diffraction examination. Typical patterns obtained are shown in Figures 2 (B, C, D, E), 8, and 9.

The increase in asterism with increasing pressure is evident, and the similarity to asterism found in shocked specimens is noteworthy (compare Fig. 8 and Fig. 4). Calcite and albite behaved similarly, but, at pressures above 90 kb, the crystals were fragmented into particles too small to be x-rayed effectively by this method. This fragmentation is attributed chiefly to cleavages in these minerals. Pressure experiments also were made using cut wafers of well-cemented Tuscarora quartzite and of mica.

Figure 10 shows the change in the Asterism/Line Breadth ratio with pressure observed for both quartz powder compacts and quartzite wafers. As expected, grains from the edge show a somewhat greater change, the reason being that, during compaction, these grains are displaced more than those at the center because of greater marginal shearing stresses. This result is consistent with the lower values obtained using wafers of Tuscarora quartzite, in which relative motion of grains is minimized by the tight cementation. Figure 10 also shows effects of varying rates of pressurization. Apparently, during rapid pressurization to about 60 kb, the deformation at grain contacts necessary to produce zero porosity in the wafer produces more local stress concentrations and asterism than are produced at slower pressurization rates. Above this pressure, the greatest part of the porosity has been eliminated, and relatively less lateral displacement, and less asterism, is caused by higher rates of pressurization.

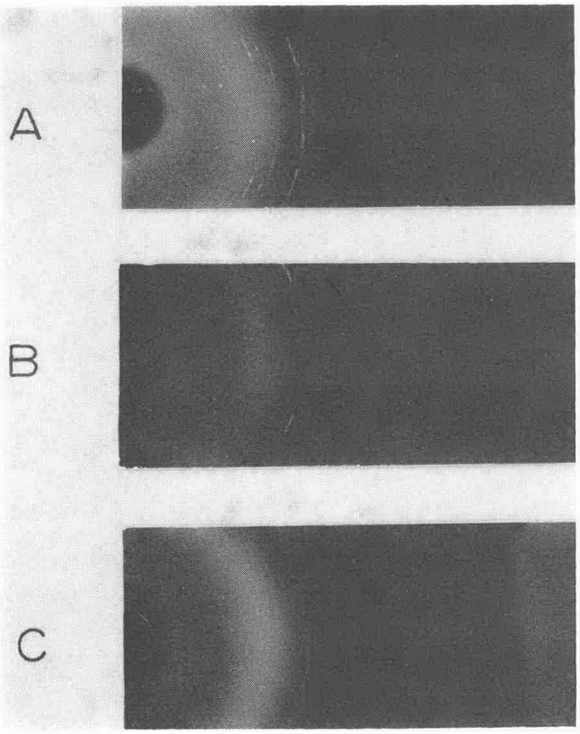

Fig. 9. Progressive asterism developed in albite grains from polycrystalline compacts with increasing pressures: 30 kb (A), 60 kb (B), 90 kb (C).

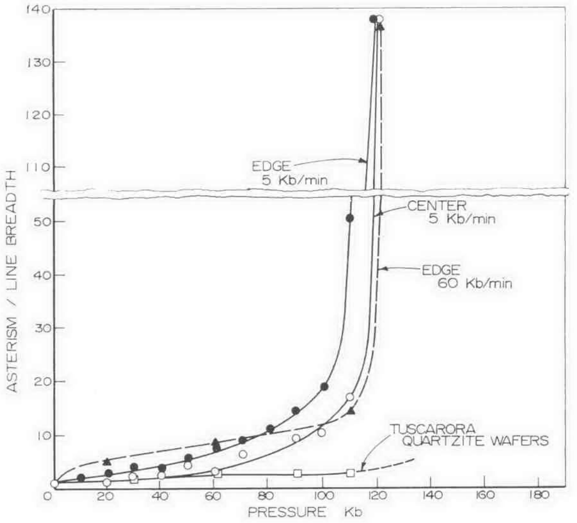

Fig. 10. Changes in Asterism/Line Breadth ratios of grains from polycrystalline quartz compacts and from well-cemented quartzite wafers as a function of applied pressure.

Results obtained for granodiorite samples from different pressure zones of the Hardhat nuclear explosion (Short, 1966) and from a granodiorite boulder subjected to more than 150 kb peak shock pressure during the Sedan cratering event are plotted in Figure 11. They illustrate the combined effects of competent rock types and of very high pressurization rates by their divergence from the opposed-anvil results.

Discussion of experimental work with opposed-anvil, high-pressure techniques never fails to raise remarks that, (1) the pressures are not "hydrostatic," (2) shear stresses may support very pro-

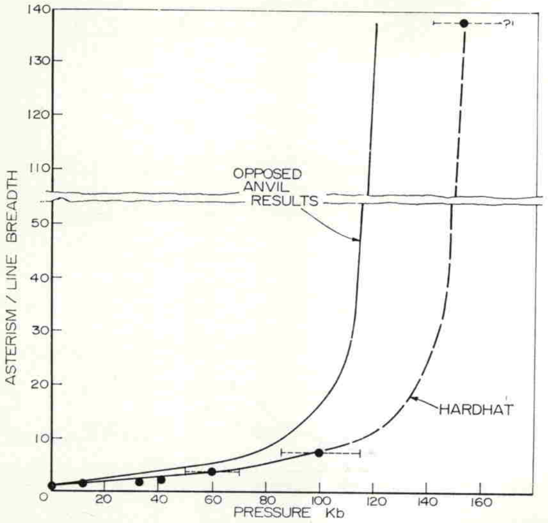

Fig. 11. Asterism/Line Breadth ratios from opposed-anvil pressurization experiments compared with data from material from known pressure zones of the Hardhat and Sedan nuclear explosions (Short, 1966). The horizontal dashed lines give the estimated pressure error (N. M. Short). The point plotted at 150 kbars is for the Sedan event for which the upper limit of pressure is not known. The other plotted points are for the Hardhat samples.

nounced pressure gradients in the samples, and (3) that shear stresses somehow change the reactions. This is hardly the place for an extended discussion of subjects which have been the concern of several high pressure conferences, but the following comments can be made. In no experimental system using bulk solid media to generate high pressures for solid state reactions can it be said that ideally hydrostatic conditions prevail. The problems of calibration of pressure against applied load are serious complications in all such apparatus. In any polycrystalline material, cemented or not, neither stress nor strain will be uniform on a grain-to-grain basis in the early stages of response to an applied force. This condition prevails in both opposed-anvil apparatus and in geological systems. As for pressure gradients in wafers, we are aware of this problem, having made studies for their control or elimination (Myers *et al.*, 1963).

The effect of shearing stresses on reactions has also been investigated in this laboratory (Dachille and Roy, 1964). The major findings are: (1) reaction rates are generally increased, probably through lowering of the activation energy in a shear stress system, (2) the increase in reaction rates is roughly equivalent to that which would be obtained by an increase of about 100° to 200°C in temperature, and (3) equilibria are not displaced significantly.

It may be concluded that the pressure history of an individual grain in a polycrystalline mass cannot be known in detail. The asterism in a crystal reflects the sum of all disturbing influences up to and during pressurization, and from the consistency evident in Figures 10 and 11, the sum is dependent on pressure. In Figure 12, the data for quartz from opposed-anvil and shock pressure experiments are plotted on the scale of Figure 6. The strong coincidence between experimental data and the measurements on natural samples indicates similarities in causes and effects. The scales constructed from the opposed-anvil and shock results allow some estimation of the approximate pressures of shock metamorphic processes.

Shock events in porous or poorly-cemented sandstones, tuffs, etc. will tend toward the values for opposed-anvil results, whereas events in strong, well-cemented rocks such as quartzites and granodiorites can be estimated from the Hardhat-Sedan data (Fig. 12). The comparatively low values for Sudbury shatter cone samples, aside from the possibility of recrystallization, may arise from the highly competent nature and great depth of the host rocks at the time of impact.

Figure 7 shows a comparison of results from opposed-anvil pressure experiments on calcite with values obtained from various limestone and shatter cone samples.

A comparison of the Asterism/Line Breadth values of crystals from the unaffected host formation and from a disturbed region in the host formation can be helpful in determining the nature and intensity of the disturbance. For example, the results of a dozen quartz crystals taken from Coconino sandstone outside Meteor Crater cluster close to the values $A/LB = 2.1$ and $A = 0.84$, whereas shocked quartz crystals from boreholes within the crater ranged to the upper limits of the scales. Similar relations were observed in samples of dolomite (Bonanza King