ment system that is oriented with respect to the axis of rotation. It is generally thought that such a lineament system is caused by stresses in the planet's crust produced by changes in the planet's rotational equilibrium figure. The NS and EW lineaments are then the tensional and compressional features, and the NE and NW lineaments, the complementary shear directions.

Unfortunately, in the Mariner IV frames studied, north is always within 10° of being perpendicular to the scan direction; thus, the major lineament directions, that is, NW and NE, always nearly cut diagonally across the checkerboard pattern produced by the TV digital system. Similarly the EW lineament direction is always nearly parallel to the scan lines. Consequently, a number of the lineaments may well be instrumental in origin.

Two differences between "low-latitude" and "high-latitude" lineaments are noted. First, in the low-latitude group (group *a*) the NW direction contains over three times as many lineaments as the NE direction, while for the high-latitude group (group *b*) the difference is a factor of 2. It is possible that the reduction in disparity in the latter group is due to lighting effects, since on the high-latitude frames the lighting favors the detection of features with a NE trend. Secondly, the angle between the shear directions is 90° to 95° for the low-latitude group and 105° for the high-latitude group. Although this difference may be accounted for by projection, or other distortions, Vening Meinesz (*10*) has indicated that in the case of the earth the angle between shear lineaments should increase in high latitudes.

Since the lineament systems of the earth and moon are probably a result of the decrease in the rotational angular velocity that the two bodies have experienced throughout their histories, it seems likely that the Martian lineament system had a similar origin. The changes in angular velocity caused by tidal interactions of Mars with Phobos and Deimos are completely negligible and that caused by the sun is a few percent at most (MacDonald, *11*); thus other mechanisms must be sought. Wise (*12*) has postulated that the earth lost a considerable amount of angular momentum by an interaction of the geomagnetic field with strong solar winds in the early history of the solar system. To apply this mechanism to Mars, it is necessary to postulate that Mars once had a magnetic field but lost it, since the Mariner IV results indicate that the Martian magnetic field is no greater than 3×10^{-4} that of the earth (*13*). According to the widely held dynamo theory, a liquid iron core is necessary for a geomagnetic-type field. Though the dynamical oblateness of Mars indicates that it is more homogeneous than the earth (*14*), studies of the internal structure by MacDonald (*15*) and many others indicate that Mars may have at least a small iron core. This core would probably have been liquid during at least some time after its formation, so the dynamo requirements may have been fulfilled for an early aeromagnetic field.

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25 February 1966

X-Ray Diffraction Study of Minerals from Shocked Iron Meteorites

Abstract. *Diffraction analysis of minerals from iron meteorites indicates a pronounced shock-induced alteration in the minerals' crystallographic character. The extent of alteration seems to be dependent on the degree of shock and can therefore serve as a measure of shock intensity. The changes appear to be due to the minerals' direct recrystallization during passage of the shock wave.*

Recent metallographic studies have shown that natural and artificial shock waves cause a number of microstructural changes in iron meteorites (*1, 2*). These changes have been used in a qualitative manner to categorize such meteorites into lightly (< 130 kb), moderately (130 to 750 kb), and heavily (> 750 kb) shocked groups (*2*). However, most of these changes can be produced either by shock or by heat-treatment in the 1-atmosphere region (*2*). Thus, in the absence of unequivocal indicators of shock, it may be difficult to decide whether a meteorite has been shocked or has been artificially heated at atmospheric pressure. Since the meteorites' shock histories can be related to other parameters, it would be very desirable to establish unambiguous shock criteria.

It occurred to us that these shock-induced microstructural changes in iron meteorites might also be accompanied by crystallographic alterations in the meteorites' constituent minerals. Ideally, such alterations would not be reproduced by simple heating and thus they would serve as unequivocal indicators that shock had occurred. In order to investigate this possibility we have studied, by x-ray diffraction techniques, a number of minerals common to iron meteorites. These minerals, which include kamacite (α-Fe), taenite (γ-Fe), troilite (FeS), cohenite (Fe_3C), and schreibersite (Fe_3P), were removed as undeformed single grains and were x-rayed without rotation in a 57.3-mm powder camera; manganese-filtered $FeK\alpha$ radiation was used. The meteorites include a suite of Canyon Diablo specimens studied metallographically by Heymann *et al.* (*2*) and natural and artificially shocked Odessa specimens (*3*). We found that shock does indeed affect the crystallographic character of minerals from iron meteorites (*4*).

For taenite and troilite our preliminary results were not conclusive. However, grains of kamacite, schreibersite, and cohenite show definite evidence of shock-induced crystallographic alteration. Figure 1 shows typical diffraction patterns for cohenite from lightly (*A*), moderately (B), and heavily (C) shocked Canyon Diablo meteorites. The only features evident in A are the spots typical of an undeformed single crystal of cohenite. In B the spots are replaced by dark line segments indicative of pronounced preferred orientation. This preferred orientation may also be responsible for the streaking observed near the outlet port at the left of the films. A combination of preferred orientation and more or less random crystallite orientation is shown in C. Complete random orientation would be indicated by the appearance of rings, of constant intensity, at d-spacings corresponding to those of cohenite. Cohenite more strongly shocked than the sample whose pattern is shown in C yields a diffraction pattern showing no preferred orientation, although the crystallite orientation is not completely random (*5*).

Figure 2 shows diffraction patterns of cohenite from the Odessa iron meteorite: A, natural cohenite; B and C, typical patterns of cohenite grains shocked artificially to 600 and 1000 kb, respectively (*3*). The features shown in Fig. 1 (B and C) are reproduced in Fig. 2 (B and C). Figures 1 and 2 indicate that the degree of crystallographic alteration of cohenite is proportional to the shock intensity up to pressures of 1000 kb. The diffraction features are not similar to those induced by the deformation of single crystals (*6*) but indicate, instead, cohenite's progressive shock-induced recrystallization.

We can eliminate the possibility that the features shown in Figs. 1 and 2 can be produced by simple heating. As is well known (*7*) cohenite is thermodynamically unstable with respect to graphite and iron unless pressures of many kilobars are applied. Thus the diffraction pattern of unshocked cohenite, annealed in vacuum, is essentially that shown in Figs. 1 and 2 (A) except for the presence of lines corresponding to those of α-iron in the annealed cohenite (*5*).

Figure 3 illustrates diffraction patterns of unshocked schreibersite (A) and schreibersite from a moderately shocked Canyon Diablo meteorite (B); C is a pattern for unshocked kamacite, and D is a pattern for kamacite from a moderately shocked specimen.

It has been shown previously that diffraction patterns of some minerals from a few stony meteorites show preferred orientation (*8*, *9*). For these cases there is evidence that this pre-

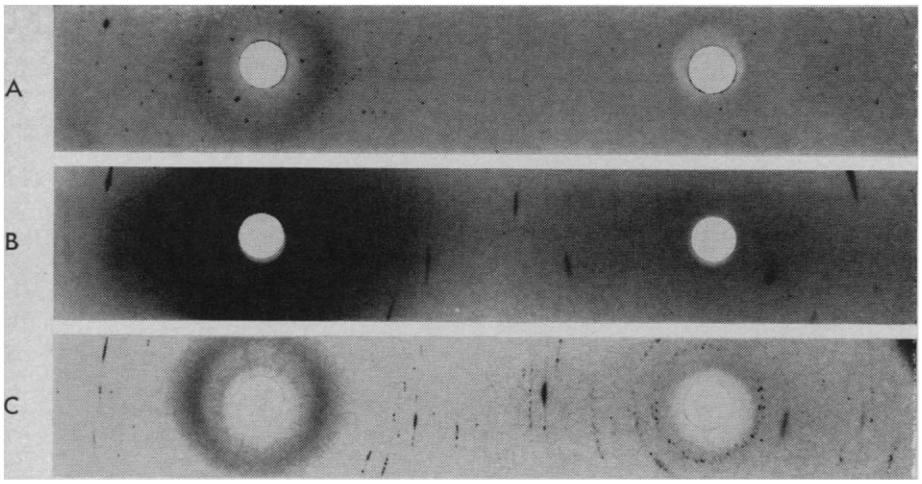

Fig. 1. X-ray diffraction photographs of cohenite grains from lightly (A), moderately (B), and heavily (C) shocked Canyon Diablo meteorites: specimens 26, 35, 50 (*2*).

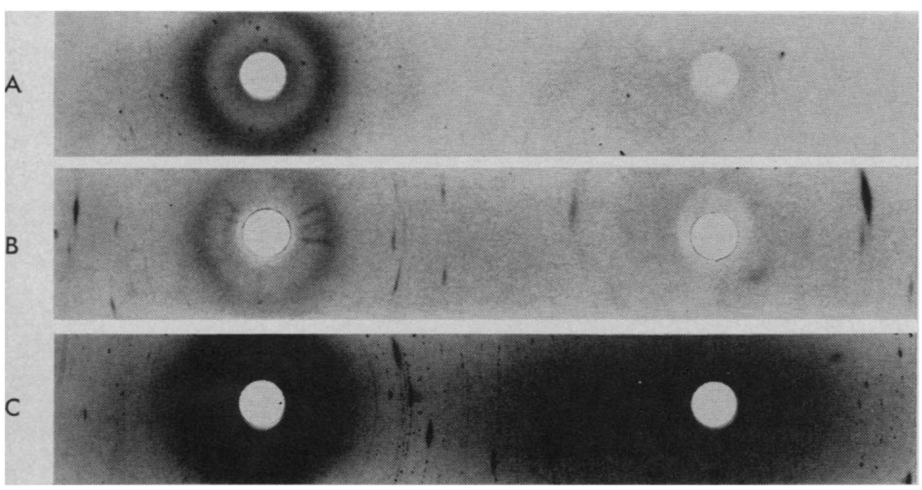

Fig. 2. Diffraction photographs from natural (A) and artificially shocked samples (B, 600 kb; and C, 1000 kb) of the Odessa meteorite. Same irradiation conditions as in Fig. 1. Note the similarities between Figs. 1 and 2. The single crystal (A) is converted to an aggregate with a strong preferred orientation (B), and then to an aggregate showing both preferred and random orientation (C).

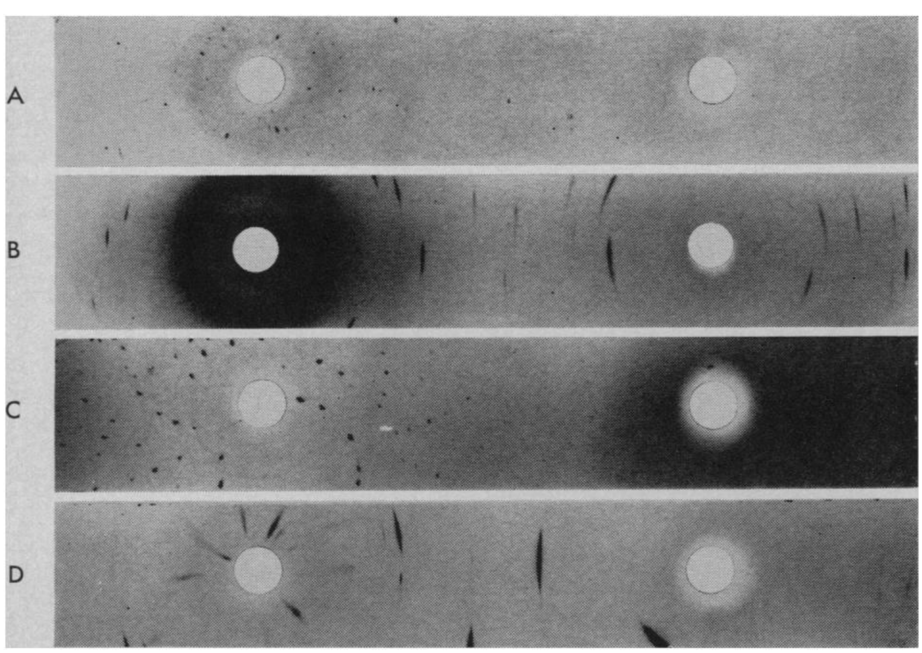

Fig. 3. Diffraction photographs of lightly (A) and moderately (B) shocked schreibersite and lightly (C) and moderately (D) shocked kamacite. The pronounced preferred orientation shown in Figs. 1 and 2 (B) are also shown in Fig. 3 (B and D). A and C are from Odessa; B and D are from specimens 52 and 28 (*2*).

ferred orientation is also shock-induced. However, it should not be concluded that recrystallization is necessarily the only mechanism by which this diffraction feature is formed. In meteoritic diamonds and in diamonds produced by anisotropic processes the preferred orientation apparently arises by preferential conversion of the basal planes of initially polycrystalline graphite to (311) planes of diamond (*9*). We can reasonably expect that, in addition to stony meteoritic minerals, terrestrial minerals from meteoritic impact sites and artifically shocked materials will also show crystallographic alteration.

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Sediments from the Lower Columbia River and Origin of Graywacke

Abstract. *The mineral and chemical composition of sediments deposited in the three lowermost reservoirs of the Columbia River is remarkably similar to the composition of many graywackes. Lithic fragments are abundant. In comparison with an "average" sandstone, the sediments have low concentrations of silica and high concentrations of all other major constituents, except calcium. Sodium is more abundant than potassium. The sediments are generally better sorted than graywackes. If graywacke texture is post-depositional in origin, Columbia River-type sediments could be expected to form graywackes upon deep burial without any significant addition or removal of material.*

Interest in recent sediments has prompted attempts to recognize the modern analogs of ancient sediments now preserved as sedimentary rocks. Graywacke-type sands, characterized by very poor sorting, have seldom been identified (*1*). This is puzzling, in view of the widespread occurrence of graywacke throughout the stratigraphic column. Since many ancient graywackes are thought to have been deposited by turbidity currents in deep water (*2*), it is surprising that most sands on the deep ocean floor are relatively well sorted (*3*).

Cummins (*4*) has suggested recently that graywacke texture is post-depositional in origin and that it occurs when chemically unstable grains are partially or completely disintegrated and form matrix during weathering, deep burial, or low-grade metamorphism. If Cummins is correct and graywacke texture has little to do with primary sorting, then textural criteria are invalid for use in identification of modern graywacke-type sands; other criteria are needed. Two possible criteria are the mineral and chemical composition of the sediments.

The sand-size fraction of most graywackes is largely restricted to lithic fragments, quartz, and feldspar regardless of the age of the rock or its geographic locality (*5*). As might be expected, there is considerable variation in feldspar composition and type of lithic fragments in most graywackes.

Pettijohn states: "there are a considerable number of chemical analyses of graywacke in the literature which show a remarkable homogeneity of composition. Almost all these rocks would qualify as graywackes by any definition" (*5*).

The sediments carried by the Columbia River bear a striking mineral and chemical resemblance to many graywackes. Sediments were obtained by a Van Veen grab sampler in 1964 and 1965 from the bottom surface (to a depth of about 15 cm) of three downstream reservoirs of the Columbia River: Bonneville, The Dalles, and McNary. In all, 53 samples from the three reservoirs have been analyzed at least partially. The mean particle sizes of samples, in "phi units," the negative logarithm (base 2) of the diameter in millimeters, are: Bonneville reservoir (31 analyses), 2.45 ϕ; The Dalles reservoir (9 analyses), 3.79 ϕ; McNary reservoir (13 analyses), 3.75 ϕ. All are in the range of coarse sand to medium silt. The relatively coarse sediment in Bonneville, the lowermost reservoir, correlates with the greater current in that section of the river.

The range and mean of the sorting coefficients (σ_I) in each of the reservoirs are: Bonneville, 0.37 to 2.34 ϕ, 0.89 ϕ (moderately sorted); The Dalles, 0.26 to 2.49 ϕ, 1.42 ϕ (poorly sorted); McNary, 0.32 to 2.01 ϕ, 1.23 ϕ (poorly sorted). The sorting coefficient generally increases with decrease in grain size. Only the very fine-grained samples have sorting coefficients comparable to those of many recognized graywackes (*4*, Fig. 1).

Sedimentary structures were not observed in any of the samples because of the sampling method. A few samples showed stratified fine and coarse sediment (and were excluded in size analyses), but most were homogeneous.

Thin sections were made from 11 samples impregnated with epoxy resin, and a summary of modal analyses (by point-counting) is given in Table 1. Modal analyses of other samples (determined by inspection) do not differ greatly from those selected for point-counting, although the latter are not necessarily representative of each reservoir (only two samples were chosen from The Dalles). The modal analyses

Table 1. Mineral composition of Columbia River sediments, based on model analyses of four samples from McNary reservoir, two samples from The Dalles reservoir, and five samples from Bonneville reservoir.

Constituents	Composition (%)		
	McNary	The Dalles	Bonneville
Quartz	41	22	33
Plagioclase	13	13	14
K-feldspar	10	8	10
Lithic fragments	24	47	30
Opaque minerals	2	1	2
Mafic minerals*	9	8	10
Other	1	1	1

* Mainly hypersthene, augite, hornblende, biotite.