The 12 notches to the west of this line symbolize the crescent moon (13 days, including the new moon). The unnotched southern side may represent the 3 days of the full moon: days 14 through 16. The 11 notches on the east side may represent the days of the waning moon: days 17 through 27. Finally, the eastern of the pair of lines may symbolize the vanished moon on the 28th day (or 29th day, if we allocate 4 days to the unnotched southern edge; the 28.5 days of the lunar cycle may have led primitive man to reckon either 28 or 29 days).

This interpretation does not prevent me from maintaining that the object is a uterus symbol, but the moon and uterus significances may be associated: the symbolisms of moon-uterus–*magna mater* are commonly associated in primitive cultic systems. I do know that cultic illustrations by primitive people can be even more complicated than this interpretation suggests; that such people conveyed their ideas in even more figurative ways. Compared with churingas or shaman's drums, carrying mythical tales, the message of the "lunar calendar" of Bodrogkeresztur is simple.

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16 June 1965

A Chondrule in the Chainpur Meteorite

Abstract. *The occurrence of glass as a major constituent in a chondrule from the Chainpur meteorite provides evidence that the chondrules formed by rapid cooling of liquid droplets. The virtual absence of nickel in the silicates suggests that it segregated into the metal phase in the molten stage, prior to crystallization of the silicates.*

The origin of chondrules has long been one of the most intriguing problems in the study of meteorites. Many diverse hypotheses had been advanced to explain these strange spherical objects before the examination of thin sections under the microscope placed severe limitations on possible modes of formation. Early investigators of chondrites recognized their similarity to volcanic rocks and concluded that their internal structure indicated that the chondrules had been quenched from high temperatures. This point of view was very clearly stated by Sorby (*1*), in 1877, when he summarized his conclusions by stating that "the conditions under which meteorites were formed must have been such that the temperature was high enough to fuse stony masses into glass; the particles could exist independently one of the other in an incandescent atmosphere, subject to violent mechanical disturbances; that the force of gravitation was great enough to collect these fine particles together into solid masses, and that these were in such a situation that they could be metamorphosed, further broken up into fragments, and again collected together." At a time when sophisticated techniques have allowed the study of many of the more esoteric properties of meteorites, it is perhaps instructive to review Sorby's conclusions, the validity of which remains unchanged.

Alternatives to the "liquid droplet" hypothesis have been proposed by several authors. The formation of chondrules by metamorphic recrystallization of solid matter has been advocated by Levin (*2*) and by Mason (*3*). The chondrule which is described here displays several features which cannot be explained by metamorphic recrystallization. Rather, it provides unusually clear evidence of having formed by quenching of a wholly or mostly liquid droplet.

The Chainpur meteorite fell as a shower of stones on 9 May 1907, beside the village of Chainpur, India (21°51′N, 83°29′E). The meteorite was described by Cotter (*4*) and, in greater detail, by Keil *et al.* (*5*), who demonstrated the unusual variability in composition of olivine and pyroxene in the chondrules. Keil *et al.* (*5*) concluded that individual silicate grains within single chondrules are not in equilibrium, as a consequence either of rapid crystallization or of crystallization at temperatures too low to allow diffusion to eliminate the compositional variations.

Thin sections of Chainpur meteorite show sharply delineated chondrules of widely varying internal structure, mostly 1 to 2 mm in diameter. Figure 1 (top) is a photomicrograph of the chondrule which has been studied in some detail. It is circular in section, except where metal and sulfide grains straddle the chondrule-matrix border. A protrusion of matrix into the chondrule can be seen in the lower right-hand corner of Fig. 1 (bottom). This indentation was apparently produced before the chondrule had completely solidified, since the olivine crystallites in the chondrule are aligned parallel to the indented margin. Either the matrix intruded the still-plastic chondrule, or the indentation formed by shrinkage on cooling.

Within the chondrule, crystals of olivine and pyroxene are set in a clear, colorless glass. The major crystalline

Table 1. Electron microprobe analysis of glass in Chainpur chondrule. Results are percentages by weight.

Compound	Analysis of the glass*	Glass analysis, recalculated to 100 percent, for $Na_2O = 8$ percent
SiO_2	67.3	64.0
Al_2O_3	16.5	15.7
MgO	5.6	5.4
FeO	2.9	2.7
CaO	1.8	1.7
K_2O	1.0	0.9
TiO_2	0.8	0.8
CoO	0.3	0.3
Cr_2O_3	0.5	0.5
MnO	0.2	0.2
Na_2O		8.0
Total	96.9	100.2

* Apparently, glass resembling some tektites can be derived from chondritic material by reduction and segregation of metal followed by crystalization differentiation and vacuum evaporation of sodium.

Table 2. Electron microprobe analysis of some mineral phases in Chainpur. Results are percentages by weight.

Mg	Fe	Ca	Mn	Ni
Olivine in chondrule				
33.4*	1.2*	0.1		
Olivine in adjacent matrix				
26.9	13.5	0.1		
23.4	18.9	0.1		
Chainpur olivines of different iron : magnesium ratios				
33.3	1.2		0.1	<0.01
29.6	8.3		0.6	<0.01
26.9	13.5			<0.01
25.7	14.1			<0.01
22.8	18.3			<0.01
Metal globule in chondrule†				
	46			53

* These are average values. The ranges were: Mg, 33.6 to 33.0; Fe, 0.8 to 1.6. The variation in magnesium and iron values is a consequence of weak normal zoning in the olivine. † Cobalt ~ 0.5.

phase is a forsteritic olivine which forms elongate crystals, some in parallel growth patterns, with well-developed crystal faces. No evidence could be seen of any reaction between the olivine and the glass. In the plane of the thin section, some olivine crystals completely enclose small areas of glass. Olivine is more abundant at the outer margins of the chondrule, which the elongate crystals tend to parallel. Pyroxene is prominent in the core of the chondrule where it forms elongate, parallel, feathery crystallites (see cover). Some of the crystallites are made up of numerous small, distinctively shaped crystalline units with a common orientation but separated by areas of clear glass. The glass itself is colorless, isotropic, and homogeneous. Metal and troilite (FeS) occur as thin seams within some of the larger olivines (Fig. 2) and as globules in the glass (Fig. 4).

Phase compositions determined with an ARL electron probe microanalyzer (*6*) are shown in Tables 1 and 2. The distribution of selected elements among the major phases are shown in Figs. 2, 3, and 4. In analysis of the pyroxene, it was found that its skeletal habit made it impossible to avoid overlapping the microprobe beam into the adjacent glass. For this reason, only minimum values of calcium and magnesium could be obtained. Figure 2 shows that the pyroxene contains less iron than the olivine or the glass. The variation in calcium and magnesium content across the pyroxene crystallites is illustrated in Fig. 5, where the peak values attained correspond to 6 percent by weight for calcium and 10 percent by weight for magnesium. These values correspond to a very low iron pigeonite with a calcium content higher than most of the pyroxene in Chainpur (*5*). Boyd and Schairer (*7*) have shown that, at atmospheric pressures, homogeneous pyroxenes with compositions midway between enstatite and diopside can be formed by quenching, but that they are metastable even at elevated temperatures and unmix to yield two pyroxenes of contrasting magnesium to calcium ratios on prolonged heating or on slow cooling. The unusual composition of the pyroxene crystallites can be explained only by rapid cooling from high temperatures, an interpretation fully in accord with the skeletal habit of the crystallites.

Rapid cooling has also allowed the preservation of forsteritic olivine in intimate contact with a silica-rich glass. Glass is a rare constituent of all but the youngest terrestrial rocks. Glass in meteorites is of particular interest, since most meteorites appear to have formed early in the history of the solar system. True glass is not common in meteorites, but the textures of many fine-grained aggregates in chondrules—in barred chondrules, for example—suggest that they have formed by the devitrification of glass. The glass in Chainpur has not devitrified because the meteorite has not been subjected to any significant thermal metamorphic effects and because of the composition of glass.

The first column in Table 1 represents the composition of the glass as analyzed with an ARL electron probe microanalyzer. Sodium is not included. Sodium in the glass presents a special problem since the sodium content of the small volume excited by the electron beam decreases to about 25 percent of its original value in 20 seconds. The first analysis in Table 1 is thus an analysis of the glass after it has lost most of the original sodium. The true soda content of the glass is approximately 8 percent. Escape of sodium from the glass, and the low counting rates make this figure less reliable than the other data presented. Sodium was determined by using low beam power per unit sample area, that is, low ac-

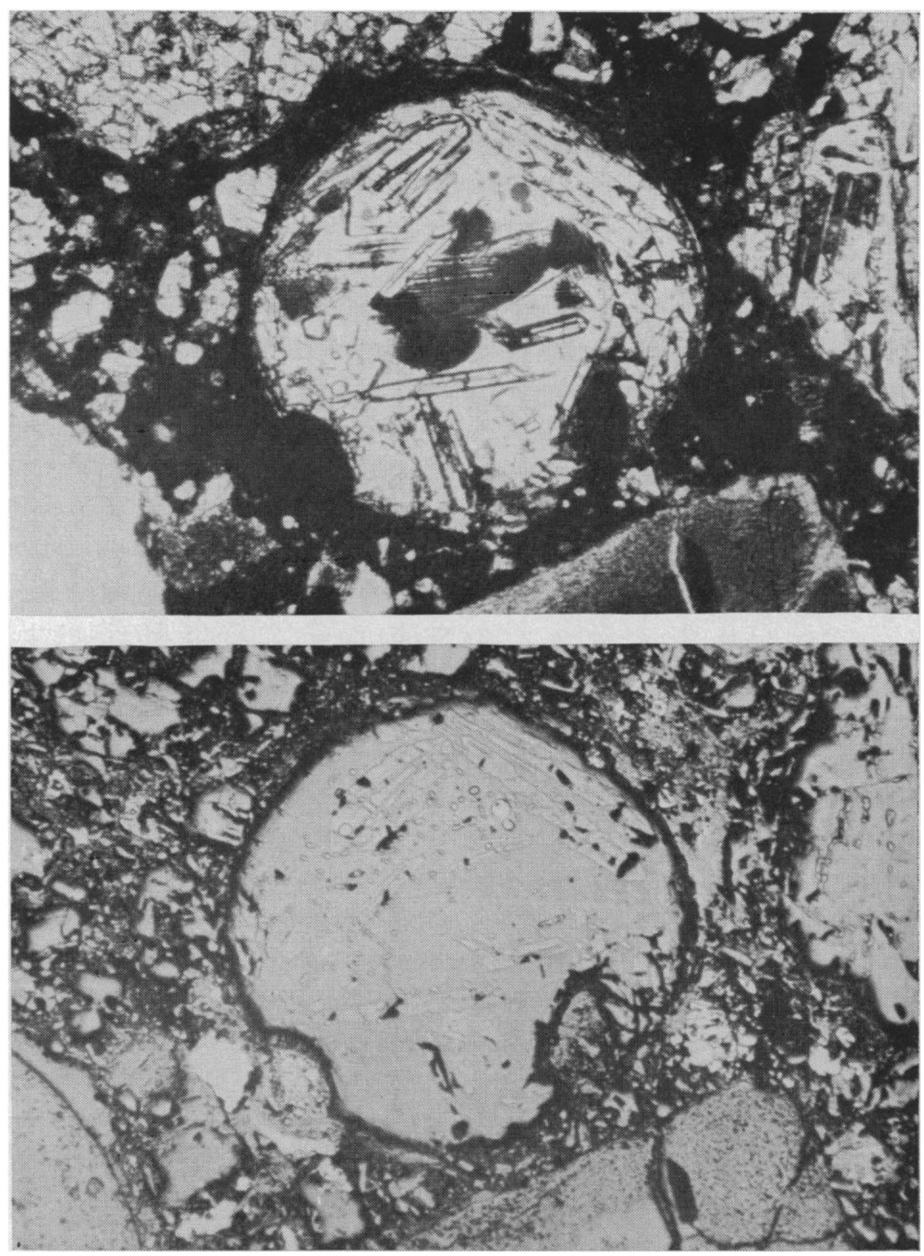

Fig. 1. Photomicrograph in (top) transmitted and (bottom) reflected light of a chondrule in the Chainpur chondrite. Euhedral olivine crystals occur in a colorless glass. Small pyroxene crystallites are abundant in the center of the chondrule. Diameter of chondrule is 0.75 mm.

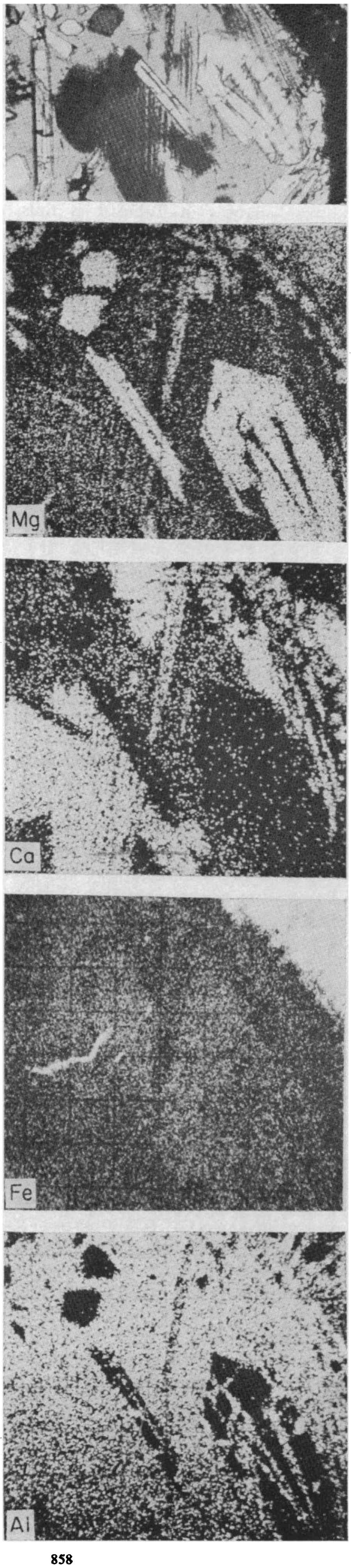

Fig. 2 (left). Photomicrograph of part of the chondrule and the adjacent matrix and pictures of the central part of the same area obtained with a scanning electron beam. The distribution of these elements in the scanned area is shown by Mg, Ca, Fe, and Al. Euhedral olivine crystals are high in Mg, and low in Ca, Fe, and Al. The pyroxene crystallites are low in Fe, lower than the olivine in Mg, and contain appreciable amounts of Ca. Note the constant composition of the glass even where enclosed by the olivine. Scanned area is 320 by 320 μ.

celerating voltage (10 and 15 kv), low sample current ($\sim$0.02 μa), and large spot size (5 to 10 μ). Sodium values were recorded continuously while analyses were performed, both as a series of discrete steps, and also by moving the sample at a constant rate so that undamaged glass was continually exposed to the electron beam. With these precautions, one and the same area could be analyzed several times with consistent results. The second column in Table 1 shows the glass composition, recalculated to 100 percent, for a value of Na_2O = 8 percent by weight.

The glass composition represents an arrested stage in the continuum of compositions embraced by the liquid portion of the chondrule as crystallization progressed. If this particular chondrule is not atypical in bulk composition, then the glass composition can indicate one direction in which differentiation of chondritic material can proceed if governed by crystal-liquid fractionation. Segregation of a liquid fraction with the composition of the Chainpur glass (Table 1) could probably be achieved only by a rapid, catastrophic process. Recalculation of the glass analysis in terms of normative minerals shows 68 percent albite, 19 percent pyroxene (3 percent diopside and 16 percent hypersthene), and 1 percent quartz; also, 4 percent anorthite, 6 percent orthoclase, and 1.5 percent ilmenite. The glass in this respect resembles the glass-like material in barred olivine chondrules in many ordinary chondrites, for example, Bjurböle.

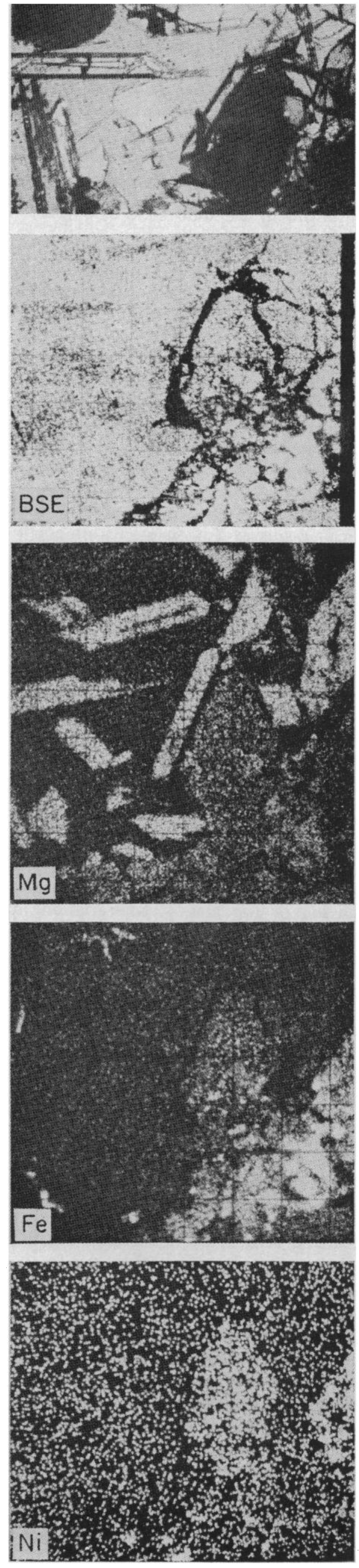

Fig. 3 (right). Photomicrograph and beam scanning pictures of an area where the matrix material protrudes into the chondrule. BSE is the back-scattered electron image and Mg, Fe, and Ni show the distribution of these elements in the scanned area. Olivine and pyroxene are much higher in Mg than the glass. Olivine, pyroxene, and glass are all much lower in nickel than the surrounding matrix. Scanned area is 320 by 320 μ.

The presence of glass in Chainpur, the association of forsterite with silica-rich glass, the composition of the pyroxene, and the skeletal habit of the crystallites all argue strongly that the chondrule formed from a "liquid droplet." Recrystallization by thermal metamorphism in the solid state cannot account for the occurrence of glass nor the lack of equilibrium in this high-temperature assemblage. This report discusses one chondrule from the Chainpur meteorite, but Chainpur contains a great diversity of chondrule types.

The few occurrences of glass studied to date are all in the more reduced chondrules; that is, those in which there is little iron in the silicates. The silicates in the glassy chondrule are low in iron and also in magnesium, some of which is present in the sulfides. The varying texture and phase compositions of the different chondrules may reflect slight variations in redox conditions, composition, cooling rate, and solidification temperature.

The manganese content of the olivine is related to the iron:magnesium ratio. As shown by Keil and Fredriksson (*8*), manganese appears in the sulfide phase under strongly reducing conditions. The distribution of nickel is quite different from that of manganese. Olivines of widely varying iron content in Chainpur all contain little or no nickel (Table 2). Apparently, nickel was effectively removed as immiscible liquid metal (Table 2 and Fig. 4) formed by reduction before crystallization of the silicates. Such a process appears necessary and sufficient to explain the formation of the high silica glass from chondritic material while keeping the overall magnesium:silica ratio practically constant. The final distribution of nickel and iron is undoubtedly influenced by this early segregation of some of the iron and virtually all of the nickel. Experimental studies presently in prog-

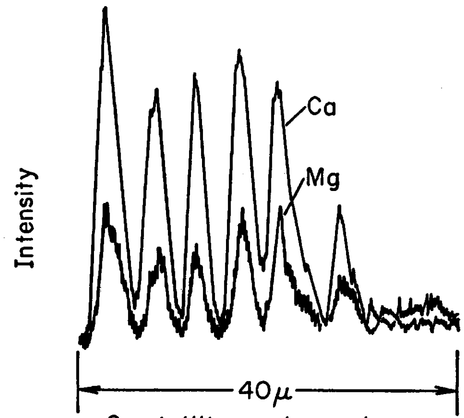

Fig. 5. Variation in Mg and Ca values in a traverse across a series of pyroxene crystallites (dark region in cover picture). Peak values correspond to 10 percent by weight of Mg and 6 percent Ca. The sharpness of the peaks indicates that the microprobe beam overlapped into the surrounding glass and that the peak values are only minimum values. Values in the troughs correspond to Mg and Ca in the glass, and there is apparently only a single crystalline phase present.

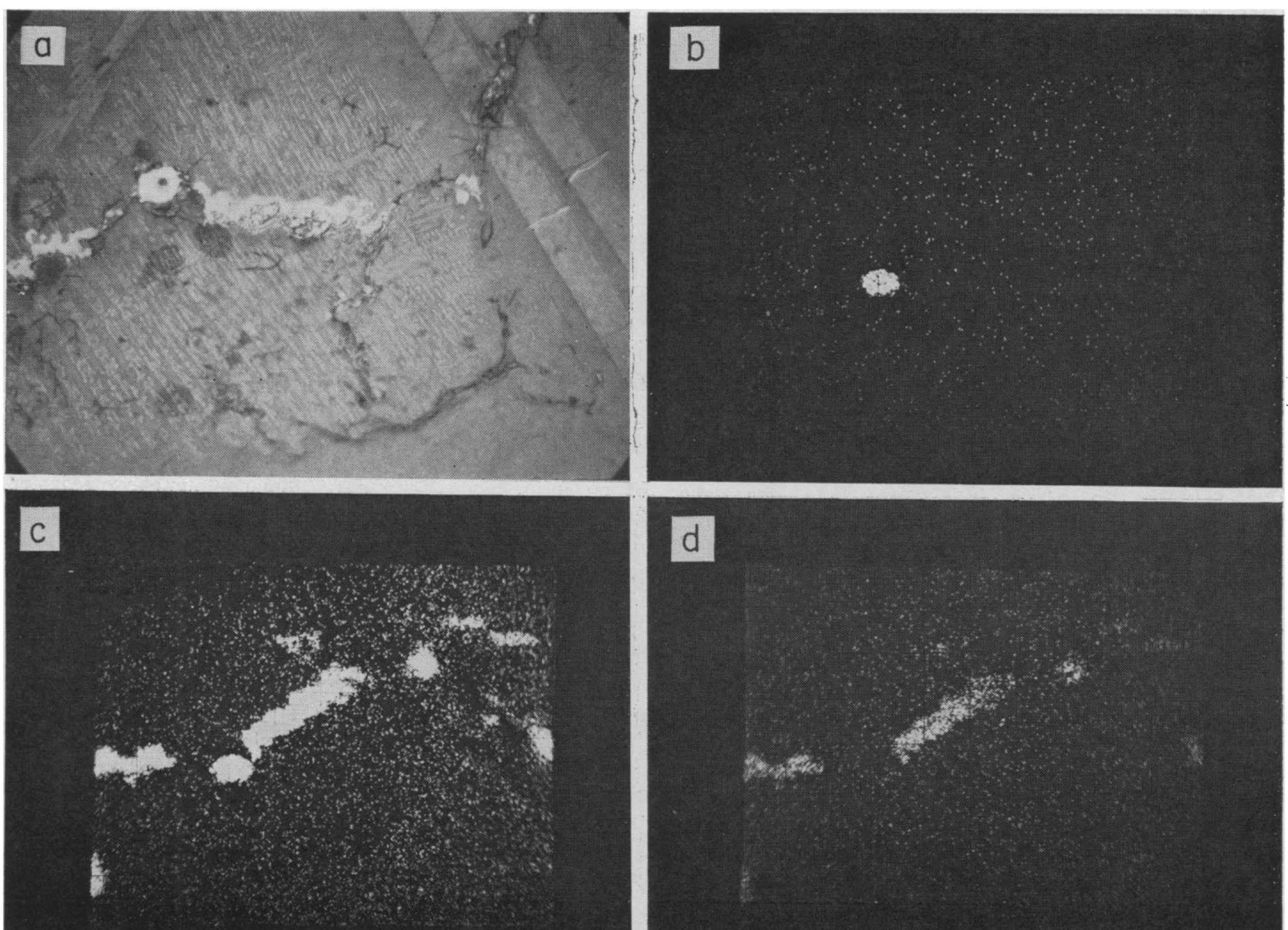

Fig. 4. Distribution of nickel-iron and troilite in chondrule. (*a*) Photomicrograph of an area corresponding to the opaque center of Fig. 1 (top). White, nickel-iron; light grey, troilite. Note the troilite seams in the olivine, left center. (*b*) Electron beam scanning picture of the nickel distribution, 53 percent Ni in the metal, 0.05 percent in troilite, and <0.01 percent in silicates. (*c*) Iron distribution, 46 percent in metal. (*d*) Sulfur distribution. Note that *b* and *d* are mirror images of the photomicrograph and cover a somewhat smaller area, 160 by 200 μ.

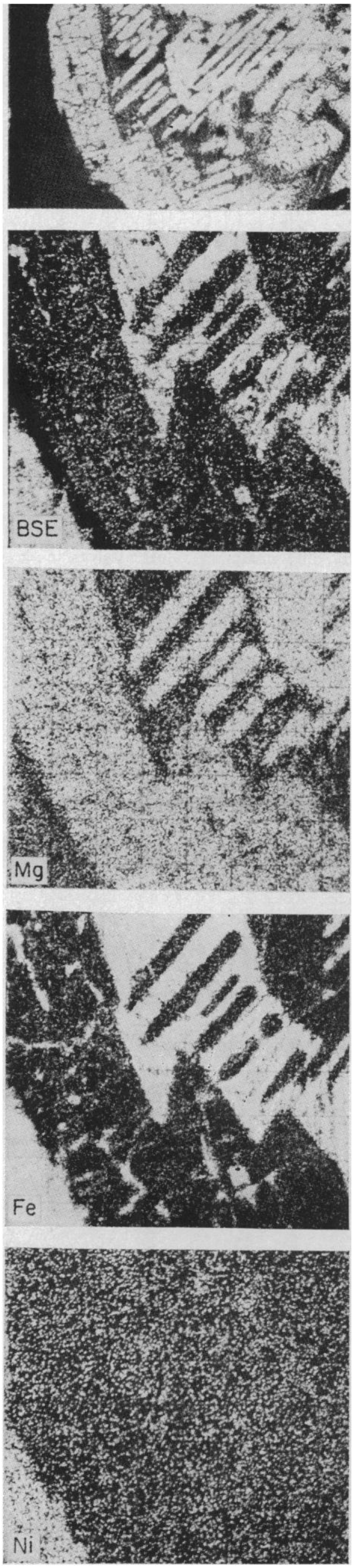

Fig. 6 (left). Photomicrograph and beam scanning pictures of part of a thin section of the Murray carbonaceous chondrite. BSE is a back-scattered electron image and Mg, Fe, and Ni show the distribution of these elements within the scanned area. The chondrule contains alternate lamellae of olivine and a darker, fine-grained, devitrified glass separated from the matrix by a rim of pyroxene. Olivine and pyroxene are both white in the Mg picture, while the devitrified glass with its relatively high iron content shows white in the BSE and Fe pictures. All the chondrule silicates contain much less nickel than the matrix. Scanned area is 250 by 250 μ.

ress, together with textural studies of chondrites, suggest that iron, nickel, and sulfur may be redistributed in a chondrite at temperatures well below the crystallization temperature of the silicates. The distribution of iron, nickel, and sulfur in chondrites may be controlled by both a high-temperature fractionation of contrasting phases and a low-temperature redistribution in the solid state.

The contrast in nickel content between the chondrule silicates and the matrix surrounding the chondrules is shown in Fig. 3. Figure 6 shows that a similar pattern exists in the carbonaceous chondrite Murray. The nickel distribution cannot be explained by an *in situ* transformation of either matrix into chondrules by solid-state recrystallization (*3*) or chondrules into matrix by weathering (*9*). The contrast in composition between matrix and chondrules in these meteorites implies that they are mechanical mixtures of materials formed under different conditions (*10*).

On the subject of meteoritic chondrules, Merrill (*11*) in 1929 wrote: "such interesting and peculiar forms are now known to be due to the cooling and partial crystallization of molten drops of stony matter; . . . their origin has been made the subject of much discussion and wordy warfare among students, but the matter need not be gone into further here." Concurrence with Merrill's conclusions and with the fact that iron was present when the chondrules solidified allows advance to the greater problem of the conditions under which these liquid droplets may form.

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Radiocarbon Date from the Lake St. John Area, Quebec

Abstract. *A radiocarbon age of 8680 ± 140 years found for fossil marine shells in the Lake St. John area, Quebec, shows that marine submergence there apparently preceded the "Tyrrell Sea" in southeastern Hudson Bay, but followed the Champlain Sea episode in the St. Lawrence Lowlands.*

Fossil marine shells collected in the Lake St. John area of Quebec (48°31′N, 71°38′W) (*1*) (Fig. 1) have been dated at 8680 ± 140 years (*2, 3*). The source of the shells is on the present 130-m contour above sea level (*4*); the bed, which is approximately 1 m thick, is overlain by 4 to 6 m of well-sorted sand which is locally cross-bedded. The uppermost part of the section appears to be windblown. *Hiatella arctica* accounted for about 80 percent of the fossil assemblage identified, the rest consisting of *Macoma balthica*. Because almost all the fossil shells had both valves together as in life, I assumed that they had not been transported far, if at all, before burial; the thickness of individual valves suggests that these mollusks had lived in an environment favorable as to salinity and temperature (*5*).

The shells are considered to be relatively shallow-water forms because of the sedimentary environment and because *M. balthica* is usually a shallow-water species.