were calculated. Their standard deviation is ± 50 percent. However, the mean percentage deviation between the two methods is only -2 percent for the 18 meteorites studied, showing that no significant positive or negative bias is introduced by the approximations to the precise theory.

Method 2. The basis for the second approximate method lies in calculating the effect of variation in cooling rate on the diffusion gradients near the kamacite-taenite border. Theoretically, the compositions at the interface of kamacite and taenite represent the equilibrium compositions at the lowest temperature at which equilibrium was maintained. However, the true interface compositions cannot be measured with the electron microprobe because of the finite size of the x-ray excitation volume. Across a typical area of x-ray excitation 2 μ in diameter (at 20 kev) the diffusion gradient might extend from 30 to 50 percent Ni, and only an average composition could be measured. A similar situation, but with a shallower gradient, prevails in kamacite.

Nevertheless, the maximum nickel content measured in taenite ($C_{\gamma\text{-max}}$), the minimum nickel content measured in kamacite ($C_{\alpha\text{-min}}$), and the cooling rate are correlated (Table 1). Meteorites with known cooling rates (*1*) were found to have proportionally higher average values of $C_{\gamma\text{-max}}$ and lower average values of $C_{\alpha\text{-min}}$ for decreasing cooling rates. We measured $C_{\gamma\text{-max}}$ and $C_{\alpha\text{-min}}$ on sections cut perpendicular to the kamacite plates. $C_{\gamma\text{-max}}$, which can be measured with ± 4 percent relative accuracy, is more sensitive to changes in cooling rate than $C_{\alpha\text{-min}}$. An ARL electron microprobe with an approximate x-ray excitation diameter of 2 μ at 20 kev was used. Under these operating conditions a least squares fit of $C_{\gamma\text{-max}}$ and cooling rate conforms to the equation

$$\log_{10} \text{(cooling rate)} = 4.77 - 0.104\ C_{\gamma\text{-max}}$$

This relation varies with different excitation conditions. Therefore, in order to use this method for determining cooling rates, for the electron probe used it is advisable to calibrate $C_{\gamma\text{-max}}$ with meteorites of known cooling rate (for example, those in Table 1). The kamacite plates chosen should intersect the top surface at or near 90° in order to avoid errors in $C_{\gamma\text{-max}}$ and $C_{\alpha\text{-min}}$ from subsurface effects.

Method 1 is recommended for meteorites showing good Widmanstätten structure. It has better precision for medium and fine octahedrites and ataxites than for coarse octahedrites and cannot be used for hexahedrites. When the cooling rates are fast and the gradients steep and hard to measure, method 1 is probably more accurate than the precise method. Method 2 supplements method 1 in such cases as pallasites which have kamacite plates in which kamacite grew by planar-front diffusion. It becomes imprecise when the cooling rate is greater than $50°C/10^6$ years, owing to the steepness of the gradient, or when impingement raises the central taenite nickel content over 20 percent by weight, thus flattening the gradient near the α/γ interface. With these restrictions both approximate methods can much more rapidly and easily give cooling rates within ± 50 percent of those obtained by the precise method.

JAMES M. SHORT*
Space Sciences Division,
Ames Research Center,
Moffett Field, California 94035
JOSEPH I. GOLDSTEIN
Geochemistry Laboratory,
Goddard Space Flight Center,
Greenbelt, Maryland 20771

References and Notes

1. J. I. Goldstein and J. M. Short, *Geochim. Cosmochim. Acta*, in press.
2. J. I. Goldstein and R. E. Ogilvie, *ibid.* **29**, 893 (1965); J. A. Wood, *Icarus* **3**, 429 (1964).
3. J. M. Short and C. A. Andersen, *J. Geophys. Res.* **70**, 3745 (1965); J. I. Goldstein, *ibid.*, p. 6223; S. J. B. Reed, *Geochim. Cosmochim. Acta* **29**, 535 (1965).
4. J. I. Goldstein and R. E. Ogilvie, *Trans. AIME* **233**, 2083 (1965).
5. C. M. Nevin, *Principles of Structural Geology* (Wiley, New York, 1949), p. 346.
6. Klaus Keil graciously provided electron microprobe facilities for part of the experimental work. One of us (J.M.S.) was supported by a National Academy of Sciences Resident Research Associateship at the Ames Research Center.
* Present address: U.S. Geological Survey, Menlo Park, California 94025.

24 February 1967

Amphibole: First Occurrence in a Meteorite

Abstract. *This is the first report of an amphibole mineral found in any meteorite. The amphibole richterite (soda tremolite),* $Na_2Ca(Mg,Fe)_5Si_8O_{22}(OH,F)_2$, *occurs as a primary (preterrestrial) mineral enclosed within graphite nodules in the iron meteorite from Wichita County, Texas.*

No member of the amphibole group of silicates, which is quite prominent in terrestrial rocks, has, until now, been found in any meteorite. I now report the finding of the amphibole, richterite (soda tremolite) in the iron meteorite from Wichita County, Texas. The x-ray powder-diffraction pattern is compared with that of a richterite from Langban, Sweden, in Table 1.

The mineral was analyzed by electron microprobe (*1*) and the results are given in Table 2. The microprobe could not, of course, provide a direct analysis of hydroxyl, nor is a direct analysis by chemical methods possible on the microgram quantities present. Similarly the small quantities also preclude determination by infrared absorption methods. Since terrestrial richterites are known to have as much as 62 percent (atom) of the hydroxyl position substituted by fluoride (*2*), a direct analysis of F was made. In addition, the mineral was analyzed for Cl, Br, and I but none were found (that is, less than 0.1 percent by weight). The analysis was then normalized to eight Si atoms. The fluoride thus calculated was 0.996 atoms (rounded to 1.00) and the remainder of the hydroxyl position was filled with OH (that is, OH = 1.00), which was then calculated to H_2O and added to the probe analysis (Table 2). During the microprobe work it was observed that there was a modest variation in Cr from grain to grain (by a factor of 1.5 from lowest to highest value) and a larger variation in Ti (by a factor of almost 1.9). The values reported in this analysis are based on the average of the counts observed. These are not major elements; however, it is suspected that their variability is causing the small variation in optical properties. Optical parameters are: biaxial, negative; weak dichroism (X, pale blue-green; Z, brown); 2V = 40 to 60°; $\alpha = 1.598$ to 1.607; $\beta = 1.616$ to 1.625; and $\gamma = 1.621$ to 1.628 (values $\pm$ 0.002).

The richterite was collected by excavating into nodules of graphite. The grains are small (the largest is 0.6 by 0.2 mm), are found near the centers of the nodules, and are completely enclosed by graphite. They occur immediately adjacent to clear, colorless olivine grains (forsterite 99). In addition the nodules contain albite (Ab 99), roedderite (*3*), and whitlockite, along with an unidentified phosphate and an unidentified silicate. In addition to the graphite nodules, separate troilite nodules occur which contain isolated specks of sphalerite, diopside, and orthorhombic enstatite.

The presence of a hydroxyl-bearing amphibole in an iron meteorite at first appeared anomalous. Terrestrial richterite, however, is a well-known skarn mineral (*2*) indicative of formation at a high temperature (300° to 800°C) and low total pressure (100 to 3000 bars) (*4*). As such it is precluded as a weathering product of, for example, a pyroxene. Furthermore, in this particular case, half the hydroxyl position is filled with fluoride, a situation which precludes a weathering phenomenon. In addition, the amphibole grains are optically clear and almost colorless, and in transmitted light they are bright and clear with good cleavages and sharp extinctions and interference figures. The x-ray pattern is extremely sharp, which indicates good crystallization. Finally, adjacent olivine, albite, and roedderite grains are completely fresh. Both optical examination and x-ray patterns of olivine show no signs of weathering or other types of alteration products. The excavations were performed on a cut surface in the interior of the iron, and all specimens came from within the graphite. Thus, although the meteorite from Wichita County is a find (*5*), the amphibole is definitely preterrestrial. Preterrestrial hydroxylated and hydrated phases are, of course, well known from the carbonaceous chondrites.

Table 1. X-ray powder-diffraction data for richterite from the Wichita County iron meteorite compared with richterite from skarn rock, Langban, Sweden. *I*, intensity; *d*, spacing.

Meteorite richterite		Langban richterite	
I/I_0 (visual)	d (Å)	d (Å)	I/I_0 (visual)
70	8.605	8.572	80
70	8.393	8.330	80
30	4.864	4.842	40
50	4.493	4.470	50
70	4.160	4.150	30
30	4.004	3.994	30
50	3.850	3.857	50
100	3.376	3.373	90
80	3.267	3.271	80
100	3.125	3.140	100
80	2.944	2.948	90
40	2.800	2.814	40
100	2.709	2.694	100
70	2.581	2.584	70
90	2.522	2.524	90
20	2.382	2.392	20
50	2.320	2.332	50
50	2.286	2.281	40
40	2.258		
20	2.203	2.201	10
70	2.160	2.161	60
40	2.048	2.051	40
10	2.020	2.020	30
10	1.952	1.962	10
20	1.893	1.906	20
10	1.857	1.860	20
10	1.794	1.798	10
30	1.676	1.679	20
60	1.650*	1.656	40

* Plus 27 additional spacings to 0.7882 Å.

Table 2. Electron microprobe analysis of richterite from the Wichita County meteorite. The calculated empirical formula is:

$$(Na_{2.02}K_{.10}Ca_{.85})_{2.97}$$
$$(Mg_{4.63}Fe_{.05}Al_{.07}Ti_{.16}Cr_{.08})_{4.99}$$
$$Si_8O_{22}(F_{1.00}OH_{1.00})_{2.00}.$$

Subscripts outside parentheses give totals of subscripts within parentheses.
The ideal empirical formula is:

$$(Na, K, Ca)_3\ (Mg, Fe, Al, Ti, Cr, Mn)_5\ Si_8O_{22}(F, OH)_2.$$

Compound	Percent by weight
SiO_2	57.8
TiO_2	1.5
Al_2O_3	0.4
Cr_2O_3	.7
FeO	.5
MgO	22.4
CaO	5.8
Na_2O	7.5
K_2O	0.6
H_2O	1.1
F	2.3
	100.6
F = 0	1.0
Total	99.6

Regarding the water content, it is possible to make some semi-quantitative estimates of the conditions implied at some time in the past thermal history of this meteorite. We may, for example, write a reaction for the hydroxyl-tremolite component of the amphibole,

$$Ca_2Mg_5Si_8O_{22}(OH)_2 + Mg_2SiO_4 = 2\,CaMgSi_2O_6 + 5\,MgSiO_3 + H_2O$$

From this we may calculate the water pressure at each temperature (*6*). Since no pyroxenes are present in the graphite nodules with the amphibole, these pressures represent the minimal ones required to stabilize it. Over the range of temperatures 300° to 800°C, these calculated pressures range from only 10^{-2} atm to a little less than 100 atm. However, since the amphibole is not pure hydroxyl-tremolite, but contains Na and F, the activity terms of these act to reduce these water pressure requirements. Thus, qualitatively, we can say that over this temperature range $P(H_2O) \ll 1$ atm. Since the magnetite-iron boundary only requires that $P(H_2O)/P(H_2)$ be $\lesssim 1$ in this temperature range (*7*), no unusual H_2 pressures are required. Thus, the amphibole can stably form with metallic iron without serious contradictions arising. Also, at least a dozen other iron meteorites show degrees of oxidation only a few orders of magnitude of $P(O_2)$ within the metallic iron field (*8*), commensurate with the most oxidized L and LL group chondritic meteorites.

EDWARD OLSEN

Department of Geology,
Field Museum of Natural History,
Chicago, Illinois 60605

References and Notes

1. ARL microprobe unit in Department of Geophysical Science, University of Chicago. All corrections applied as given in J. V. Smith, *J. Geol.* **73**, 830 (1965).
2. W. A. Deer, R. Howie, J. Zussman, *Rock-Forming Minerals* (Longmans, Green, London, 1963), vol. 2, pp. 352–58.
3. L. H. Fuchs, C. Frondel, C. Klein, *Amer. Mineral.* **51**, 949 (1966).
4. F. Turner and J. Verhoogen, *Igneous and Metamorphic Petrology* (McGraw-Hill, New York, ed. 2, 1960), p. 509.
5. M. H. Hey, *Catalogue of Meteorites* [British Museum (Natural History), London, ed. 3, 1966].
6. Thermochemical data obtained from: R. Robie, thesis, Univ. of Chicago, 1957; ———, *U.S. Geol. Surv. Rep. TEI-816* (1962); W. Weeks, *J. Geol.* **64**, 456 (1956); K. Kelley, *U.S. Bur. Mines Bull.* **584** (1960).
7. E. Olsen, *Amer. J. Sci.* **261**, 943 (1963).
8. ——— and K. Fredriksson, *Geochim. Cosmochim. Acta* **30**, 459 (1966); E. Olsen and L. Fuchs, *Icarus*, in press.
9. I thank Drs. P. B. Moore, N. Stalica, and R. F. Mueller, and I. S. McCallum and L. H. Fuchs for specialized assistance. Supported by NSF grant GA-307.

16 January 1967

Middle and Late Eocene Mammal Communities: A Major Discrepancy

Abstract. *The multituberculate* Parectypodus lovei *has been found in late Eocene rocks in Montana, together with 11 other mammal species similar to those found in the late Eocene Tepee Trail Formation in Wyoming. The multituberculate and six other species are unknown in rocks of equivalent age or of middle Eocene age elsewhere. It is suggested that the known middle Eocene faunas are all taken from a similar ecological situation and do not reflect the true diversity of middle Eocene life. Middle Eocene faunas of different ecological aspect may be recovered from sediments along, and in, the mountain fronts of northwestern Wyoming.*

The unexpected discovery in central Wyoming (*1*) in a fauna of late Eocene age of several groups of archaic mammals, previously thought to have become extinct in earliest Eocene time, stimulated efforts to recover a comparable faunal assemblage from rocks of late Eocene age in other areas. During the summer of 1966 such a fauna was recovered from the Climbing Arrow Formation (*2*) near Three Forks, Montana.

Previous work in this area (*2, 3*) had indicated that some part of the Climbing Arrow Formation was of late Eocene age, but no attempt had been made to collect a representative fauna. With the use of washing techniques (*4*), 12 species of mammals have now been collected. Although the Montana