pression axis) is inclined 45° to e_1,[9] or to the normal to e_1, and 71° to c_v; and σ_3' (extension axis) is inclined 45° to e_1, or to the normal to e_1, and 19° to c_v. For any calcite grain, therefore, the positions of σ_1' and σ_3' for $S_0 = 0.5$ can be determined (fig. 2, *b*) by measuring and plotting e_1 and c_v. This technique was applied to the study of naturally deformed marbles by Turner (1953), McIntyre and Turner (1953), Gilmour and Carman (1954), and Weiss (1954). These workers concluded that the calcite twin lamellae developed during the last stages of deformation. Crampton (1958) and Christie (1958) extended the technique to deformed dolomites utilizing the information on the glide mechanisms in dolomite determined by Handin and Fairbairn (1955), Turner, Griggs, Heard, and Weiss (1954), and Higgs and Handin (1959). Hansen *et al.* (1959) studied deformed calcite cement in three oriented specimens of folded Oriskany sandstone. They found that the compression axes deduced from the best-developed sets of *e* twin lamellae were grouped essentially normal to the fold axis. This is the first published account of the use of this technique on a sedimentary rock.

FRACTURE

Many theoretical and experimental studies on fracturing are available dating from the early work of Coulomb (1776) to the current experimental studies of Handin and of Griggs. The following discussion pertains to microfractures[10] as well. Two kinds of fracture (extension and shear) are recognized (Griggs and Handin, 1960), and each bears consistent geometric relationships to the three principal stresses (fig. 3). Extension fracture is characterized by displacement normal to the fracture surface at the time of formation, and is oriented parallel to σ_1 and σ_2 and perpendicular to σ_3, as shown in figure 3, *A*. Shear fracture is characterized by shearing displacement along the fracture surface at the time of formation, and is inclined in rocks approximately 30° to σ_1 and 60° to σ_3, and is parallel to σ_2, as shown in figure 3, *B*. Theoretically, two sets of shear fractures form a conjugate system, with an included angle of approximately 60° which is bisected by σ_1. The angle between a shear fracture and σ_1 varies within narrow limits. Handin and Hager (1957, 1958) show that in seventy compression experiments this angle ranges from 25° to 35° in two-thirds of the cases and from 20° to 40° in nearly all the cases. Although no completely satisfactory theory of rock fracture has been found up to the present time, the Coulomb-Mohr, or "internal-friction," theory best predicts the empirical results. Accordingly, from both theoretical and experimental considerations, the genetic relationships between the types of fractures and the principal stresses are known qualitatively.

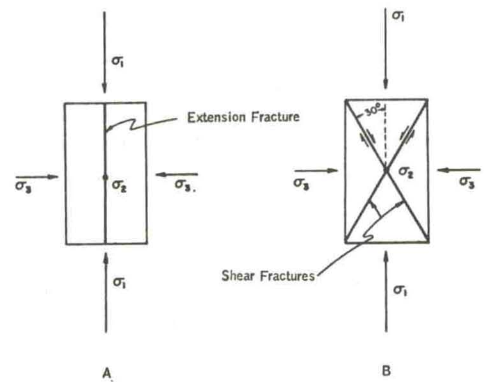

FIG. 3.—Orientation of fractures with respect to principal stress directions. *A*, extension fracture; *B*, shear fractures.

QUARTZ-DETRITAL GRAINS

Previous studies of the deformation of sand and sandstones have dealt primarily

[9] By convention the three twin planes in each calcite crystal are designated as e_1, e_2, and e_3; e_1 is identified as the plane of highest spacing index and/or widest-developed lamellae, and e_3 is identified as the plane of lowest spacing index and/or least-developed lamellae. In a calcite crystal in which at least one set of twin lamellae is developed (e_1), the positions of the other two potential sets can be determined.

[10] The term "microfracture" is used to denote a fracture or fault within an individual detrital grain. The scale of the feature is determined by the grain size.

with quartz-rich aggregates. Work on the other common detrital elements as such is lacking. Data on the strength of quartz is reviewed in detail in Griggs, Turner, and Heard (1960, p. 67, fig. 12) and in Borg, Friedman, Handin, and Higgs (1960, p. 181). What is generally important here is that the strength even of unconfined quartz is enormous. The fact that grains in quartz aggregates can be broken under relatively small loads applied to the aggregate as a whole implies great stress concentrations in the individual grains.

Fracturing is the most conspicuous deformation mechanism in quartz detrital grains.[11] Griggs and Bell (1938), Fairbairn (1939), Ingerson and Ramisch (1942), Anderson (1945), Rowland (1946), Borg and Maxwell (1956), Bloss (1957), and Borg, Friedman, Handin, and Higgs (1960) have described fractures in a variety of quartz occurrences in both experimentally and naturally deformed environments. Their data indicate a tendency of quartz to fracture primarily parallel to $r\{10\bar{1}1\}$, $z\{01\bar{1}1\}$, $c\{0001\}$, $m\{10\bar{1}0\}$, and $a\{11\bar{2}0\}$. Recently, Christie, Heard, and LaMori (1960) have experimentally deformed single quartz crystals at 25 kilobars confining pressure in a bismuth medium and at room temperature. The crystals failed by faulting parallel to $c\{0001\}$, $r\{10\bar{1}1\}$, $z\{01\bar{1}1\}$, and rarely parallel to $m\{10\bar{1}0\}$ and $a\{11\bar{2}0\}$, respectively, even though these planes were not necessarily oriented favorably for shear fracturing. In experimentally deformed loose, dry sand aggregates. Borg and Maxwell (1956, p. 77) found that (1) the microfractures radiate from grain contacts, (2) the quartz tends to fracture primarily parallel to *r* and *z*, and (3) the microfractures tend to lie approximately 15° to the known position of σ_1. In a study of deformed St. Peter sand aggregates, Borg, Friedman, Handin, and Higgs (1960, p. 165–181) also found that quartz has a certain tendency to fracture parallel to *r* and *z*. More important, they demonstrated that the microfracture orientation patterns are nearly random in undeformed samples and in specimens subjected to uniform confining pressure only. In compression and extension experiments, however, the microfracture patterns exhibit a definite relationship to the principal stresses across the boundaries of the specimens and indicate that both shear- and extension-type fractures had formed. Bonham (1957) has made a descriptive study of microfractures in the quartz grains of the Miocene and Pliocene sandstones in the Pico anticline, Los Angeles County, California. He found that microfracture maxima correlate well with other geometric features of the anticlinal structure.

The evidence to date indicates that fracture in quartz tends to be controlled by two factors: (1) the crystal structure and (2) the orientation of the principal stresses across the boundaries of the specimens. In most of the experiments and studies mentioned above it is difficult to evaluate which of these factors is the more important. Certainly, the latest experiments of Christie, Heard, and LaMori (1960) conclusively demonstrate that the quartz structure controls the fracturing in deformed single crystals. Yet it has been a moot question which factor is more important in the quartz-sand aggregate. The present study adds to the understanding of this problem.

Methods of Study

Optical Measurements and Plotting of Data

All measurements are made with the aid of a petrographic microscope equipped with a Zeiss-Winkel universal stage and object traverser. The probable error in locating c_v by optical means is $\pm 2°$. Lamellae and microfractures can be located to within 1° when they are inclined to the plane of the section at angles greater than 70°. For inclinations of 30°–70°, the error may be $\pm 2°$. The total probable error in the position of any fabric element with respect to the known load axes is due to (1) fabrication of

[11] Other mechanisms of deformation that give rise to, e.g., undulatory extinction and deformation lamellae are not discussed here because these features were not produced in the deformed specimens of the current study.