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Biological Material in Meteorites: A Review

If found in terrestrial objects, some substances in meteorites would be regarded as indisputably biological.

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The carbonaceous chondrites have occupied an interesting place in the study of meteorites for many years. Some 17 stones belonging to this general classification are known, and authorities agree on their classification, but perhaps another half-dozen stones might be of this type. They contain carbon in easily detectable amounts, and in some of them there is easily recognized carbonaceous material. They represent some 3 percent of the total observed falls, and though they are a minor fraction of the total their number is far from negligible.

The first stone of this class fell on 15 March 1806 in Alais, France. This stone was sent to Berzelius, who in 1834 examined it chemically (*1*). He appears to have been the first scientist of reputation to have remarked on the similarity of its carbonaceous compounds to terrestrial biological material, and he asked the questions, "Does this carbonaceous earthy material truly contain humus or a trace of other organic compounds?" "Does this possibly give a hint concerning the presence of organic structures in other planetary bodies?" These questions have been asked repeatedly since then, but only in very recent years have techniques developed to a point where a definite answer may be given.

Wöhler and Hörnes (*2*) in 1859 investigated another stone, Kaba, which fell in Hungary, and believed that the carbonaceous compounds they found in this stone were of biological origin. In 1864 a stone fell near the village of Orgueil, France. The stones were picked up immediately after the fall and were analyzed by Daubree (*3*) and Cloëz (*4*). The fresh stone contained an ammonium salt, probably ammonium chloride, which was reported to accumulate on the fused crust of the stone in the course of time. Cloëz found organic matter comparable to peat, lignite, and organic matter found in soils. The total carbonaceous material amounted to 6.4 percent, according to these workers, an amount close to that reported by Wiik (*5*) in 1956.

Berthelot (*6*) examined the Orgueil meteorite in 1868 and reported material similar to hydrocarbons of the formula C_nH_{2n+2}. In fact, he concluded that the compounds were saturated hydrocarbons. It is interesting to note that during the 19th century chemists investigating these meteorites reported finding material similar to material which is found on earth and confidently described as decomposition products of biological material.

In 1953 Mueller (*7*) investigated the Cold Bokkeveld meteorite and reported that carbonaceous material containing carbon, nitrogen, oxygen, hydrogen, sulfur, and chlorine could be extracted from the stone. His observation is somewhat different from that of the earlier investigators, for his description of the material would hardly correspond to Berthelot's description of hydrocarbons. Of course any extract is likely to consist of a mixture of compounds.

During recent years careful studies have been made of the chemical composition of the inorganic materials. Berzelius observed clay-like minerals, and his observation has been confirmed by later workers. Pisani (*8*) and Cloëz (*4*) independently demonstrated the presence of soluble salts of ammonium, potassium, magnesium, and sodium, with sulfate and chlorine as the anions. Ammonia was not found by Wiik (*5*). It probably has escaped from the stone during the century of storage, for ammonium salts would hydrolyze, the acid thus formed would react with the silicates, and the ammonia present would escape.

The Orgueil meteorite contains considerable amounts of water. Wiik reported 19.89 percent, but earlier observers found somewhat less. It appears that these stones absorb water from the atmosphere in variable amounts, though Boato (*9*) showed, on the basis of the isotopic composition of the water extracted, that the water removed at higher temperatures is definitely different from water from any terrestrial sources. It appears, therefore, that some of the water has remained in these stones from the time of fall. The difference in isotopic composition is not so great that chemical fractionation of the isotopes of hydrogen may not account entirely for the difference in the observed compositions.

In 1924 Spielmann (*10*) suggested that the carbonaceous materials were produced by the action of terrestrial water on indigenous metal carbide minerals in the meteorites. But no one has ever found carbides in the car-

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bonaceous chondrites, and the observation that fatty acids, as well as other complicated compounds to be discussed later, are present in these meteorites shows definitely that the action of terrestrial water cannot account for the carbonaceous materials.

Minerals and Inorganic Chemicals

More recently Nagy *et al.* (*11*) and DuFresne and Anders (*12*) and their co-workers have studied the mineral composition of meteorites and have reported the presence of ferrous magnesium carbonate, calcium magnesium carbonate, and magnesium sulfate. They have concluded that at least certain of the meteorites they studied consist of original mineral mixtures which have been acted upon by water.

The chemical composition of these objects varies considerably with respect particularly to the content of iron, water, sulfur, and carbon; in order to make a comparison with other objects in regard to the more abundant elements, analyses calculated with the sulfur, carbon, and water eliminated are listed in Table 1. The table gives the chemical analyses of the Orgueil and Mighei meteorites and the average for the high-iron group of chondrites. The analyses of Orgueil and Mighei are from the work of Wiik (*5*), who classified the carbonaceous chondrites into three groups: Type 1 containing 15 to 20 percent water and no metal; Type 2, containing about 10 percent water and very small amounts of metal; and Type 3, containing considerable amounts of metal, very little water, and small amounts of carbon. This last group has been reclassified by Mason (*13*) as the olivine-pigeonite chondrites. Orgueil and Mighei are Types 1 and 2, respectively. It will be noted from Table 1 that the composition of the carbonaceous chondrites with respect to substances other than sulfur, carbon, and water is very similar to that of chondrites of the high-iron group as classified by Urey and Craig (*14*). It will be noted, however, that the ratio of iron to silicon is slightly higher for the chondritic meteorites of Type 1 than for the high-iron chondrites as a group.

Table 2 gives the percentages of total sulfur, water, and carbonaceous material according to Wiik's analyses (*5*). There are substantial amounts of sulfur, as sulfur, sulfate, and sulfide, and of water and carbonaceous material in these objects.

The salts observed are characteristic of those believed to have been present in the primitive oceans of the earth. In the absence of an oxidizing atmosphere we would expect to find such reduced substances as the ferrous ion,

Table 1. Elementary compositions (atomic percentages with S, C, and H_2O excluded) of two carbonaceous meteorites and the average composition of the H-group chondrites. The carbonaceous chondrites show close agreement (with the exception of metallic Fe and iron oxides and sulfides) with the noncarbonaceous chondrites.

Substance	Type 1 Orgueil	Type 2 Mighei	Average for H chondrites
Fe (metal)	0.00	0.00	16.18
Fe (oxide-sulfide)	27.34	26.18	10.05
Ni	1.37	1.41	1.57
Co	0.07	0.06	0.09
Si	31.12	31.85	33.12
Ti	0.09	0.09	0.09
Al	2.68	2.90	3.60
Mn	0.22	0.19	0.25
Mg	32.48	33.19	31.68
Ca	1.81	2.04	1.60
Na	1.97	1.40	1.56
K	0.12	0.07	0.19
P	0.33	0.29	0.19
Cr	0.40	0.33	0.33
Total	100.00	100.00	100.00

ammonium ion, sulfide, and sulfur, though probably, as time progressed, carbonaceous material was oxidized to carbonate and sulfide to sulfate. As has been pointed out elsewhere, hydrogen peroxide would probably be produced by ultraviolet light on such a primitive earth, and Lewis (*15*) has shown that hydrogen peroxide will produce both sulfur and sulfate from sulfide. Probably one of the first oxidation products of iron acted upon by water would be magnetic iron oxide, which is also observed in the Orgueil and Mighei meteorites. The minerals observed are indeed those that would be characteristic of a primitive ocean, but since in chemical composition these meteorites are so similar to others whose composition approximates the probable primitive abundances of the elements, it seems that no sorting by running water can have occurred.

The mineral texture of the Orgueil meteorite is quite remarkable. Figure 1 shows a mineral aggregate at the lower right-hand side and a vertical magnesium sulfate vein toward the middle of the picture. The other minerals are similar to clays. In Fig. 2 we see some lath-like minerals. Their texture closely resembles what are called *pyroclastic sediments*—that is, sediments of volcanic ash or something of the sort settling in water. This indicates that this material has had a history of low temperatures. In physical appearance it is similar to terrestrial ash flows, although the Orgueil meteo-

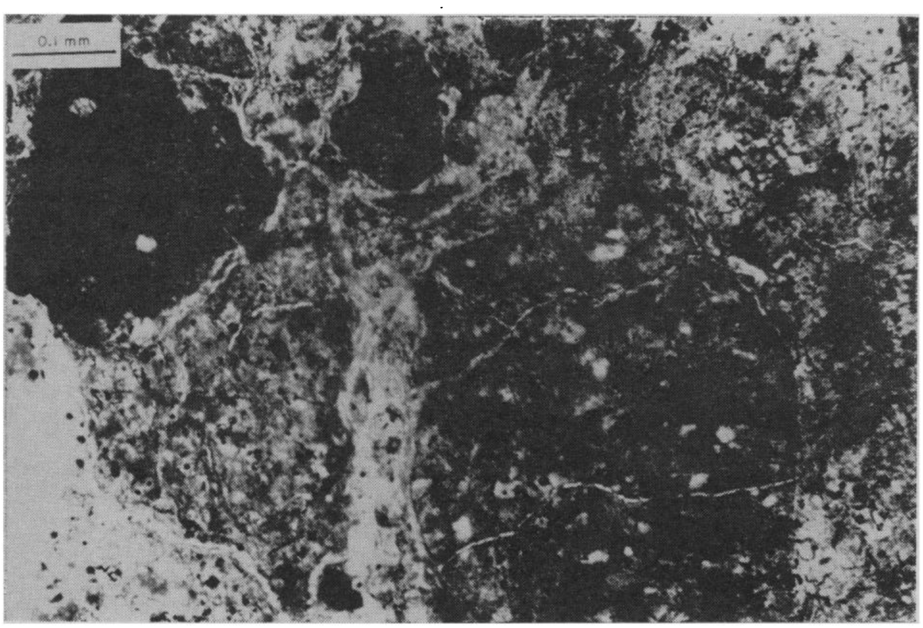


Fig. 1. Petrographic thin-section of the Orgueil meteorite. Such sections are prepared by the careful grinding of a meteorite fragment cemented to a glass microscope slide. This photomicrograph shows the fragmental (brecciated) texture of Orgueil (note granule at upper left corner) and a magnesium sulfate vein (in vertical position, just to the left of center). Such textural features are not present in unaltered igneous rocks. The mineral matrix, with the exception of opaque granules and the magnesium sulfate vein, consists of clays. The width of this section is 0.7 mm.

rite has a completely different chemical composition: terrestrial ash flows have an approximately granitic composition and contain much more aluminum oxide, silicon oxide, and calcium oxide and less magnesium than the meteorite contains. There is general agreement that the carbonaceous chondrites did not originate on the surface of a planet such as the earth.

Reports of Biological Material

In 1961, Nagy, Meinschein, and Hennessy (*16*) presented results of their studies on carbonaceous chondrites, and this paper and their subsequent work raised much controversy in regard to the character of the organic material present in these objects. They found, on the basis of tests similar to those which they had been using in petroleum chemistry, that the material in the Orgueil meteorite was very similar to biological material present in terrestrial fossils. Students of meteorites, including myself, were immediately certain that this could not be true, because of the indications, discussed above, that no sorting such as is found in sedimentary rocks had occurred. It is difficult to believe that biological material could have evolved in the absence of water, and hence the inorganic constituents should have been subjected to the sorting effects observed as a result of the presence of water.

In their first analysis, Nagy, Meinschein, and Hennessy extracted organic material from the Orgueil meteorite and then subjected it to mass spectrometric analysis of the type regularly used in studying biological material in soils, petroleum, and materials of this kind. They believed that they found the same pattern of molecular fragments, including fragments of aliphatic and aromatic carbon compounds, in the meteorite as they had observed in terrestrial fossil biological material.

Subsequently, Claus and Nagy (*17*) observed small, rounded objects in this meteorite which they interpreted as fossil microorganisms and classified them into various groups. Some were of quite simple structure, while others were of a very complicated kind. Staplin (*18*), who is a micropaleontologist working on problems of petroleum deposits, also found objects which he interpreted as fossils. There is some similarity between the groups of objects observed by these men. Anders and Fitch (*19*) showed quite conclusively that some of the observed forms were indeed recent contaminants, namely, pollen grains. They found that some of the more complicated structures could be produced by the action of the staining reagents they had used. However, it seems certain today that the more simple forms that have been observed are indeed indigenous to the meteorite, although of course they may be artifacts rather than fossils.

Working with the Mighei meteorite, which is a Type 2 carbonaceous chondrite, Timofejev (*20*) also extracted what he believed to be fossilized objects similar to algae such as the dinoflagellates. Other micropaleontologists have also extracted what they regard as possible fossil forms.

Figures 3 and 4 show reproductions of various objects that have been found in the Orgueil and Mighei meteorites. Many other examples have been published. Nagy *et al.* (*21*) have extracted such objects, investigated them with the aid of an electron microprobe, and found that some are impregnated with limonite, probably, and contain small amounts of nickel, while others are impregnated with silicates. Using hydrochloric acid and hydrofluoric acid, they removed these mineral constituents and showed that at least in some cases there remained a body which could be seen under the microscope but which contained no elements heavier than magnesium; thus the objects were probably composed of carbonaceous material. This indicated that carbonaceous material had been fossilized by minerals much as terrestrial microfossils have been. An example of their pictures is reproduced in Fig. 5.

Table 2. The sulfur, water, and carbonaceous matter content (percentage by weight) of carbonaceous meteorites and of the H-group chondrites. Data from Wiik (*5*).

Substance	Type 1 Orgueil	Type 2 Mighei	Average for H chondrites
S	5.50	3.66	1.57
H_2O	19.89	12.86	0.37
Carbonaceous matter	6.96	2.48	

To a chemist, morphological forms appear to be an unsatisfactory basis for identification of biological remains because so many artifacts of approximately the size of microorganisms can be made, both from organic material and from inorganic material. However, since common contaminants, if present, should be recognized by specialists such as Staplin and Timofejev, it seems to me that we should take these studies as not of negligible importance in connection with this problem.

Organic Chemical Studies

Fatty acids. More recently, studies using modern methods of organic geochemistry have revealed the presence of some very interesting chemical sub-

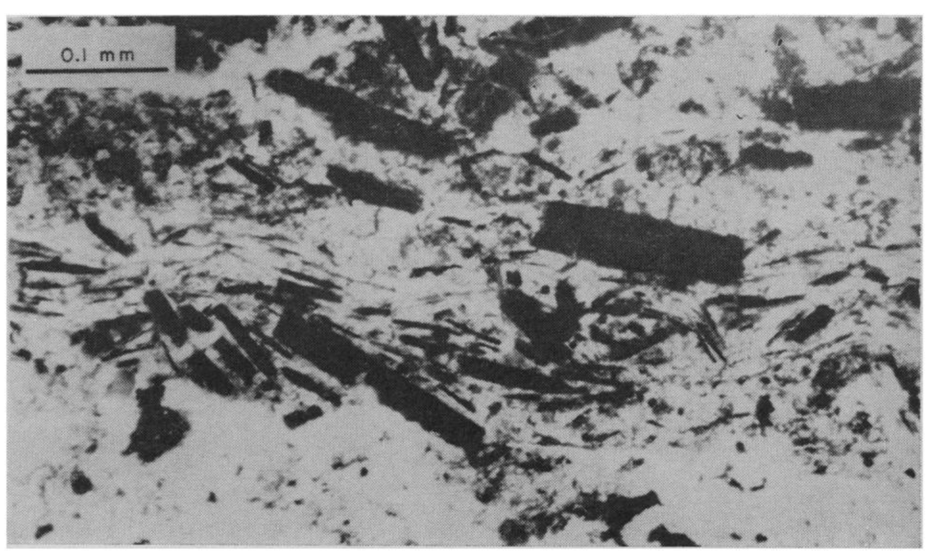


Fig. 2. Another petrographic thin-section of Orgueil. This one shows preferred orientation of the opaque lath-like minerals. This textural pattern is probably the result of plastic flow of the clay matrix (not the result of the grinding of the thin-sections) on the parent body. Such localized flow structures are characteristic of pyroclastic sediments (such as volcanic tuffs). Pyroclastic sediments are the agglomerated debris of broken up igneous rock bodies.

stances in these carbonaceous chondrites. A valuable review of this subject has been given by Briggs and Mamikunian (*22*). The Orgueil meteorite, particularly, has been studied in this way (*23*). Figure 6 shows infrared spectra of samples of carboxylic acids extracted from the Orgueil and Holbrook meteorites, a sedimentary rock, soil, granite, and of the solvent blank; Fig. 7 shows similar spectra of the esterified carboxylic acid derivatives of the same materials. The material used for these spectra was extracted by benzene and methanol mixtures and saponified with potassium hydroxide, then extracted with water, acidified with HCl, reextracted with ether, dried in nitrogen gas, and finally dissolved in carbon tetrachloride, in which the absorption spectrum was observed.

It is evident that the extract from the Orgueil meteorite is very similar to what is observed from soil and the fatty acid standard and that this material is not present in the Holbrook meteorite, the solvent blank, or the granite sample. The absorption peaks characteristic of the acids and esters are indicated in the figures. The marked similarity between these curves is indeed striking. The question immediately arises as to whether contamination of the Orgueil meteorite did not occur as a result of the growth of the biological organisms that supplied the material observed in the test. Of course the Orgueil meteorite would have been biologically contaminated when it fell in France, but a museum shelf does not appear to be a particularly likely place for the growth of biological organisms, particularly when the material contains solid magnesium sulfate, which in the presence of a slight amount of absorbed moisture would give a concentrated solution of magnesium sulfate. Oro has informed me that his sample of the Orgueil meteorite is sterile and points out that this was reported by students of a century ago. Claus and Nagy (*17*), however, reported some evidence of contamination by viable organisms in both the Orgueil and Holbrook meteorites.

Figure 8 shows thin-layer chromatograms of the Orgueil extract. The material was placed at the bottom of the plate and migrated upwards. The vertical columns 1 to 7 and 10 and 11 are saponifiable extracts from the Orgueil meteorite; columns 8 and 12 are prepared by the same procedure from petroleum naphthenic acids, and similarly columns 9 and 13 from an alga. Plate *a* was developed with normal hexane-ether (97:3), *b* with the same solvents (95:5), and *c* with a mixture of chloroform, methanol, and water (65:25:4). The adsorbent was a silicagel layer, and the components were made visible by spraying with Rhodamine 6G and photographed under ultraviolet light. Compound *A* is saturated hydrocarbons, *B* is elementary sulfur, and *C* is the acidic compounds. These chromatograms show the absence from Orgueil of certain biochemicals that are always present in terrestrial samples. In columns 12 and 13 note the two light spots, which are absent from Orgueil. These spots correspond to esters and sterols and are present in the alga and petroleum-naphthenic-acid fractions but not in Orgueil. This study indicates that the simple supposition that an alga grew in the Orgueil rock on the museum shelf is not correct, or that if such an alga did grow, it is a different one from those investigated in this work.

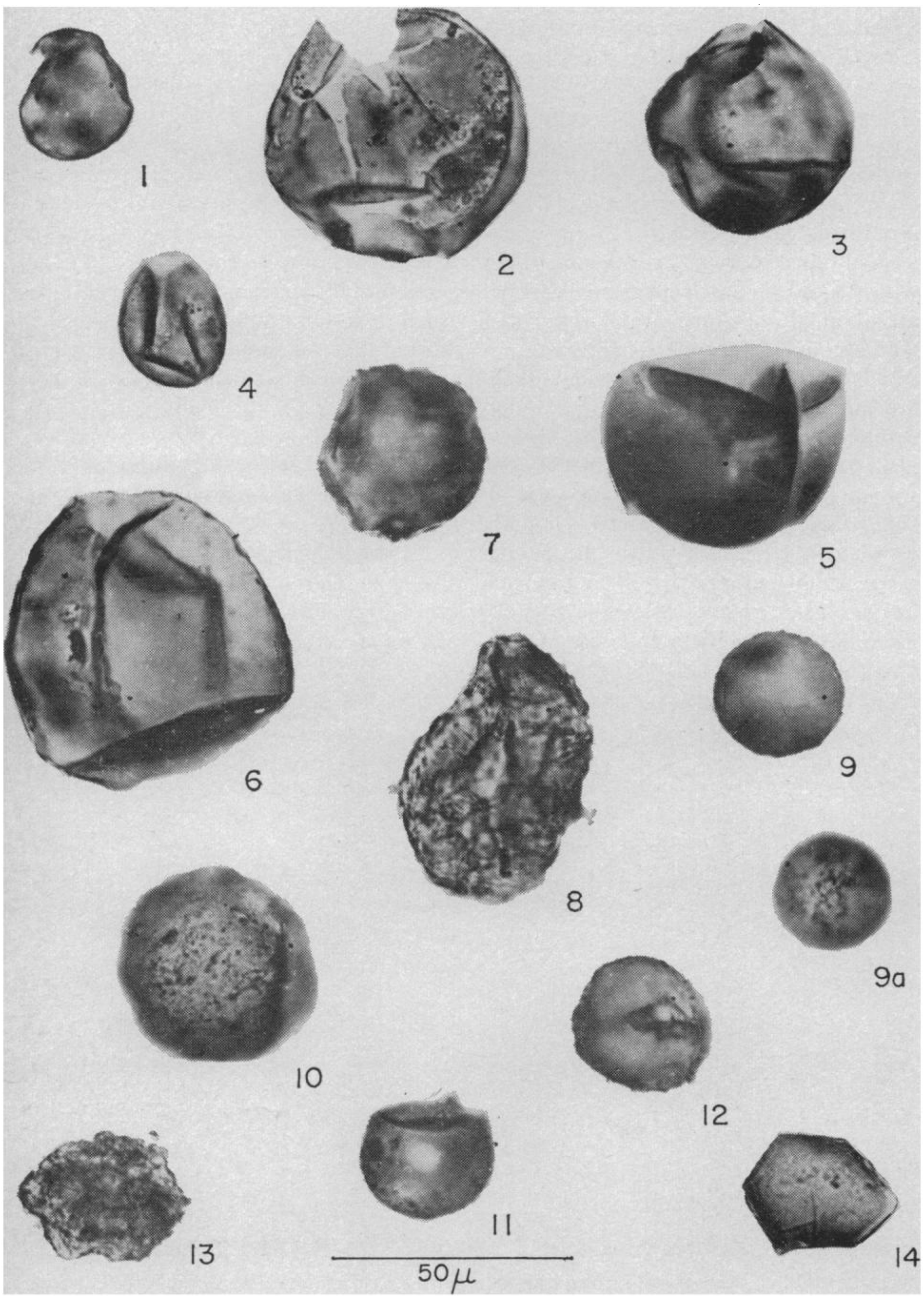


Fig. 3. Acid-insoluble residues of organized elements from the Mighei meteorite. The mineral matter was removed with concentrated solutions of HNO_3 and potassium permanganate. The organic residues were separated by centrifugation. Magnification ~ 600. [After Timofejev (*20*)]

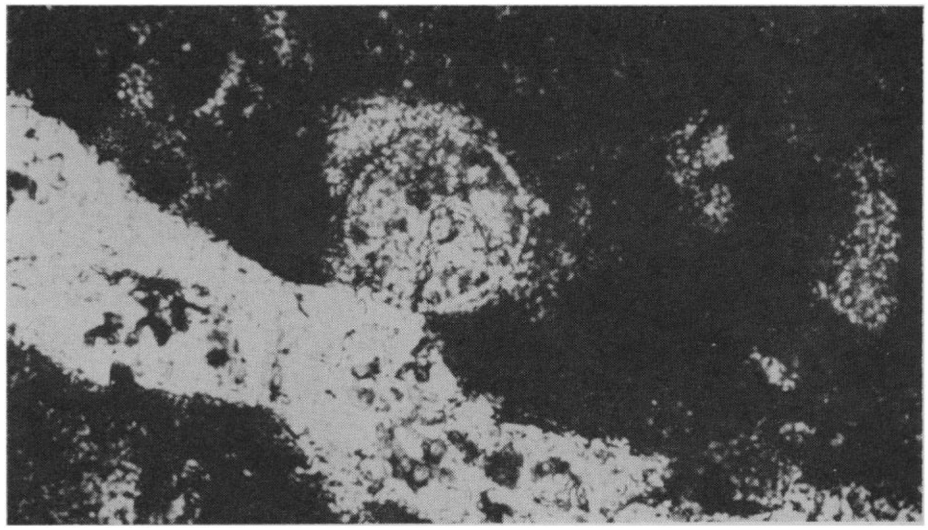


Fig. 4. Petrographic thin-section of the Orgueil meteorite, showing an organized element embedded in the mineral matrix.

Optical activity. Optical activity of organic compounds has not been observed in natural nonbiological sources or in artificial preparations, but it is characteristic of biological compounds. Only the most careful and intricate technical processes have succeeded in separating the two optical isomers from the racemic mixture. It is conceivable that in nature a saturated solution of an optical isomer could be seeded by a crystal of the isomer and hence the isomer would separate out to a slight extent, but the probability that this would occur in a given stone is negligible. Thus optical activity can be regarded as most convincing evidence for the presence of biological material.

Figure 9 shows the results of measurements made by Nagy and his co-workers (*23a*) on the same extracts of the Orgueil material as used in the tests for the presence of carboxylic acids shown in Fig. 8. The extraction procedure isolated lipids. The solutions are colored, and hence tests can be made only in the visible region. But these tests were carried out in three different laboratories and by different investigators. The Orgueil meteorite is not similar in its optical activity to pollen grains, soil, or museum dust samples that were treated in the same way. Also, the blanks, though they scatter somewhat, seem to be definitely different from the Orgueil meteorite. Colored solutions in some instruments give a fictitious rotation, and hence, in order to check on the possibility of error, Nagy *et al.* used a blank containing sulfur and organic dye to imitate the color and opacity of the solutions being studied. The specific rotations in Orgueil extracts observed are in the neighborhood of $-1°$. This is a surprisingly large effect for a mixture of compounds, though recent unpublished work by Nagy on terrestrial materials shows activities of similar magnitude.

Recently, Hayatsu (*24*), using a substantially different method of extraction involving different solvents and the use of a colloidal copper column, found no optical activity. Attempts by Nagy and his co-workers to reproduce Hayatsu's work have failed. They have not been able to remove sulfur from the solutions by the methods that Hayatsu describes, and they have found optical activity in their extracts at points where he finds none. Interestingly enough, they are able to get two fractions which show opposite optical activity. The extractions were made in their laboratories at the University of California, San Diego, and the tests for optical activity were made by W. D. Rosenfeld at California Research Corporation, La Habra. Though the effects are small, they nevertheless appear to be definite.

Table 3 briefly summarizes some of the results for a fraction, labeled A_3 by Hayatsu, which was not passed through the collodial copper. A colored blank prepared by refluxing sulfur with benzene-methanol as described by Hayatsu gave no rotation, whereas Hayatsu reported rotation. It seems that some error is involved if inorganic preparations give optical rotation. This was not the case for the California sample. It may be that the difference in the results from the two laboratories is due to some difference in the samples, that is, Hayatsu may have been using a sample which did not contain biological material, whereas Nagy and his co-workers were using samples that had been contaminated by biological material. It is my conclusion that optical activity is present in some samples. Contamination due to the growth of organisms after the meteorite arrived on earth is a possible explanation, though, as remarked above, this does not seem probable. Such organisms could have left residues of the compounds they had synthesized or could have consumed one optical isomer from an indigenous racemic mixture. There is some evidence that this is not the case, but the subject must be pursued further in the future.

Porphyrins. Hodgson and Baker (*25*) have published the results of a very detailed and careful study of the possible existence of porphyrins in the Orgueil meteorite. The central chemical structure of the porphyrins is a plane structure formed by four pyrrole rings linked together by four methine bridges (—CH—). Hemin,

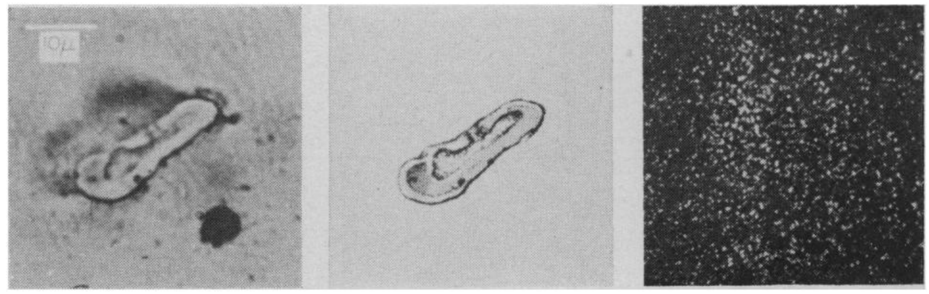


Fig. 5. An organized element from the Orgueil meteorite. The organized element was freed from mineral matter by being boiled in 6*N* HCl for 1 hour. A photomicrograph of the particle is shown on the left and a drawing of it in the center. The lack of a backscattered electron image (right) of this acid-insoluble residue demonstrates that elements heavier than Na were absent and suggests that the residue is composed of organic matter. [Reprinted from (*21*)]

which gives the red color to blood, is a porphyrin, and other biochemical compounds have this fundamental ring in their structure. On the other hand, chlorin is a name given to a group of compounds which differ from the porphyrins only in that two hydrogen atoms are added at one of the double bonds on one pyrrole ring. Chlorophyll has this central chlorin ring with characteristic side chains. The central ion in chlorophyll is magnesium. Chlorophyll has a very characteristic side chain, namely, one long alcohol group called phytol with 20 carbon atoms attached to a carboxylic group.

Studies on the distribution of porphyrins and chlorins in recent terrestrial deposits show that chlorins which have obviously been obtained from chlorophyll and most of which contain magnesium are prominent constituents. As the sediments become older, vanadyl and nickel porphyrins appear, indicating that the chlorins are oxidized by the removal of two hydrogen atoms and that the magnesium (Mg^{++}) is replaced by vanadyl (VO^{++}) and nickel (Ni^{++}). The ancient sediments and petroleum deposits contain only these porphyrins, in which both vanadyl and nickel are prominent.

The porphyrins have absorption bands, referred to as the Soret bands, in the neighborhood of 4000 angstroms. They also have much weaker absorption bands at longer wavelengths, as do the chlorins. The porphyrins are soluble in certain organic solvents and can be separated from the hydrocarbons by solution techniques. The exact details of these processes are available in the literature of this subject and need not be repeated here.

Hodgson and Baker studied samples of the Orgueil meteorite and of two ordinary meteorites, Bruderheim and Peace River. Two Orgueil samples, one of 9 grams and another of 7 grams, were used for this study, and two other samples consisting of solutions which had been subjected to saponification procedures were also investigated for porphyrins. It was found that extracts from the ordinary chondrites, Bruderheim and Peace River, showed no absorption bands in the region expected for porphyrins, that extracts from the 9-gram and 7-gram Orgueil samples showed a band at 412 microns which Hodgson and Baker interpret as being due to vanadyl porphyrin, whereas the two samples which had been treated by saponification techniques contained no vanadyl porphyrin at all. But it was subsequently shown that when treated by similar saponification processes, the Posidonia shale from Germany also was depleted in its vanadyl porphyrin. Thus the meteorite samples treated by the saponification technique before extraction with the organic solvents were probably depleted in vanadyl porphyrin.

It was the conclusion of Hodgson and Baker that "the Orgueil carbonaceous chondrite exhibits many of the organic components of ancient terrestrial rocks, and a detailed consideration of the environment of the Orgueil meteorite parent body by Nagy *et al.* led to the indication that the environment was a low-temperature aqueous system with alkaline *p*H and slightly reducing redox potential. It is therefore not surprising to find what pres-

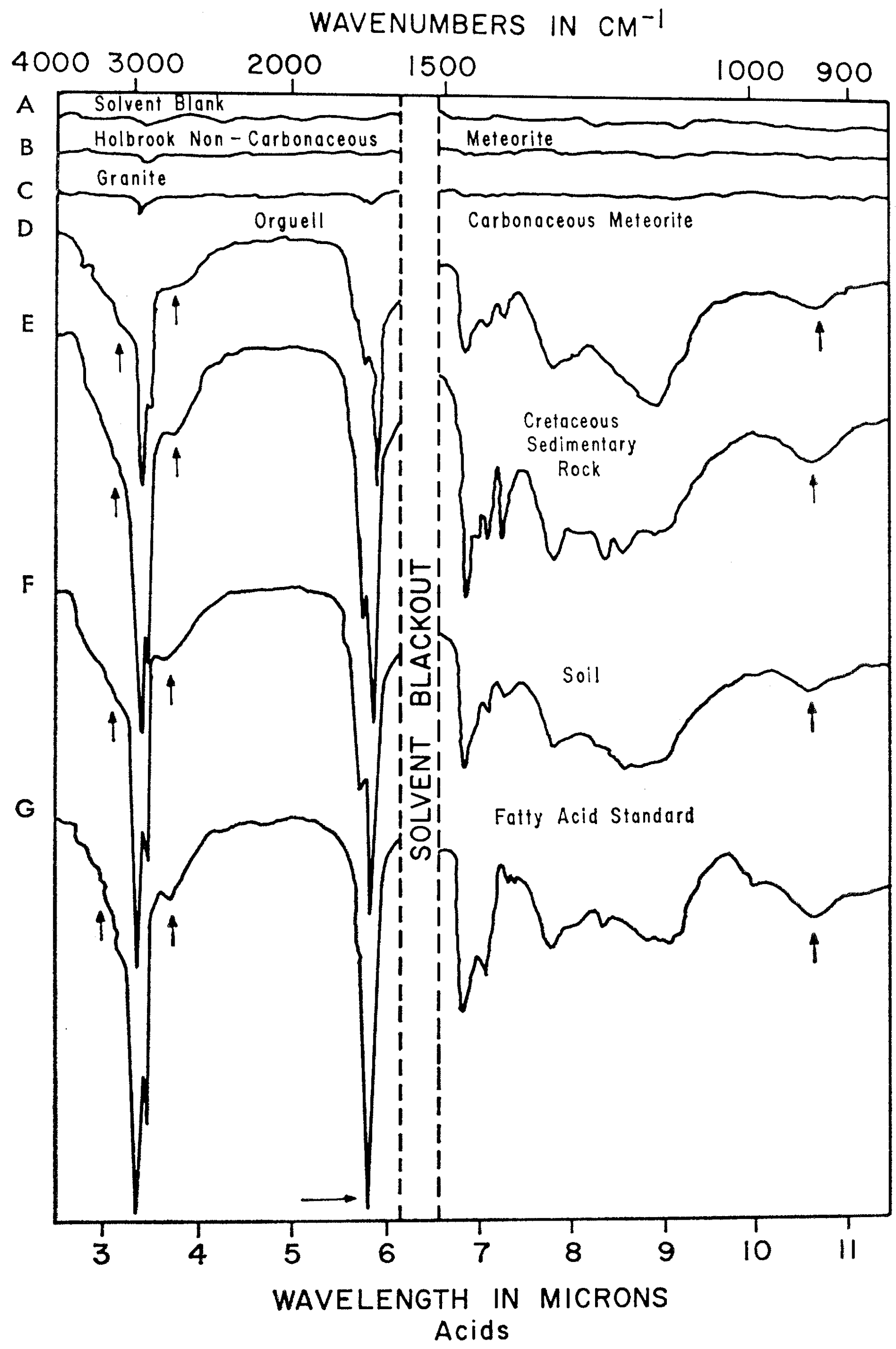


Fig. 6. Infrared spectra of the carboxylic acid fractions from: *A*, solvent blank-run; *B*, Holbrook, noncarbonaceous meteorite; *C*, granite; *D*, Orgueil, carbonaceous meteorite; *E*, Cretaceous sedimentary rock (Navesink Formation); *F*, Recent soil; and *G*, behenic acid (docosanoic acid, C_{22}) from Nutritional Biochemicals Corporation, Cleveland, Ohio. Note the carboxylic acid bands at 3.3, 3.7, 5.85, and 10.7 microns on curves *D*, *E*, *F*, and *G*. [Reprinted from (23)]

ently appear to be indigenous porphyrin pigments in the Orgueil stones suggesting a strong possibility of biogenic agencies in the origin of the organic matter of the meteorite." They found no evidence for nickel porphyrin, which is surprising in view of its appearance in old sediments of the earth. Figure 10 shows the absorption curves which they obtained. The didymium peak is for calibration purposes only. It will be noted that the shale and the Orgueil meteorite give curves which are very similar. Figure 11 summarizes the features in the Orgueil extracts which led to the identification of vanadyl porphyrin.

Nucleic acid bases. Calvin (*26*) reported a cytosine-like feature in his investigation of the Orgueil meteorite. Oro *et al.* (*27*) have suggested that this may be an impurity, and as of the present this disagreement has not been satisfactorily solved. Hayatsu reported the presence of adenine and guanine and possibly a uracil-type compound. It should be noted that uracil and cytosine are the pyrimidine bases and adenine and guanine are the purine bases of ribonucleic acid; the last three also occur in deoxyribonucleic acid. Hayatsu (*24*) also reported other compounds that apparently have no biological significance and argues that for this reason these bases are abiotic in origin. However, many terrestrial deposits of organic material confidently believed to be of biological origin also contain compounds that have no known biological significance. Hence the presence of such compounds does not disprove the biological origin of other compounds.

Amino acids. Amino acids have been reported from the carbonaceous meteorites by Kaplan *et al.* (*28*), Hamilton (*29*), and others. It appears certain that some of these are contaminations, possibly by present-day organisms growing in the solutions being investigated or from human hands. The amount of the amino acids is very small and at present it is not possible to argue for an indigenous origin for these compounds, but it is also not possible to exclude the possibility of such an origin. It should be noted that amino acids may decompose in terrestrial sediments more rapidly than the hydrocarbons, porphyrins, fatty acids, and other biological compounds of this kind.

Free radicals. Duchesne, Depireux, and Litt (*30*), using electron-spin-resonance techniques, have investigated the carbonaceous material of the Mighei and Nagoya meteorites (both Type 2) and report concentrations of free radicals up to 10^{17} per gram of carbon. They conclude that such concentrations are characteristic of biogenic material. However, it is possible that nonbiogenic carbonaceous material subjected to the radiations to which these meteorites were exposed would imitate the free-radical concentrations observed in terrestrial fossil carbonaceous material.

Hydrocarbons. Oro *et al.* (*27*) identified hydrocarbons in a very considerable number of carbonaceous chondritic meteorites; they particularly noted the probable presence of pristane and phytane, two hydrocarbons

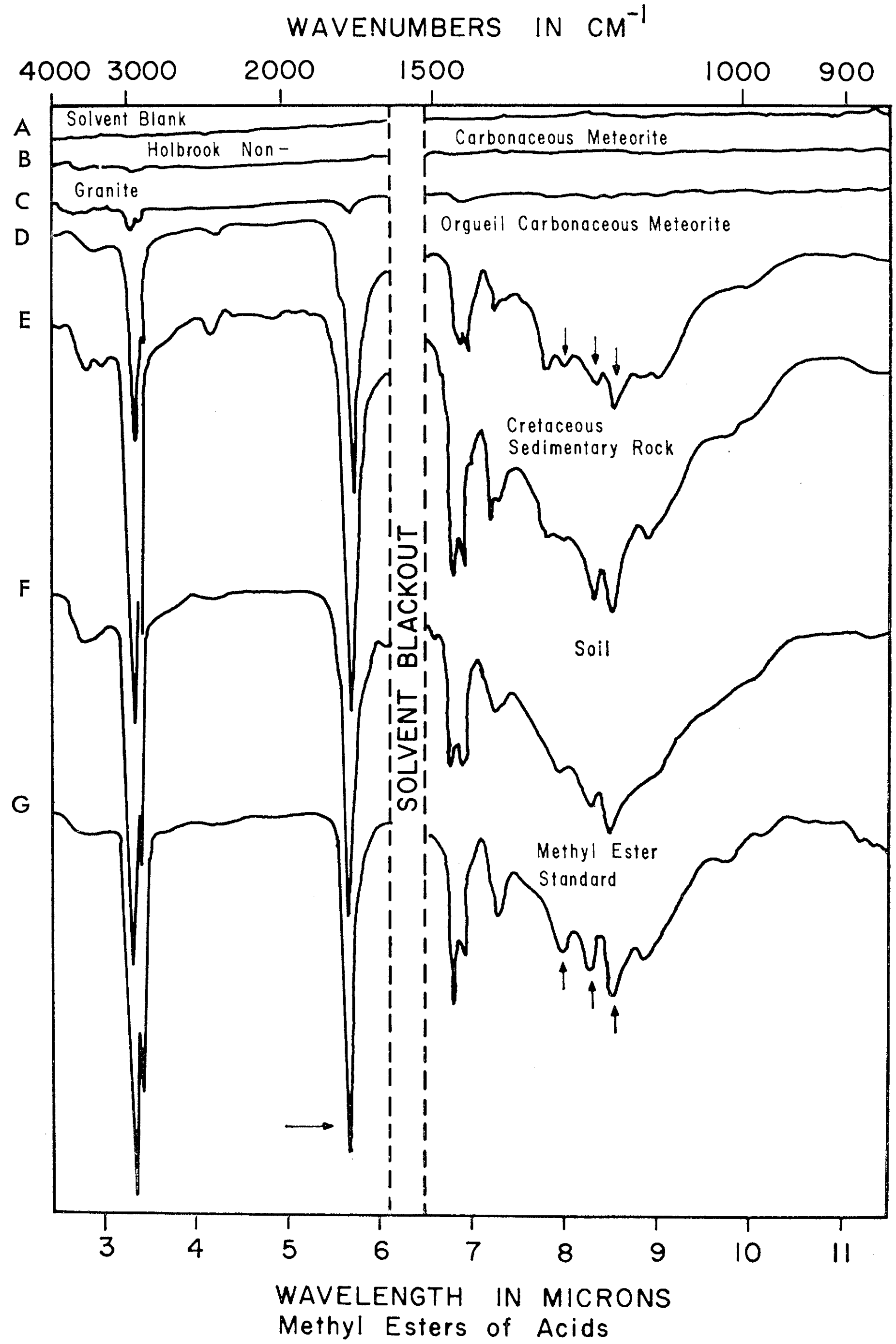


Fig. 7. Infrared spectra of the esterified carboxylic acid fractions from: *A*, solvent blank-run; *B*, Holbrook, noncarbonaceous meteorite; *C*, granite; *D*, Orgueil, carbonaceous meteorite: *E*, Cretaceous sedimentary rock (Navesink Formation); *F*, Recent soil; and *G*, methyl ester of docosanoic acid, C_{22}, from Nutritional Biochemicals. Note the ester bands at 5.7, 8.0, 8.3, and 8.5 microns on curves *D, E, F,* and *G*. [Reprinted from (*23*)]

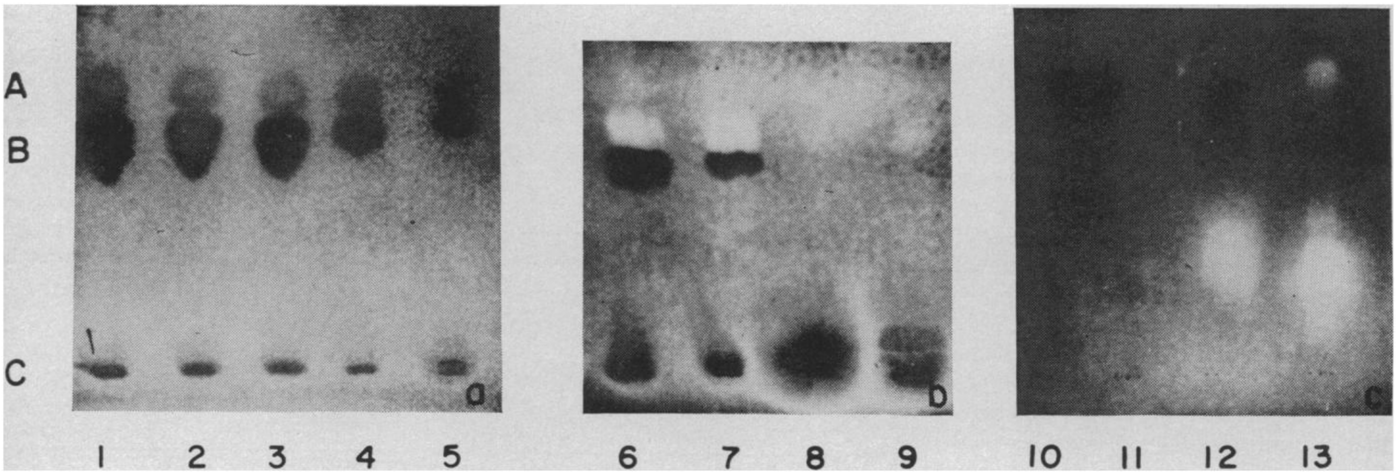
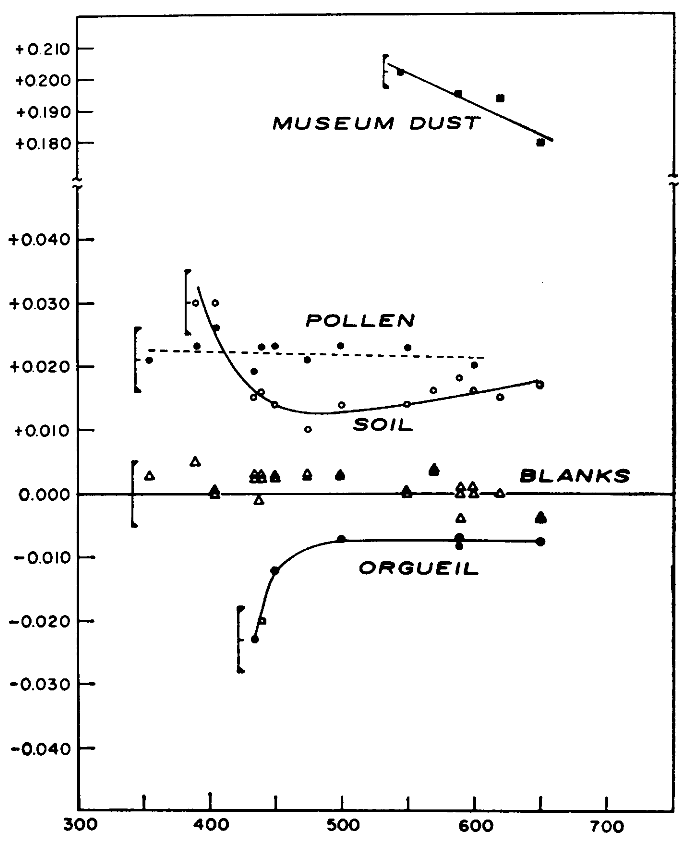


Fig. 8. Thin-layer chromatograms of the Orgueil extract, the infrared spectra of which were shown in Fig. 7. The vertical columns (that is, applications) 1 to 7, 10, and 11 are from the same Orgueil extract, 8 and 12 are identically prepared extracts from petroleum naphthenic acids, and 9 and 13 from an alga. Component *A* in Orgueil is saturated hydrocarbons, *B* is elementary sulfur, and *C* is the acidic compounds. [Reprinted from (*25*)]

generally believed to be degradation products of the phytol side chain of chlorophyll, though the phytol as well as pristane and phytane are found in other biological sources. Pristane is a hydrocarbon having 15 carbon atoms in a straight chain with methyl groups on the 2nd, 6th, 10th, and 14th carbon atoms, and phytane has one additional carbon atom in the chain and the same methyl side groups. The general patterns of hydrocarbons in meteorites resemble those present in ancient sediments, for example, the Gunflint chert and Soudan shale. The prominence both of straight-chain hydrocarbons and of pristane and phytane shows that the hydrocarbons of



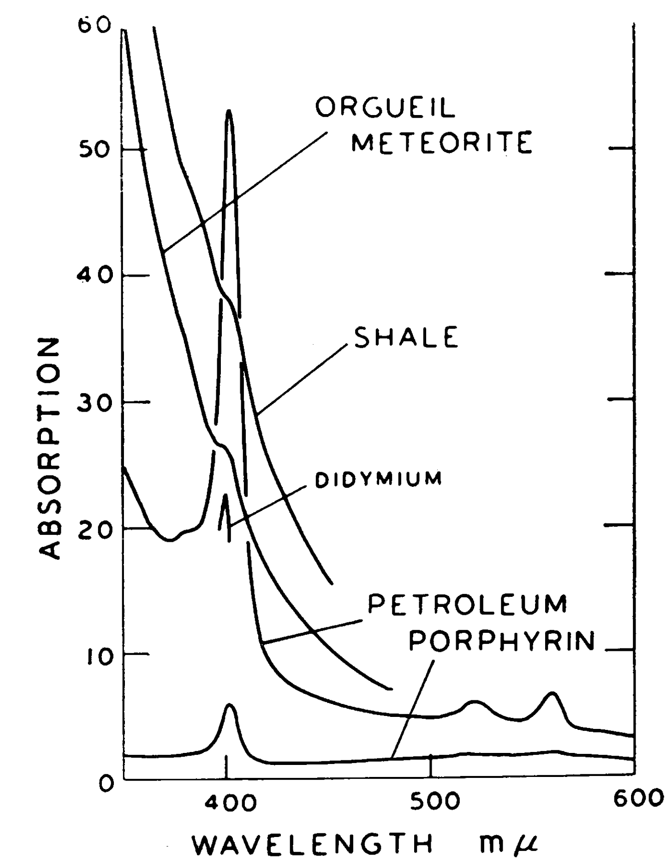


Fig. 9 (left). Optical activity of the Orgueil extract shown in Fig. 8. Two other Orgueil extracts (shown in Figs. 6 and 7), prepared identically but from two other stones, are also included. Range of instrumental error is shown by vertical lines; α is the observed rotations. The specific rotation of Orgueil is approximately $-1°$. Fig. 10 (right). Spectra of a chromatographic fraction of the Orgueil meteorite, showing absorption bands characteristic of vanadyl porphyrins. Note that the Orgueil band intensity is approximately the same as that of the Posidonia shale from Germany, which is a classical source of ancient porphyrins. Didymium is a wavelength calibration standard. [Reprinted from (*25*)] both carbonaceous and other chondrites are of biological origin. Internal evidence shows that the observed patterns of hydrocarbons are not due to laboratory contaminations, for the Ornans meteorite is evidently not similar to others, and in fact the patterns of the different meteorites differ from each other in small but definite details. Meinschein (*31*) and Frondel (*32*) have made similar experiments on the Holbrook meteorite and come to similar conclusions. They find that other museum rocks do contain similar hydrocarbons. Contamination, if that is what it is, is surprisingly more massive in the meteorites than in other rocky materials stored in museums, to judge from present information. Meinschein at present believes that these hydrocarbons in ordinary chondrites are very similar to common contaminants possibly from petroleum products. Oro believes he has evidence that these hydrocarbons are due to contaminations by bacteria and other products of biological origin after arrival on the earth.

Summary

If the materials discussed here were of terrestrial origin, it would be firmly suggested that the materials were of biological origin and indigenous to the samples. This by all odds would be the most simple and direct interpretation of the results. A contrary explanation would be that some organisms invaded these meteorites, which have fallen all over the earth during more than a century, and which have been stored on dry museum shelves, and that they grew vigorously for a short period and produced a record that in many ways duplicates what we find in very old terrestrial sediments, particularly in that they appear to lack important compounds such as those found in more recent soils and sediments of the earth—that is, chlorins—but contain compounds present in very old sediments—that is, porphyrins, fatty acids, hydrocarbons, and so on.

Many lines of evidence, as briefly reviewed above, strongly suggest that biogenic material exists in these meteorites and that it may be indigenous. Since we know that life has evolved on earth, the primary question, and by all odds the most important question, is decided for all samples of terrestrial origin. Certainly sufficient evidence has been found to justify further work on the subject of biological material in meteorites, and I am sure that such work will be carried out.

Origin of Meteorites with Fossils

Nagy, Meinschein, and Hennessy's paper in 1961 (*16*) aroused great opposition because of the chemical composition of the meteorites. Those of us who had been working on meteorites for some years were certain that there could not be the residue of living things in them. Had the meteorites had the composition of sedimentary rocks on the earth, no great surprise would have been expressed. It would have been assumed that they came from some planet, probably in the asteroidal belt, which had been broken up some time in the past. The fact that the chemical composition of carbonaceous chondrites with respect to the nonvolatile fraction of primary matter, namely, the silicates and related compounds, is approximately that of the sun made it exceedingly difficult to understand how biological material could have originated in these objects.

We are asking whether the carbonaceous chondrites contain biological material closely related to terrestrial life; if so, such terrestrial life is of a type which, as we know it, exists only in water. Also, the evolution of the complicated and intricate processes of living things requires a source of free energy. Hence the surface of a planet which is large enough and has the proper temperature to retain liquid water, and which receives solar radiation, provides the only possible conditions for the evolution of life. If such a planet was partially covered with water, then oceans, rivers, and all the erosional processes found on the earth would be present. Sedimentary rocks should have been formed, and such sedimentary material should be arriving at the earth as meteorites. This is definitely not the case. No meteorite has ever been shown to be sedimentary. It should be noted that the falls of all the carbonaceous chondrites have been observed. If these fragile objects can be observed to fall and be recovered, then any sedimentary meteorites could also have been observed.

The other possibility is that the planet was completely covered with water. In this case we would expect

Table 3. Measurements of optical activity in Orgueil extracts prepared by the method of Hayatsu. Activity was measured at 546 mμ. Measurements in column 2 were made by the California Research Corporation on samples prepared at the University of California at San Diego and results were corrected for complete process blanks; error, $\pm$ 0.005°.

Sample	Hayatsu's result	San Diego result
Saponifiable (A_3)	−0.001°	−0.025°
Nonsaponifiable (A_2)	−0.001°	+0.014°

Main spectral absorption features in the Orgueil extracts

387–388 mμ — not porphyrin
410–412 mμ — probably porphyrin
430–445 mμ — not porphyrin

Examination of 410–412 mμ pigment

Extractability from carbonaceous rock	— similar to porphyrins in terrestrial sediments
Chromatography on silica gel	— similar to porphyrins in terrestrial sediments
Spectral shift of Soret band with solvent	— similar to porphyrins in terrestrial sediments
Chemical reactions	
HBr—HOAc decompositions (limited test)	— similar to porphyrins in terrestrial sediments
KOH and sulfur decomposition	— similar to porphyrins in terrestrial sediments

Origin of 410–412 mμ pigment

Contamination by dusts, soils and recent sediments	— unlikely, because of virtual absence of chlorins
Indigenous	— likely

Probable identity and concentration of 410–412 mμ pigment

Esterified vanadyl porphyrin	— 0.01 ppm

Fig. 11. Evidence for the presence of porphyrins in the Orgueil meteorite. [Reprinted from (*25*)]

no sedimentary rocks, but also the biological remains would be deposited only in thin layers at the bottoms of the oceans. The probability of securing a sample of this material would be very small, whereas, as noted above, the carbonaceous chondrites make up approximately 3 percent of the total observed falls. Hence this assumption is improbable or impossible.

There is left only the possibility that life evolved on one planetary object and was transferred to another planetary object of primitive composition. Of course the example of this in the solar system that immediately comes to mind is the earth, where we know life has evolved, and the nearby moon, which may have a composition consistent with that of the carbonaceous chondrites. It is an old suggestion that the meteorites have been coming from the moon, but the recent evidence, though not conclusive, is suggestive at least.

If the moon escaped from the earth it is not at all impossible that it could have been temporarily contaminated with terrestrial water. If the moon was captured by the earth, the process may have been very complicated and violent; such a capture hypothesis almost surely implies that many moon-like objects were about and that they and fragments of them were accumulated into the earth, a hypothesis that I put forward some time ago. If indeed the surface of the moon carries a residue of the ancient oceans of the earth at about the time that life was evolving, the Apollo Program should bring back fascinating samples which will teach us much in regard to the early history of the solar system, and in particular with regard to the origin of life. The possibility that water has been present on the moon has been pointed out recently by a number of students of the subject (*33*).

Some people are exceedingly skeptical with regard to the interpretation of life in meteorites, and probably the great importance of the subject justifies skepticism. On the other hand, one of the most fascinating results of all the planned exploration of the solar system would be the proof that life may exist somewhere else than on earth. It seems that we should be willing to consider the evidence for a residue of life in meteorites objectively, and that we should not draw final negative conclusions before all the evidence has been secured. It is not surprising that many investigators, including myself, are reluctant to accept these conclusions, for very considerable modifications of conventional hypotheses regarding the origin of meteorites and the composition of the lunar surface are involved. However, if the residue of indigenous biological activity in meteorites is indeed real, and if the meteorites do not come from the moon, other more complicated and possibly more interesting histories for these objects must be devised. In the meantime, until definite conclusions can be drawn, evidence should not be suppressed, and in fact people who obviously hope that life has existed in these objects should be encouraged to secure definite, positive evidence if they are able to do so.

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