nuclear quadrupole splittings, area ratios of the doublets, and disordering parameters p are reported in Table 1. In Table 1 the degree of cation disorder is expressed in terms of p, where

$$p = \frac{X_1(1-X_2)}{(1-X_1)X_2} \quad (1)$$

and X_1 and X_2 are the site occupancy numbers for Fe^{2+} at the $M1$ and $M2$ positions, respectively.

The natural distribution in the Bamle enstatite, which comes from a metamorphic rock of the granulite type, is highly ordered (Fig. 1A). This ordering indicates that this pyroxene was slowly cooled between its crystallization temperature and approximately 480°C (1). No significant increase in disorder occurs in the specimens shocked to 250 and 450 kb. The differences in the p values relative to those of the natural material are not much larger than the experimental error, which is approximately ± 0.01. However, the specimen shocked to 1000 kb exhibits a marked increase in cation disorder (Fig. 1B), but the isomer shifts and quadrupole splittings are not affected. There is no trace of Fe^{3+} in any of the Mössbauer spectra.

Shocked materials are subjected to subsequent heating as an integral part of the shock effect. Pollack and De-Carli estimated that their specimens shocked to 1000 kb were exposed to a temperature peak of approximately 500° to 1400°C (7). We conclude from our heating experiments that the significant increase in cation disorder observed in the specimens shocked to 1000 kb results primarily from the elevated temperatures associated with the shock. The cation distributions in these specimens correspond to equilibrium temperatures of at least 1000°C. Equilibrium temperatures higher than 1000°C are also possible since the degree of disorder will not substantially increase any more above 1000°C, as the specimens heated to 1100° and 1200°C show (Table 1). This observation is in accord with earlier studies on the equilibrium relationships and kinetics of the Mg,Fe exchange reaction in orthopyroxenes (1). However, the rate constants for the disordering reaction

$$Mg(M1) + Fe(M2) \rightarrow$$
$$Fe(M1) + Mg(M2) \quad (2)$$
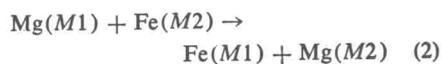
do suggest temperatures higher than 1000°C. At 500°C this rate constant is approximately 6×10^{-5} per pair of $M1,M2$ sites per minute (1). At 1000°C it increases to a value of approximately 10^{-2}. Only at temperatures nearer to 1400°C would the rate constant become large enough to account for the observed degree of disorder.

Pollack and DeCarli found considerable stacking disorder of the SiO_3 chains in the specimens shocked to 1000 kb, in contrast to the case for the specimens shocked to 250 and 450 kb, which did not reveal stacking disorder (7). This observation parallels our results on the increase of cation disorder. Specimens shocked to 1000 kb exhibit disordering parameters that are somewhat larger than those obtained merely by heating. This result may be attributed to alterations in the crystal structure caused by the 1000-kb shock as described by Pollack and DeCarli.

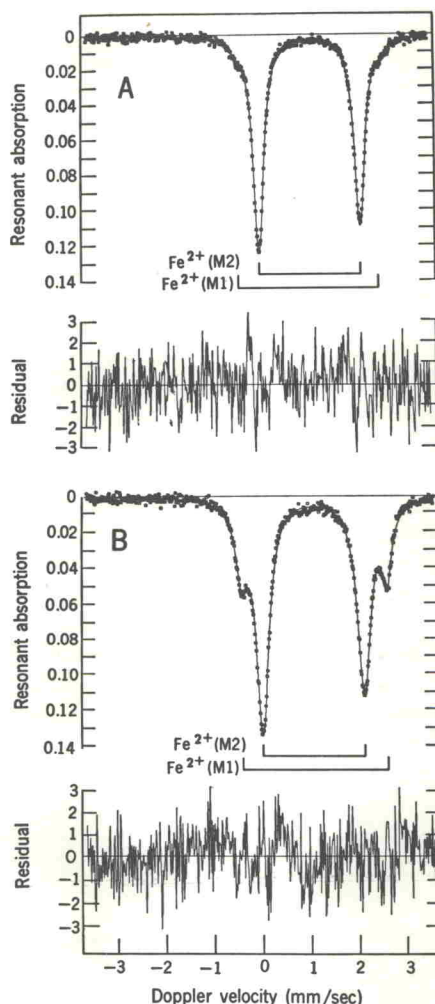The Mössbauer absorption lines of all specimens except one of the speci-

Fig. 1. Mössbauer spectra (^{57}Fe) of natural (A) and shocked (B) Bamle enstatite. The solid line is a least-squares fit to the data on the assumption of four Lorentzian lines. The count rate per data point is $\sim 1 \times 10^6$ (500 points). The deviations are shown as "residuals" below the spectra. Typical average χ^2 values per data point are between 1.0 and 1.5 units.

mens shocked to 1000 kb (Table 1, specimen 5) show typically small widths of 0.27 to 0.30 mm/sec. Such widths are characteristic for well-crystallized solids. They indicate that the shock left the short-range periodicity of the lattice relatively undisturbed. This conclusion is confirmed by the absence of any anomalous optical effects. No optically isotropic regions, microstructures, or any other features indicative of shock were found in a thin section made from one of the specimens shocked to 1000 kb. Specimen 5 exhibits somewhat broadened lines of 0.30 to 0.33 mm/sec as well as the maximum cation disorder observed in our samples. This sample was taken from the rim of the shocked disk, where it may have been quenched more rapidly than other portions of the disk. The increase in line width may indicate the onset of short-range lattice disorder. The increase in line width is much too small to be interpreted in terms of partial vitrification (8).

The x-ray diffraction patterns of the specimens shocked to 1000 kb reveal considerable loss of long-range periodicity in the lattice as indicated by the diffuseness of the lines, whereas the lines of the specimens shocked at lower intensities are not markedly diffuse. Detailed x-ray diffraction studies of these samples have been reported by Pollack, who compared them with patterns of meteoritic pyroxenes (9). In contrast, our Mössbauer spectra have narrow line widths and nearly invariant isomer shifts and quadrupole splittings (Table 1). These parameters are primarily determined by the local environment of the Fe atoms within the unit cell and are not critically affected by lattice disorder as long as the undisturbed single-crystal domains comprise dimensions of a few unit cells. The effect of stacking disorder on the quadrupole splittings is small.

On the basis of the results presented here, we conclude that the shock intensity barrier above which the cation distribution in pyroxenes will be affected is somewhere between 450 and 1000 kb. Pyroxenes from intensely shocked meteorites or lunar basalts are therefore expected to be disordered, and, as a result, the thermal record prior to the event will have been erased.

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