Forsterite chondrites; the meteorites Kakangari, Mount Morris (Wisconsin), Pontlyfni, and Winona

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SUMMARY. Pontlyfni and Mount Morris (Wisconsin) are briefly described. Chondrule structure is absent from both, the latter is coarsely crystalline and both are sulphide-rich and contain forsterite and enstatite. Kakangari has well-defined chondrules; its silicate and sulphide minerals are unequilibrated, but similar to those of Pontlyfni and Mount Morris (Wisconsin). New bulk chemical analyses are presented; Pontlyfni has 33·84 % total Fe and 7·04 % S; Mount Morris (Wisconsin) has 19·88 % total Fe and 4·72 % S; and Kakangari has 22·79 % total Fe and 5·30 % S. These three meteorites, together with Winona, have ordinary chondritic Mg/Si ratios, which result in their having abundant forsterite; this distinguishes them from E-chondrites. The four meteorites have Mg/Si ratios lower than those of C-chondrites, and they are more reduced than C or ordinary chondrites. These four unusual stones, therefore, have some chemical similarities, for example all have Mg/Si (atomic) of about 0·95, mean olivine composition ranging from Fa_1 to Fa_5, and significant Cr in the sulphide. Cumberland Falls chondritic xenoliths and other exotic fragments in polymict meteorites may be related to the four stones, which may ultimately prove to belong to a distinct chemical group of chondrites related to the irons of Group IAB.

These meteorites are described and discussed together because they have similarities in mineralogy, bulk composition, and oxidation state. All have more than 10 % forsterite (i.e. an olivine in the range $Fa_{0\text{ }10}$). In our study we investigated the mineral chemistry of, first, Kakangari (Graham and Hutchison, 1974), and then Mount Morris (Wisconsin), with cursory examination of the previously described Winona (Mason and Jarosewich, 1967) and Cumberland Falls chondritic fraction (Binns, 1969; Jarosewich, 1967). By chance, the British Museum (Natural History) acquired the Pontlyfni stone during the course of this work. Pontlyfni fell in Wales in 1931, but is so far undescribed; it proved to be chemically and mineralogically similar to Kakangari. We thank Mr. J. R. Owen, the original owner, for its timely addition to the Museum's Collection.

Pontlyfni

A small stone weighing about 150 g fell at 11·53 a.m. on 14 April 1931 at Coch-y-Bug farm (53° 2′ 11″ N, 4° 19′ 10″ W), one mile SE of Pontlyfni (Pont Llyfni) bridge and post office and 7·5 miles SSW of Caernarvon, Wales. After hearing a series of detonations and a low whistling, Mr. Lloyd Jones, a farmer, was further startled by a thud as an object fell only six paces from where he was standing in a grassy field, making a hole about nine inches deep. His son, Mr. Aneurin Jones, recovered the meteorite from this hole, shortly after the fall. In 1931 the stone passed into the possession of Mr. J. R. Owen from whom it was acquired by the British Museum (Natural History) in 1975; the stone then weighed 146 g. It was an almost complete ovoid individual (BM 1975, M.6), with fusion crust over most of its surface. The interior is dark, hard, and coherent, and metal and sulphides are abundant. See also Hey (1966).

In thin section the high abundance of opaque minerals is striking and a point count recalculated to weight gave sulphide 21 %, metal 25 %, and silicate 54 % (weight). The proportion of opaques gives a calculated total iron content of 32 % (neglecting any Fe^{2+} in silicates), any iron abundance much higher than that of almost all ordinary chondrites; this was subsequently confirmed by wet-chemical analysis (see Table IV). Texturally the stone is fine grained and contains no chondrules or chondrule relics. The silicate comprises a mosaic of sub-rounded crystals of olivine and orthopyroxene, mostly about 20 μm in diameter but some up to 100 μm across occur with a very few even larger (0·5 mm across). A few rounded silicate grains are

poikilitically enclosed in metal or troilite or both. Most of the silicates are speckled with rounded inclusions, principally of metal but also, more rarely, of sulphide. The size of these inclusions varies from < 1 μm to 25 μm across, the majority being about 1 μm in diameter but the size range grades into that of the non-inclusion opaques. Most of the metal grains that are not inclusions are about 0·1 mm across but a few are 0·5 mm and very rarely they are up to 1 mm in length. The largest of these contain the rounded silicates mentioned earlier. Sulphide 'grains', daubréelite and troilite, appear to be somewhat smaller than those of metal, but the troilite is in optical continuity over distances of about 0·1 mm. Schreibersite is also present. Some areas of the meteorite are relatively poor in opaque grains larger than 50 μm in diameter and in these areas the silicates are also smaller (about 10 μm across) than elsewhere in the stone, though in this fine 'matrix' are set a few larger crystals. Microprobe analyses of minerals in Pontlyfni are given in Tables I–III; these data suggest that the olivines and the ortho-pyroxenes are slightly unequilibrated although texturally the stone shows no evidence of lack of equilibration. Variation in iron content of these phases may be caused by the presence of sub-microscopic metallic inclusions. Though the orthopyroxene compositions are quoted as varying from $Fs_{0.5}$ to $Fs_{2.6}$ the great majority fall between $Fs_{0.8}$ and $Fs_{1.5}$. Pontlyfni contains small grains of plagioclase, $An_{12}Or_3$; this is somewhat lower in potassium than those of H-group chondrites $An_{12}Or_6$ (Van Schmus and Ribbe, 1968).

The textures and grain sizes of the silicates suggest that the stone has been shocked. The metal, however, is clear and is present either as rounded grains or in larger masses with amoeboid outlines concave towards adjacent silicate. The abundant troilite is not intergrown with metal, indicating that metal/sulphide eutectic melting did not occur, and that either no significant heating accompanied the shock or cooling was slow enough to enable complete recrystallization to have occurred. The fine grain-size and lack of chondrules suggest that Pontlyfni can be assigned to petrologic grade 6.

Mount Morris (Wisconsin)

Very little is known about the history of this weathered stone, which is classified in Hey (1966) as an enstatite chondrite. It is, however, mineralogically and texturally very similar to Pontlyfni. Mount Morris (Wisconsin) was briefly mentioned as being similar to the Winona stone (Mason and Jarosewich 1967), another weathered meteorite.

Mount Morris (Wisconsin) is a compact aggregate of granular, equant crystals of olivine, orthopyroxene, and opaques, all of which range in diameter from 30 μm to 150 μm; minor plagioclase and diopside are also present. Neither chondrules nor chondrule relicts were found and the stone appears equilibrated and unshocked. The olivines and orthopyroxenes contain fewer opaque inclusions than Pontlyfni, but rounded metal and sulphides are much the same size as the silicates and are often interstitial grains with concave edges abutting silicates. Most of the metal grains are rimmed by oxidation products and thin veins of iron oxides permeate the meteorite. The sulphides and schreibersite seem to be more resistant to oxidation and have much thinner oxide rims than metal grains. The high degree of crystallinity is consistent with petrologic grade 7. The compositions of the phases are given in Tables I–III, and a bulk analysis in Table IV.

Kakangari

This meteorite has been described by Mason and Wiik (1966) and also by Graham and Hutchison (1974). In the latter paper it was suggested that this stone may be an unequilibrated petrologic grade 3 representative of a new chondritic group. At the time the parameters defining this group were unknown because they could not be obtained from a single representative.

TABLE I. *Olivines and feldspars in forsterite chondrites: Kakangari, Mount Morris (Wisconsin), and Pontlyfni*

	Kakangari Olivine*		Mount Morris (Wisconsin)		Pontlyfni	
	A	B	Olivine	Feldspar	Olivine	Feldspar
SiO_2	41.1	40.8	42.6	62.5	42.1	66.1
Al_2O_3	–	–	–	24.1	–	19.4
MgO	56.0	50.1	55.2	–	57.0	–
FeO	3.5	8.2	2.6	–	1.1	–
CaO	0.02	0.02	0.03	4.8	<0.02	2.4
Na_2O	–	–	–	8.7	–	9.9
K_2O	–	–	–	0.5	–	0.6
Sum	100.62	99.12	100.43	100.6	100.2	98.4
	$Fa_{3.4}$	$Fa_{8.4}$	$Fa_{2.6}$	An_{23} Or_3	$Fa_{1.1}$	An_{12} Or_3
Range	$Fa_{3.2}$–$Fa_{9.3}$		$Fa_{2.6}$–$Fa_{3.2}$		$Fa_{0.8}$–$Fa_{1.3}$	
Mean	Fa_5		Fa_3		Fa	

* Unequilibrated, two representative analyses given; modal (i.e. most abundant) composition $Fa_{3.5}$
– Not determined   Analysts: A.L.G. and R.H.
Analytical conditions: Cambridge Instruments 'Geoscan' microprobe, accelerating voltage 15 kV, sample current 0.1 μA. All microprobe data corrected for matrix effects using program Mk5 (Mason et al., 1969).

TABLE II. *Pyroxenes in Kakangari, Mount Morris (Wisconsin), and Pontlyfni*

	Kakangari*	Mount Morris (Wisconsin)		Pontlyfni	
	opx.	opx.	di.	opx.	di.
SiO_2	57.6	58.8	55.3	58.7	55.7
Al_2O_3	–	0.3	0.6	0.45	0.5
TiO_2	–	–	0.3	–	0.02
MgO	36.5	37.5	19.2	39.5	19.8
FeO	4.3	2.8	1.0	0.55	0.7
CaO	1.4	0.9	23.3	0.92	23.5
Cr_2O_3	0.3	0.1	0.4	<0.05	<0.05
Na_2O	–	0.04	0.4	–	–
Sum	100.1	100.44	100.5	100.12	100.22
Wo	2.5	1.6	45.9	1.6	45.5
Fs	6.1	4.0	1.5	0.8	1.1
Range in Fs	3.3–14.3	–	–	0.5–2.6	–
Mean	Fs_6	$Fs_{4.1}$	$Fs_{1.5}$ Wo_{46}	$Fs_{1.2}$	Fs_1 Wo_{46}

* Unequilibrated; representative analysis. – not determined
Analysts: A.L.G., and R.H. Analytical conditions as for Table I.

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TABLE III. *Sulphides and metal in Kakangari, Mount Morris (Wisconsin), and Pontlyfni, with data for Cumberland Falls (chondritic portion) for comparison*

	Kakangari	Mount Morris (Wisconsin)	Pontlyfni	Cumberland Falls*
Troilite:				
Fe	62.1	62.5	61.3	63.9
Mn	–	0.1	–	<0.05
Ti	<0.02	<0.02	<0.02	<0.02
Cr	0.30	0.37	0.85	0.39
Zn	–	<0.02	–	<0.02
Ni	–	0.03	–	–
S	36.1	37.3	35.9	33.9
Sum	98.5	100.3	98.05	98.19
Taenite:				
Ni	26–32	35–44	23–28	} ‡
Co	0.31	0.07	0.33	
Daubréelite:				
Fe		19.4	18.6	18.1
Ti		<0.02	<0.02	<0.02
Cr		35.6	37.5	35.7
Mn	‡	0.43	–	0.44
Ni		0.03	–	–
Zn		<0.02	–	<0.02
S		44.6	43.3	44.0
Sum		100.06	99.4	98.24
Kamacite:				
Fe	93.1	93.3	93.2	92.6†
Ni	6.0	6.0	6.1	6.2
Co	0.7	0.5	0.67	0.3
Sum	99.8	99.8	99.97	99.1

* Chondritic inclusion
† Unpublished analysis by S. J. B. Reed
‡ Taenite not found in Cumberland Falls; daubréelite not found in Kakangari
– Not determined

Analysts: A.L.G., R.H.

TABLE IV. *Bulk analyses and norms of Kakangari, Mount Morris (Wisconsin), and Pontlyfni*

	Kakangari*	Mount Morris (Wis.)†	Pontlyfni‡
Non-magnetic, attacked (sulphide):			
Fe	9.15	8.23	11.50
Mn	0.04	0.02	0.14
Ca	0.04	0.02	–
Cr	0.01	0.04	0.13
S	5.30	4.72	7.04
Magnetic, attacked (kamacite and schreibersite):			
Fe	11.94	6.87	19.75
Ni	1.27	0.57	1.76
Co	0.057	0.029	0.085
Schr.‖	0.09	0.11	0.04
Magnetic, unattacked (Ni-rich metal):			
Fe	0.20	–	1.91
Ni	0.12	–	0.43
Co	0.0011	–	0.007
Part sum	28.22	20.61	42.79

	Kakangari	Mount Morris (Wis.)	Pontlyfni
Non-magnetic, unattacked (silicates, phosphates, etc.):			
SiO_2	36.09	39.07	30.98
TiO_2	0.10	0.06	0.10
Al_2O_3	2.16	2.42	2.47
Cr_2O_3	0.39	0.19	0.14
Fe_2O_3	–	0.78	–
FeO	1.89	5.45	0.87
MgO	23.62	26.15	19.77
MnO	0.29	0.15	0.06
CaO	1.66	1.22	1.39
Na_2O	0.90	0.80	0.89
K_2O	0.11	0.05	0.09
P_2O_5	0.30	0.14	0.09
NiO	–	0.76	0.19
C	0.98	0.47	0.05
H_2O^+	0.56	0.39	0.23
H_2O^-	2.18	2.21	–
Sum	99.45	100.92	100.11
Total iron	22.79	19.88	33.84

	Kakangari	Mount Morris (Wis.)	Pontlyfni
Wahl norms:			
Olivine	18.2	26.3	14.8
Enstatite	35.4	37.8	28.1
Diopside	2.2	0.7	3.0
Anorthite	1.5	2.9	1.9
Albite	7.6	6.8	7.5
Orthoclase	0.7	0.3	0.5
Apatite	1.0	0.4	0.3
Ilmenite	0.2	0.1	0.2
Chromite	0.6	0.3	0.2
Nickel-iron	13.7	8.6	23.9
Troilite	14.5	13.0	18.8
Rest	3.7	3.1	0.3

* From BM 69092; 3.46 g taken for analysis
† From BM 1959,891; 2.3 g taken for analysis
  Fe_2O_3 and NiO recalculated as metal in the norm
‡ From BM 1975, M6; 3.7 g taken for analysis
‖ Schreibersite

Analyst: A. J. Easton

A new bulk analysis of Kakangari was made using the chlorination technique (Moss et al., 1967) and is quoted in Table IV. This analysis in the main confirms that of Wiik (Mason and Wiik, 1966) except that our oxidized iron value is much lower, 1·89 % FeO as against 6·90 % FeO. Using the FeO figure obtained here, the molecular 100 FeO:(FeO+MgO) is 4·3 as against 13·7. The silicate phases are unequilibrated and the olivines range from $Fa_{3.2}$ to $Fa_{9.3}$ and the low-Ca pyroxenes are $Fs_{3.3}$ to $Fs_{14.3}$ so a bulk 100 FeO:(FeO+MgO) (mol.) of 4·9 seems to be more in agreement with the silicate compositions obtained using the microprobe (see Tables I–III). For trace-element contents and a further discussion see Davis et al. (1977a).

Mineral chemistry

Representative analyses of olivines of Kakangari, Mount Morris (Wisconsin), and Pontlyfni are presented in Table I. CaO is never more than 0·03 % (wt.) although the FeO content of Kakangari olivines is variable. The olivines of Pontlyfni are more magnesian and poorer in FeO than in Mount Morris (Wisconsin), indicating that the slight difference in fayalite content is real and not due to minute metal inclusions in Pontlyfni olivine.

Differences in FeO content are also apparent in the respective Ca-poor pyroxenes and diopsides (Table II). The undetectable level of Cr_2O_3 and the very low TiO_2 content in Pontlyfni diopside may reflect the more highly reduced state of this stone relative to Mount Morris (Wisconsin); however no Ti was detected in Pontlyfni sulphide. No feldspar was found in Kakangari, this being consistent with its classification in petrologic grade 3. The other two stones have well-formed feldspar grains; those of Pontlyfni are of composition $An_{12} Or_3$, like those of equilibrated ordinary chondrites (Van Schmus and Ribbe, 1968), but in Mount Morris (Wisconsin) feldspar is significantly more calcic, $An_{23} Or_3$ (Table I).

Analyses of sulphides (Table III) indicate that troilites have significant Cr contents; this is especially so for Pontlyfni, with 0·85 %. In Kakangari, high concentrations occur in a few small, S-free grains (? chromite) but daubréelite was not found. This last mineral is present in Mount Morris (Wisconsin), Pontlyfni, and Cumberland Falls chondritic inclusions. Kamacite is much more abundant than taenite; indeed the latter was not found in Cumberland Falls chondritic inclusions (Binns, 1969). Taenite was found in the meteorites studied, the Ni content being highest in Mount Morris (Wisconsin) (Table III).

Bulk chemistry

Kakangari, Mount Morris (Wisconsin), and Pontlyfni were analysed by the chlorination technique (Table IV); the method is basically that of Moss et al. (1967), but with a number of modifications and improvements. The essence of the technique is the use of a magnetic separation together with the preferential attack by dry chlorine gas to analyse separately: sulphide, low-Ni metal plus schreibersite, high-Ni metal, and silicates plus phosphates and oxides. The agreement between normative and measured mineral compositions, Table IV, testifies to the success of the technique; bulk chemical and microprobe analyses were carried out independently.

The oxidized Mount Morris (Wisconsin) has some NiO, Fe_2O_3, and a higher FeO content than is indicated by the olivine and low-Ca pyroxene compositions. However, the 100 FeO: (FeO+MgO) molecular ratio is only 11·3 and significantly lower than in H-group chondrites. Total Fe ranges from 19·88 % (wt.) in Mount Morris (Wisconsin) through 22·79 % in Kakangari to 33·84 % in Pontlyfni, and thus covers the wide range found in E-chondrites (Keil, 1968). However, the crystallized Pontlyfni has much more total Fe than the unequilibrated Kakangari, which is the reverse of the situation in E-chrondrites (Keil, 1968). It is possible that in
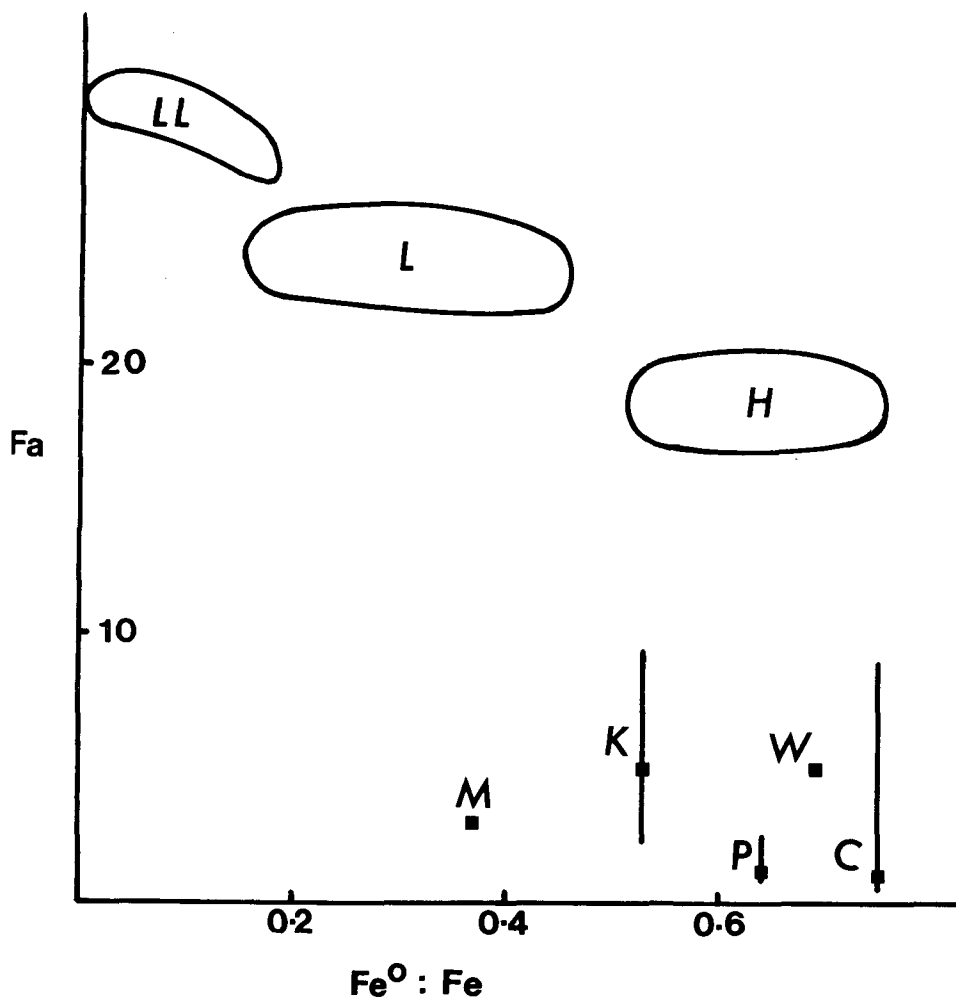
FIG. 1. Olivine composition (mol % Fa) plotted against Fe°:Fe ratio. Fe° = metallic iron, Fe = total iron (in wt. %). H, L, LL mark the fields of the ordinary chondrite groups. M = Mount Morris (Wisconsin), W = Winona, P = Pontlyfni, K = Kakangari, C = Cumberland Falls (chondritic clasts). The vertical lines signify the extent of inhomogeneity of olivine. Data from this work, from Table VI references, and Van Schmus and Wood (1967).

Pontlyfni metal and sulphide are not homogeneously distributed and hence our figure could be abnormally high; Mason and Jarosewich (1967) argued that their low Fe total (16·2 %) for Winona may be the result of such a cause, and in the H-group chondrites, one sample of the shocked Rose City had 36·4 % total Fe (Mason and Wiik, 1966). In the sulphide, Cr was only 0·07 % in Kakangari, but in Mount Morris (Wisconsin) and Pontlyfni Cr accounts for 0·3 % and 0·7 % (wt.) respectively, these values being close to the microprobe analyses (0·37 % and 0·85 %). The feldspar compositions also show good agreement between norm and microprobe analysis, e.g. An_{28} (normative) and An_{23} (microprobe) in Mount Morris (Wisconsin).

Discussion

Mineralogy. In these meteorites and in the chondritic xenoliths of Cumberland Falls enstatite is more abundant than forsterite, but the latter is too abundant for it to be considered as

merely a trace mineral. From Table V, all five representatives have forsterite and enstatite with mean composition of Fa_{1-5} and Fs_{1-6}, respectively. Similar ranges of about 4 % Fa and 5 % Fs occur within each of the three ordinary chondrite groups (Van Schmus and Wood, 1967; Fredriksson *et al.*, 1968).

Ranges of metal and sulphide content are much the same in these forsterite chondrites as in the E-chondrites, but variation in the former group appears to be less systematic. It is probably significant that Pontlyfni troilite has the highest Cr content while the olivine has the lowest FeO; this stone appears to be the most highly reduced of the forsterite chondrites, but it is not possible to fit Winona into this sequence because olivine was determined optically and by X-ray diffraction (Mason and Jarosewich, 1967).

TABLE V. *Comparative mineralogy of forsterite chondrites*

	Kakangari	Cumberland Falls (chondritic clasts)	Pontlyfni	Winona	Mount Morris (Wisconsin)
Reference	(1)	(3)	(1)	(5)	(1)
Olivine (Fa)	3.2– 9.3	0.5– 9.0	1	5	3
Low-Ca pyroxene (Fs)	3.3 –14.3	2 –16	1.2	6	4.1
Feldspar	–	–	$An_{12}Or_3$	An_{10}	$An_{23}Or_3$
Cr in Troilite wt %	0.30	0.39[1]	0.85	0.4[1]	0.37
Schreibersite	Present	3.8	Present	Present	Present
$\dfrac{Fe^{2+}}{Fe^{2+}+Mg}$ (bulk, mol.)	4.3		2.4		11.3*

* Probably Fe^{2+} includes oxidised metal
References as for Table VI

Chemistry. Mason and Jarosewich (1967) noted that Winona and Cumberland Falls chondritic inclusions have Mg/Si ratios like those of ordinary chondrites; this is true of the other meteorites discussed here (Table VI). Our new figure for Mg in Kakangari is lower than that of Wiik (Mason and Wiik, 1966), and so the Mg/Si ratio is closer to that in ordinary chondrites. The Mg/Si ratio for Mount Morris (Wisconsin) is, however, high.

Relative to Si, Ca and Al are more variable than would be expected for ordinary chondrites (Table VI). Some of the variation may be due to analytical uncertainty, but at least some of the variation in the Ca/Al ratio appears to be real. In particular, the low ratio (0·46) in Mount Morris (Wisconsin) is reflected in the high anorthite content of the plagioclase as measured by microprobe. Loss of diopside (and albite?) by crystal/liquid fractionation may be an explanation, but it is difficult to reconcile this with retention of sulphide (see Table VI). Whatever the explanation, it seems that in the formation of these meteorites a mechanism operated by which Ca became fractioned from Al; we believe that here is a case in which constancy of Ahrens' (1970) Ca/Al ratio (1·08 [wt.], 0·73 [atomic]) is not maintained.

The S contents of Winona and Cumberland Falls chondritic inclusions are significantly lower than those of the other three meteorites. This element must have been fractionated relative to Si and Mg by a process unrelated to crystallization, for Winona is crystalline and Cumberland Falls chondritic inclusions are chondrule-bearing and unequilibrated; both textural types are represented in the three S-rich meteorites. Fractionation of S relative to Si does not occur to any significant extent within any group of the ordinary chondrites.

Pontlyfni, Mount Morris (Wisconsin), and Winona are crystalline and without recognizable chondrules, but their chemistry and mineralogy suggest links with the chondrule-bearing Kakangari and Cumberland Falls chondritic inclusions. We therefore prefer to treat them as chondrites.

TABLE IV. *Comparative elemental abundances (in atoms /10^4 Si atoms) and total iron and nickel contents (in weight %)*

Meteorite	Reference	Mg	Ca	Al	Na	S	Ca/Al (atomic)	Total Fe (wt. %)	Ni (wt. %)	Fe:Ni (wt. %)
Kakangari	(1)	9750	500	705	484	2750	0.67	22.79	1.42	16.0
	(2)	10200	480	730	554	2800	0.66	22.47	1.27	17.7
Mount Morris (Wisconsin)	(1)	9930	334	724	400	2270	0.46	19.88	1.10	18.1
Pontlyfni	(1)	9510	481	939	555	4267	0.51	33.84	2.2	15.4
Cumberland Falls (chondritic	(3)	9380	413	837	580	890	0.50	19.5	1.07	18.2
portion)	(4)	9319	568	601	609	1269	0.95	19.0	0.96	19.8
Winona	(5)	9680	340	670	440	680	0.51	16.2	1.2	13.5
'O'-chondrites	(6)	9500	480	610	430	1000	0.79	20–28	1.0–1.8	~17
'E'-chondrites	(6)	7500	355	480	590–340	3000–1500	0.74	35–20	1.8–1.5	~16
Carbonaceous chondrites	(6)	10500	730	850	600–300	5000–1200	0.86	18–26	1–1.5	~18

References
(1) This work
(2) Mason and Wiik (1966)
(3) Binns (1969)

(4) Jarosewich (1967)
(5) Mason and Jarosewich (1967)
(6) Mason (1971)

Conclusions

The data outlined in this paper are sufficient to distinguish Kakangari, Mount Morris (Wisconsin), Pontlyfni, and Winona from E, H, L, LL, or C chondrite groups. Except for S, and Ca/Al, chemical variation between the four stones (plus Cumberland Falls chondritic inclusions) is similar to that within, say, the H-group chondrites (fig. 1). On the plot of Fa content of olivine against (Fe in metal):(total Fe) (after Van Schmus and Wood, 1967), the four stones plus Cumberland Falls chondritic inclusions plot in the same restricted field. Mount Morris (Wisconsin) is low in Fe°/Fe because it is oxidized (Fe° is the sum of metallic Fe plus Fe_2O_3 converted to metal). In the analysis, 0·76 % NiO was found, so it is likely that about 3 % FeO is from the oxidation of metal. When this FeO is calculated as Fe°, the Fe°/Fe ratio becomes 0·46, and close to that of Kakangari. The 100 FeO:(FeO+MgO) molecular ratio then becomes 4·9 and close to that of the Ca-poor pyroxene. The ranges in Fa content of the olivine and the Fe°/Fe are therefore similar to those in the other chondritic groups. The ordinary chondritic Mg/Si ratios serve to distinguish the four stones plus Cumberland Falls chondritic inclusions from E- or C-chondrites, but the oxidation state is equally distinct.

Mason and Jarosewich (1967) remarked that material like Winona occurs as xenoliths in Woodbine and other irons with silicate inclusions (Group IAB). Leitch and Grossman (priv. comm.) have found in the H-group chondrite Supuhee an S-rich inclusion, the bulk composition of which (to R. H.) appears to resemble Kakangari. It is therefore probable that forsterite chondrite material is more widely distributed than is suggested by the four meteorites discussed here.

R. N. Clayton (1976, and priv. comm.) has measured oxygen isotope ratios of Kakangari, Pontlyfni, Winona, and Cumberland Falls chondritic inclusions. Together with a xenolith from Bencubbin, the bulk meteorite data plot collinearly on a δ^{18}o v. δ^{17}o diagram, within experimental error. The line has a slope greater than 0·52 but less than 1, so that it could be a mixing line with genetic significance. The very low δ^{18}o and δ^{17}o values of Kakangari plot on the lower extension of a C2 matrix mass-fractionation line (Clayton *et al.*, 1976) so there may

be some genetic relationship between forsterite chondrites and C2 matrix. In fig. 1 (this paper) the sequence Kakangari to Cumberland Falls chondritic inclusion (i.e. increasing Fe°/Fe) corresponds to that of increasing $\delta^{18}o$ and $\delta^{17}o$ along the 'mixing' line. If this has any genetic significance, Mount Morris (Wisconsin) should have values close to or lower than Kakangari. The suggestion that the oxygen isotope ratios of the forsterite chondrites lie on a mixing line indicates that more than one isotopically distinct component was involved in their formation. In this the forsterite chondrites are similar to the carbonaceous chondrites and different from each of the E, H, L, and LL groups of chondrites.

The relationship of the forsterite chondrites to each other and to other meteorite groups is not clear. Although all four meteorites plus Cumberland Falls chondritic inclusions have uniform Mg/Si ratios and similar oxidation states, the variable Ca/Al ratios and S contents suggest that crystal/liquid fractionation may have played a part in their formation. If they are related to the irons with silicate inclusions of Group IAB (as suggested for Pontlyfni by Davis, Ganapathy, and Grossman, 1977*b*), the igneous fractionation must have taken place before mixing of metal plus sulphide with silicate, otherwise sulphide and diopside would have been removed together by settling out of the main melt. We believe that in time samples of forsterite chondrite material will become sufficiently numerous to be regarded as members of an independent chemical group or groups.

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