form confining pressure simulating 15,000 feet of overburden, is highly significant. It indicates that uniform pressure alone cannot produce twinned calcite cement or fractured detrital grains in these rocks. Accordingly, the microfeatures suggest the influence of differential loading, that is, tectonism.

RELATIONSHIP OF PRINCIPAL STRESS ORIENTATIONS AND OBSERVED MICROFRACTURES

Stresses must be transmitted to the individual grains of a sand aggregate through grain contacts. Borg and Maxwell (1956) found that microfractures tended to radiate from point contacts in deformed unconsolidated sand, but in the cemented materials the microfractures are principally of the extension type and tend to transect grains. They are clearly related to the known principal stress axes across the whole rock rather than to local stress concentrations at grain contacts. These results hold at least over the 0–18 per cent porosity range.

STRESS-STRAIN RELATIONSHIPS

At what differential stress will these deformation features began to develop? As mentioned in the section on previous work, experiments on calcite single crystals have established that the critical resolved shear stress to induce twinning on *e* is low. On the other hand, the breaking strength of quartz in short-time tests at atmospheric pressure and room temperature is extremely high. One might suppose, therefore, that in deformed calcite-cemented sandstones, calcite would twin in response to a very small differential stress, and that quartz would fracture only under a large load. The present work amply demonstrates that this need not be so.

In this regard, it is instructive to compare the stress-strain curves for sand crystals (fig. 4) and calcite-cemented sandstones (fig. 13). In the former, the detrital grains tend to "float" (the average number of contacts per grain in thin section is 0.71) in the calcite crystal, and the porosity approaches zero. In the latter, the higher number of contacts per grain and the higher porosity suggest that calcite tends to occupy interstitial areas surrounded by voids and detrital grains in contact. These differences are reflected by the different shapes of the stress-strain curves from the origin to the onset of yielding. The calcite-cemented sandstones exhibit **S**-shaped curves (fig. 13), which, according to Handin (personal communication), are characteristic of porous rocks deformed under moderate confining pressures. The application of differential pressure collapses pore spaces, so that the initial strain is relatively large. Thereafter, the rock is strained essentially elastically to the yield stress. No visible permanent deformation need be associated with these events. Specimen 763 exhibits a typical **S**-shaped curve, has obtained a maximum differential stress of 1,160 bars at 1,000 bars confining pressure, and yet contains no twin lamellae in the cement or fractures in the detrital grains. These microfeatures are present, however, in specimen 745, which also exhibits an **S**-shaped curve but has obtained a maximum differential stress of 1,690 bars at 2,000 bars confining pressure. Accordingly, microfeatures develop in these extension experiments at differential stresses of between 1,200 and 1,700 bars, if the difference between the confining pressures of the two experiments can be neglected. In the compression experiments permanent deformations are not important until the yield stresses are attained. Accordingly, in specimens 762 and 725 (deformed at 1,000 bars confining pressure and 150° C.), microfeatures begin to form at differential stresses of 4,500 and 4,800 bars, respectively. At higher temperatures, the yield stresses are lower—1,500 and 2,000 bars for specimens 778 and 780, respectively. Clearly, the nature of the tectonic environment would greatly affect the magnitude of the differential stress at which permanent deformation in the rock would begin.

The stress-strain curves for the sand-crystal experiments (fig. 4) show linear relationships between stress and strain up to the yield stresses. Since the porosity of the sand crystal is essentially zero, an **S**-shaped curve would not be expected. Generally, for the same experimental conditions, permanent deformations were recorded at lower differential stresses in the sand-crystal specimens than in the calcite-cemented sandstones. For example, specimen 878 (sand crystal), which was deformed under the same conditions as specimens 762 and 725 (sandstones), exhibits microfeatures in the calcite and in the detrital grains and yet has obtained a maximum differential stress of only 515 bars.

It is reasonable to conclude that the calcite cement in the sandstones tends to be "protected" by surrounding detrital grains in contact. Twinning occurs in the calcite only after the detrital grains begin to fracture. The grains fracture under relatively small loads on the aggregate as a whole, because the stress concentrations at points of contact are very large. However, perhaps surprisingly, the fractures do not radiate from points of contact, but form as if each grain reacted to the forces applied to the aggregate in bulk. From this reasoning, it also follows that for the same confining pressure, twinning and grain-fracturing should take place in the sand crystals at lower differential stresses. Since the grains tend to "float" in the crystal, the calcite is "unprotected" and twins in response to smaller loads. In addition, the detrital grains exhibit fewer contacts per grain, so that the stress concentrations per contact are higher. This permits the grains to fracture at lower differential stresses on the aggregate as a whole.

In the experimentally deformed materials, both the twin lamellae in the calcite cement and the fractures in the detrital grains developed concomitantly in response to the same simulated tectonic conditions.

Summary and Conclusions

The consistent results from experimentally deformed sand crystals and Tensleep and Supai calcite-cemented sandstones indicate that, statistically, both the calcite cement and the detrital grains deform in response to the principal stresses across the boundaries of the specimen as a whole rather than to local stress concentrations at grain contacts. The facts that lead to this conclusion are:

1. The most conspicuous feature of deformed calcite is twin lamellae that develop parallel to $e\{01\bar{1}2\}$.

2. The twin-lamellae spacing index increases with increased strain of the specimen (table 1). This effect is clear when different specimens or differently strained parts of the same specimen are compared (e.g., specimen 911).

3. Resolved shear-stress coefficient data indicate that (*a*) 74 per cent of the best-developed set of lamellae (e_1) form with respect to the load on the specimen as a whole, (*b*) the average resolved shear-stress coefficient on e_1 lamellae is 0.27, and (*c*) the reliability of correctly identifying e_1 lamellae is good in specimens with spacing-index values less than 250. In more highly deformed specimens (e.g., specimen 780) identification of true e_1 lamellae is more difficult (table 2).

4. Orientations of principal stresses deduced from e_1 lamellae are in good agreement with the known orientations (fig. 16, *a–d*).

5. Strain calculated from rotated lamellae correlates with that measured experimentally (e.g., specimen 877).

6. The majority of microfractures in all specimens are oriented perpendicular to σ_3; that is, they are extension fractures (figs. 5, 7, and 14).

7. Microscopic and macroscopic shear zones are inclined at approximately 30° to σ_1 (pls. 2*B*, *c*, and 4).

8. The fracture index increases with increased strain of the specimen (table 1).

9. Orientation and spacing of microfractures tend to be independent of mineralogy, particularly in the sand crystals, where quartz and feldspar grains occur in about equal abundance.

10. The marked relationship between microfractures and principal stresses greatly overshadows the slight tendency for microfractures in quartz grains to parallel *r* and *z*. Accordingly, these microfractures are little affected by crystallographic control.