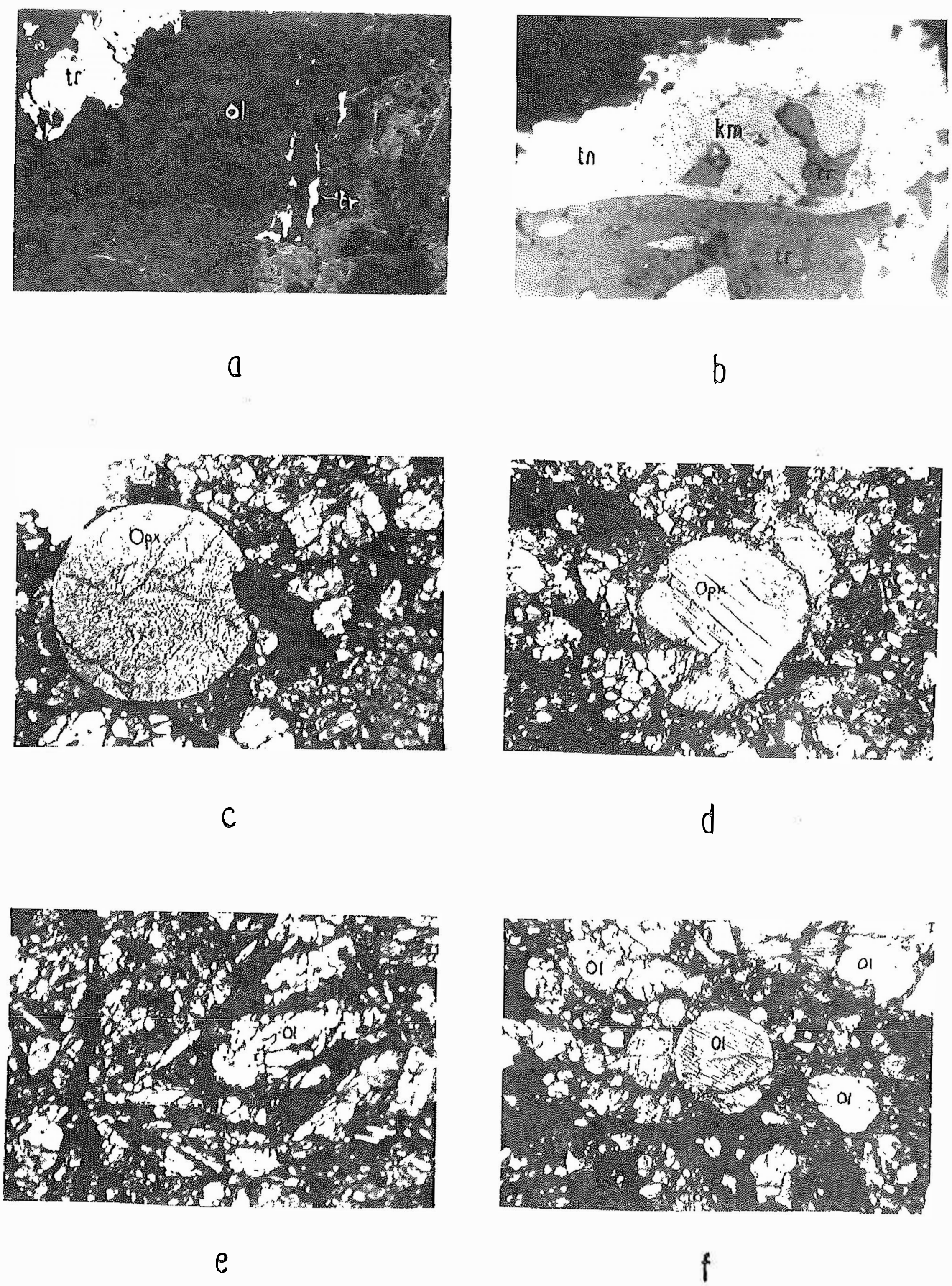

PLATE 6