4×10^{-5} atm and the gas density 4×10^{-9} g cm^{-3} (*9*). Thus, the required total release of energy by lightning to "treat" the gas would be $(1.3 \times 10^9)/(4 \times 10^{-9}) \geqq 10^{18}$ erg g^{-1}. This corresponds to the kinetic energy at a velocity of more than 10,000 km sec^{-1}, much too high to be supplied by turbulence fed by gravity. At most, we can expect parabolic orbital velocities of the order of 20 km sec^{-1}.

We see from Eq. 2 that the equivalent kinetic velocity to feed the lightning process within the total volume varies as $(E_L)^{-1/2}$. Hence, if lightning flashes of 10^5 to 10^6 times greater energy per unit length than those typical of our atmosphere can occur in the primitive nebula, the energy requirement can be reduced to a reasonable velocity, equivalent to some tens of km sec^{-1}. The maximum-energy lightning flashes observed in the atmosphere are 10 times more energetic than our adopted average. At lower densities, however, the breakdown voltage decreases (*10*), and thus possibly reduces the linear energy of lightning in the primitive nebula. We can reduce the energy discrepancy only slightly by postulating that the energy of the lightning is not entirely lost to the system by kinetic motion of the gas and subsequent radiation to space. Only a moderate fraction could appear again as lightning. Nor will raising the temperature of the gas near to the limit for glass formation provide much assistance. Radiation from the young Sun seems to serve no useful end in the process.

On the other hand, the energy adopted above for a lightning flash may be much overestimated, and we should look at the phenomenon differently. Uman and Orville (*11*) find that the maximum temperature indicated by the N II lines in lightning is some 25,000°K. For N atoms this corresponds to a kinetic equivalent velocity of only 7 km sec^{-1}. Adding dissociation (9.8 ev), ionization (14.5 ev), and excitation for N_2, we find a total equivalent kinetic velocity of just under 20 km sec^{-1}. Thus, all the matter in a Laplace nebula could, by these crude energetic considerations alone, be subjected to lightning. If, then, the pinch effect acts on all of the dust balls in the original gas column collapsed by a lightning flash, we may reasonably postulate enough energy to produce chondrules by this process.

The lightning might be somewhat confined to the turbulent temporary atmospheres of developing asteroids. Here the heated droplets could fall immediately into place, and the requirement that all of the material be heated by lightning would be reduced.

Note that lightning could provide free energy for forming complex carbon compounds in asteroidal bodies, as in Miller's (*12*) experiment. Thus, the occurrence of such material (*13*) in carbonaceous chondrites might be anticipated.

The little-understood process of particle aggregation in the Laplace nebula could be greatly accelerated by the occurrence of charges on the small condensed flakes or on chondrules. It is possible that the restricted limits to chondritic dimensions were controlled by electrostatic-charge limitations on the original dust balls as well as by limitations in the lightning processes.

Clearly much research, theoretical, observational, and experimental, is needed to evaluate this suggestion that lightning produced the chondrules. I note that, for at least two decades, Bruce has advocated that lightning plays an important role in cosmic phenomena. In none of his papers, however, have I been able to find a suggestion regarding its possible occurrence in the primitive solar-system nebula or as a factor in the production of chondrules (*14*).

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21 March 1966

Martian Wave of Darkening: A Frost Phenomenon?

Abstract. *A new hypothesis attributes the Martian "wave of darkening" to soil frost phenomena. Diurnal thawing and freezing of the ground, which uses moisture transported by the atmosphere from the melting polar cap, can produce various minute, frost-heaved, soil surface features. These microrelief features result in a complex porous surface structure, which causes optical darkening. The boundary at which the wave of darkening terminates on the winter hemisphere correlates with the latitude at which the diurnal peak surface temperature drops below 0°C. The hypothesis is examined in terms of known properties of the Martian atmosphere and surface and the availability of water.*

The Martian "wave of darkening" is ascribed to frost phenomena in a new hypothesis not based on vegetation. It is suggested that freezing during the Martian afternoon and evening produces one or more types of surface microrelief features similar to those observed in areas where frost action occurs on Earth. These frost features can diminish reflectivity by increasing the complexity of the surface.

Miniature soil columns and similar features, referred to here as "microhills," raised by formation of needle ice, have been observed in Pennsylvania to form in certain areas of wet soils after freezing nights. Typically, the microhills are very rough columns, from a few millimeters to several centimeters high, with a height-diameter ratio of 2 to 5, spaced singly or in clusters or subparallel ridges over many square meters. The observed microhills fall into the category of frost phenomena associated with needle ice described by Troll (*1*), who states: "Needle ice formed in fine-grained bare or sparsely vegetated soils (clay, loess, marl, shale and peat) with no snow cover or at most a slight covering of snow, by the abrupt freezing on the surface of the ground, most frequently by night freezing due to radiation loss."

Typical natural occurrences of needle ice are shown in Figs. 1 and 2. Space chamber experiments which we have recently begun and experiments outdoors in containers produced a variety of frost surfaces, including columns in assorted sizes and near-vertical flakes approximately 0.1 millimeter thick (Fig. 3).

The general process through which the wave of darkening takes place is postulated to occur as follows: Early in the Martian spring, direct solar heat begins to sublimate the polar cap, which makes water available to the atmosphere, first in small amounts, then, as the polar region warms up, in increasing quantity. The atmosphere transports the water from the polar region toward the equator, but, each afternoon or evening, water is deposited on the surface and is absorbed by the upper few millimeters of soil through mechanisms which are discussed later. Water trapped in the soil freezes as night approaches and, by its expansion, produces the microrelief frost features. On the following day, the midday solar heating causes the ice to sublimate and thus makes H_2O available for further transport toward the equator and beyond.

An important aspect of the hypothesis is that microhills in the maria do not entirely collapse upon sublimation of the ice, but retain enough of their structural identity to account for seasonal persistence of the "wave of darkening." The water moves on and is used over and over, acting somewhat like a catalyst in the process. Darkening spreads as a result of progressive recycling of water.

If microhills do retain their approximate shape when they are dry, a method of their eventual destruction has to be postulated. Wind erosion seems to be the most logical process; it normally operates toward the gradual wearing down of microhills, but in some cases it attains sufficient velocity to effect rapid destruction.

To explain why maria are subject to seasonal darkening and deserts are not, it is postulated that the two areas differ in some soil characteristics. It is possible that the difference is in permeability, so that water percolates through the top few millimeters of soil more rapidly in deserts. The difference appears to be only in degree of affinity for microhill formation. When unusually high local concentration of water occurs as a result of storms, as took place during the 1956 opposition [Slipher (*2*), p. 13], frost features and the resultant darkening can occur both inside and outside the usual areas. The ephemeral character of these occasional features can be explained as being due to their destruction upon sublimation of ice crystals by strong winds associated with storms.

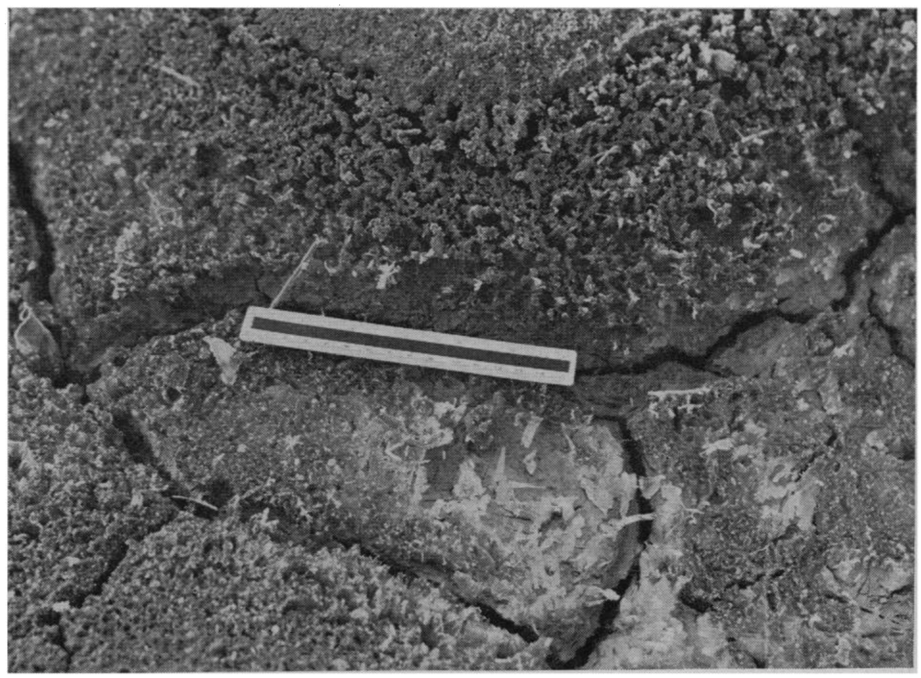

Fig. 1. Needle-ice and microhill formation.

The darkening effect of microrelief features in soils characterized by low albedo is readily understood. Since microhills are in most cases isolated from each other, the surrounding cavities are interconnected, and the structure is quite porous. Such surfaces have been studied by Hapke and Van Horn (*3*), with applications to the moon. When an observer looks at such a surface in a direction transverse to the direction of incidence, light illuminating the cavities is effectively blocked, and he sees light from areas near the top of the structure only. When an ob-

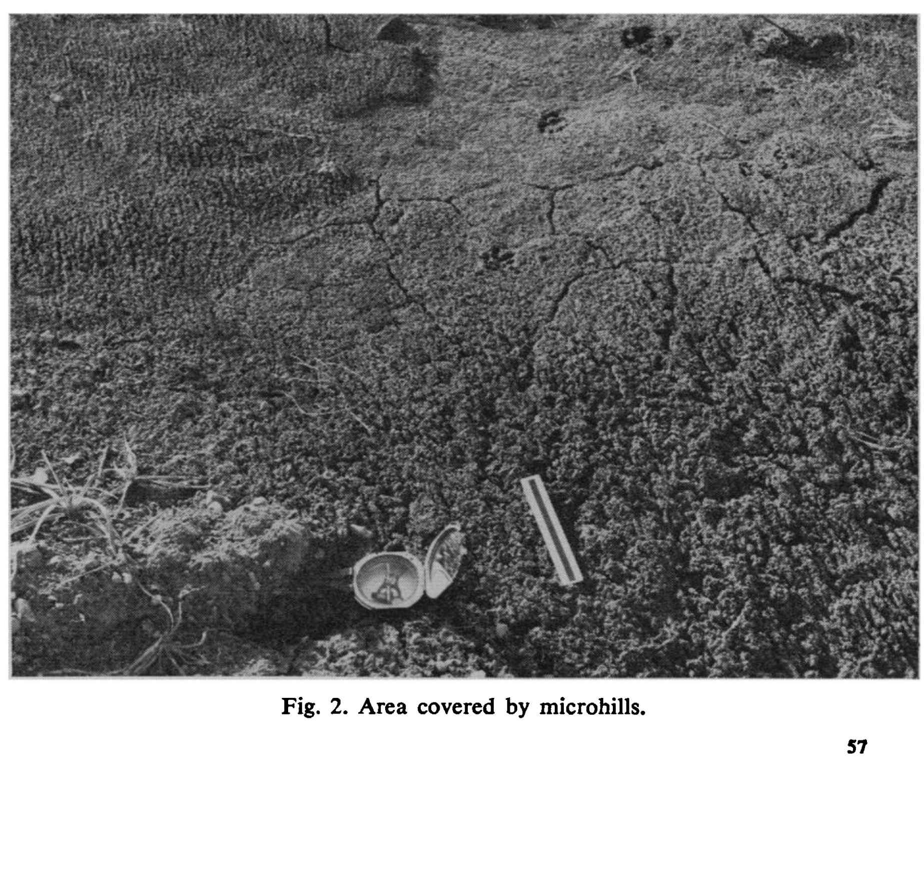

Fig. 2. Area covered by microhills.

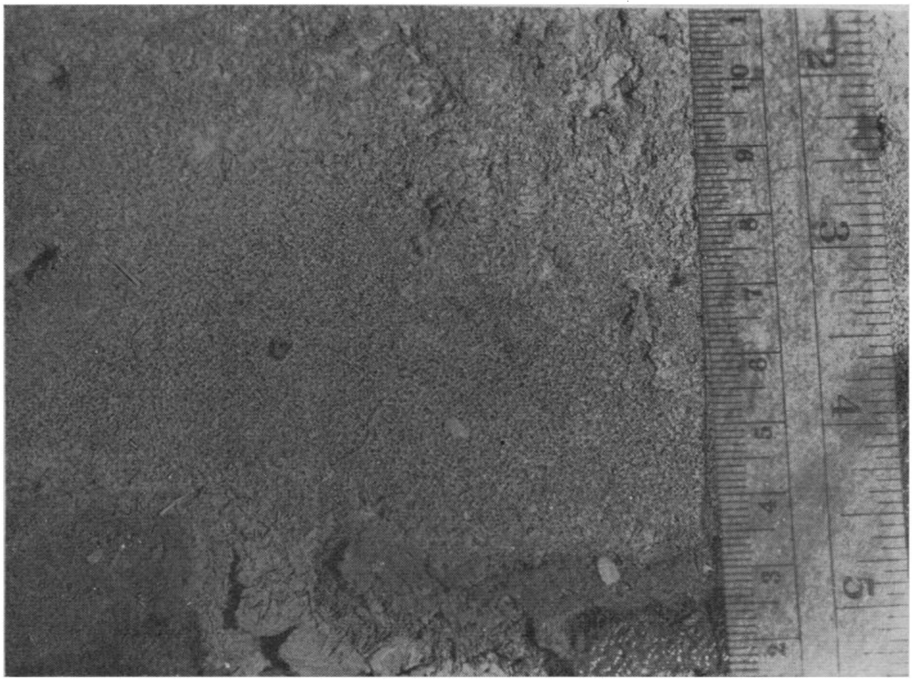

Fig. 3. Microhills in clay loam produced in environmental chamber.

server looks parallel to the direction of incidence (that is, zero phase angle), he sees light from both the top and the deep surfaces. The porous structure thus backscatters light pronouncedly. But even when the surface is backscattering, that is, when the observer looks in a direction parallel to the direction of incidence, a darkening effect takes place in the region near the center of the disk. This can be explained by the fact that much of the incidence and reflection relative to the microsurfaces occurs at small angles. At such angles, perfectly diffuse (Lambertian) reflection will result in a decreased observed intensity. Moreover, diffuse reflection is known to fail at small angles for a wide range of materials, from magnesium oxide (*4*) to the Kodak white paper (*5*) (the actual reflection is smaller than Lambertian).

The complexity of microhill surfaces would thus decrease the difference in brightness of maria in the center of the disk versus maria at the edges, in agreement with photometric observations. Under full phase (opposition) conditions, brightness dependence on angle i between the surface normal and the coinciding directions of illumination and observation can be represented by an analytical expression used by Sytinskaya (*6*), $B = B_0 \cos^q i$. Sharonov (*7*) reports that the value of the smoothness factor q for Martian maria ranges from 0.5 to 1.0. This indicates a moderately complex surface. The fractional void volume of the surface structure should be lower than that of the moon, for which $q = 0$.

An increase in surface complexity accompanying the darkening is indicated by polarization studies of Dollfus (*8*) and Focas (*9*). Dollfus suggested, "The dark areas may consist of very small opaque granules which change shape or size during Martian seasons." This description can fit both plants and microhills with appropriate statistics of displayed surface irregularities.

Thus, the frost hypothesis appears to be as tenable, from the change in reflectivity and polarization point of view, as the vegetable hypothesis. Seasonal changes in color are not very definitely established [Kuiper (*10*)]. Some color changes could be expected because of slight encrustation of the microhills. Experimentally produced microhill surfaces in limonite appear brown yellow, whereas powdery limonite is mustard yellow. Limonite is believed by many to be the dominant mineral in the reddish Martian deserts, while limonite mixed with other undetermined minerals is ascribed to the maria. An alternative explanation of color change could be in terms of frost phenomena on a surface covered by small stones, as observed by Mohaupt (*11*) and quoted by Troll (*1*): ". . . in stony soils deficient in fines, the freezing of needle ice produced little columns and mounds of soil which appeared swelled up or pressed up between stones and are not unlike the excrement of earthworms." Soil columns would represent a color change as compared to stones. However, stones cannot cover large areas, as evidenced by the average thermal properties of the surface.

Minimum water requirements of the process as it occurs in nature have not been firmly established, but an estimate is possible from observations of soil frost features at a number of sites. Ice develops several modes of expression, and there is little size correlation between soil columns and ice needles. On some slopes, well-developed microhills were produced by small ice crystals in the form of hollow pyramids. The amount of water which soil has to absorb to produce terrestrial microrelief features appears to be a few centimeters. Extrapolating to Martian conditions, it would appear that the weaker gravitational field would permit ice needles to heave the soil more effectively. Even more important, the abrupt drop in temperature in the afternoon will prevent deep percolation by freezing the trapped water near the surface. Based on rapid cooling experiments with water sprayed on lightly packed limonite, 1 millimeter or less of water might produce small, but still optically effective, microrelief features. It should be pointed out that actual spraying alone changes the nature of the surface noticeably. This amount of water locally available on Mars appears plausible, as the following discussion of a combination of transportation and deposition processes shows.

The amount of water in polar caps has been analyzed by de Vaucouleurs (*12*, p. 200) on the basis of solar heating and the heat of transformation of ice. His estimate ranges from a few millimeters to a few decimeters of water. The figures do not include water in the polar winter clouds. Sytinskaya (*13*) essentially concurs with these results, saying that "heat balance calculations, which have not yet been disputed, give the very low value of 2-3 cm for the possible thickness of polar caps consisting of frozen water." Slipher (*2*) states, in discussing the Martian water, "As to its actual presence, the polar caps have most to say; as to its relative absence, the great clarity of the Martian sky speaks."

Darkening progresses over a period of about 130 Martian days, during which the polar cap shrinks down to an insignificant remnant. The total area ultimately swept by the dark fringe and the wave of darkening is larger than the maximum polar cap by a factor of about 10. In view of this ratio, it appears possible to postulate local surface concentrations of water approaching, and even possibly exceeding, the water thickness of the cap, if a large fraction of the traveling water is precipitated nightly on the surface and if the wave of moisture is nonuniform; that is, local depositions of water occur in patches and exceed the average moisture content within the wave. These two important points are discussed below. Concentrations of the same order of magnitude as even the lowest quoted thickness of the cap appear sufficient to cause formation of needle ice. However, in order to postulate such concentrations, we would like to see a larger fraction of the total Martian water content available at the onset of the wave of darkening (heliocentric longitude of 270° in the southern hemisphere) than de Vaucouleurs' Fig. 29 (*12*) would indicate (*14*).

It is hypothesized that a large fraction of water is precipitated from the atmosphere daily, possibly around mid-afternoon, and is sublimated from the surface the next day, around the diurnal maximum of surface temperature. The effective "traveling" time of only a few hours per day for this fraction is not inconsistent with the rate of advancement of 45 km/day, in view of observed low-level velocities of Martian wind. It can be postulated that "For one or two hours after the diurnal maximum is reached, enormous upward convection takes place, accompanied by strong winds" (*15*). This phenomenon is prevalent in the Chang Tang region of Tibet, which, as first discussed by Schilling (*16*), is the only region on Earth which approaches the Martian maria in general climatic and temperature conditions. The postulated Martian upward convection into colder regions of the atmosphere correlates with afternoon clouds as observed by Slipher (*2*), which "began to appear weakly around two o'clock in the afternoon and grew brighter and more conspicuous, until near sunset, they rivaled the brilliance of the south polar cap." Afternoon depositions have been observed by Barabashov (*17*) and by Tombaugh (*18*), among others, who link it temporally in the Elysium region to the wave of darkening: " . . . in the late Martian afternoon in certain seasons when the moisture from the north has reached that latitude, even though other areas are growing dark, this area gets white. Considering the sharpness of the details in the general area, I have to interpret this whiteness as hoar frost forming on high land."

Daily deposition, on the surface, of a large fraction of total H_2O would tend to reconcile the apparent disparity between spectroscopic observations of 10 to 20 microns (*19*) of atmospheric water and the amount of Martian water derived from the estimated thickness of the polar cap. As de Vaucouleurs (*12*, p. 219) points out, spectroscopic observations of the atmosphere can detect only a fraction of the total amount of Martian water and cannot be taken as an indication that thermal balance calculations are incorrect. The hypothesized intermittent transport would result in little spectroscopically detectable water on the morning side of the disk, as compared to the early afternoon—and invites an appropriate study.

Nonuniformity, or "patchiness" of depositions in the wave of moisture, that is, in areas between the front of the wave of darkening and the shrinking polar cap, increases the level of locally available water. Primarily, it has to be assumed to account for the "regeneration" phenomenon. Occasionally, premature brightening of the darkened maria is reported, and "regeneration" refers to the observation of a subsequent darkening. According to the microhill hypothesis, microhills that were destroyed prematurely are recreated when a patch of H_2O deposition covers the area. Had the depositions been highly uniform, the destroyed microhills would be recreated overnight, and destruction would probably go undetected. "Patchiness" of the wave of darkening would fit the observations of Slipher (*2*) (" . . . the photographs of the larger dark areas reveal a great amount of structure, consisting principally of dark spots and bands and lighter areas"), Dollfus (*8*), and Focas (*9*) (" . . . very large dark nuclei separated by interstices of a dark tonality").

The pronounced day-night temperature range, which is on the order of 100°C in equatorial regions, would favor frost phenomena. Day-night variation will be somewhat smaller within the patches of moisture because of local and ephemeral increase in the thermal inertia of soil. Darkened maria will again exhibit the very low thermal inertia of desiccated soil. Sinton (*20*) rules out the possibility of extensive coverage by leafy plants or rock formation since dark areas seem to warm and cool about as rapidly as deserts. His important point does not create difficulties in the microhill hypothesis if localized and ephemeral departures from average temperature profiles are postulated.

The wave of darkening spreads across the equator into the winter hemisphere and stops at an ill-defined boundary above 20° latitude [Dollfus (*8*), Figs. 27 and 28, pp. 29 and 30]. This fact is attributed to all-day frost conditions; that is, impossibility for liquid water to exist beyond this boundary. The boundary roughly coincides with latitude 22° where maximum daily temperature drops to below 0°C, according to empirically derived temperature-versus-latitude profile by Mintz (*21*) for the winter solstice.

At water vapor pressures assumed to exist on Mars, phase transitions of H_2O will be from ice to vapor. However, water can be absorbed by soil (*22*), even if the pressure is below 4.6 mm-Hg, and undergo a change from liquid to solid as the temperature drops. Direct absorption by soil of wind-carried water in vapor form is thought to be unlikely by Öpik (*23*). In this connection, the reaction

$$Fe_2O_3 \cdot H_2O(s) \leftrightarrows Fe_2O_3(s) + H_2O(g)$$

has been discussed by Adamcik (*24*). Alternatively, atmospheric water carried as ice crystals can be deposited on and absorbed by the relatively warm soil. Such deposition would occur in the afternoons, at the time of upward convection and formation of afternoon clouds. Because of the low thermal capacity of soil, only a thin layer of H_2O can be melted and absorbed, but this is the most efficient process from the point of view of water requirements since freezing follows immediately and percolation is minimal. Still another mechanism could be the formation of hoarfrost on cold soil toward evening or at night. Next day, hoarfrost is in part sublimated and in part absorbed by soil during heating by the midday sun—" . . . Martian vegetation may utilize hoar-frost, deposited at night and melting in the morning sun, by absorbing the liquid before it evaporates" (*23*).

If the hypothesis is correct, all of the daily advance in a given longitude band should occur as a "jump" in the afternoon or evening, as the temperature plunges below 0°C. Test of this conclusion by observation from Earth is problematical since the average daily advance of 45 kilometers about equals the resolution limit under best seeing conditions and since microhills might form because of only partially absorbed H_2O deposit; that is, they might be covered by ice when freshly formed. The rate of advance as a function of Martian time of day could be established by photography from a Martian orbiter programmed to take observations of the same selected areas two or three times daily over a sufficiently long period. A highly suitable opportunity to accomplish this will occur in 1973.

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21 March 1966

Cohenite in Meteorites: A Proposed Origin

Abstract. *Cohenite [$(Fe, Ni)_3C$] is found almost exclusively in meteorites containing from 6 to 8 percent nickel (by weight). On the basis of iron-nickel-carbon phase diagrams at 1 atmosphere and of kinetic data, the occurrence of cohenite within this narrow composition range as a low-pressure metastable phase and the nonoccurrence of cohenite in meteorites outside the range 6 to 8 percent nickel can be explained. Cohenite formed in meteorites containing less than 6 to 8 percent nickel decomposed to metal and graphite during cooling; it cannot form in meteorites containing more than about 8 percent. The presence of cohenite in meteorites cannot be used as an indicator of pressure of formation. However, the absence of cohenite in meteorites containing the assemblage, metal plus graphite, requires low pressures during cooling.*

Cohenite [$(Fe, Ni)_3C$] is structurally identical to cementite (Fe_3C) and occurs mainly in metallic meteorites. It contains 0.5 to 3 percent (by weight) of Ni (*1*) and is metastable at all temperatures at low pressures (*2*). Thermodynamic calculations suggest that cohenite is stable at high pressures (*3*). Ringwood (*3*) concluded that the presence of cohenite in a meteorite indicates a pressure of formation of at least 25 kb and therefore a parent body of approximately lunar size. Since the appearance of Ringwood's paper, research on cohenite has been active (*1, 4–6*).

Cohenite has been sought in many iron meteorites, but it has been unequivocally identified in only 26 (*7*); of these, 20 meteorites are coarse octahedrites and have nickel contents between 6 and 8 percent. Iron meteorites having this composition make up less than one-third of those analyzed (*8*). Of the remaining six meteorites that contain cohenite, three are nickel-poor ataxites (Ni, 5 to 6 percent) and the rest are medium octahedrites (Ni, 7 to 10 percent). It would therefore seem that the distribution of cohenite in meteorites is not random and that, with certain exceptions, cohenite is restricted to meteorites containing between 6 and 8 percent nickel. Carbon occurrence in iron meteorites is not similarly restricted; the average carbon content is about 0.2 percent (*9*).

The phase-equilibrium relations along the bounding binaries of the ternary system Fe-Ni-C have been investigated in some detail; however, little work has been done in the ternary owing to experimental difficulties. The suggested phase relations in the ternary (Figs. 1 and 2) have been drawn by projection from the existing data along the binaries (*10*). Assemblages involving cohenite in Figs. 1 and 2 decompose in time to

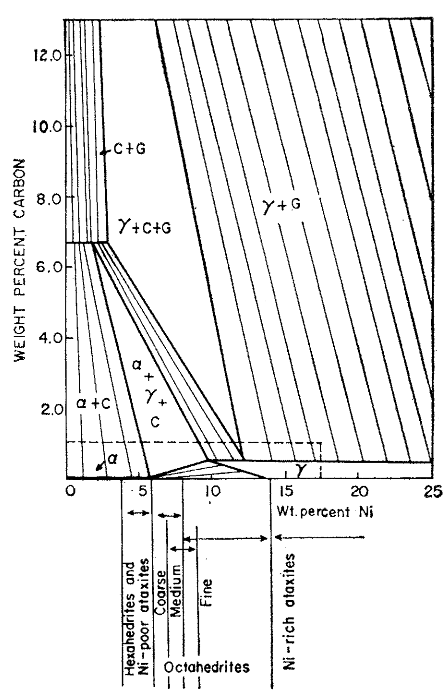

Fig. 1. Isothermal section of portion of the system Fe-Ni-C at 650°C, in which the metastable phase cohenite is included. α, kamacite; γ, taenite; G, graphite; C, cohenite. Dashed line indicates composition range of Fig. 2. Composition ranges of iron meteorites are shown.