THE MIGHEI METEORITE*

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Abstract. The Mighei meteorite is generally considered to be unique amongst the group of stony meteorites known as the carbonaceous chondrites in a number of scientifically interesting aspects. The meteorite, which is related to the type II carbonaceous chondrites of Wiik's classification (or type C2 according to van Schmus and Wood), contains extraterrestrial organic compounds (general C content=2.6%), and extraterrestrial water associated with iron-magnesium silicate crystals (general H_2O content=12%).

The meteorite fall occurred in 1889, over a region in the Ukraine. In structure it was found to be a chondritic meteorite, having chondrules of order 0.5 mm in size. The composition of the meteorite is inhomogeneous. In mineralogical terms the meteorite is composed of two paragenetic associations, described as 'high' and 'low temperature', which are generally distributed in equal proportions. The 'low temperature' associations are a characteristic only of carbonaceous chondrites: the minerals involved are chlorites or the serpentine group, carbonates, free sulphur, sulphates and 'low temperature' glass. In chemical terms the Mighei meteorite is somewhat enriched in the volatile elements S, C, H, N, O in comparison to the usual chondrites. These elements are found in different forms and the isotopic composition of the elements S, C, O, is different for different phases. The meteorite is also rich in a number of other fairly volatile element admixtures such as: B, F, Cl, Cu, Zn, Ga, Ge, Br, In, Te, I, Hg, Tl, Pb, Bi, and contains somewhat enhanced initial quantities of rare gases.

The organic compounds are of an abiological nature in the meteorite and are located in finely dispersed distributions between the chondrules. They are present in the main, as polymerized organic compounds. Among these polymers there are gaseous hydrocarbons (saturated and non-saturated) and extractable organic compounds. In the latter condition the following organic compounds have been identified: aliphatic hydrocarbons, aromatic hydrocarbons, amino acids and others. The meteorite contains free organic radicals (10^{17} centres g^{-1}), uncoupled π-electrons which are delocalized in the aromatic structure of the polymeric matter.

The radiogenic age of the meteorite has been determined as from 2.4 to 3.2×10^9 yr (by the K–Ar method) and up to 4.54×10^9 yr (by the Rb–Sr method), while the radiation age is put at 0.5 to 2.4×10^6 yr. Details of the meteorite structure give evidence of at least two processes in its formation; the accretion of the meteoritic matter, together with the simultaneous formation of organic compounds could have taken place at temperatures between 450 and 300K.

1. Introduction

Meteorites falling on the Earth from outer space are very special objects. From the many different kinds of investigation of them a great variety of information can be gathered which is of weighty scientific significance, concerning the origins of their material, the different conditions of formation of cosmic bodies and the general environment of cosmic space – and so on. A great deal of attention attaches to that group of stony meteorites – the carbonaceous chondrites – which contain organic matter of extraterrestrial and abiological origin, as well as extraterrestrial water which is linked with the iron-magnesium silicate crystals. Results of the study of the meteoritic organic

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material affords insight into such problems as the transformation of organic compounds in cosmic conditions and the possible manner of the origin of living material in terrestrial and other conditions.

About thirty carbonaceous chondrites are known. Details of the structure of these rare, but very interesting meteorites have been examined in the works of Mason (1963, 1971), Kvasha (1968), Vdovykin (1967) and a number of other publications. Carbonaceous chondrites differ significantly from other meteorites in their mineral composition and structure, and also in their chemical composition. They are relatively rich in certain volatile elements (S, C, H, N, O) which occur in different forms. These meteorites are also somewhat over-abundant in a number of other volatile element-admixtures (Cl, Cu, In, Hg and others).

These meteorites also tend to have higher oxidized materials than other meteorites, and, moreover, the matter in between the chondrules is more oxided than that of the chondrules. There are even inhomogeneities within the chondrules themselves.

According to chemical composition the chondrites had been subdivided into three (Wiik, 1956) or four (van Schmus and Wood, 1967) types. The most abundant in organic compounds and volatile chemical elements are in Wiik's type I.

The abundances of the elements in these meteorites is related to their cosmic abundances. Thus the Orgueil meteorite (which fell on May 14, 1864 in France), is a type I carbonaceous chondrite, and many of its fragments, distributed in many meteorite museums throughout the world, have given rise to detailed studies of meteoritic organic compounds and structural peculiarities, the results of which may be found in the works of Meinschein (1963), Nagy (1966) and others. However, the Orgueil meteorite is composed, almost entirely, of minerals of the 'low temperature' formation and chondrules are not present, i.e. the meteorite could hardly be taken as a typical chondrite.

In the carbonaceous chondrites of Wiik's second type, chondrules may attain sizes of 0.3 to 0.5 mm, and there are often roughly equal amounts of 'low' and 'high temperature' minerals (Anders, 1964). The Mighei meteorite is typical of this class, containing some 2.6% C and 12% H_2O.

The stony Mighei meteorite (the synonyms – Migei and Elizabethpol) fell in the Ukraine in the territory of Odessa district, in the Pervomaisky region around the village of Mighei on June 18 (or June 21 according to Krinov (1960)) in 1889, at a time of 8 hr 22 min, in the evening. The co-ordinates of the fall are 48°4N, 30°58E. The meteorite fall was observed by eye-witnesses, who remarked on the bolide and sonic effects which accompanied the meteorite flight. After the fall one individual meteorite specimen was recovered which had a weight of about 8 kg. The circumstances of the fall and a preliminary investigaton of the Mighei meteorite were set out in the Simashko's booklet (1890).

The single specimen of the Mighei meteorite was broken into pieces shortly after the fall. At the present time fragments of the meteorite exist in many meteorite collections. In the Meteorite Museum of the Academy of Sciences of the U.S.S.R. in Moscow there is a fragment of mass about 1.5 kg, in the Natural History Museum of Chicago in the U.S.A. there is about 2.2 kg, there are also fragments of the meteorite at the Geological Institute of the Ukrainian Acad. of Sciences in Kiev, the University of Odessa, the Leningrad Mining Museum, the collection of British Natural History Museum (London), the American Natural History Museums in New York and Yale University and in many other collections. The Mighei meteorite has been studied in great detail, especially in recent years, by very many scientists.

In this paper a survey of the structure and composition of this unique meteorite from the Ukraine is given. The author of this survey studied samples of the Mighei meteorite from the collection of the Soviet Academy of Sciences.

2. Structure and Mineral Composition

The form of the original single Mighei meteorite was a cone-shaped, irregular polyhedron (Figure 1a). The entire outer surface was covered with a thin dull black crustal layer. In section the meteorite also has a dark colour (Figure 1b) as a result of its high carbon content. As with other carbonaceous chondrites the Mighei meteorite is brittle and rather loosely packed, so that it may be ground up by finger pressures. The density of the material is 2.70 g cm^{-3}.

The structure and mineral composition of the Mighei meteorite has been described in the monographs of Zavaritsky and Kvasha (1952) and Vdovykin (1967). Recrystal-

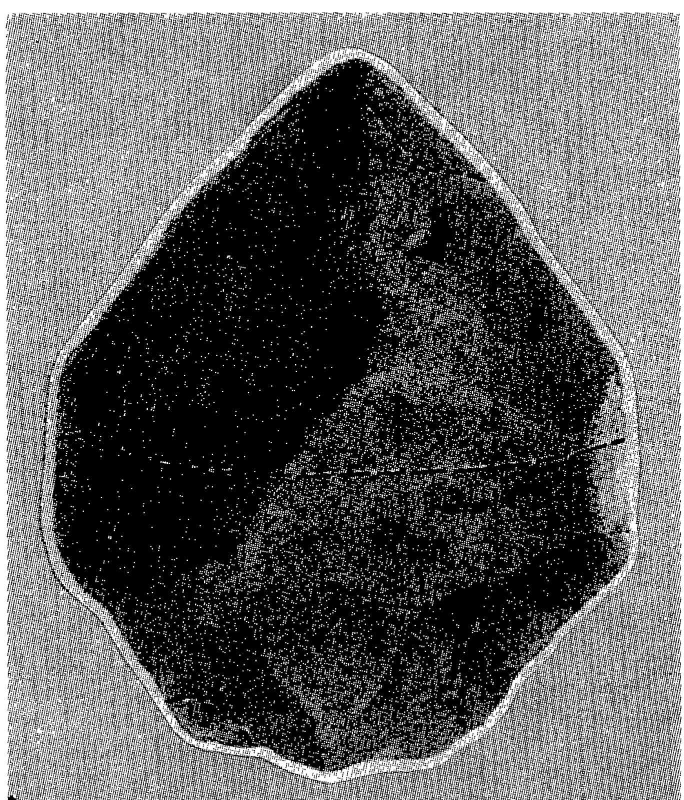


Fig. 1a. The individual specimen of the Mighei meteorite in two aspects.
The dotted line shows the direction along which the meteorite was broken (Decreased).

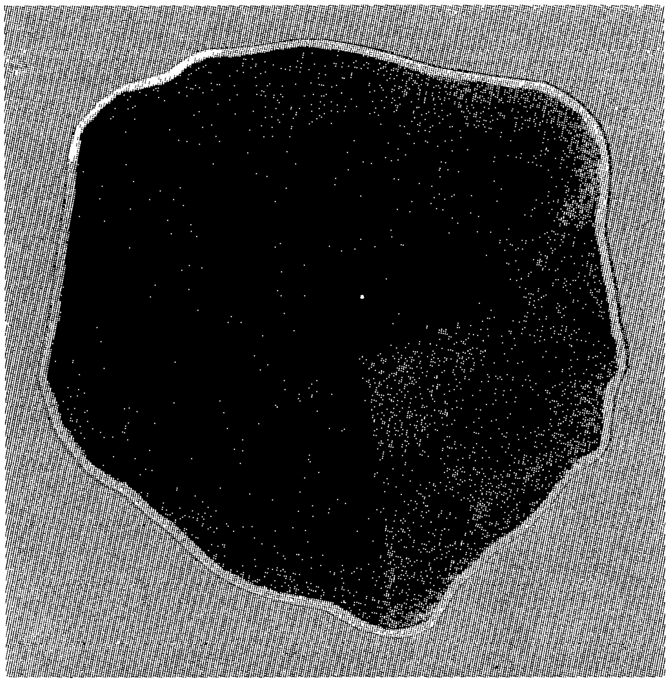


Fig. 1b.

lized chondrules (Kvasha, 1968) and petrographically inhomogeneous zones (Mueller, 1966a) have been observed in the meteorite. Mueller observed in a meteorite slice angular inclusion of size 4×2.5 mm, the petrographic structure of which resembled the structure of type III carbonaceous chondrites.

The structure of the Mighei meteorite is chondritic. Under the microscope in direct light (sample No. 1856) it is evident that the meteorite is composed of a dark material (Figure 2), in which small chondrules and separate mineral granules are scattered. The chondrules have a circular or elongated form (Figure 3) and sizes of from 0.08

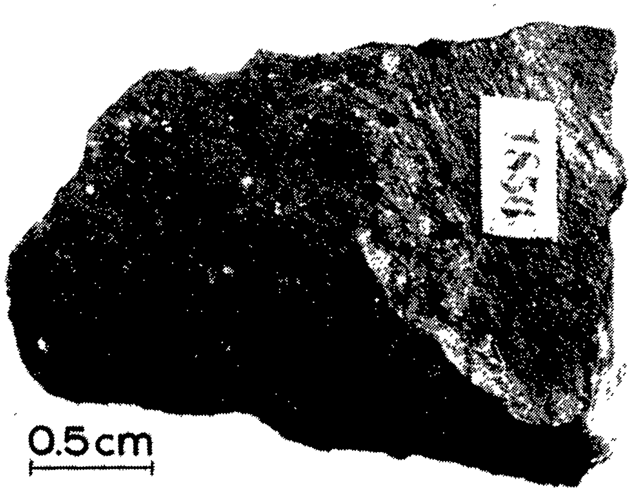
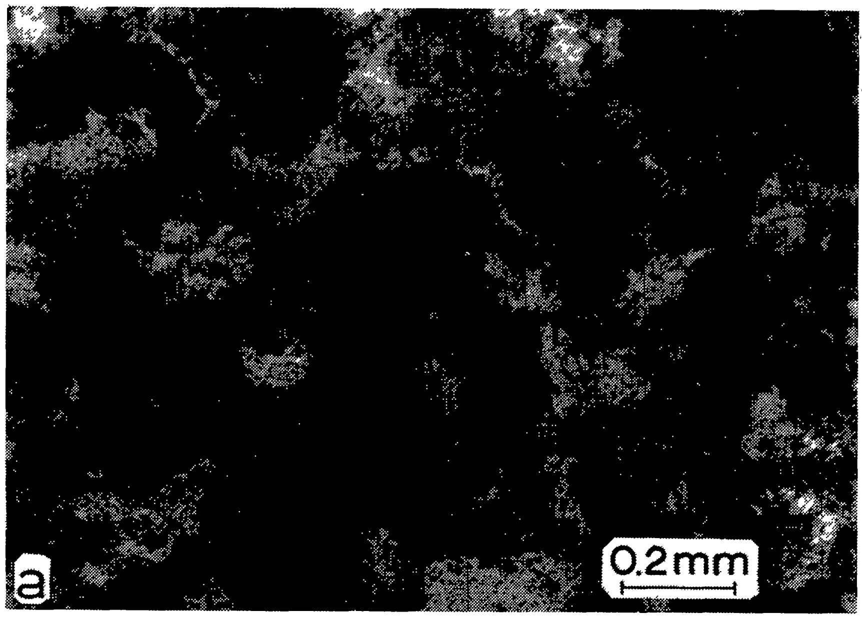


Fig. 2. A piece of the Mighei meteorite.



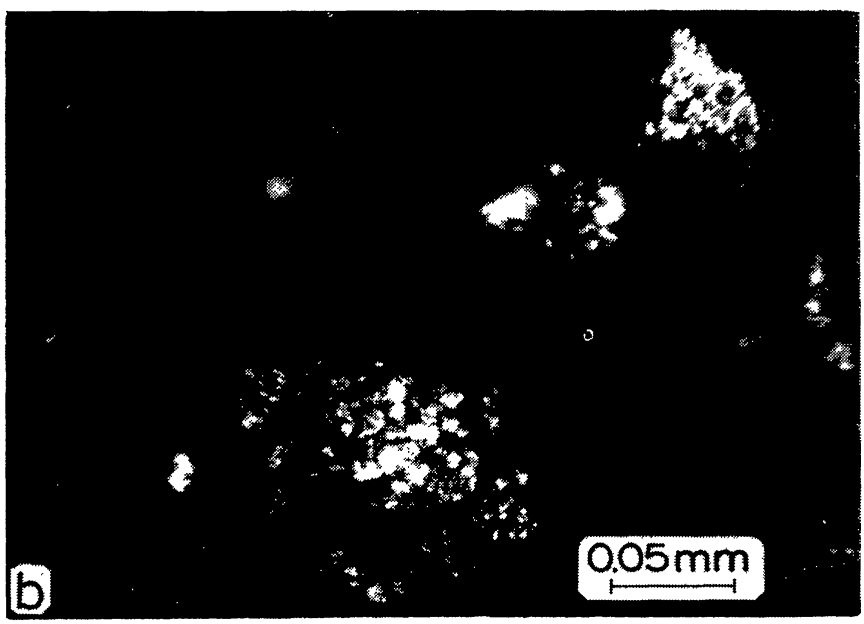


Fig. 3. Microphotograph of a slice of the Mighei meteorite, (a) the basic material of the meteorite, (b) chondrules in the carbonaceous matter.

to 0.5 mm, whereas in more typical chondrites the chondrules may measure up to 2 mm or more. The chondrules of the Mighei meteorite are essentially composed of olivine and minerals of the chlorite – serpentine group in secondary olivine substitutes. Sometimes chondrules composed entirely of olivine are encountered. It is more common, however, to find the olivine grains in the chondrules separated by opaque carbonaceous material. The sizes of olivine crystals occurring in the chondrules are usually no greater than 0.05 mm. The structure of these chondrules is microporphyritic. Mueller (1966b) called such chondrules, which are found in carbonaceous chondrites, the 'bunch of grapes' type. Certain chondrules have a 'firegrate' structure.

The admixtures of chondrule minerals are of the chlorite – serpentine type and the carbonaceous material often occurs around the peripheries in chondrules having a broken up form. Over the exposed faces of the meteorite chondrules are encountered, which are made up of chlorite – serpentine minerals surrounded by envelopes of carbonaceous material. Moreover, in these envelopes there are distributed separate extended granules of water-containing silicates, which are of a similar outline to the chondrules. Evidently such chondrules represent the remnants of the interiors of previous, considerably larger chondrules which were broken up and mixed about in subsequent processes.

The material between chondrules is rather porous, sometimes containing minute crevices and having a lumpy composition. The shapes of the lumps are irregular, but for the most part they are roughly spherical with diameters, generally, of 0.2 to 0.3 mm. The borders of the lumps are dark grey, sometimes with a greenish tint. The reason for this is that in such cases the carbonaceous particles are mixed up with traces of the chlorite – serpentine which has a green colour. The lumpy structure of these parts of the meteorite is clearly visible in reflected illumination, in which they have a brownish tinge.

The interrelation of the particles of carbon rich material and mineral particles were investigated by Vdovykin (1967) by means of electron microprobe analysis of a specially prepared slice of the Mighei meteorite. For this purpose the slice was carefully polished and its surface was judiciously treated with HF and HCl for the separation and removal of silicates. After this treatment the slice was thoroughly washed in distilled water. After all this the resulting surface showed microprotuberances of carbonaceous particles. On the photograph of a collodion duplicate of this surface, by the chrome shading (Figure 4), it is evident that the carbonaceous material forms small

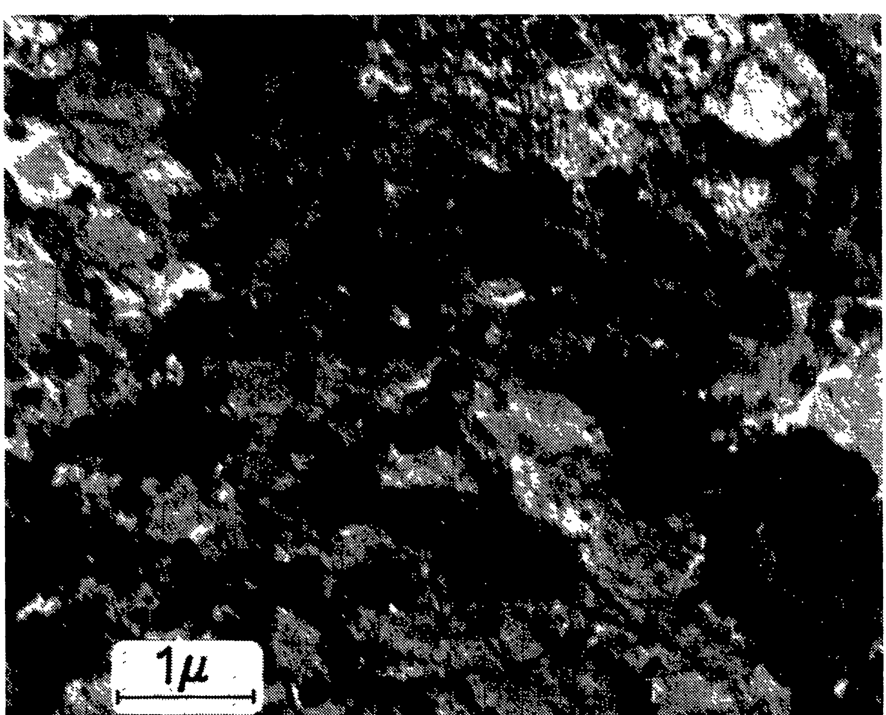


Fig. 4. Electron-microscope photograph of a slice of the Mighei meteorite.

TABLE I

Material composition of the Mighei meteorite from the data of X-ray investigations

Mighei meteorite						Olivine		Pennine		Magnetite	
Mikheev and Kalinin (1958)		Yudin and Obotnin (1961)		Vdovykin (1967)							
1	$\frac{d_\alpha}{n}$	1	$\frac{d_\alpha}{n}$	1	$\frac{d_\alpha}{n}$	1	$\frac{d_\alpha}{n}$	1	$\frac{d_\alpha}{n}$	1	$\frac{d_\alpha}{n}$
1	2	3	4	5	6	7	8	9	10	11	12
3	7.82	–	–	2	7.93	–	–	2	7.92	–	–
6	7.11	6	7.16	9	7.12	–	–	9	7.18	–	–
–	–	–	–	2	6.95	–	–	–	–	–	–
–	–	–	–	1	5.86	1	5.84	1	5.84	–	–
2	5.41	–	–	1	5.36	–	–	5	5.29	–	–
1	5.01	–	–	–	–	–	–	10	4.79	–	–
1	4.74	–	–	1	4.54	–	–	4	4.60	–	–
1	4.36	–	–	1	4.40	2	4.29	–	–	1	4.21
6	3.91	2	3.92	1	3.84	7	3.871	–	–	–	–
1	3.76	–	–	–	–	–	–	–	–	–	–
9	3.58	8	3.56	9	3.53	–	–	10	3.585	–	–
1	3.50	–	–	–	–	6	3.491	–	–	–	–
1	3.31	–	–	1	3.29	–	–	1	3.311	–	–
3	3.17	–	–	1	3.11	–	–	3	3.152	–	–
6	3.03	1	3.02	–	–	–	–	–	–	–	–
6	2.985	–	–	3	2.985	5	2.995	–	–	6	2.99
3	2.880	–	–	1	2.841	–	–	9	2.864	–	–
4	2.781	3	2.80	2	2.787	9	2.770	–	–	–	–
6	2.702	3	2.70	1	2.686	–	–	4	2.705	–	–
10	2.529	8	2.54	10	2.530	–	–	10	2.538	10	2.541
10	2.450	4	2.45	4	2 445	10	2.455	10	2.445	–	–
1	2.382	–	–	–	–	–	–	6	2.385	–	–
6	2.261	–	–	2	2.263	9	2.253	7	2.286	–	–
1	2.212	–	–	–	–	–	–	–	–	–	–
2	2.156	5	2.16	7	2.145	5	2.165	–	–	–	–
1	2.112	–	–	–	–	–	–	–	–	7	2.098
5	2.023	4	2.03	1	2.014	2	2.032	–	–	–	–
–	–	–	–	1	1.988	–	–	10	2.008	–	–
4	1.912	–	–	1	1.917	–	–	6	1.893	–	–
2	1.875	–	–	1	1.861	3	1.877	–	–	2	1.884
1	1.837	–	–	–	–	–	–	–	–	–	–
4	1.787	2	1.794	6	1.785	2	1.788	–	–	4	1.785
7	1.746	5	1.747	6	1.734	10	1.747	6	1.741	–	–
1	1.691	–	–	–	–	–	–	–	–	5	1.710
1	1.665	–	–	1	1.673	5	1.671	4	1.670	–	–
6	1.630	–	–	–	–	–	–	–	–	–	–
1	1.606	–	–	1	1.612	6	1.619	–	–	9	1.612
6	1.571	4	1.576	6	1.571	4	1.572	9	1.575	–	–
4	1.536	3	1.541	4	1.537	3	1.539	10	1.535	–	–
4	1.495	2	1.495	3	1.489	8	1.493	7	1.503	–	–
1	1.472	3	1.479	2	1.477	9	1.481	4	1.462	9	1.479
2	1.446	2	1.447	–	–	2	1.437	–	–	–	–
1	1.429	–	–	1	1.429	–	–	4	1.432	–	–
1	1.407	–	–	–	–	–	–	9	1.405	2	1.411
2	1.390	2	1.395	2	1.390	9	1.397	–	–	–	–

Table I (continued)

Mighei meteorite						Olivine		Pennine		Magnetite	
Mikheev and Kalinin (1958)		Yudin and Obotnin (1961)		Vdovykin (1967)							
1	$\frac{d_\alpha}{n}$	1	$\frac{d_\alpha}{n}$	1	$\frac{d_\alpha}{n}$	1	$\frac{d_\alpha}{n}$	1	$\frac{d_\alpha}{n}$	1	$\frac{d_\alpha}{n}$
1	2	3	4	5	6	7	8	9	10	11	12
1	1.372	–	–	–	–	–	–	–	–	–	–
2	1.349	–	–	1	1.337	9	1.350	–	–	–	–
–	–	–	–	1	1.326	–	–	7	1.320	3	1.325
2	1.311	–	–	2	1.309	9	1.316	–	–	–	–
1	1.289	–	–	–	–	3	1.295	7	1.295	–	–
1	1.260	–	–	2	1.262	2	1.267	–	–	2	1.264
1	1.244	–	–	1	1.239	3	1.238	–	–	–	–
1	1.207	–	–	–	–	1	1.209	–	–	–	–
1	1.185	–	–	–	–	7	1.188	–	–	–	–
1	1.165	–	–	1	1.164	–	–	–	–	–	–
–	–	–	–	1	1.137	7	1.137	–	–	–	–
1	1.128	–	–	1	1.122	5	1.125	–	–	4	1.119
1	1.103	–	–	–	–	–	–	–	–	–	–
1	1.096	–	–	1	1.096	8	1.098	–	–	8	1.091
1	1.078	–	–	–	–	–	–	–		–	–
1	1.070	–	–	–	–	–	–	–	–	–	–
1	1.062	–	–	–	–	–	–	–	–	–	–
3	1.041	–	–	–	–	–	–	–	–	–	–
3	1.034	–	–	–	–	–	–	–	–	–	–

clumps of sized up to 2 or 3μ or more, and it occurs in a mixture with mineral grains of about the same size.

Under the microscope in reflected illumination small grains of nickel iron and also sulphides may be seen to be distributed in the carbonaceous matter and sometimes within the chondrules. Yudin and Obotnin (1961), as a result of a mineragraphic study of three Mighei meteorite slices, obtained mean contents (in % by volume) of 0.29 troilite, 0.08 nickel-iron, and rare chromite grains.

In order to estimate phase composition (basic mineral phases) of the Mighei meteorite, the meteorite powders were investigated by X-ray methods (Mikheev and Kalinin, 1958; Yudin and Obotnin, 1961; Vdovykin, 1967). All three X-ray patterns were similar (Table I). It was observed that the meteorite is composed to a large extent of olivine and minerals of the chlorite – serpentine group. X-ray lines due to magnetite were in evidence, although graphite was not observed in the patterns.

Consequently, olivine and minerals of the chlorite – serpentine class appear to be the most important mineral constituents of the Mighei meteorite. Particles of rhombic pyroxene are present in small quantities. Glass also has a structural significance in the meteorite.

A particularly important feature of the Mighei meteorite is the simultaneous presence of two paragenetic associations – the 'high and low temperature' minerals, which are found in approximately equal proportions (DuFresne and Anders, 1962; Vdovykin, 1967).

A. 'HIGH TEMPERATURE' MINERAL ASSOCIATION

Minerals of the 'high temperature' group include olivine, pyroxene, glass, nickel-iron, troilite, pentlandite, chromite and magnetite.

Olivine $(Mg, Fe)_2SiO_3$ is found in the Mighei meteorite in the form of chondrules and finely distributed grains. By the use of a centrifuge on finely powdered meteoritic material Vdovykin (1964a) managed to separate small fragments of different densities from the powder. Among the fragments were some very small spherical chondrules of olivine of diameter 64μ and some olivine grains of irregular form. In X-ray studies of the olivine grains from the Mighei meteorite there was noticeable asterism of the X-ray diffraction patterns (DuFresne and Anders, 1963). Wood (1967a) studied the olivine composition of type II carbonaceous chondrites; he showed that in the majority of cases olivine contained 0.6 to 2 and rarely up to 69 mol. % Fe. This agrees with the electronographic investigations of Kerridge (1964). Kerridge discovered forsterite in the Mighei meteorite.

Rhombic pyroxene is found in the meteorite in comparatively small quantities. It occurs in the chondrules in the form of thin, prismatic crystals. Pyroxene may form entire chondrules, or it may occur in chondrules of microporphyritic structure together with olivine, or else it is found in substituted chondrules.

Glass of a brownish colour is found, together with grains of other minerals, most frequently in chondrules of a microporphyritic structure. Mueller (1964) noticed spherical glass inclusions in the meteorite.

Nickel iron in the form of granules, often having a spherical or droplike form, is distributed in the interchondrule material and in the chondrules. Sometimes the granules attain a size of 0.2 mm, but more often they are of size 10μ or less. The presence of finely dispersed nickel iron granules has also been confirmed by the method of Mössbauer spectroscopy (Herr and Skerra, 1969).

Troilite FeS is distributed in the form of small granules the sizes of which attain 0.2 mm in rare cases. Yudin and Obotnin (1961) observed enriched sections of troilite of up to 10 to 15% by volume, in slices of the meteorite measuring 0.4 by 0.3 mm. FeS may also be detected in the Mighei meteorite by Mössbauer spectroscopic method (Herr and Skerra, 1969).

Pentlandite $(Fe, Ni)_9S_8$ in the form of small particles was separated by the use of a centrifuge (DuFresne and Anders, 1962). It was found in association with minerals of the chlorite – serpentine serie.

Chromite, $FeCrO_4$, has been found rarely in meteorite slices, where it occurs in the form of isometric grains.

Magnetite, Fe_3O_4, was discovered in the Mighei meteorite by means of X-ray investigations (Table I), it was also discovered by examination of meteoritic powder under the microscope (Mueller, 1964) and by the study of heavy fractionations, separated centrifugally from the pulverized meteorite in fluid suspensions (Vdovykin, 1964a). Magnetite is found in finely dispersed distributions.

B. 'LOW TEMPERATURE' MINERAL ASSOCIATION

Minerals characteristic of only carbonaceous chondrites are joined in certain paragenetic 'low temperature' associations. These minerals are of the chlorite – serpentine group, carbonates, free sulphur, sulphates and 'low temperature' glass.

Minerals of the chlorite – serpentine group are widely distributed in the meteorite, occurring in different chondrules, or in carbon-rich mixtures in the interchondrules material. The exact identification of hydrous silicates in the meteorite is difficult. Kvasha (1950, 1968) established these to be chlorite or possibly serpentine. Zachariasen

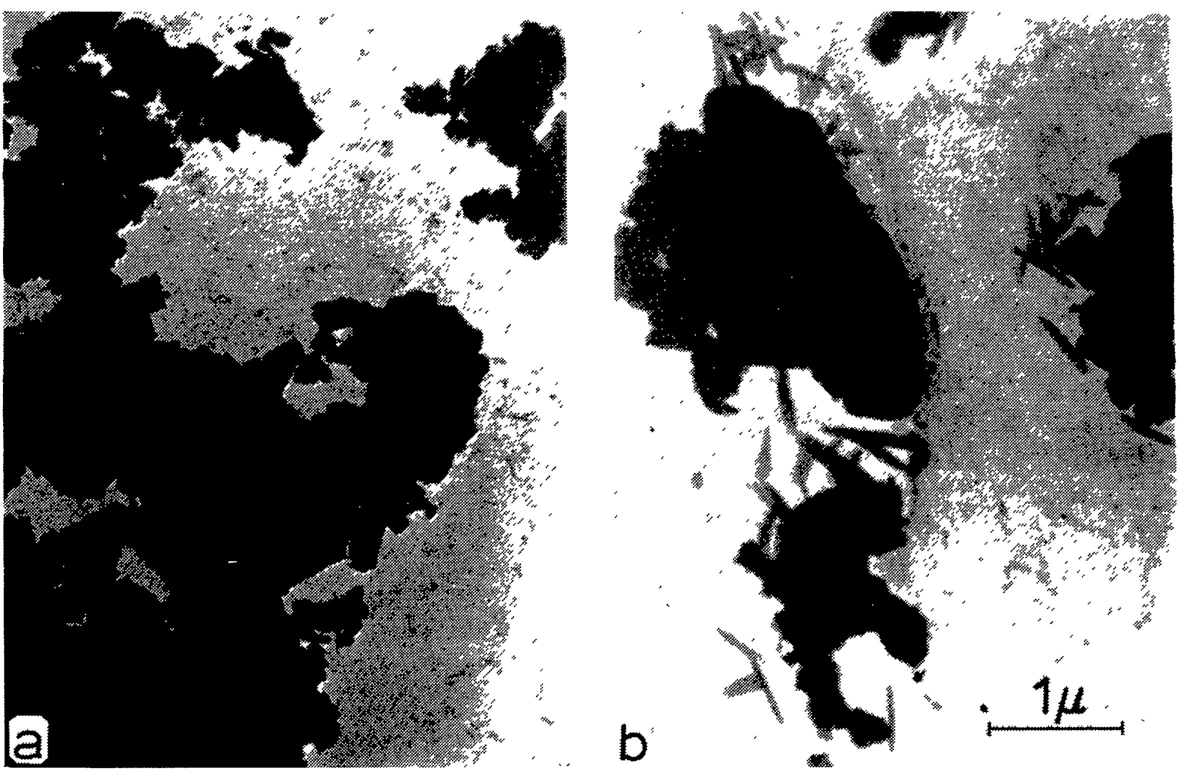


Fig. 5. Electron-microscope photographs of dispersed particles of a Mighei meteorite fragment. Mineral granules with adjoining platelets (a), and needles (b) of hydrous silicates.

(DuFresne and Anders, 1962), from a diffraction analysis of the Mighei meteorite, provisionally identified these minerals with chrysotile. Vdovykin (1967) from electron microscope investigations of powder of the Mighei meteorite observed the hydrous minerals having the form of thin tablets and needles of sizes less than 1 μ (Figure 5). Constitutional H_2O is liberated at $\sim$900 °C (Figure 6).

DuFresne and Anders (1962) centrifugally separated and investigated individual fraction of hydrous silicates. Their specific gravities were found to be from 2.57 to 2.60 gm cm^{-3}. Spectrographic analysis revealed the following composition (in %): Fe 17, Mg 15, Si 14, Al 1.1 and also Ni 1.2, Cr 0.4, Ca 0.3, Mn 0.2, Co 0.13, Pb 0.12, Ti 0.09, Cu 0.06, Zn 0.02, B 0.009, V 0.003, Sn 0.003, Ba 0.002, Zr 0.001, Se 0.0006,

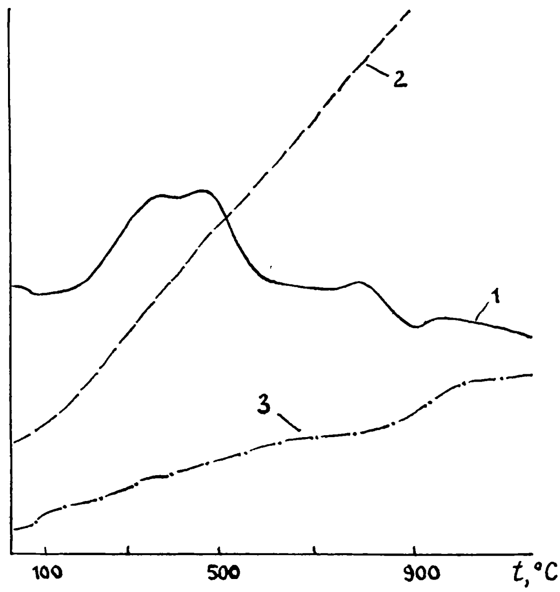


Fig. 6. Thermogram of powdered material of the Mighei meteorite. (1) Differential curve, (2) temperature curve, (3) curve of increase of weight.

Ge traces. The hydrous silicates in carbonaceous chondrites have unit cells b from 8.7 to 9.3 Å with a maximum at 8.9 to 9.0 Å which is characteristic for aluminium containing layer silicates (Kerridge, 1964).

Carbonates in the Mighei meteorite in the form of very finely dispersed crystals were observed by Simashko (1890) and Zavaritsky and Kvasha (1952). Semimicro titration method in the Mighei meteorite revealed 2.58% CO_2 (Greenberg and Salamin, 1963). In the meteorite 0.21% of carbon in carbonates has been found (Smith and Kaplan, 1970).

Free sulphur is present in many carbonaceous chondrites. It is found, however, in a finely dispersed distribution and is not evident under the microscope. Vdovykin (1965) found it in extracts of the Groznaya meteorite, and also in powdered material from the Orgueil meteorite by electron microscope technique. In the Mighei meteorite free sulphur was observed in certain ether extracts by DuFresne and Anders (1962) and Anders (1964). Using extraction techniques on a Mighei meteorite fragment by a mixture of benzol and acetone Kaplan *et al.* (1963) found sulphur in traces, but later extraction by a mixture of methanol and acetone revealed 1.58% sulphur.

Sulphates in the Mighei meteorite, as in other carbonaceous chondrites, are found chiefly as the water-soluble sulphate magnesium-epsomite $MgSO_4 \cdot 7H_2O$ (DuFresne and Anders, 1962; Larimer and Anders, 1970). The content of sulphates is 0.46% (Kaplan and Hulston, 1966). Apart from this DuFresne and Anders (1962) found small crystal of gypsum $CaSO_4 \cdot 2H_2O$ in the meteorite.

In powdered specimens of the meteorite DuFrense and Anders (1961) discovered particles of ‘low temperature’ glass. The particles were studied by annealing methods at various temperatures (Figure 7). The particles were found to be unstable at temperatures higher than 300 °C.

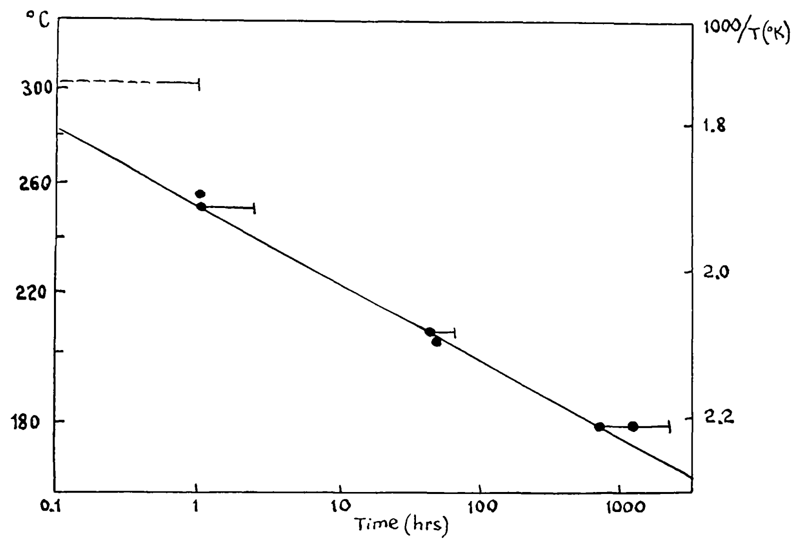


Fig. 7. Curve of annealing of 'low temperature' glass in the Mighei meteorite (DuFresne and Anders, 1961).

Among the secondary minerals, formed as a result of terrestrial weathering, Yudin (1958) observed in the Mighei meteorite small quantities of a mineral of a uniform greyish colour with reflection coefficient $R=10$ to 13%. This is probably goethite, and it is found in nickel-iron accretions.

3. Chemical Composition

A. Major Elements

Soon after the fall of the Mighei meteorite it was thoroughly analysed by Mennier (1889) and Melikov and Krzhizhanovsky (1896). In these analyses (Table II) the presence of SiO_2, MgO and FeO was noted. Iron was detected in the form of metallic Fe.

A more recent analysis by chemical method for the Mighei meteorite was carried out by Wiik (1956, 1969) (Table III). The meteorite was found to be composed of 27.81% SiO_2, 19.46% MgO, 19.13% FeO and other components in lesser quantities. Wiik found that the meteorite had high contents of S, C and H_2O.

The contents of a number of fundamental elements in the Mighei meteorite was recently established also by the methods of X-ray fluorescence (Michaelis *et al.*, 1969), and neutron activation (Kiesl and Hecht, 1969; Schmitt *et al.*, 1970). These results are compared with Wiik's data in Table IV. The agreement of the various values is quite good. Certain differences, for instance in the overall iron content, may be explained by inhomogeneous distribution of the different forms of iron in different specimens of the meteorite, as well as differences in the methods of analysis.

Fe – this is the most widely distributed element in the meteorite. In its general iron content, the Mighei meteorite, and other carbonaceous chondrites, was identified with the H group of Urey and Craig (1953). The total Fe content of the meteorite from chemical analysis is 21.24%, from X-ray fluorescence it is 19.95% whilst from neutron activation it is 22.7%.

TABLE II

Chemical composition of the Mighei meteorite, as determined by early analyses (% by weight)

Components	Meunier (1889)		Melikov and Krzhizhanovsky (1896)	
	1	2	1	2
SiO_2	31.00	5.63	24.29	54.27
MgO	29.73	2.83	18.10	29.68
FeO	24.44	2.10	22.63	3.42
Al_2O_3	–	0.11	1.38	4.04
CaO	–	0.31	1.85	4.35
Na_2O	–	–	1.25	2.02
MnO	–	tr.	0.55	1.73
K_2O	–	–	0.13	0.62
Fe_{met},	–	–	2.94	–
$Ni + Co$	–	–	1.01	–
FeS	–	–	0.46	–
$S_{free} + SO_3$	–	–	3.52	–
Organic Material	–	4.72	–	–
Total	85.17	15.70	78.11	100.17

1. dissolved in HCl, 2. not dissolved in HCl.

TABLE III

Chemical composition of the Mighei meteorite (Wiik, 1956, 1969)

Components	Contents, % by weight	Elements	Contents % of atoms (volatile elements excluded)
SiO_2	27.81	Mg	33.19
MgO	19.46	Si	31.85
FeO	19.13	Fe	26.18
Al_2O_3	2.15	Al	2.90
CaO	1.66	Ca	2.04
NiO	1.53	Ni	1.41
Na_2O	0.63	Na	1.40
Cr_2O_3	0.36	Cr	0.33
P_2O_5	0.30	P	0.29
MnO	0.21	Mn	0.19
TiO_2	0.08	Ti	0.09
CoO	0.07	K	0.07
K_2O	0.05	Co	0.06
FeS[a]	10.05		
H_2O	12.86		
C	2.48		
Lost by heating	0.36		
Total	99.19		100.00

[a] All S is taken to be in FeS.

TABLE IV

Element composition of the Mighei meteorite (% by weight)

Elements	Chemical analysis (Wiik, 1969)	Analysis by means of X-ray florescence (Michaelis *et al.* 1969)	Neutron activation analysis (Kiesl and Hecht, 1969)	Instrumental neutron activation analysis (Schmitt *et al.*, 1970)
Fe	21.24	19.95	–	22.7
Si	12.98	12.63	–	–
Mg	11.73	11.51	–	–
S	3.66	–	–	–
C	2.48	–	–	–
H	1.44	–	–	–
Ni	1.20	–	–	–
Ca	1.18	1.203	–	–
Al	1.14	1.11	–	–
Na	0.47	–	0.498	0.415
Cr	0.24	–	0.357	0.296
Mn	0.16	0.162	0.201	0.164
P	0.13	0.092	–	–
Ti	0.05	0.057	–	–
Co	0.05	–	–	0.056
K	0.042	0.043	–	–
(O)	41.81	–	–	–

Fe enters into the composition of many mineral phases of meteorite. The forms in which Fe may appear in the Mighei carbonaceous chondrite and in a number of other meteorites have been studied by the method of Mössbauer spectroscopy by Herr and Skerra (1969) (Figure 8). The iron content of different phases of the Mighei meteorite has been presented in Table V. In the Mighei meteorite a large part of the iron is present in the composition of hydrous silicates (10.4%) and also in olivine (6.15%), a lesser proportion is in troilite (1.9%), nickel-iron (1.9%) and pyroxene (0.9%). Altogether 17.5% of the iron was found in silicates. The iron content of silicates determined by chemical methods was less (14.9%), but this is related to the difficulty of separation of the compounds in the chemical analysis of carbonaceous chondrites, in which minerals may be found in very minute aggregations and mixed in with the carbonaceous matter. For comparison purposes the data from the ordinary Knyaginya chondrite has been entered into Table V. The Knyaginya meteorite fell in the U.S.S.R. on the 9th June, 1866. Detailed results of a study of this meteorite have been given in Lazarenko's monograph (1963). The results of a chemical analysis on the phases of Fe and of an analysis on them by the Mössbauer spectroscopic method, in the case of the non-carbonaceous Knyaginya meteorite were very close: the chemical method yielded an iron content of 12.8% in the silicates, while the Mössbauer spectroscopic method gave 12.6%. The corresponding Fe contents in troilite were 4.0 and 3.6%.

In different carbonaceous chondrites the content of oxidized Fe, according to the findings of Mössbauer spectroscopy, depends on the content of reduced iron (Figure 9). Moreover a definite trend has been observed with the passage from the studied

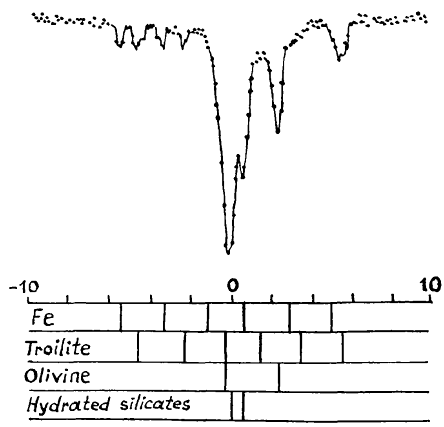


Fig. 8. Mössbauer spectrum of the Mighei meteorite (Herr and Skerra, 1969).

TABLE V

The content of Fe in various mineral phases in the Mighei and Knyaginya meteorites (Herr and Skerra, 1969)

Contents of Fe in % by weight	Meteorites	
	Mighei	Knyaginya
	Chemical analysis	
Total Fe	21.24	20.2
Fe in silicates	14.9	12.8
Fe in troilite	–	4.0
Metallic Fe	–	3.4
	Mössbauer spectroscopic analysis	
Fe in olivine	6.15	9.0
Fe in pyroxenes	0.9	3.6
Fe in hydrous silicates	10.4	–
Fe in troilite	1.9	3.6
Metallic Fe	1.9	–
Fe in oxides	–	0.6

type I meteorites to those of type III. Herr and Skerra also pointed out that the greater is the content of Fe^{3+} in carbonaceous chondrites the less is that of total iron.

Si – in the Mighei meteorite a content of 12.98% was found by chemical analysis, X-ray fluorescence gave a value of 12.63% (Table IV), while the neutron activation method yielded 13.3% (Vogt and Ehmann, 1965). Schmitt *et al.* (1967) by instrumental neutron activation analysis found the Si content for 27 chondrules of the meteorite. The mean content of Si in the chondrules was found to be 19.1%, which is in agreement with the forsterite composition of olivine for chondrules. Mason (1965) took the mean content of Si in chondrites to be 17%. Ahrens (1965) used values for the ratios of Si to a number of other related elements for a discussion on the fractionation of lithophillic elements in stony meteorites of different classes. For the Mighei meteorite the following ratios were used: Si/Mg, 1.102; Si/Ca, 10.76; Si/Al, 11.64; Si/Ti, 256.

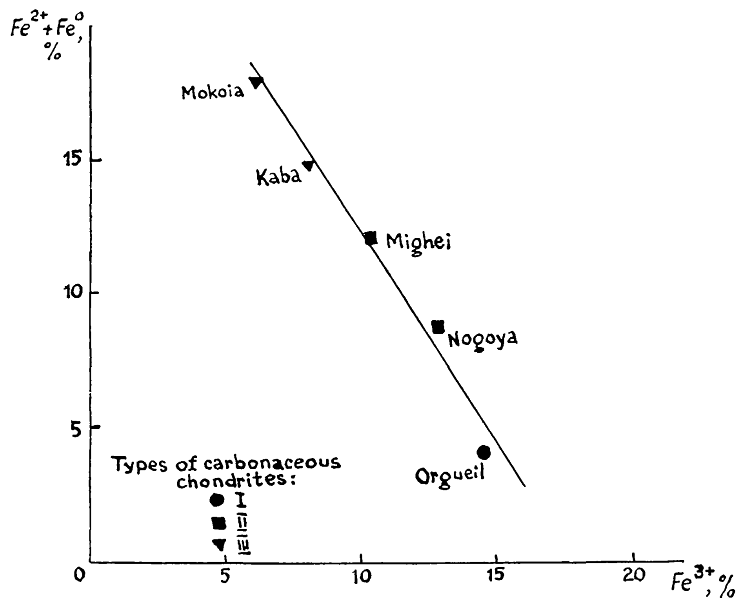


Fig. 9. The relationship of the Fe^{3+} content on Fe^{2+} +Fe in the Mighei meteorite and other carbonaceous chondrites from Mössbauer-spectroscopic data (Herr and Skerra, 1969).

Mg – the Mg content of the meteorite also gives close values as determined by chemical analysis (11.73%) and X-ray fluorescence (11.51%). In the Mighei meteorite Mg is found in silicates and sulphates.

Ni – the content of this element in the meteorite, as determined by chemical analysis, is 1.20%. In carbonaceous chondrites variations of the Ni content are small. In stony meteorites as a whole, the average Ni content is 1.7% – its ratio to iron by weight corresponds to 17; in the Mighei meteorite this turns out to be about 13. Using the electron microprobe analysis Wood (1966) investigated a number of carbonaceous chondrites and found that the Ni content in the interchondrule material of the meteorite was higher than its mean content in the meteorite as a whole. In the Mighei meteorite Ni is found as a constituent of the nickel-iron alloy together with the sulphides – troilite, pentlandite and probably also magnetite. Ni has also been found by spectral analysis (DuFresne and Anders, 1962) to be present in certain water-soluble salts.

Ca – according to the data of chemical analysis, has a content in the meteorite of 1.18%; according to X-ray fluorescence methods it has a content of 1.203%. The average content of Ca in chondrites as a whole is 1.4%. It is found in the meteorite in silicates, sulphates and carbonates.

Al – from the results of chemical analysis, has a content of 1.14% in the meteorite, X-ray fluorescence gives 1.11% (Table IV) and values of 1.11 and 1.04% have resulted from neutron activation method (Leveland *et al.*, 1969). Ca/Al ratio (1.083) is close to the mean value of this ratio (1.087) for type II carbonaceous chondrites and chondrites as a whole (Ahrens *et al.*, 1969). Al is found in the meteorite as a constituent of silicates.

Na – has been studied in the Mighei meteorite many times: by chemical analysis its content has been put at 0.47%, by neutron activation method a value of 0.498% was obtained (Table IV), while flame photometry has yielded 0.56% (Edwards, 1955). Schmitt *et al.* (1970), using instrumental neutron activation analysis, found Na in three specimens of the meteorite in the amounts by weight, of 521, 53, and 179 mg. The Na-contents were correspondingly found to be 0.384, 0.402 and 0.459% (with a mean value of 0.415%), i.e. Na is distributed non-uniformly in the meteorite. In ordinary chondrites there tends to be more Na, with a mean content of 0.68% (Edwards, 1955; Edwards and Urey, 1955). Lower values of the Na content than are found in carbonaceous chondrites is a characteristic of ureilites (Vdovykin, 1970b). In the Mighei meteorite Na is found as a constituent fo silicates and water soluble salts.

Cr – has been found, by chemical analysis, to have a mean content of 0.24% in the Mighei meteorite. The methods of neutron activation give values of 0.357% and 0.269% (Table IV), and the X-ray fluorescence method gave 0.31% (Yates *et al.*, 1968). In ordinary chondrites Cr has a mean content of 0.35%. It is found in the meteorite as a constituent of chromite and also, to some extent, in silicates.

Mn – has been found to have a content of 0.16% (by chemical method), 0.162 and 0.14% (by X-ray fluorescence, Michaelis *et al.*, 1969, and Yates *et al.*, 1968), 0.201% (by neutron activation), which is close to the mean Mn content for ordinary chondrites. In three fragments of the Mighei meteorite Schmitt *et al.* (1970) determined Mn contents of 0.164, 0.160 and 0.167% (average 0.164%), i.e. the Mn was distributed rather uniformly. It is present in the composition of iron-magnesium silicates in which Fe acts as an isomorphic substitute. Apart from these, Mn is found in the meteorite in the composition of water-soluble salts (DuFresne and Anders, 1962).

P – has been found to have a content of 0.13% in the meteorite (chemical method) and 0.092% (X-ray fluorescence), which is close to the average value of P in stony meteorites. It is found in silicates.

Ti – has been found with contents of 0.05 and 0.057% in the meteorite, which differs little from its average content for ordinary chondrites. It is also found in silicates.

Co – has been found with contents of 0.05 and 0.056%, which are also close to the average content in ordinary chondrites. Mason (1965) took the weight ratio Ni/Co to be 17 for chondrites; in the Mighei meteorite this ratio is about 23. Co is found mainly in the metallic phase.

K – in the Mighei meteorite has been studied repeatedly in recent years, particularly in connection with age determinations. Its content has been found to be (in %) 0.053 (Edwards, 1955), 0.040 (Gerling and Knorre, 1955), 0.043 (Michaelis *et al.*, 1969), 0.0423 and 0.0432 (Kaushal and Wetherill, 1970). The mean K content of the meteorite works out at 0.044%. In ordinary chondrites the K content is from 0.088 to 0.10% (Mason, 1965). In the meteorite K is found in silicate phases.

The Mighei meteorite, like other carbonaceous chondrites, is particularly rich in the volatile elements – S, C, H, N, and O. The content of 'volatile' elements, as found by Mueller (1966), by a weight-thermal analysis of powder from the Mighei meteorite heated up to 1000°C in a nitrogen atmosphere, was 16.23%.

S – The mean S content in all chondrites is 2.1%, while in the Mighei meteorite it has been quoted as 3.66% (Wiik, 1956), 2.37% (Kaplan and Hulston, 1966) and 3.91% (Mueller, 1966b). In ordinary chondrites sulphur is almost entirely to be found as a constituent of troilite, FeS, whereas in carbonaceous chondrites it is present in various finely dispersed compounds, where it is very difficult to distinguish by chemical analysis. Thus Wiik (1956) took the total sulphur content to be that occurring in FeS (10.05% in the Mighei meteorite), although he had pointed out that this would not entirely correspond to the naturally occurring forms of S. Mueller's thermal-weight analysis (1966) revealed a content of 'volatile' sulphur of mean value 36.3% in all S.

S does occur in the form of free sulphur in the meteorite (it may be dissolved in organic solvents), in the composition of water-soluble sulphates, in troilite and in pentlandite. In the last century Melikov and Krzhizhanovsky (1896) found FeS with a content of 0.46%, free sulphur at 3.19%, and also SO_3, and S_2O_3 by chemical analysis (see Table II). In a more recent analysis, Kaplan and Hulston (1966) found 1.58% free sulphur, 0.46% sulphates and 0.18% troilite in the meteorite.

C – is found in varying amounts in different meteorite specimens. It has been given a content of 2.5% (Trofimov, 1950), and 2.6% (Boato, 1954) from mass-spectrometer analyses, by thermal-weight analysis a value of 2.76% was arrived at (Mueller, 1966b). Wiik (1956) found a content of 2.48% C from chemical analysis, Belsky and Kaplan (1970) determined 2.85% C. Not long ago Moore and Lewis (1965, 1967) by a method of combustion with subsequent chromatographic analysis determined the C content of a number of meteorites. In ordinary chondrites the C content was from 0.016 to 0.57%, and, moreover, the C was distributed nonuniformly among different fragments of one and the same meteorite. Gibson *et al.* (1971) after thoroughly analysing the carbon distribution in two specimens of the Mighei meteorite found C contents (in %) to be, in the first fragment 2.60, 2.74 and 2.42; and in the other fragment 2.62 and 2.45.

The mean C content of the Mighei meteorite is 2.60%. The ratio C/S is 0.8. According to Mueller's analysis the proportion of 'volatile' C in total C is 89.6%.

The forms of occurrence of C in the meteorite are various. In the last century Meunier (1889) found 4.72% of organic matter in meteorite (Table II). According to Vdovykin's analysis (1967), the most important part of the carbon containing material in the meteorite is in the form of organic compounds with high molecular weights and only 0.156% of the organic material may be extracted by organic solvents. According to the analysis of Smith and Kaplan the content of soluble organic C in the meteorite is 0.09%, while that in carbonates is 0.21%. The forms of occurrence of C in different meteorites has been studied by Vdovykin (1969) and Vdovykin and Moore (1971).

H – has been found in the analyses of carbonaceous chondrites as a constituent of H_2O (free and combined water). From chemical analysis, the content of H_2O^- has been found to be 2.15%, that of H_2O^+ is 8.35% (Zavaritsky and Kvasha, 1952). From mass spectrometry the H_2O^- content was 1.7% (from heating up to 180°), that of H_2O^+ was 8.6% (180–800 °C) (Boato, 1954). As a result of the heating of the Mighei meteorite up to 80 °C in vacuum conditions in the presence of anhydrous P_2O_5 Kaplan

(1971) obtained a content of 2.3% for H_2O. Wiik (1956) found an general content of 12.86% for H_2O, which corresponds to a content of 1.44% for H. An H content of 1.30% in the meteorite was found by Mueller (1966b) using a thermalweight method and, moreover, 98.5% of all the H was in the form of 'volatile' H.

Vdovykin (1972) studied the contents and forms of occurrence of H_2O in various meteorites. In the Mighei meteorite an H_2O^- content of 2.40% was found by heating the material up to 110 °C, whilst from heating up to 800 to 900 °C an H_2O^+ content of 9.61% was obtained. The adsorptional water causes an endothermal effect at about 100 °C on thermal differentiation curves. Charged water molecules, entering into the lattices of minerals of the chlorite-serpentine group have a similar effect at a temperature of about 900 °C. Hydrous silicates are clearly visible in meteorite slices under a polarization microscope, and in the meteoritic powder by the electron microscope (Figure 5). A significant part of the H in the meteorite also is present in the composition of organic compounds.

N – Carbonaceous chondrites are significantly enriched in their N contents in comparison to the ordinary type. Moore and Gibson (1969) found the N-content of a number of ordinary chondrites to be from 0.0018 to 0.0075%. From an analysis of three specimens of the Mighei meteorite N was found with contents varying between 0.095 and 0.144%, with a mean value of about 0.13% (Gibson *et al.*, 1971). In the meteorite N is found in the composition of organic material, and possibly also in certain water-soluble ammonical compounds.

O – Carbonaceous chondrites are the most oxidized of all meteorites. In ordinary chondrites the mena O-content is 33% (determined by Mason from calculations on chemical analysis data), whereas in the Mighei meteorite it is 41.81% (Wiik, 1956). The ratio C/O for the Mighei meteorite is 0.06, while for ordinary chondrites this ratio is about 0.001 on average (Vdovykin, 1970b). In the meteorite O is to be found in the composition of all phases (including organic compounds), apart from sulphides and the nickel-iron alloy.

Thus the Mighei meteorite (as also other carbonaceous chondrites), as distinct from ordinary chondrites, is particularly enriched in light elements. However, if the results of chemical analysis of the meteorite are presented in terms of the atomic % of elements excluding the volatile ones (Table III), the differences between this carbonaceous chondrite and others would become significantly smoothed out, which may be taken as evidence for the common origin of chondrites.

B. MINOR AND TRACE ELEMENTS

The distribution of trace elements in type I carbonaceous chondrites relates to their cosmic distribution. Therefore in recent years there have been many detailed investigations by neutron activation methods for trace elements in carbonaceous chondrites. Their contents in the Mighei meteorite are given in Table VI.

Among the trace elements in the stony Mighei meteorite there are distributed certain elements possessing a lithophilic character. Their contents in different meteorite speci-

TABLE VI

Minor and trace elements in the Mighei meteorite

Atomic no.	Element	Content $n \times 10^{-4}$ %	References
3	Li	0.5	Mason, 1963
9	F	220	Fisher, 1963
17	Cl	350	Reed and Allen, 1966
		430; 510	Goles *et al.*, 1967
21	Sc	8.6	Haskin *et al.*, 1968
		4.44	Kiesl and Hecht, 1969
		6; 8.6	Schmitt *et al.*, 1970
		122; 180	Nishimura and Sandell, 1964
29	Cu	135; 144; 149	Greenland and Goles, 1965
		168	Kiesl and Hecht, 1969
		114; 126	Schmitt *et al.*, 1970
30	Zn	199; 201; 230	Greenland and Goles, 1965
		150	Greenland, 1967
		178	Kiesl and Hecht, 1969
		242	Wiik, 1969
31	Ga	10.4	Greenland, 1965
		8.2	Fouché and Smales, 1967a
		4.9	Kiesl and Hecht, 1969
32	Ge	25	Greenland, 1965
		25	Fouché and Smales, 1967a
33	As	2.1	Fouché and Smales, 1967b
		1.7; 2.2	Hamaguchi *et al*, 1969
		1.71	Kiesl and Hecht, 1969
34	Se	5.0; 6.1	Akaiwa, 1966
		14	Greenland, 1967
		23	Kiesl and Hecht, 1969
35	Br	3.5	Reed and Allen, 1966
		2.64; 3.9	Goles *et al.*, 1967
37	Rb	1.7; 3	Mason, 1963
		1.66	Smales *et al.*, 1964
		2.3	Michaelis *et al.*, 1969
		2.32	Kiesl and Hecht, 1969
		1.75; 1.79	Kaushal and Wetherill, 1970
38	Sr	9	Michaelis *et al.*, 1969
		8.62	Kaushal and Wetherill, 1970
39	Y	1.8	Haskin *et al.*, 1968
40	Zr	9; 12	Schmitt *et al.*, 1964
		46	Setser and Ehmann, 1964
		10	Michaelis *et al.*, 1969
		5.8	Ehmann and Rebagay, 1970
42	Mo	1.47	Kiesl and Hecht, 1969
44	Ru	0.85	Crocket *et al.*, 1967
46	Pd	0.59; 0.59	Fouché and Smales, 1967b
		1.26	Crocket *et al.*, 1967
		1.3	Greenland, 1967
47	Ag	0.15	Greenland, 1967
48	Cd	1.16	Schmitt *et al.*, 1963
		0.011	Greenland, 1967
49	In	0.07	Vinogradov, 1965

Table VI (continued)

Atomic no.	Element	Content $n \times 10^{-4}\%$	References
		0.29	Greenland, 1965
		0.046; 0.054	Akaiwa, 1966
		0.049	Fouché and Smales, 1967a
		0.064	Schmitt, Smith, 1968
		0.42	Kiesl and Hecht, 1969
50	Sn	0.50; 0.84	Hamaguchi *et al.*, 1969
		0.8	Kiesl and Hecht, 1969
51	Sb	0.11	Fouché and Smales, 1967b
		0.11	Tanner and Ehmann, 1967
		0.118	Kiesl and Hecht, 1969
		0.12; 0.16	Hamaguchi *et al.*, 1969
52	Te	1.88; 2.63	Goles and Anders, 1962
		1.2	Greenland, 1965
		1.82; 2.01	Akaiwa, 1966
		1.88	Reed and Allen. 1966
53	I	0.27; 0.35	Goles, and Anders, 1962
		0.55	Reed and Allen, 1966
		0.48	Goles *et al.*, 1967
55	Cs	0.12	Mason, 1963
		0.125	Smales *et al.*, 1964
		0.17	Kiesl and Hecht, 1969
56	Ba	2.5	Reed *et al.*, 1960
57–71	TR[a]	5.1	Haškin *et al.*, 1968
72	Hf	0.26	Setser and Ehmann, 1964
		0.14	Ehmann and Rebagay, 1970
75	Re	0.07	Perezhogin, 1965
		0.046	Fouché and Smales, 1967b
		0.0546	Morgan and Lovering, 1967a
		0.032	Kiesl and Hecht, 1969
76	Os	0.73	Crocket *et al.*, 1967
		0.707	Morgan and Lovering, 1967a
		0.12	Kiesl and Hecht, 1969
77	Ir	0.64	Crocket *et al.*, 1967
		0.20	Kiesl and Hecht, 1969
		0.55	Ehmann *et al.*, 1970
78	Pt	1.3	Crocket *et al.*, 1967
79	Au	0.14	Perezhogin, 1965
		0.13	Crocket *et al.*, 1967
		0.15; 0.15	Fouché and Smales, 1967b
		0.15	Kiesl and Hecht, 1969
		0.13	Ehmann *et al.*, 1970
80	Hg	6.82	Ehmann and Lovering, 1967
		4.9	Reed and Jovanovic, 1967
		3.77	Kiesl and Hecht, 1969
81	Tl	0.097	Reed *et al.*, 1960
		0.140	Anders and Stevens, 1960
		0.0451	Laul, Pelly, and Lipschutz, 1970
82	Pb	1.36; 1.75	Reed *et al.*, 1960
83	Bi	0.180	Reed *et al.*, 1960
		0.0794	Laul, Case *et al.*, 1970
90	Th	0.0456	Morgan and Lovering, 1967b

Table VI (continued)

Atomic no.	Element	Content $n \times 10^{-4}\%$	References
92	U	0.016	Reed *et al.*, 1960
		0.008; 0.021	Goles and Anders, 1962
		0.008	Reed and Allen, 1966
		0.0169	Morgan and Lovering, 1967b
		0.015	Morgan, 1971

[a] La 0.29, Ce 0.76, 0.71, Pr 0.13, Nd 0.61, Sm 0.20, Eu 0.078, 0.077, Gd 0.38, Tb 0.047, Dy 0.36, Ho 0.076, Er 0.24, 0.17, Tm 0.030, Yb 0.17, 0.17, Lu 0.032.

mens vary, which may be explained by non-uniformity of the element distribution and differences in the adopted investigation methods.

The Mighei meteorite, together with other carbonaceous chondrites, is relatively rich in a whole range of volatile element traces in comparison to ordinary chondrites, including: B, F, Cl, Cu, Zn, Ga, Ge, Br, In, Te, I, Hg, Tl, Pb, Bi (Vdovykin, 1967). The contents of certain of these elements have a correlation with the C content for carbonaceous chondrites.

While the mean F content for ordinary chondrites has been put at $28 \times 10^{-4}\%$ (Vinogradov, 1962), that of the Mighei meteorite, according to neutron activation method, is $220 \times 10^{-4}\%$ (Table VI). Cl has been found to have a content of 350 to $510 \times 10^{-4}\%$ in the meteorite, while its content in ordinary chondrites is $70 \times 10^{-4}\%$.

The distribution of Cu, Zn, Ga, and Ge in the meteorite, is presented in Table VI. The average contents of these elements in ordinary chondrites is as follows (in $10^{-4}\%$): Cu 100, Zn 10, Ga 3, Ge 10.

The Rb content of carbonaceous chondrites correlates with the K content. Kaushal and Wetherill (1970) measured the contents of K, Rb and Sr in a number of meteorites and found that for carbonaceous chondrites the ratio K/Rb was close to 240, whereas for olivine bronzite and amphoterite chondrites this number varies considerably. The The Sr content of the Mighei meteorite according to their data was $8.62 \times 10^{-4}\%$.

Using the neutron activation method Setser and Ehmann (1964) determined a Zr content of $46 \times 10^{-4}\%$. Later investigations by other methods have shown that the Zr content of the meteorite is less than this. Emission spectroscopy revealed a Zr content of $11 \times 10^{-4}\%$ (Schmitt *et al.*, 1964), while X-ray fluorescence indicated $10 \times 10^{-4}\%$ (Michaelis *et al.*, 1969). Recently Ehmann and Rebagay (1970) studied the Zr contents of a number of meteorites by neutron activation method. They found the Zr content of the Mighei meteorite to be $5.8 \times 10^{-4}\%$. These authors found that carbonaceous chondrites are slightly richer in Zr than ordinary chondrites. Ehmann and Rebagay studied fragments from the Allende carbonaceous chondrite, which fell in Mexico in 1969, and found a Zr content of $13 \times 10^{-4}\%$. The chondrules in the Allende meteorite contained $25 \times 10^{-4}\%$ Zr; certain white inclusions gave $24 \times 10^{-4}\%$ Zr, while the dark interchondrule material gave $1.6 \times 10^{-4}\%$ Zr.

Mo, Ru and Pd have a siderophilic character in meteorites, while Ag and Cd are chalkophilic. The contents of these elements in the Mighei meteorite, with the probable exception of Cd, differ little from their contents in ordinary chondrites.

The contents of In, Te and I in the Mighei meteorite are significantly greater than those of ordinary chondrites, in which their contents are (in $10^{-4}\%$): In 0.001; Te 0.5; I 0.04. The concentrations of these elements vary among different fragments of the meteorite.

The distribution of rare earth elements among different meteorites, terrestrial rock samples and lunar specimens is of considerable interest in connection with the fractionation of matter under different conditions. In the Mighei meteorite Haskin and co-authors (1968) found a content of $5.1 \times 10^{-4}\%$ for these elements by neutron activation method.

A Hf content of $0.14 \times 10^{-4}\%$ was recently determined for the Mighei meteorite by Ehmann and Rebagay (1970), and the ratio Zr/Hf was found to be 41. In the Allende carbonaceous chondrite (Hf content $0.16 \times 10^{-4}\%$) they found $0.39 \times 10^{-4}\%$ Hf in the chondrules, in the white inclusions $0.36 \times 10^{-4}\%$ Hf was found, while in the dark interchondrule material a Hf content of $0.14 \times 10^{-4}\%$, was found.

Re, Os Ir, Pt and Au have a siderophilic character in meteorites. Their content in the Mighei meteorite differs little from those in ordinary chondrites.

As distinct from these elements Hg, Tl Pb and Bi are somewhat more plentiful in the Mighei carbonaceous chondrite. In ordinary condrites these elements have contents (in $10^{-4}\%$): Hg 3; Tl 0.001; Pb 0.2; Bi 0.003. The results of earlier investigations on these elements in the Mighei meteorite sometimes gave content values which were probably a little excessive. For instance, the Tl content as determined by the method of isotope dilution (Anders and Stevens, 1960), was $0.140 \times 10^{-4}\%$ and the value of $0.097 \times 10^{-4}\%$ was obtained by Reed *et al.* (1960) using the neutron activation method. More recently the neutron activation method used on the meteorite produced a value of $0.045 \times 10^{-4}\%$ Tl (Laul *et al.*, 1970). A lower Bi content than previously observed – $0.079 \times 10^{-4}\%$ has also been found (Laul, Case *et al.*, 1970).

The Th and U contents in the Mighei meteorite (Table VI) are of considerable interest in connection with determinations of the radiogenic age of the meteoritic material. Their contents as determined by neutron activation analysis are correlated with the Ca content (Mason, 1965). The Th/U ratio for the Mighei meteorite is 2.7 (Morgan and Lovering, 1967b).

The higher abundances in the Mighei meteorite of a whole range of relatively volatile trace elements, in comparison to ordinary chondrites, and the higher abundances of basic volatile elements, may thus be taken as evidence for the formation of meteoritic material at relatively low temperatures and in a medium enriched with volatile elements.

4. Organic Compounds

Carbonaceous chondrites are also considerably more enriched in organic compounds than other meteorites. The compounds were formed as a result of chemical synthesis in the early stages of development of the meteoritic material (Vdovykin, 1967). The presence of extraterrestrial organic compounds in meteorites, which must be distinguished from those of biogenic origin on the Earth, is of exceptional interest both with regard to the cosmochemistry and geochemistry of carbon, particularly in connection with explaining the problem of the origin of living material, as well as the origin of hydrocarbons in rock specimens.

In the Mighei meteorite organic compounds are found in a finely dispersed distribution, more concentrated in the inter-chondrule material but also occurring within chondrules and mineral grains.

The organic compounds were discovered in the last century shortly after the meteorite fall but they were not then studied in detail.

In 1889 Meunier extracted from the meteorite, using alcohol, 0.056% of an ozocerite-like substance with a peculiar smell. After chemical analysis he observed that, in actuality, the contents of organic compounds in the meterite were much higher – amounting to 4.72%.

At the same time Simashko (1890) also showed that the meteorite had an overall content of about 4% of organic material. Using alcohol and ether extraction agents Simashko extracted some 0.230% of organic compounds from the meteorite. The extract did not dissolve in water or in hydrochloric acid. It took the form of a viscous yellowish crystallized into small needles and platelets. Upon heating in air the extract easily melted and frequently vapourized, leaving a dark, oily substance. Simashko called the organic material of the meteorite – erdelite, and supposed that it was formed by chemical synthesis at conditions of relatively low temperatures.

Later Melikov and Krzhizhanovsky (1896) found, by chemical analysis, 2.63 of an amorphous carbonaceous material in the Mighei meteorite, and noticed the presence of organic compounds closely resembling the heavy fractions of petroleum. Moreover they extracted 10 gm of the meteorite in distilled water and in the water extract they found 0.53% of organic compounds, chiefly fatty acids which evaporated with boiling of the water. Prendel (1897) noticed that when grinding specimens of the Mighei meteorite in a mortar a self-produced 'bitumen-like' odour could be sensed.

Detailed investigations of organic compounds in carbonaceous chondrites in general, as well as the Mighei meteorite in particular, have been carried out in recent years with the application of modern methods of analysis. In the Mighei carbonaceous chondrite gaseous hydrocarbons have been detected; in extracts of organic material the aliphatic hydrocarbons of the series C_{15} to C_{26} (including isoprenoid hydrocarbons), aromatic hydrocarbons (including multinuclear aromatics), fatty acids, carbohydrates and aminoacids have been identified; and the predominating part of the carbonaceous material of the meteorite, which consists in the main of polymerized organic material containing free organic radicals, has been investigated.

A. GASEOUS HYDROCARBONS

Belsky and Kaplan (1970) have studied light hydrocarbon gases from the Mighei meteorite. The gases separate from broken up meteorite fragments (~1 gm) in a

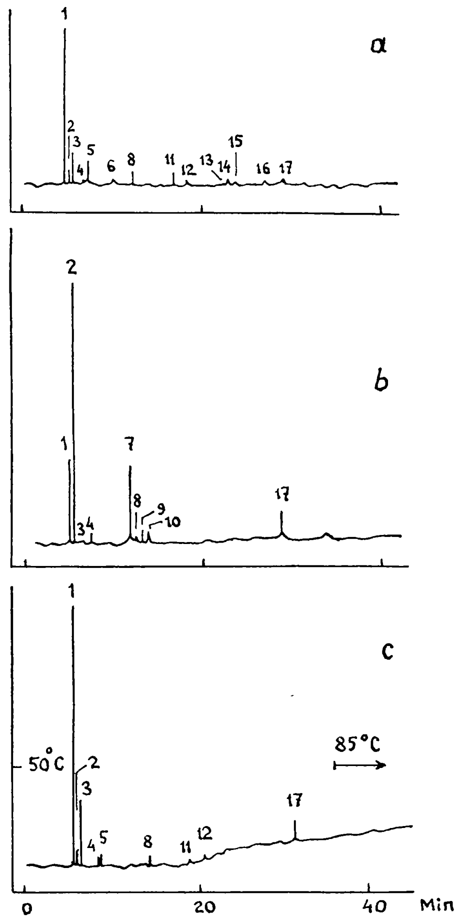


Fig. 10. Gas-chromatograms of hydrocarbon gases separated from the Mighei meteorite and from the Onverwacht precambrian shale (Belsky and Kaplan, 1970). (a) The Mighei meteorite-gases separated by crushing of sample in a vacuum. (b) The Mighei meteorite-gases separated by heating of sample at 210°C. (c) Onverwacht Chert-gases separated by crushing of sample in a vacuum. The numbers in the diagram correspond to the numbers in Table VII.

vacuum, and they may then be analysed by the method of gas chromatography. Chromatograms of hydrocarbon gases are given in Figure 10a. Both saturated and and non-saturated hydrocarbons of the series C_1 to C_6 are found. The greatest proportion occurs as methane (318.10^{-7}%, Table VII), the content of which is some 4.5 times higher than that of ethane. A predominance of methane over ethane and other gases liberated from broken up shale has been observed at Onverwacht (the Swaziland system, S.Africa, shale age 3.3×10^9 yr) (Figure 10c). The ratios of the hydrocarbon gases to methane for the Mighei meteorite and for the Onverwacht shales also compared quite well (Table VIII), although the ratios of ethylene and *n*-butane to methane were three times less, and iso-butane some twenty times less than for the Mighei meteorite. Similar hydrocarbons but in rather different proportions were observed when the meteorite was heated up to 210°C (Figure 10b). Controlled studied of the liberation of gases from the crushing of fragments compared with those of gases from various rock powders showed that the identified gases were characteristic of the meteorite.

The presence of light hydrocarbon gases of the series C_1–C_4 (methane, ethane,

TABLE VII

Hydrocarbons C_1–C_6, identified in the Mighei meteorite (Belsky and Kaplan, 1970)

Order number	Hydrocarbons	Contents in the meteorite in 10^{-7}%
1	Methane	318
2	Ethylene	41
3	Ethane	70
4	Propene	13
5	Propane	48
6	Isobutane	2
7	1-butene and isobutene	3
8	*n*-butane	35
9	unidentified	–
10	*cis*-2-butene	–
11	isopentane	45
12	n-pentane	20
13	4-methyl-*cis*-2-butene	10
14	2-methylpentane	23
15	3-methylpentane	15
16	methycyclopentane	10
17	benzol	–

TABLE VIII

Ratios of hydrocarbon gases in the Mighei meteorite and in precambrian shale (Belsky and Kaplan, 1970)

	Mighei meteorite	Onverwacht Chert
Ethane/methane	0.22	0.26
Ethylene/methane	0.13	0.04
Propane/methane	0.15	0.10
Propene/methane	0.04	0.02
Isobutane/methane	0.06	0.003
n-butane/methane	0.11	0.04
Butene/methane	0.01	0.02

propene, propane and hydrocarbons of the series C_4) was also confirmed by Ponnamperuma *et al.* (1970) using gas-chromatography method (Figure 11), after treatment of a meteorite sample of 0.05 gm in 6N HCl. The distribution of hydrocarbons in the Mighei meteorite differed from a similarly treated 0.1 gm specimen of lunar dust.

B. EXTRACTABLE ORGANIC MATERIAL

Among the dark, opaque polymerized carbonaceous matter of the Mighei meteorite, organic compounds may be seen under the microscope as finely dispersed inclusions which luminesce in ultra-violet radiation (=365 nm). When separated from the meteorite by means of organic extraction solvents, these organic compounds have a sticky consistency and luminesce with a bluish colour. After extraction by a series of organic solvents (without any applied heating) Vdovykin (1962, 1967) determined a value for the content of extracted organic material in the Mighei meteorite (specimen weight

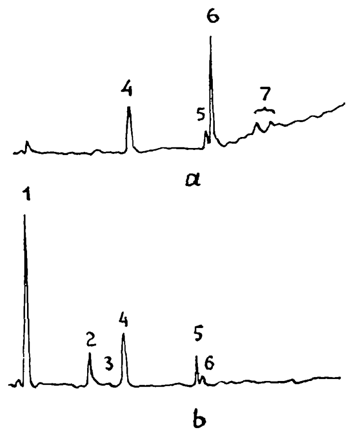


Fig. 11. Gas chromatograms of hydrocarbon gases separated from the Mighei meteorite (a), and from a specimen of lunar soil (b), after treatment with 6N HCl (Ponnamperuma *et al.*, 1970), (1) Methane and non-condensing gases, (2) ethene, (3) acetylene, (4) ethane, (5) propene, (6) propane, (7) the C_4 hydrocarbons.

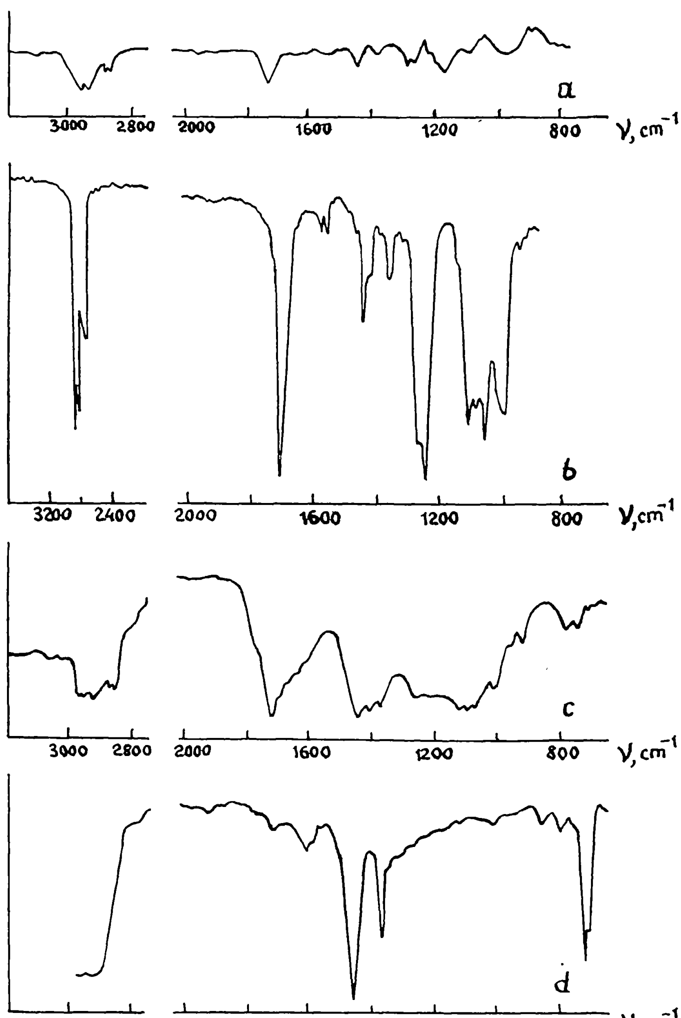


Fig. 12. Infrared absorption spectra of organic matter extracted from the Mighei meteorite and terrestrial samples by organic solvents. (a) The Mighei meteorite, taken without solvent (Vdovykin, 1962), (b) The Mighei meteorite, taken with the solvent CCl_4 (Kaplan *et al.*, 1963), (c) Argillaceous shale of the Southern Urals, (d) Ozocerite, Ukr.S.S.R. (Vdovykin, 1967).

0.24 gm) as 0.156%. Extracting with a mixture of benzol and methanol Smith and Kaplan (1970) extracted 0.09% from the Mighei meteorite as organic material. This substance contained some 47% of a 'greasy' fraction (Vdovykin, 1967) and was represented chiefly by hydrocarbons. The extracted Mighei organic material wasstu died by the methods of IR, UV and NMR (nuclear magnetic resonance) spectroscopy.

On the infrared spectrum (Figures 12a, b) there were clear indications of absorption bands, caused by the presence of the CH_3 and $=CH_2$ groups (2960, 2930 and 1460, 1380 cm^{-1}) and also the carbonyl group $-C=O$ (1730 cm^{-1}), aromatic groupings and others. The extracts were made up of a complicated mixture of compounds, some quite similar to a bituminous material of argillaceous shale (Figure 12). Ozocerite absorption in the infrared spectrum (Dzvinyach, U.S.S.R.), shown in Figure 12 for comparison, allows the clear location of only those absorption bands caused by the presence of paraffin hydrocarbons.

The spectral absorption of extracts separated from the Mighei meteorite in the visible region is not characterized by any noticeable absorption bands. On ultraviolet spectra, however, there are absorption bands with maxima occurring at 222, 274 and 280 nm (Figure 13) (Kaplan *et al.*, 1963). These latter may testify to the presence of multinuclear aromatic hydrocarbons.

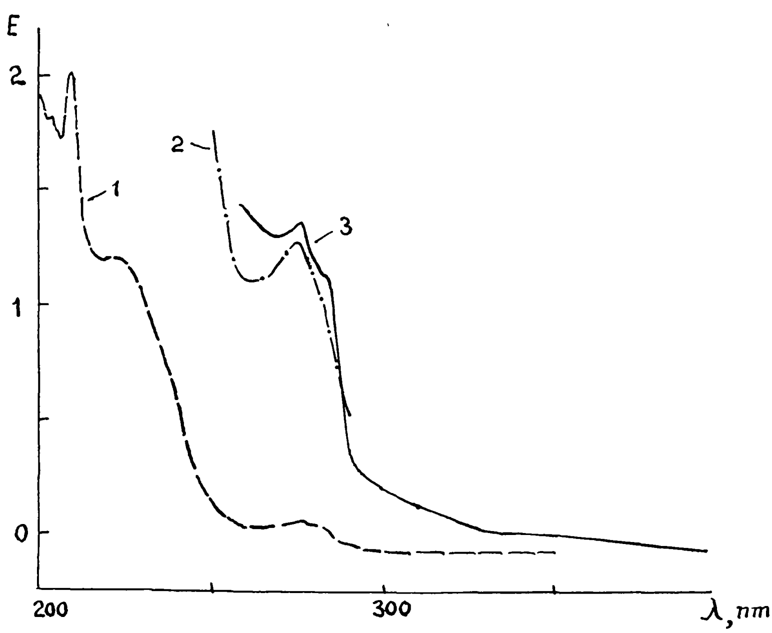


Fig. 13. Ultraviolet absorption spectra of extracted organic matter from the Mighei meteorite (Kaplan *et al.*, 1963), (1) Concentration 1 μl in 0.5 ml CH_3OH, (2) Concentration 5 μl in 0.5 ml CH_3OH, (3) Concentration 1 μl in 0.5 ml CCl_4.

Hydrocarbons in the extracted organic material of the meteorite are clearly indicated, and have been studied by the method of NMR spectroscopy (Figure 14). From the NMR spectrum of Mighei extracts, dissolved in methanol, Kaplan *et al.* (1963) observed methyl (0.6 and 1.0 ppm) and aromatic (7.3 ppm) groupings. From the spectrum of extracts dissolved in carbon tetrachloride it was moreover found (at

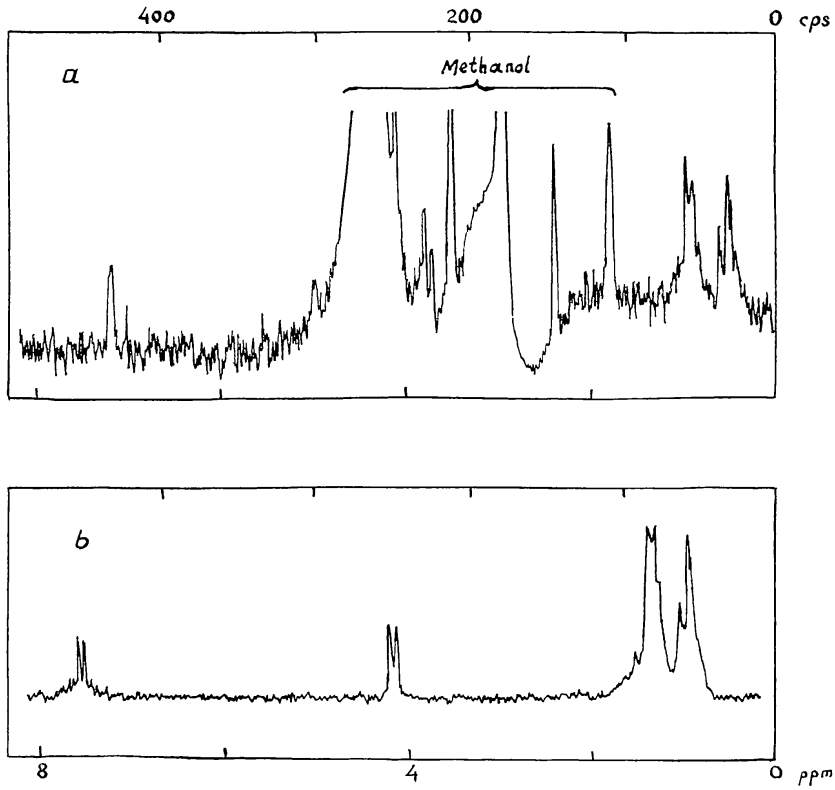


Fig. 14. Nuclear magnetic resonance spectra of matter extracted from the Mighei meteorite (Kaplan *et al.*, 1963), (a) Solvent CH_3OH, sp. amp. 20, (b) Solvent CCl_4, sp. amp. 12.5.

4.1 ppm) that alyl groups or groups containing N or O were also possible present.

From polarimetric investigations of extracted organic material of the Mighei meteorite Vdovykin (1965, 1967) found no signs of optical activity – in contradistinction to biogenic organic material.

Aliphatic compounds (alkanes) The distribution of aliphatic hydrocarbons in fractionated extracts of organic material from the Mighei meteorite has been studied by Nooner and Oró (1967) using the methods of gas chromatography and mass-spectrometry. Two little powders (100 mesh) of the fragments of the meteorite, of weight

TABLE IX

Contents of hydrocarbons and fatty acids in three fragments of the Mighei meteorite ($n \times 10^{-4}\%$)

Organic compound	Fragment 1	Fragment 2	Fragment 3 (Smith and Kaplan, 1970)
	Nooner and Oró, 1967	Olson *et al.*, 1967	
Alkanes	27.8	127.7	71
n-alkanes	22.8	103.5	+
Isoprenoids	4.97	24.18	+
Pristane	2.31	12.55	
Phitane	1.83	8.02	
Norpristane	0.83	3.61	
Aromatic hydrocarbons	7.2	5.5	
Fatty acids			91

about 0.22 gm, were extracted in Soxlete's apparatus in a mixture of benzol and methanol 3:1. After separating the free sulphur (by means of colloidal copper) the extracts were fractionated on silica gel with the following solvents: *n*-heptane, CCl_4, benzol, methanol (Oró *et al.*, 1966). The eluates of n-heptane and benzol solutions were analysed for their aliphatic hydrocarbon contents. In both specimens alkanes were found of the series C_{15}–C_{25} with corresponding contents of $27.8.10^{-4}$ and $127.7.10^{-4}$% (Table IX). The basic components were *n*-alkanes ($22.8.10^{-4}$ and $103.5.10^{-4}$%) with *n*–C_{19} and *n*–C_{18} being predominant. Also found were the saturated isoprenoidal hydrocarbons norpristane (2, 6, 10-trimethylpentadecane), pristane (2, 6, 10, 14-tetramethylpendecane), and phitane (2, 6, 10, 14-tetramethylhexadecane) with the general content of isoprenoidal hydrocarbons as 4.97×10^{-4} and $24.18 \times \times 10^{-4}$%.

The alkane fractions from the Mighei meteorite were also studied by Smith and Kaplan (1970). These determined a mean alkane content of 71×10^{-4}%. *N*-alkanes are composed of hydrocarbons of the series C_{15}–C_{26} with a maximum for *n*–C_{19} (Figure 15). The most widespread form of isoprenoidal hydrocarbons is pristane.

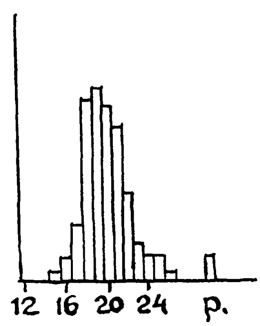


Fig. 15. The distribution of n-alkanes of the series C_{15}–C_{26} in the Mighei meteorite (Smith and Kaplan, 1970). p corresponds to pristane.

Isoprenoidal hydrocarbons were considered to be characteristic only of biogenic compounds, but recently they were synthesized in a series of experiments by the heating of CO and H_2 (Studier *et al.*, 1968; Gelpi and Oró, 1970).

Aromatic hydrocarbons, in extracts from the Mighei meteorite in benzol eluates, were studied by Olson *et al.* (1967) by the methods of gas-liquid chromatography and ultraviolet spectrophotometry. In two meteorite samples the contents of aromatic hydrocarbons were found to be 7.2×10^{-4}% and 5.5×10^{-4}% (Table IX), composed, by and large, of single compounds. Among the multinuclear aromatic hydrocarbons of the Mighei meteorite there was present anthracene, 1,12-benzoperilene, 3,4-benzopyrene, perilene and coronene.

Fatty acids Smith and Kaplan (1970) managed to separate fractions of fatty acids by treatment of benzol-methanol extracts from the meteorite with a 2% KOH solution. The mean fatty acid content was found to be 91×10^{-4}%. They make up normal fatty acids of the series C_{12}–C_{20} (Table X). The most widespread are the fatty acids C_{16} and C_{18}, and on chromatograms these are accompanied by peaks caused by the corre-

TABLE X

Fatty acids in the Mighei meteorite (Smith and Kaplan, 1970)

Number of C-atoms in the chain	Percentage of the total
12	14
14	4
15	2
16[a]	4
16	20
17	2
18[a]	4
18	20
20[b]	30

[a] Unsaturated.
[b] Unidentified.

sponding unsaturated acids. This may indicate the influence of certain contaminants.

Carbohydrates The method of paper chromatography revealed (Kaplan *et al.*, 1963) quantities of glucose and mannose in an uncombined condition. In ultraviolet spectra broad absorption bands showed up with maxima at 225 and 265 nm.

Amino acids were studied by paper chromatography methods. Kaplan *et al.* (1963) found amino acids in the meteorite both in uncombined and combined conditions in the ratio 1:3. Altogether 12 amino acids were identified and quantitatively established

TABLE XI

Amino acids identified in three fragments of the Mighei meteorite

Amino acid class	Amino acids	Fragment 1 (Kaplan *et al.*, 1963)		Fragment 2 (Vdovykin, 1970)	Fragment 3 (Drozdova, 1968)
		Free amino acids	Bound amino acids	Bound amino acids	Bound amino acids
Basic	lysine	1.2	0.8	+	–
	histidine	–	–	+	+
Acidic	asparaginic	–	1.9	+	–
	glutaminic	–	3.9	+	+
Neutral	glycine	1.6	3.8	+	+
	alanine	1.7	3.0	+	+
	serine	1.2	3.4	+	–
	proline	–	1.6	–	–
	valine	tr.	0.2	+	+
	threonine	–	1.6	+	–
	leucine	1.9	2.1	+	+
Aromatic	tyrosine	–	0.7	–	–
	phenylalanine	–	0.5	–	–

(with a certainty of ±25%) (Table XI). The probability of the uncombined amino acids (as also for the uncombined carbohydrates) and part of the combined amino acids, appearing as a result of contamination has not as yet been finalized. Most interesting is the identification of combined amino acids after HCl hydrolysis. Among the amino acids the most widely distributed are glutaminic acid (acidic), glycine, alanine and serine (neutral).

The basic and aromatic amino acids were found in the least quantities. In ultraviolet spectra fractions containing free amino acids produced an absorption band with a maximum at 240 nm, and also a weak band at 280 nm, while fractions containing bound amino acids produced bands at 250, 255 and 280 nm.

Vdovykin (1970a) investigated combined amino acids in hydrolized polymerized Mighei material by the method of paper chromatography. Contaminants were excluded as the meteorite specimen (of weight 2 gm) was specially removed from the interior of a large fragment. The following amino acids were found: lysine, histidine, asparaginic, glutaminic, glycine, alanine, serine, valine, threonine and traces of leucine. The most widely distributed were glycine and alanine. Another specimen of the meteorite (weight 2 gm) was dissolved in a similar way for chemical separation of the polymerized material. After HCl hydrolysis it was studied for its contents of combined amino acids by the method of paper chromatography by Drozdova (1968, p. 386). The following amino acids were found: histidine, glutaminic, glycine, alanine, valine and leucine.

Among amino acids formed by abiogenic synthesis by proton irradiation of a mixture of simple initial compounds (Vinogradov and Vdovykin, 1969) the amino acids glycine and alanine were predominant as they are in meteorites.

C. POLYMERIC ORGANIC MATERIAL

The largest part of the carbonaceous material of the Mighei meteorite (up to 80 or 90%, excluding carbonates) is insoluble in solvents and forms the polymerized organic component, which occurs in a finely dispersed condition in the regions between

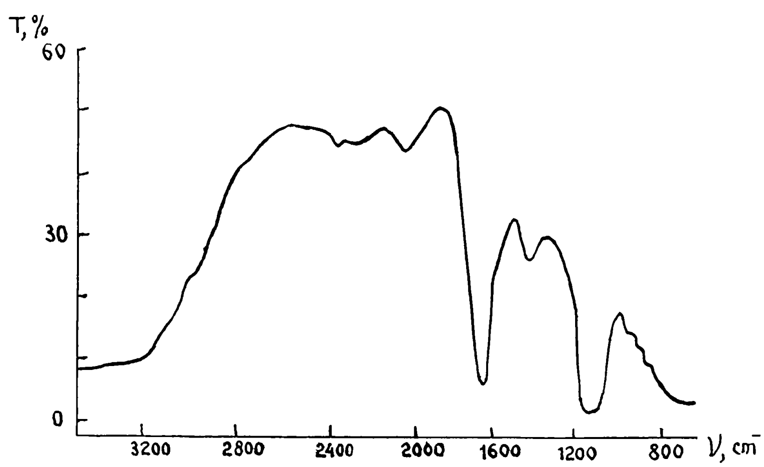


Fig. 16. The infrared absorption spectrum of the polymerized organic material of the Mighei meteorite (Vdovykin, 1967).

chondrules. In order to study this material it was separated by means of chemical treatment of ground up meteorite specimens in HCl and HF acids, together with a little warming up (Vdovykin, 1967; Smith and Kaplan, 1970). On an infrared spectrum of the polymerized material (Figure 16) absorption bands are present caused by the aromatic C–H connections (1080–1175 cm^{-1}), the OH-group (1440 cm^{-1}) and the –C=O group (1660 cm^{-1}) (Vdovykin, 1967). The polymerized material of the meteorite has an aromatic condensed structure of carbon skeleton with lateral groupings. This aromatic condensed structure of the polymerized material has been confirmed by X-ray analysis (Vdovykin, 1967). The particles of polymerized meteoritic material, according to the data of our microdiffraction studies, have an amorphous structure. As well as these, particles of polymerized material of a crystalline structure were observed as also were very small inclusions of a finely dispersed material with graphitization in individual particles. This agrees with the results of Grinberg (1964), that in certain regions of the carbonaceous material of the Mighei meteorite elementary carbon was present. In the differential thermal curves of powder from the Mighei meteorite (Figure 6) there is an exothermal effect, caused by the presence of organic compounds, which has a maximum at 360 to 460°C. The results of studies of polymerized organic material from the Mighei meteorite shows up certain similarities of this matter with terrestrial humus compounds, and, in particular, with coal.

Free organic radicals in the Mighei meteorite have been established by the method of electron paramagnetic resonance.

In our studies of the EPR of carbon containing material taken from various meteorite fragments, paramagnetic absorption lines with similar parameters distinctly appeared. A g-factor was found to be 2.002 to 2.003 and $\Delta H \approx 3$ Oe (Figure 17a) which indicates that in complicated aromatic structure of polymerized organic material from the meteorite, like that of coal, were delocalized uncoupled π-electrons (Vinogradov *et al.*, 1964; Vdovykin, 1967).

Duchesne *et al.* (1964) studied a fragment of the Mighei meteorite without separating the carbon containing material from it. On the EPR spectrum, at the broad

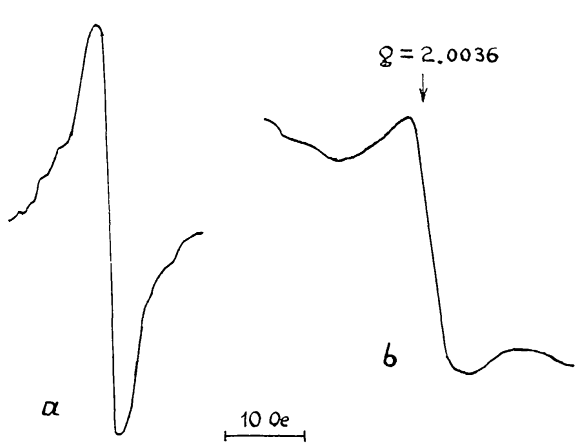


Fig. 17. Electron paramagnetic resonance spectrum of the Mighei meteorite. (a) Polymerized material of the Mighei meteorite (Vdovykin, 1967). (b) Meteorite specimen from which polymerized material has not been separated (Duchesne *et al.*, 1964).

absorption line background caused by the presence of Fe containing particles, a signal appeared which was due to the presence of free organic radicals (Figure 17b), the parameters of which were as follows: g-factor 2.002, ΔH in the atmosphere 8, in a vacuum 6 Oe. The concentration of the free radicals was estimated to be 10^{17} centres per gram of carbon containing material. For the purpose of comparative analysis Duchesne *et al.* (1965) carried out investigations of saturation effects of EPR signals from the Mighei meteorite, stony coal, lignite and sacharose in a vacuum at 300 °C. For the organic Mighei material and coal the saturations practically coincided (Figure 18), which is evidence for the structural similarity of the carbonaceous meteoritic material and terrestrial coal.

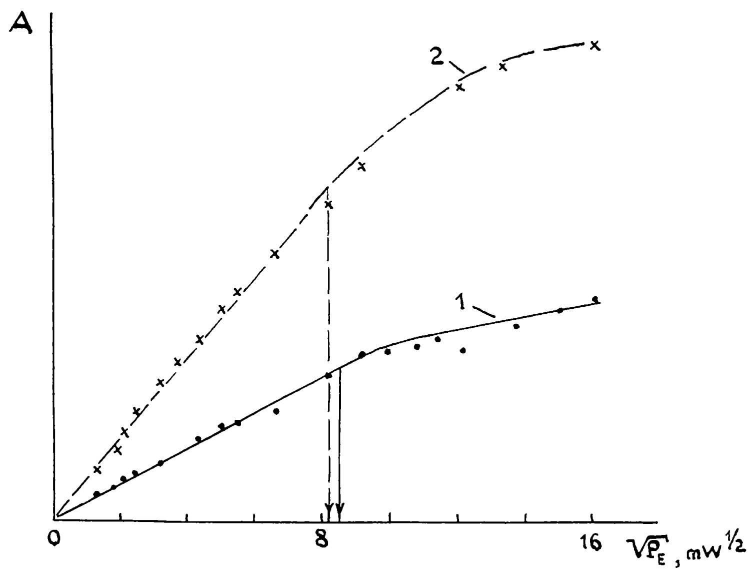


Fig. 18. Curves of saturate of EPR signal of the Mighei meteorite (1) and coal (2) (Duchesne *et al.*, 1965). A. ratio of signal amplitude to weight (in gm).

In this way, the presence of free radicals in the Mighei meteorite indicates that organic material is inherent in the meteorite, and it allows the question of the presence of energy sources (in particular cosmic irradiation and/or heating) with chemical synthesis and transformation of complex meteoritic organic compounds to be decided.

D. 'ORGANIZED ELEMENTS'

At the same time as the study of organic compounds in carbonaceous chondrites investigations were carried out for a number of years into the 'organized elements' – microinclusions with morphological resemblances to living forms. Such inclusions were found by Claus and Nagy (1961) in the Orgueil and Ivuna carbonaceous chondrites. In a subsequent series of studies about 30 kinds of 'organized elements' from various carbonaceous chondrites were described having sized of up to 60 μ, circular, hexagonal or other shapes and luminescing in ultra-violet radiation, with a yellowish-green colour. The nature of the 'organized elements' was discussed in detail in the literature, a review of which was provided in work of Vdovykin (1967).

From a microphytological study of a 5 gm specimen of the Mighei meteorite Timofeyev (1962) described more than 20 different forms of cells. These measured 10 μ to 60 μ across, with a yellowish-grey or dark grey colour and having smooth surfaces, covered with small bumps, and sometimes having tiny orifices. Certain of these forms resembled those characteristic of spores in precambrian rocks of the Baltic shield.

Vdovykin (1964a) studied the morphology of the 'organized elements' in a pure uncontaminated specimen of the Mighei meteorite, of weight about 0.4 gm. The rock particles were separated centrifugally as a series of fractions in liquids of differing densities – chloroform, a bromoform-acetone mixture and bromoform. In the fractions (Figure 19) were contained circular mineral granules-olivine microchondrules (olivine enveloped by a coating of sticky carbonaceous material), magnetite and so on, similar to what was earlier described as 'organized elements'. Inclusions of organic material in the meteorite may in reality luminesce. Studies of the 'organized elements' of the Mighei meteorite as carried out by Mueller (1964) also testified to the mineral nature of these particles. Consequently, 'organized elements' in reality appear to be mineral granules, sometimes covered with envelopes of polymerized material. A number of papers relate to different meteorite fragments which may not have been cleaned over their surfaces prior to analysis, so that the possibility of contamination cannot be ruled out. Probable contamination may not only account for the presence of 'organized elements', but in certain cases, as was remarked before, be related to the values of the contents of certain peculiar forms of organic compound, which can be extracted from the meteorite by solvents. This issue brings out the point that prior to meteoritic investigations samples should be carefully purified, and in order to study the organic material it is necessary to maintain very clean conditions.

5. Isotopic Composition of the Elements

The basic rock-forming elements in meteorites (Fe, Si, Ca, O and others) have an isotopic composition which is typically just the same as that of terrestrial rocks.

In the Mighei meteorite the mass-spectrometry method has determined stable isotopes of the volatile elements S, C, H and O. Their content in the meteorite should characterize the conditions of formation of meteoritic material.

Sulphur, a constituent of meteorites of various classes and found, for the main part, in the composition of troilite, has a practically constant isotopic composition. Therefore meteoritic sulphur, and in particular sulphur of the troilite from the iron meteorite Canyon Diablo is used as an international standard for study of the isotopic composition of terrestrial sulphur. For meteoritic sulphur the ratio of the stable isotopes S^{32}/S^{34} is 22.22. In carbonaceous chondrites, in which sulphur is found in different forms, it has a different isotopic composition. The isotopic composition of sulphur (S^{32}, S^{34} and also S^{33} and S^{36}) in different forms in the Mighei meteorite has been investigated by Hulston and Thode (1965) and Kaplan and Hulston (1966) (Figure 20 and Table XII). Early determinations of the isotopic composition of carbon in the Mighei meteorite, carried out by mass-spectrometric studies with an accuracy of

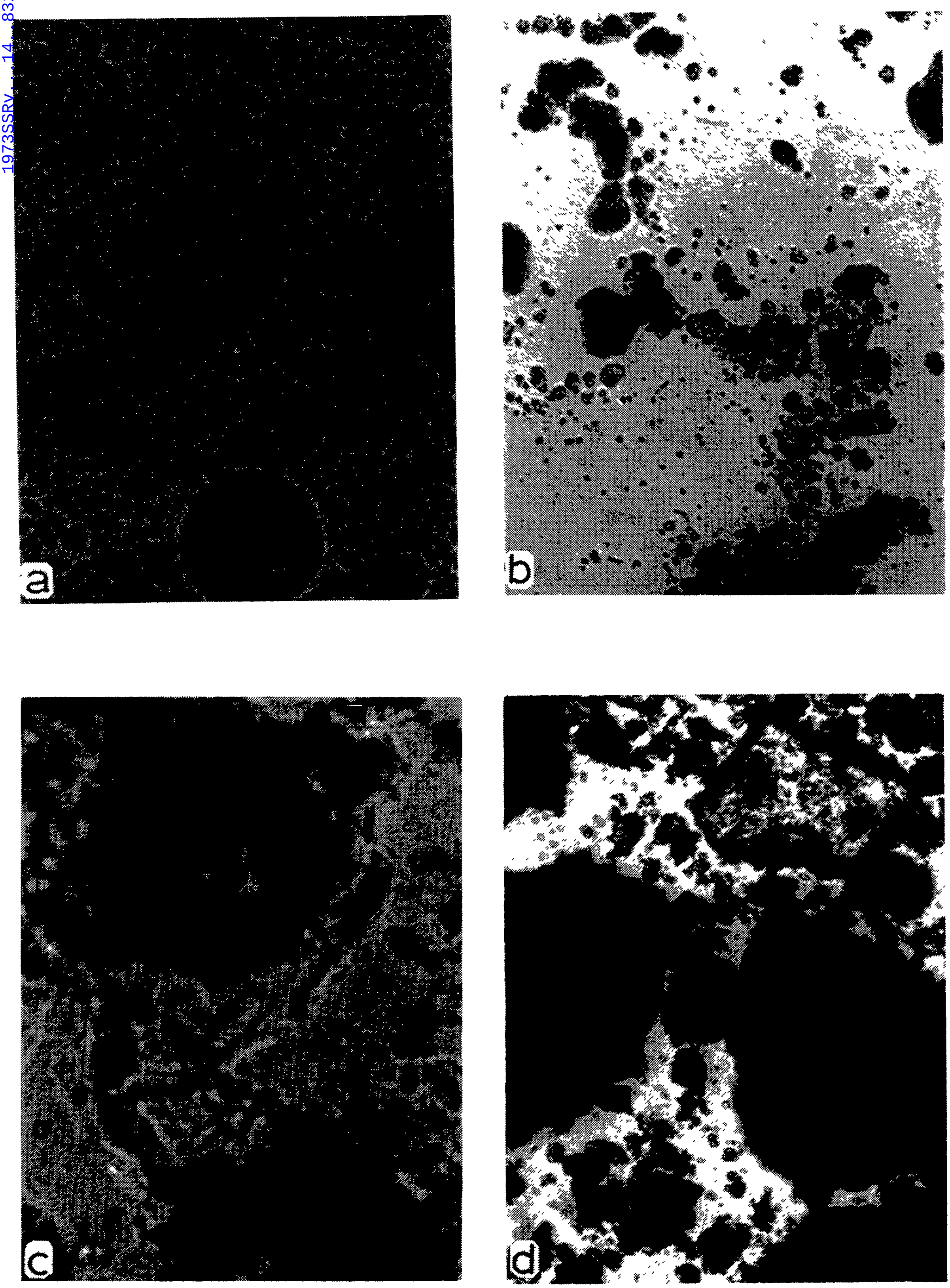


Fig. 19. Powdered preparations of the Mighei meteorite (Vdovykin, 1964), (a) Fraction $\varrho < 1.5$, (b) Fraction $1.5 < \varrho < 2.31$, (c) Fraction $2.31 < \varrho < 2.88$, (d) Fraction $\varrho > 2.88$.

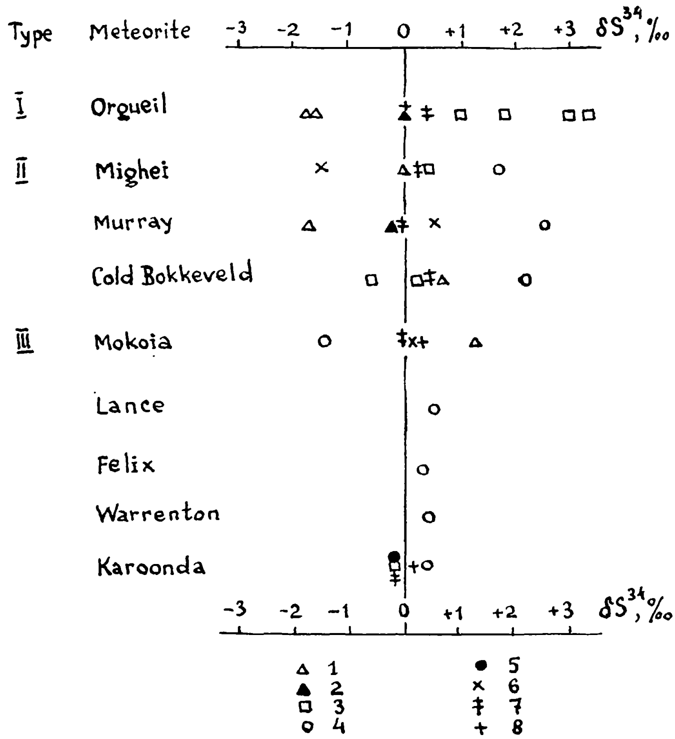


Fig. 20. Variations of the isotopic composition of sulphur (S^{34}) in different forms in the Mighei meteorite and in other carbonaceous chondrites (Kaplan and Hulston, 1966). (1) SO_4^{2-}, dissolved in H_2O, (2) SO_4^{2-}, dissolved in HCl, (3) S^0, (4) FeS, (5) other sulphides, (6) residual sulphur, (7) mean weight from the total S, (8) measured total S.

TABLE XII

Isotopic composition of sulphur in the Mighei meteorite (Kaplan and Hulston, 1966)

Fraction	S content in the meteorite %	δS^{34}, ‰
Free sulphur	1.58	+0.4
Sulphates	0.46	+0.0
Troilite	0.18	+1.7
Other forms	0.15	−1.5
Total sulphur	2.37	+0.3

±0.3% (Trofimov, 1950), did not show significant differences of the isotopic composition of the carbon of this meteorite from those of other carbonaceous chondrites. The ratio C^{12}/C^{13} for the Mighei meteorite was found to be 90.9.

Subsequent mass-spectrometric studies of the meteorite, with an accuracy of ±0.05% established variations in the isotopic composition of carbon among different fragments of the meteorite and in different parts of one and the same meteorite fragment, and among different phases.

Three determinations of the tot. isotopic composition of carbon (carbonate standard PDB) for the Mighei meteorite carried out by Boato (1954) gave the values δC^{13} −8.7, −9.1, and −11.8% with a mean of −9.9‰. Other investigations of δC^{13} in this meteorite have yielded −11.1‰ (Vinogradov *et al.*, 1967) and −10.3‰ (Belsky and Kaplan, 1970; Smith and Kaplan, 1970) (Table XIII). In comparison to the values for general carbon, organic compounds are enriched in the lighter isotope C^{12}, whereas carbonates are richer in the heavier isotope C^{13}. The carbon of the polymerized material, in terms of its isotopic composition, is somewhat heavier in comparison to the carbon of organic compounds extracted by organic solvents. Carbonates of the meteorite have δC^{13} at +41.6‰, i.e. they are some 4% heavier than terrestrial carbonates.

TABLE XIII

Isotopic composition of carbon in the Mighei meteorite

Fraction of carbon containing material	C content in the meteorite (%)	δC^{13}, ‰	References
Total carbon	2.6	−8.7; −9.1; −11.8	
		mean −9.9	Boato, 1954
	–	−11.1	Vinogradov *et al.*, 1967
	2.85	−10.3	Belsky and Kaplan, 1970
			Smith and Kaplan, 1970
Organic material extracts	–	−22.0	Vinogradov *et al.*, 1967
	0.09	−17.8	Smith and Kaplan, 1970
Polymerized organic material	–	−21.1	Vinogradov *et al.*, 1967
	0.72	−16.8	Smith and Kaplan, 1970
	1.56	−14.2	Belsky and Kaplan, 1970
Carbonates	0.21	+41.6	Smith and Kaplan, 1970

The isotope content of total hydrogen has been studied by Boato (1954) for a number of chondrites. He found that in some carbonaceous chondrites (Ivuna, Orgueil, Murray, Mokoia) hydrogen of H_2O fraction, separated by heating in the range 180–800 °C there was a considerably enhanced proportion of D in comparison to terrestrial hydrogen; the value of δD varied between +9.6 up to 35.8%. This testifies to the extraterrestrial origin of the meteoritic hydrogen. For the Mighei meteorite two determinations of the quantity δD from the H_2O fraction, separated by heating at temperatures of from 180 to 800 °C gave δD as −5.4 and −7.4%, with a mean value of −6.4%. The δD value for the H_2O fraction separated by heating at less than 180 °C was −4.2%.

Vinogradov and colleagues (1960) investigated the isotopic composition of oxygen in meteorites and demonstrated that the ratio O^{16}/O^{18} was 490.3, which is quite close to the O^{16}/O^{18} ratio for ultra magic rocks. The Mighei, Staroye Boriskino, Groznaya carbonaceous chondrites have a noticeably more abundant content of the heavy isotope O^{18}. For the Mighei meteorite the ratio O^{16}/O^{18} amounts to 489.0. The isotopic composition of oxygen in various mineral phases, chondrules and matrices, according to the findings of Taylor *et al.* (1965) and Onuma *et al.* (1971), varies in carbonaceous chondrites.

In connection with age determinations, the stable isotopes of Tl and Pb and the radioactive isotopes K^{40} and Rb^{87} together with the cosmogenically radioactive isotope Al^{26} have been studied for the Mighei meteorite.

It has been assumed that in the early material of the solar system there was a number of short-lived radioactive isotopes (I^{129}, Pu^{244}, Pb^{205} and others), which disintegrated with the formation of the stable products (Xe^{129}, Xe^{136}, Tl^{205} and so on). Anders and Stevens (1960) looked for traces of the radioactive isotope Pb^{205} in meteorites by means of variations of the ratio Tl^{205}/Tl^{203}. The isotopic composition of thallium for the Mighei meteorite was found not to differ from its terrestrial one. The ratio Tl^{205}/Tl^{203} amounted to 2.37 ± 0.02 in the meteorite, while the ratio Pb^{204}/Tl^{203} was 0.57 (the content of Pb^{204} was $23 \times 10^{-7}\%$). Reed and co-authors (1960) showed that the lead of the Mighei meteorite had a primary isotopic composition. The ratio Pb^{208}/Pb^{204} was 31.1 ± 1.2 for the meteorite. The isotope K^{40} was found to have a content of 4.8×10^{-8} gm gm^{-1} in the meteorite, while the ratio K^{40}/Ar^{40} was 1.062 (Gerling, 1961). Kaushal and Wetherill (1970) determined the isotopic composition of Rb and Sr for the Mighei meteorite. The Rb^{87} content was found to be 0.4921, that of Sr^{86} 0.8309 μg gm^{-1}; while the atomic ratios of Rb^{87}/Sr^{86} and Sr^{87}/Sr^{86} were 0.5854 and 0.7397 respectively.

The content of the cosmogenic radioactive isotope Al^{26} for the Mighei meteorite was found to be 26 ± 3 distgr. min kg^{-1} (Heymann and Anders, 1967) and 35.6 ± 2.0 distgr. min kg^{-1} (Fuse and Anders, 1969).

6. Rare Gases

Carbonaceous chondrites contain rare gases (He, Ne, Ar, Kr and Xe) which are preserved in them, both from the time of the original formation of the meteoritic material and in their creation as a result of the radioactive decay of elements, and also as a result of the irradiation of the meteoritic material by galactic and solar cosmic rays. With occurrence of shocks in cosmic space, or as a result of other processes which are accompanied by localized heating, rare gases in dislocated sectors of mineral grains may be partially liberated. On the other hand, in the meteoritic particles which are close to the meteorite surface there may accumulate a greater amount of cosmogenic isotopes of rare gases as a result of cosmic ray irradiation. Apart from this, the content of rare gases shows the effects of erosion in cosmic space and so on. Therefore the contents of rare gases and their isotopes will vary even in one and the same meteorite.

In meteorites one may distinguish between three components of rare gases: initial, radiogenic and cosmogenic.

Carbonaceous chondrites are more rich in the primary rare gases moreover they contain a predominantly fractionated component, i.e. the light gases in them, in comparison to the Solar composition, are relatively reduced in relation to the heavier gases.

In 1955 Gerling and Knorre found an Ar^{40} content of 28.7×10^{-6} cm^3 gm^{-1} for the Mighei meteorite. Recently the isotopic composition of rare gases in the meteorite was studied by Zähringer (1962, 1968), Kirsten *et al.* (1963), Vinogradov and Zadorozhny (1964), Mazor *et al.* (1970), and discussed by a number of investigators (Pepin and Signer, 1965; and others). The contents and the isotopic composition of rare gases in the Mighei meteorite are given in Table XIV.

TABLE XIV

Contents and isotopic composition of rare gases in the Mighei meteorite ($n \times 10^{-8}$ cm^3 gm^{-1})

Isotopes and Ratios	Zähringer (1962)	Vinogradov and Zadorozhny (1964)	Mazor, *et al.* (1970)
He^3	2	<1	2.12
He^4	3700	2760	3500
Ne^{20}	12.3	27.5	14.2
Ne^{21}	0.65	1.22	0.74
Ne^{22}	2.2	3.60	2.50
Ar^{36}	58	56	55.7
Ar^{38}	10.5	10.4	10.9
Ar^{40}	850	900	1480
Kr^{84}	0.92	–	1.18
Xe^{132}	1.0	–	0.82
He^3_c	1.6	<0.1	1.73
Ne^{21}_c	0.61	1.14	0.70
Ne^{20}_p	11.8	26.4	13.5
Ar^{36}_p	58	56	55.7
Kr^{84}_p	0.92	–	1.18
Xe^{132}_p	1.0	–	0.82
$(Ne^{20}/Ne^{22})_p$	7.72	11.19	7.76
$(Ar^{36}/Ar^{38})_p$	5.42	5.42	5.15

In the Mighei meteorite the content of cosmogenic isotopes of rare gases is lower than in ordinary chondrites: He^3_c in the Mighei meteorite attains a content of $1.73 \times \times 10^{-8}$ cm^3 gm^{-1} (Table XIV), whereas in ordinary chondrites its content is 5 to 50×10^{-8} cm^3 gm^{-1} (Vinogradov and Zadorozhny, 1964), Ne^{21}_c has contents, correspondingly, of up to 1.14×10^{-8} in the Mighei and up to 16×10^{-8} cm^3 gm^{-1} for ordinary chondrites.

Pellas *et al.* (1969) studied the tracks of the cosmic rays in a number of meteorites. They did not observe any significant concentration of tracks in the Mighei meteorite.

The contents of initial rare gases (Ne^{20}, Ar^{36}, Kr^{84}, Xe^{132}) in the Mighei meteorite is quite considerable (Table XIV). The ratio of the initial Ne^{20}/Ne^{22} is from 7.7 to 11.2 in the meteorite, that of Ar^{36}/Ar^{38} is from 5.2 to 5.4. The ratio of initial Ar^{36} to Kr^{84} is 67, that of Ar^{36} to Xe^{132} is 62 (Zähringer, 1962, 1968).

Important information about the manner of formation of the material of carbonaceous chondritic accrues from the study of the isotopic composition of xenon. This has been studied for the Mighei meteorite by Reynolds (1960), Krummenacher *et al.* (1962) and Mazor *et al.* (1970).

The isotope ratios of Xe (relative to Xe^{130}) for the Mighei meteorite are as follows: Xe^{124}, 0.0299; Xe^{126}, 0.0271; Xe^{128}, 0.521; Xe^{129}, 6.71; Xe^{131}, 5.11; Xe^{133}, 6.32; Xe^{134}, 2.38; Xe^{136}, 2.01 (Reynolds, 1960, Krummenacher *et al.* 1962), and in relation to Xe^{136} there corresponds Xe^{131}, 0.7 ± 0.4; Xe^{132} 2.3 ± 0.6; Xe^{134} 1.3 ± 0.2 (Clarke and Thode, 1964). Mazor *et al.* (1970) determined Xe contents of (in 10^{-10} cm^3 gm^{-1}) initial Xe^{132}, 82; radiogenic Xe^{129}, 4.9; captured Xe^{136}, 0.97. The isotopic composition of Xe in relation to Xe^{132}, the content of which is taken to be 100, is given in Table XV.

TABLE XV

Content and Isotopic composition of xenon in the Mighei meteorite

Xe isotopes	Reynolds (1960)	Mazor *et al.* (1970)
	Contents $n \times 10^{-10}$ cm^3 gm^{-1}	
Xe^{132}	–	82
Xe^{136}_{rad}	–	4.9
Xe^{136}_{capt}	–	0.97
	Isotopic composition ($Xe^{132} = 100$)	
Xe^{128}	8.23	8.4
Xe^{129}	108	108
Xe^{130}	16.1	16.4
Xe^{131}	81.9	81.7
Xe^{134}	38.2	38.4
Xe^{136}	32.3	32.4

7. Ages

Study of the isotopic composition of chemical elements in meteorites allows the dating of the major evolutionary stages of the meteoritic matter from the time of nucleosynthesis up to the terrestrial fall. Methods of dating and the cosmochronology of meteorite have been reviewed by Anders (1963), Sobotovich (1970) and other investigators.

For the Mighei meteorite and other chondrites, Kuroda *et al.* (1967) calculated the formation interval between nucleosynthesis and cooling of the meteoritic matter, by means of the relationship of Te^{128} to Xe^{129}, in the supposition that I^{129} was formed from Te^{128} with neutron irradiation of the meteoritic matter in the early stages of the Solar system. This formation interval for the Mighei material worked out at about 69×10^6 yr.

The duration of the solidification stage of the Mighei material was obtained from the ratio Rb^{87}/Sr^{87} (Kaushal and Wetherill, 1970). Within the limits of experimental error the results are placed on an isochrone of timespan 4.54×10^9 yr (Figure 21). The radiogenic age of the meteorite from the K^{40}/Ar^{40} ratio was found to be $4.6 \times \times 10^9$ yr (Gerling and Knorre, 1955). On the basis of more recent K–Ar determinations

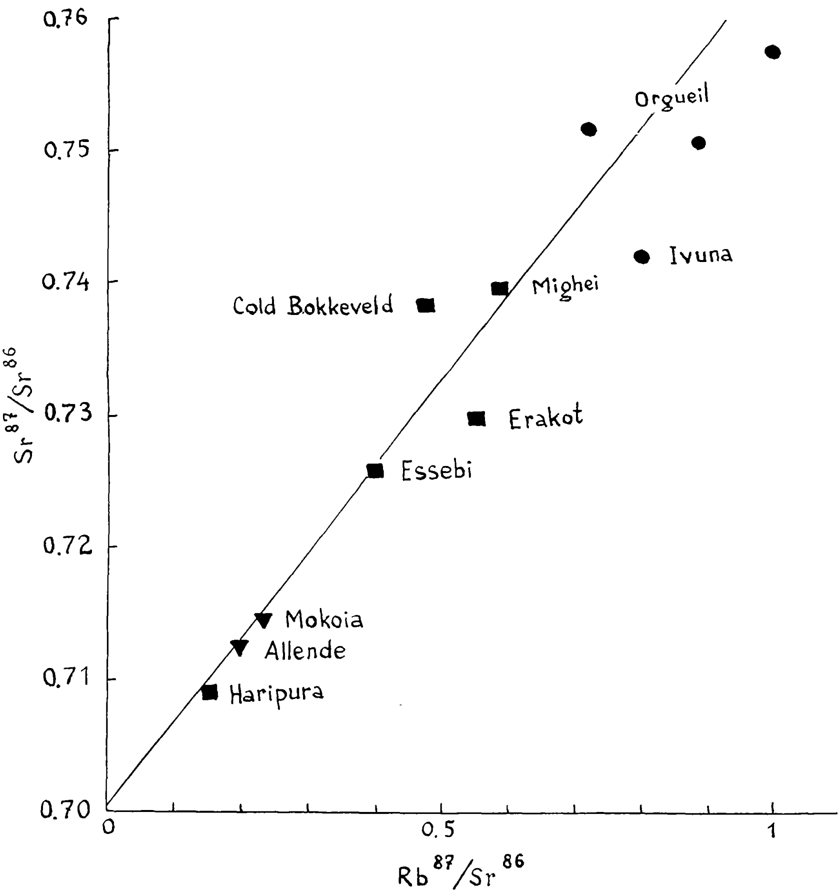


Fig. 21. Isochrone of the radiogenic Rb^{87}–Sr^{87} age of the Mighei meteorite and other carbonaceous chondrites (Wetherill, 1972). The age 4.54×10^9 yr, the initial ratio $(Sr^{87}/Sr^{86}) = 0.7001$.

TABLE XVI

Radiogenic and radiation ages of the Mighei meteorite

Age		Kirsten *et al.* (1963)	Vinogradov and Zadorozhny (1964)	Mazor *et al.* (1970)
Radiogenic (K–Ar), 10^9 yr		2.4	2.7	3.2
Radiation, 10^6 yr	He^3	0.7	<0.5	0.8
	Ne^{21}	2.1	–	2.4
	Al^{26}	–	–	1.47

the radiogenic age of the meteorite has been found to be within the limits 2.4 to 3.2×10^9 yr (Table XVI).

The radiational age characterises the time during which the meteorite's divided parts were subjected to the irradiation of cosmic rays. The age is determined from the contents of the stable (He^3, Ne^{21} and Ar^{38}) and the radioactive (Al^{26} and others) cosmogenic isotopes. Mazor *et al.* (1970) adopted the following rates of accumulation of the cosmogenic isotopes of rare gases for carbonaceous chondrites of the Mighei type (in 10^{-8} cm^3 gm^{-1} 10^6 yr) He^3, 2.17; Ne^{21}, 0.288; Ar^{38}, 0.0534. The age of the

Mighei meteorite calculated from the contents of these isotopes is then not very great (0.5 to 2.4×10^6 yr, Table XVI) in comparison with the ages of ordinary chondrites, i.e. the Mighei carbonaceous chondrite has been subject to more break-ups in cosmic space than ordinary chondrites. A lower value for the radiational age of the Mighei meteorite is also found from the cosmogenic Al^{26} content, i.e. $1.0 \pm 0.3 \times 10^6$ yr (Rowe *et al.*, 1963), 1.47×10^6 yr (Mazor *et al.*, 1970) (Figure 22).

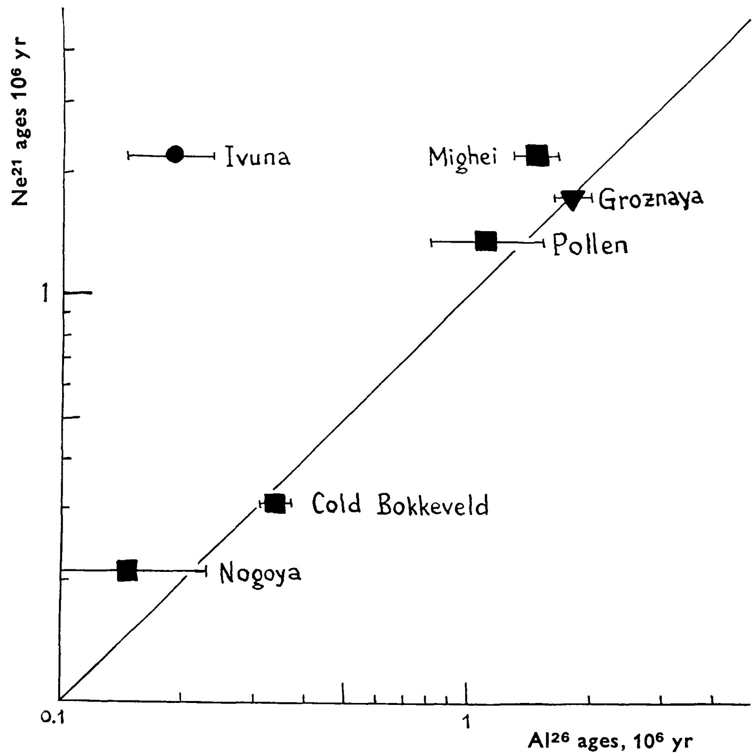


Fig. 22. The radiation age, as determined from Ne^{21} and Al^{26}, for the Mighei meteorite and other carbonaceous chondrites (Mazor *et al.*, 1970).

8. Origin

The Mighei meteorite is a typical member of the carbonaceous chondrites. As with other carbonaceous chondrites, it is characterized by a whole range of genetic structural details which make it different from other meteorites, and in particular from ordinary chondrites. The most significant structural details of the Mighei carbonaceous chondrite are the following.

(1) The meteorite as a whole is characterized by a non-equilibrium in composition. The non-uniformity of the mineral composition amounts to the presence of two mineral associations (the 'high-temperature' and the 'low-temperature' associations), which bear witness to at least a two-stage process of formation of its material.

(2) The non-equilibrium of chemical composition may provide evidence for the superposition of secondary mixing processes (with the participation of simple compounds containing volatile chemical elements).

(3) In terms of chemical composition, excluding the light elements, the composition of

the material of the meteorite approximates that of the H-group of chondrites, which may indicate a common formation of the 'high-temperature' phases of chondrites.

(4) The meteorite is enriched in the volatile elements S, C, H, N and O, which are found in different mineral phases in the meteorite. This could show that the formation of the meteoritic matter as a whole took place at relatively low temperatures in a medium rich in volatile elements.

(5) The meteorite is also enriched in a number of relatively volatile trace elements.

(6) The isotopic composition of S, C and O in different phases of the meteorite differs, which testifies to an isotopic fractionation at the formation of the meteoritic material.

(7) The meteorite is rich in primary rare gases.

(8) The meteorite is rich in organic compounds. The presence of organic material in the meteorite occurred as a result of natural chemical synthesis.

(9) The organic compounds in the meteorite are found in paragenetic associations with minerals of 'low-temperature' origin (inclusions of hydrous silicates), which should provide evidence for the synchronous formation of organic matter and 'low-temperature' minerals at the early stages of development of the meteoritic material.

The definite structural details of the material of carbonaceous chondrites have attracted a great deal of attention in recent years by a number of investigators studying the origin problem. Many points of view about the genesis of the carbonaceous chondrites are set out in the works of Mason (1963, 1971), Anders (1964) and Vdovykin (1967).

At the present time the most widely accepted model is the condensation model of the formation of meteoritic matter (Larimer and Anders, 1970; Wood, 1971; Onuma *et al.*, 1971 and others). Anders (1971), on the basis of detailed thermodynamical data, postulates a two-component model for the fractionation of the material of the carbonaceous chondrites in the cooling solar nebula. According to this idea, the carbonaceous chondrites were formed in the outer zone of the asteroid belt, or else from cometary material ($\sim$5 to 40 AU). Anders separates the stages of the early formation of the condensing matter at $T \geqslant 1300$ K, the fractionation of metal and silicates, the partial melting of the material, subsequent accretion in a temperature region of 450 to 300 K, together with the simultaneous formation of organic compounds and a number of 'low-temperature' minerals, isotopic fractionation and finally a further stage of relatively low heating. Such a model as has been considered by Anders on the basis of extensive numerical data is not contradicted by the structural details of the Mighei carbonaceous chondrite, and agrees with the studies of Vdovykin (1967) for a model of the formation of organic compounds in carbonaceous chondrites together with the simultaneous agglomeration of the meteoritic matter.

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