Quartz is perhaps the most useful mineral in the recognition of impact structures, because of its abundance, distribution, and durability, together with the fact that, in impact structures, it is the major host for the high-pressure minerals coesite and stishovite (Chao *et al.*, 1960, 1962). Figure 4 shows typical patterns obtained from quartz shocked by high explosives and by the impact which formed Meteor Crater, Arizona. In Figure 4C are seen the strongly "asterized" spots of the host quartz crystal as well as fainter powder arcs of coesite formed by the shock. A greater amount of coesite apparently occurs in the more severely deformed quartz crystal (Fig. 4D). The severity of asterism produced by the impact is remarkable.

Asterism is defined by Guinier (1952, p. 192–194) as the solid angle within which the normals to a family of lattice planes of a single crystal are to be found after deformation. The solid angle containing plane normals from the mosaic blocks of perfect single crystals is small, and a small spot is therefore produced on the film. As this solid angle increases, because of deformation or fragmentation, the diffraction spot becomes larger, and, in Debye–Scherrer geometry, the diffracted spot becomes longer along an arc of constant 2θ. It is this length which provides a measure of asterism.

Consider now a crystal of constant volume: the more numerous are the blocks into which it has been broken, the more chance there is for *any*, and *every* set of plane normals to describe large solid angles. This effect, together with the effects of specimen rotation and multiplicity of reflections, causes the scattered diffraction spots to merge and to produce a typical "powder arc" pattern as block sizes approach the lower limit still capable of diffraction.

Asterism in single-crystal diffraction patterns is usually associated, not with the Debye–Scherrer method, but with the Laue method of diffraction. Metallurgists have used the latter for decades to study deformation in metals. Bailey *et al.* (1958) used the Laue method in a study of polygonization in quartz; using the same method, we have also found diffraction effects consistent with those which they reported. However, we have emphasized the Debye–Scherrer technique for the following reasons:

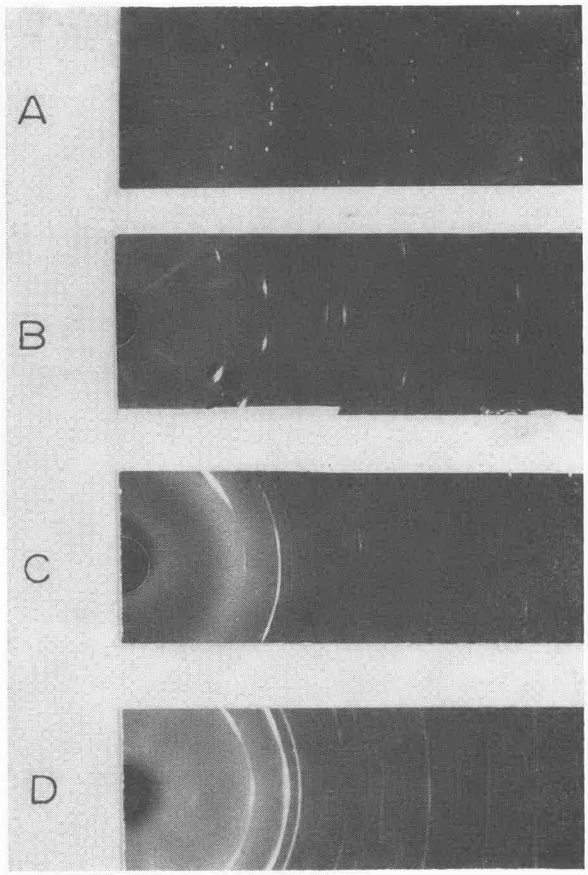

Fig. 4. X-ray diffraction patterns of quartz crystals: (A) typical, undeformed; (B) subjected to 1000 lb. TNT blast; (C) and (D), from Coconino sandstone, Meteor Crater, Arizona. Notice, in (C) and (D), the complete powder arcs of coesite (just to right of the strongest quartz reflection) associated with pronounced asterism of the quartz.

(1) It is simpler and faster, since exact orientation of the specimen is not necessary. Grains from many shocked rocks are small and anhedral, and many have indefinite crystal orientations under polarised light.

(2) Our primary aim was to detect and to qualitatively compare the extent of internal deformation in crystals, but not to investigate in detail the complex mechanisms inducing rupture of crystals within aggregates under shock conditions. However, study of specific mechanisms of

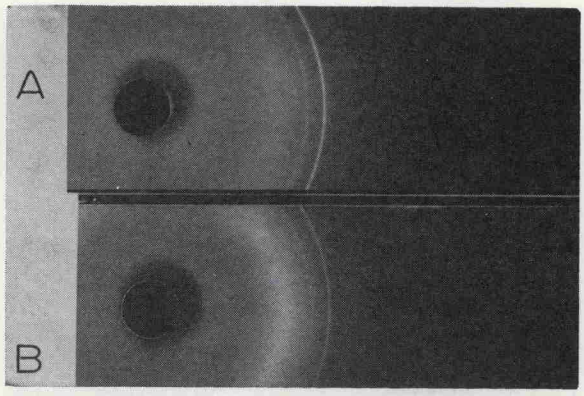

Fig. 5. X-ray diffraction patterns of coesite, identified in single grains in a specimen of shocked rock collected as ejecta from the Sedan nuclear cratering event (A, upper) compared with synthetic coesite (B, lower). In addition to the two strong reflections, there is good agreement with several weaker reflections that are clearly evident in the original films.

shock damage, using carefully controlled materials and conditions, may be facilitated with the use of the Laue method.

(3) The Debye–Scherrer method is highly effective for identification of minerals and also makes possible a sensitive scanning of host crystals for the presence of minor amounts of polymorphs or alteration products formed as a consequence of shock.

This last advantage is demonstrated by our detection of coesite in rocks from the Sedan nuclear event. To our knowledge, this is the first positive identification of coesite at the site of a nuclear explosion (Short, 1965).[1] We could not find the mineral by microscopic examination of thin sections or grain mounts, nor was it observed by standard x-ray powder diffraction methods of powdered bulk sample.

The coesite was found in a portion of the surface of the rock specimen which was finely crushed and compacted to a depth of about 2 mm. Most of this material was white and "sugary," but included a few scattered grains having a pale orange color. The latter amounted to about 0.1 volume percent. Under the microscope, both the white and orange grains appeared to consist of highly compacted, very fine fragments. Very few of the grains were transparent. Coesite was found only in the orange colored grains by means of the "single crystal" x-ray diffraction method. The diffraction patterns obtained are identical with that of a powder of coesite prepared in this laboratory (Fig. 5). The white grains gave diffraction patterns characteristic of "glass" or of polycrystalline quartz (with traces of unidentified minerals). By emission spectroscopy it was found that the white and orange grains did not differ noticeably in their elemental content.

No orange grains were found in the bulk of the sample which was very friable, although it had a granular texture similar to unaltered granite or granodiorite. The asterism of quartz crystals from the interior portion of the sample was pronounced, indicating exposure to severe shock.

It is suspected, from the appearance of the compacted portion of the surface and its relation to the bulk of the specimen, that the coesite was formed by the shock in a pre-existing fracture in the massive rock.

A second parameter useful in the assessment of damage sustained by crystalline materials is the width of the x-ray diffraction spot or line in the direction of 2θ. In a nominally "perfect" crystal, the blocks making up its mosaic structure are 2000 A to 20,000 A on edge. Theoretically, the width of diffraction spots from such crystals is of the order of 0.01 mm. However, because of the overlaid effects of sample, camera, and incident beam geometries, the actual width is closer to the 0.2 mm calculated for 500 A blocklets. Therefore, without rigid control of many factors, this method is not accurate for determining polygonization down to the 500 A range, and is even less so for blocklets of about 25 A or less. Although accuracy may be wanting, the procedure is sensitive enough to register spot broadening. It is noteworthy that, of hundreds of crystals examined, not one produced the very

[1] [*Editor's note.* Coesite has previously been identified in ejecta from the Scooter 500-ton conventional high explosive cratering test at the Nevada test site; it is estimated that peak pressures in this explosion reached 150 kb. (Milton, D. J., J. Littler, J. J. Fahey, and E. M. Shoemaker, Petrography of glassy ejecta from the Scooter 0.5-kiloton high-explosive cratering experiment, Nevada. *U.S. Geol. Survey Astrogeol. Studies Semiann. Progr. Rept., Feb. 26, 1961 to Aug. 24, 1961* (*March, 1962*), 88–92, 1962.]