INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps.

ProQuest Information and Learning
300 North Zeeb Road, Ann Arbor, MI 48106-1346 USA
800-521-0600

UMI®
Petrofabric Analysis of Experimentally Deformed Calcite-Cemented Sandstones

by

Melvin Friedman

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

Doctor of Philosophy

Houston, Texas
May, 1961

approved by

John J. W. Rogers
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>1</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>2</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>4</td>
</tr>
<tr>
<td>BASIC PRINCIPLES</td>
<td>4</td>
</tr>
<tr>
<td>Twin Gliding</td>
<td>4</td>
</tr>
<tr>
<td>Fracture</td>
<td>6</td>
</tr>
<tr>
<td>Extension Fracture</td>
<td>6</td>
</tr>
<tr>
<td>Shear Fracture</td>
<td>8</td>
</tr>
<tr>
<td>PREVIOUS WORK</td>
<td>9</td>
</tr>
<tr>
<td>Calcite</td>
<td>9</td>
</tr>
<tr>
<td>Quartz - Detrital Grains</td>
<td>14</td>
</tr>
<tr>
<td>Strength</td>
<td>14</td>
</tr>
<tr>
<td>Fracture</td>
<td>15</td>
</tr>
<tr>
<td>Gliding, Undulatory Extinction, and Deformation Lamellae</td>
<td>19</td>
</tr>
<tr>
<td>METHODS OF STUDY</td>
<td>19</td>
</tr>
<tr>
<td>Optical Measurements and Plotting of Data</td>
<td>19</td>
</tr>
<tr>
<td>Technique for Dynamic Interpretation of Calcite Twin Lamellae</td>
<td>21</td>
</tr>
<tr>
<td>Technique for Dynamic Interpretation of Microfractures</td>
<td>22</td>
</tr>
<tr>
<td>SAND CRYSTALS</td>
<td>24</td>
</tr>
<tr>
<td>Undeformed Sand Crystals</td>
<td>24</td>
</tr>
<tr>
<td>Deformation Favorable for Twin Gliding</td>
<td>25</td>
</tr>
<tr>
<td>Experimental Deformation</td>
<td>25</td>
</tr>
<tr>
<td>Petrographic Observations of Deformed Specimens</td>
<td>25</td>
</tr>
<tr>
<td>Specimen 878</td>
<td>28</td>
</tr>
<tr>
<td>Specimen 915</td>
<td>28</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
</tr>
<tr>
<td>-------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Specimen 877</td>
<td>28</td>
</tr>
<tr>
<td>Specimen 911</td>
<td>30</td>
</tr>
<tr>
<td>Deformation Unfavorable for Twin Gliding</td>
<td>36</td>
</tr>
<tr>
<td>Experimental Deformation</td>
<td>36</td>
</tr>
<tr>
<td>Stress-Strain Relationships</td>
<td>38</td>
</tr>
<tr>
<td>Petrographic Observations and Comparisons</td>
<td>39</td>
</tr>
<tr>
<td>Discussion</td>
<td>44</td>
</tr>
<tr>
<td>CALCITE-CEMENTED SANDSTONES</td>
<td>45</td>
</tr>
<tr>
<td>Undeformed Tensleep Sandstone</td>
<td>45</td>
</tr>
<tr>
<td>Undeformed Supai Sandstone</td>
<td>46</td>
</tr>
<tr>
<td>Experimental Deformation</td>
<td>46</td>
</tr>
<tr>
<td>Petrographic Observations of Deformed Specimens</td>
<td>50</td>
</tr>
<tr>
<td>Specimen 724</td>
<td>50</td>
</tr>
<tr>
<td>Specimen 763</td>
<td>50</td>
</tr>
<tr>
<td>Specimen 745</td>
<td>50</td>
</tr>
<tr>
<td>Specimens 762, 725, 778, and 780</td>
<td>52</td>
</tr>
<tr>
<td>DISCUSSION OF RESULTS</td>
<td>57</td>
</tr>
<tr>
<td>Relationship between Principal Stress Orientations and Observed Twin Lamellae</td>
<td>57</td>
</tr>
<tr>
<td>Relationship between Principal Stress Orientations and Observed Microfractures</td>
<td>63</td>
</tr>
<tr>
<td>Stress-Strain Relationships</td>
<td>63</td>
</tr>
<tr>
<td>SUMMARY AND CONCLUSIONS</td>
<td>66</td>
</tr>
<tr>
<td>APPENDIX I - CRYSTALLOGRAPHIC NOTATIONS</td>
<td>69</td>
</tr>
<tr>
<td>Forms, Planes, and Letter Symbols</td>
<td>69</td>
</tr>
<tr>
<td>Zone Axes</td>
<td>69</td>
</tr>
<tr>
<td>APPENDIX II - GLOSSARY</td>
<td>73</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>79</td>
</tr>
</tbody>
</table>
PETROFABRIC ANALYSIS OF EXPERIMENTALLY DEFORMED
CALCITE-CEMENTED SANDSTONES

ABSTRACT

Cylinders of sand crystals, composed of single crystals of calcite that poikilitically enclose detrital grains, and calcite-cemented sandstones from the Tensleep (Pennsylvanian, Wyoming) and Supai (Permian, Nevada) formations were experimentally deformed dry at confining pressures of 1-5 kilobars and temperatures of 150°-300°C. Thin sections of the undeformed and deformed specimens were studied microscopically to gain a better understanding of the behavior of sandstones in simulated tectonic environments. The calcite and the detrital grains (quartz, feldspar, and others), which have radically different physical and mechanical properties, are shown statistically to have deformed with respect to the principal stresses across the boundaries of the whole specimens rather than with regard to local stress concentrations at grain contacts.

The deformation mechanisms of calcite and quartz are the same in the sandstones as in monomineralic aggregates, e.g., marbles and quartz sands. Statistically, twin lamellae are developed in those calcite grains which are favorably oriented for twin gliding with respect to the load axes. The resolved shear-stress coefficient for these twin planes averages 0.27. Compression and extension axes deduced from the best developed set of twin lamellae in each calcite grain (Turner, 1953) yield derived positions for the principal stress axes that are in excellent agreement with those known from the experiments. In addition, the number of lamellae per millimeter increases with increased strain of the specimens.
Quartz, feldspar, rock fragments, and garnet grains comprise the bulk of the detrital material. These deform primarily by fracturing. The microfractures in the grains are nearly planar features which, because of their geometric relationship to the known principal stress directions, are recognized as extension and shear fractures. They develop independently of the grain mineralogy and, in quartz grains, greatly overshadow a slight tendency for fractures to parallel \( \{10\bar{1}1\} \) and \( \{01\bar{1}1\} \). The degree of fracturing in a specimen, expressed as a fracture index, tends to increase with increased strain of the specimen. In sand crystals loaded unfavorably for twin gliding in the calcite crystal, extension fracturing in the detrital grains causes local reorientation of the stresses and produces twin lamellae in the adjacent calcite.

Twin lamellae in calcite and fractures in detrital grains are shown to be criteria for simulated tectonism. The development of lamellae and microfractures is directly related to the orientations of the principal stresses in heterogeneous, sedimentary rocks at the time of deformation.

**INTRODUCTION**

Structural configurations are dependent upon stress conditions in rocks during tectonic events. This has been demonstrated theoretically by the treatments of Anderson (1951), Hafner (1951), Hubbert (1951), Hubbert and Rubey (1957 and 1959), Odé (1957), and Sanford (1959), to name a few. Moreover, the fact that the behavior of rocks with respect to states of stress and other tectonic environmental factors can be predicted has been experimentally demonstrated primarily by the studies of Griggs (1936, 1938, 1939, 1951a, 1951b, 1953, 1960a, and 1960b),
Handin (1951, 1953, 1955, 1957, 1958), and their associates. Until recently, however, it has not been possible to augment these treatments by direct determination of the principal stress orientations in rocks at the time of deformation. Petrofabric techniques, based upon detailed knowledge of the mechanisms of deformation in a number of commonly occurring minerals, now permit such determinations. Some of these techniques have been applied successfully to the study of monomineralic, metamorphic rocks (Turner, 1953; McIntyre and Turner, 1953; Gilmour and Carman, 1954; Weiss, 1954; Crampton, 1958; and Christie, 1958).

The present study was designed to evaluate twin lamellae in calcite and fractures in detrital grains as sound criteria of deformation in deformed, heterogeneous, sedimentary rocks. If these microfeatures constitute a deformation record and can be used to obtain a stress pattern, a potentially valuable technique would be added to the tools of petrofabric analysis. It must be demonstrated, however, that these features are meaningful—that in a heterogeneous, porous aggregate, the individual mineral components react relative to the principal stresses across the boundaries of the rock as a whole rather than to local stress concentrations at grain contacts. Accordingly, experimentally deformed sand crystals and calcite-cemented sandstones were studied to evaluate the significance of the microfeatures in the calcite and quartz of these materials for which the stress situations across the boundaries of the specimens are known.
ACKNOWLEDGEMENTS

The writer wishes to thank D. V. Higgs and J. W. Handin of Shell Development Company for their guidance in initiating the study and for their helpful suggestions in the preparation of this paper. The writer is also grateful to J. J. W. Rogers of the Rice University for his suggestions and assistance. In addition, the writer wishes to thank J. W. Handin, R. V. Hager, Jr., and J. N. Feather for experimentally deforming the specimens studied in this investigation.

BASIC PRINCIPLES

The study is based upon the relationships between the three principal stresses (greatest, $\sigma_1$; intermediate, $\sigma_2$; and least, $\sigma_3$) and (1) twin gliding in calcite and (2) fractures in detrital grains such as quartz, feldspars, and rock fragments. Since the concept of stress and its application to geological problems have been treated by Anderson (1951) and by Hafner (1951), they need not be elaborated upon here. However, the relationships between the principal stresses and twin gliding and fracturing must be emphasized.

Twin Gliding

Mechanical twin gliding involves simple shear which takes place by movements along a series of parallel planes, in a fixed direction, and with a specific sense of shear. The glide planes are defined by layers of atoms in a crystal structure, the glide direction by rows of closely spaced atoms in the glide plane, and the sense of shear by minimum energy requirements. The magnitude of shear is constant for a given twin-gliding
system in a mineral. In this process of simple shear, volume remains constant, planes remain planes, straight lines remain straight lines, and spheres become ellipsoids.

Although twin gliding is known for a large number of minerals, calcite is used as the typical example. A schematic section through the calcite structure is shown in Figure 1. The plane of the section is normal to the twin plane $e_1$ and contains the glide line $[e_1:r_2]$\textsuperscript{1}. Layers of atoms or ions above the twin plane are displaced to the right from their original untwinned positions. The displacements are fixed in magnitude and in direction sense because (1) all positions in the twinned part of the lattice must be symmetrically disposed with respect to the host, and (2) energy requirements are minimal. Gliding in the opposite sense would require greater shear and is further prohibited by size and charge barriers. As a result of the gliding, the crystal structure and its optical properties are symmetrically arranged across the glide plane. This discontinuity in the lattice permits twin lamellae (layers of the crystal in the twinned position) to be easily recognized in thin section (Figure 2). For a more detailed treatment on the morphology of the twinning process, see Bell (1941), Mall (1954), Pabst (1955), and Higgs and Handin (1959), among others.

Twin gliding is dependent upon a critical resolved shear stress ($\tau_c$) on the twin plane, but is essentially independent of normal stress across the twin plane. For calcite, Turner et al. (1954, p. 889)

\textsuperscript{1}See Crystallographic Notations in Appendix I.
found $\tau_c$ at atmospheric pressure and room temperature to be $15 \pm 5$ kg/cm$^2$,
whereas measurements at 5000 and 10,000 atmospheres and room temperature
gave $\tau_c$ equal to $60 \pm 20$ kg/cm$^2$. They concluded that "normal stress on
the twin plane increases the critical resolved shear stress by less than
one percent of the normal stress." This means that twinning occurs most
readily on those twin planes where $\tau_c$ is highest. Geometrically then,
the load axes that would be most effective in causing twin gliding are
inclined at 45° to both the glide plane and the glide direction, i.e., at
a resolved shear-stress coefficient ($g_o$) of 0.5.$^{1}$ Moreover, since the
sense of shear is fixed, the directions of loading that will most
effectively produce twinning are restricted and can be uniquely located.
Fracture

Many theoretical and experimental studies on the nature of
fractures 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$^{2}$ as well. Two kinds of fractures
(extension and shear) are recognized (Griggs and Handin, 1960a), and each
bears consistent relationships to the three principal stresses.

Extension Fractures

Extension fractures are characterized by displacement normal
to the fracture surfaces at the time of formation. They are oriented
parallel to $\sigma_1$ and $\sigma_2$ and perpendicular to $\sigma_3$, as shown in Figure 3a.

$^{1}$For a detailed discussion with specific reference to calcite, see p. 21 in
section on Technique for the Dynamic Interpretation of Calcite Twin Lamellae.

$^{2}$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.
Figure 1 - Diagrammatic representation of a section through the calcite structure. Section is drawn normal to the $a_0$ axis. The structure is twinned on the $e_0$ plane, with the glide direction and the sense of shear indicated. $r_1$ and $f$ translation glide planes, glide directions, and senses of shear are also indicated.

Figure 2 - Development of e twin lamellae in a Precambrian marble. Diameter of the specimen is one-half inch.
Shear Fractures

Shear fractures are characterized by shearing displacement along the fracture surface at the time of formation. They are inclined in rocks approximately 30° to σ₁ and 60° to σ₃, and are parallel to σ₂, as shown in Figure 3b. Theoretically, there are two sets forming a conjugate system, with an included angle of approximately 60° which is bisected by σ₁. The angle between a shear fracture and σ₁ varies within narrow limits. Handin and Hager (1957 and 1958) show that in 70 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. Statistically, the angle is smaller in extension experiments, but the difference is small—about 5°. Although no completely satisfactory theory of rock

Figure 3 - Orientation of fractures with respect to principal stress directions. (a) Extension fracture. (b) Shear fractures.
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.

PREVIOUS WORK

Calcite

Knowledge of the deformation mechanisms in calcite has evolved from Brewster's observations of mechanical twins in 1826 to a firm understanding 125 years later of the glide systems operative in calcite under a wide range of pressure and temperature conditions. This knowledge has been gained primarily through comprehensive experimental studies of the deformation of calcite single crystals and marbles and by careful petrofabric analysis of the deformed materials (Knopf, 1949; Turner, 1949; Griggs and Miller, 1951a; Handin and Griggs, 1951; Turner and Ch'ih, 1951; Griggs et al., 1951b, 1953, 1960b; Borg and Turner, 1953; Turner et al., 1954a, 1956). As a result, flow in calcite can be primarily explained by three glide systems (Figure 1). These systems are (after Turner et al., 1954a):

1) Twin gliding parallel to \( e \{01\overline{2}\} \) with \( e_1 : r_2 \) as the glide direction, and with a positive sense of shear.\(^1\) This mechanism predominates over those listed below throughout the temperature range of 20°-800°C (Turner et al., 1954a; Griggs et al., 1960b).

\(^1\) Arbitrarily, relative displacement of the upper layers of the lattice upward toward the optic axis \( c_\gamma \) is called gliding in the positive sense; relative displacement of the upper layers downward from the upper end of the \( c_\gamma \) is called gliding in the negative sense.
2) Translation gliding on \( \mathbf{r} \{10\overline{1}1\} \) with \([r_1:r_2]\) as the glide direction, sense of shear negative. It is effective over the temperature range 20°-800°C.

3) Translation gliding on \( \mathbf{r} \{02\overline{2}1\} \) with \([r_1:r_2]\) or \([r_1:r_3]\) as the glide direction, sense of shear negative. It is effective at 20°C and at 500°-800°C, and in the latter temperature range, it predominates over \( \mathbf{r} \) translation.

In addition, Turner et al. (1954a, pp. 906 and 925) and Griggs et al. (1960b, p. 87) make reference to twin gliding on \( \mathbf{r} \{10\overline{1}1\} \) in the positive sense and, with Handin et al. (1960, p. 273), to translation gliding on \( \mathbf{c} \{0001\} \). These mechanisms, if valid, are rarely observed.

Not only does twin gliding predominate over the other deformation mechanisms, but it produces lamellae which are optically the most conspicuous feature of deformed calcite (Figure 2).\(^1\) In some cases, the lamellae are broad enough to permit observation of the difference in extinction position between lamellae and host; that is, in twin gliding on \( \mathbf{e} \), the \( \mathbf{c}_v \) in the twinned portion of the crystal is displaced 52 1/2° from its position in the untwinned host (Figure 1). Commonly, however, the lamellae appear as thin, dark, planar features in which the difference in extinction cannot be observed because the width of material in the twinned position is beyond the resolving power of the microscope. These are the "nontwinned lamellae" of Borg and Turner (1953, p. 1345). As both

\(^1\) Translation gliding does not result in reorientation of the crystal structure as in twin gliding. Moreover, visible evidence of translation (such as slip lines) is rare. Because of this, translation gliding systems were not utilized in this study.
the visbly twinned and the "nontwinned lamellae" commonly occur within the same grain and parallel to the same \( e \) plane, it is illogical to think that they are genetically different. Irrespective of their appearance, \( e \) twin lamellae can always be recognized by the angle \( \{26 1/4^\circ\} \) between the normal to the set of lamellae and the \( c_v \).

In a calcite crystal, twinning can occur on any of three glide planes—\((10\bar{1}2)\), \((1\bar{1}02)\), and \((01\bar{1}2)\)—that constitute the form \( e \{01\bar{1}2\} \). \(^1\) Turner and Ch’ih (1951, pp. 898-900) found in experimentally deformed Yule marble that "in each grain (deformed favorably for twinning) the lamellae tend to develop most profusely on that \( e \{01\bar{1}2\} \) plane for which the resolved shear stress coefficient is highest." Thus, they demonstrated that the deformation features of individual grains reflect reaction to loading of specimens as a whole rather than to local stress concentrations. More specifically, they showed that in a deformed calcite grain, the \( e_1 \) twin lamellae rather than \( e_2 \) or \( e_3 \) lamellae are parallel to planes for which the resolved shear stress is highest and in the correct sense for twinning.

From his study of the experimentally deformed materials, Turner (1953) was able to use twin lamellae in a dynamic interpretation of naturally deformed marbles. He employed the petrofabric technique\(^2\) of

---

\(^1\) 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.

\(^2\) See section on Methods of Study for details of the technique.
locating the mutually perpendicular directions of compression and extension that most favored development of the observed twin lamellae. The geometry of these relationships was initially set forth by Handin and Griggs (1951, pp. 866-869). Turner (1953, p. 297) concluded that the visibly twinned lamellae developed during the last stages of deformation. McIntyre and Turner (1953, p. 239) employed the same methods in a study of three marbles from Mid-Strathspey and Strathavon, Scotland. They also concluded that twinning in calcite is the expression of minor postcrystallization deformation, probably compression transverse to the regional fold axis. Gilmour and Carman (1954, pp. 58-59), taking the same approach in a study of the Loch Tay limestone from Strachur, Argyll, Scotland, found that the fabric studied exhibited the same monoclinic symmetry, and that the compression axis deduced from postcrystallization twin lamellae confirmed the direction of movement derived from macroscopic structures. Weiss (1954, pp. 56-57) investigated the dynamic significance of visibly twinned lamellae in a marble-quartzite complex in southern California. He applied Turner's method to various types (Borg and Turner, 1953) of lamellae developed at several stages in the complex deformational history of the rocks. Weiss found that only the twin lamellae formed during the last stages of deformation in response to compression or extension yielded consistent results, and that the lamellae formed earlier were disturbed by later differential movement of the grains and yielded inconclusive, nearly random stress patterns. Crampton (1958, p. 156) made similar petrofabric analyses chiefly on dolomite and on calcite marbles in the Cambro-Ordovician succession of the northwest
Highlands of Scotland. Since gliding mechanisms in dolomite had been determined from studies of experimentally deformed dolomite single crystals and dolomite rocks (Handin and Fairtairn, 1955; Turner et al., 1954b; Higgs and Handin, 1954 and 1959), Crampton determined the compression and extension axes from \{0\overline{2}21\} twin lamellae in dolomite as well as from the e twin lamellae in calcite. He found the calcite fabrics to be symmetrically similar to the dolomite fabrics, except that the calcite deformed in response to a late minor phase in the deformation. Similarly, Christie (1958, pp. 166-169) studied deformed dolomite from the Moine thrust zone. He concluded that the compression and extension axes inferred from twinned f lamellae are statistically parallel to those determined from intragranular rotation phenomena (Turner et al., 1954a), and that both the twin lamellae and the internal rotation of lamellae reflect the final stage of deformation of the rock.

Hanson, Borg, and Maxwell (1959) studied deformed calcite cement in two oriented specimens of folded Oriskany sandstone. They found that the compression axes deduced from the best-developed sets of e twin lamellae are grouped essentially normal to the fold axis. This finding represents the first published account of the use of this technique on a sedimentary rock.

In summary, the mechanisms of deformation in calcite are well known. The e twin-gliding system predominates in all simulated tectonic environments and produces twin lamellae, which are the most conspicuous feature of deformed calcite. Compression and extension axes, which correspond to the greatest and least principal stresses in the rock at the time of deformation, can be oriented from study of the best-developed
sets of twin lamellae. This technique has been tested on experimentally
deformed Yule marble and on naturally deformed marbles in several differ-
ent tectonic settings. The present study demonstrates that the technique
is equally valid when applied to study of deformed calcite in hetero-
geneous aggregates.

Quartz - Detrital Grains

Previous studies of the deformation of sand and sandstones have
dealt primarily with quartz-rich aggregates. Accordingly, this review of
the literature is concerned with the strength of quartz, its mechanisms
of deformation, and its behavior in deformed sand aggregates. Work on
the other common detrital elements as such is lacking.

Strength

Under high confining pressures and temperatures, the strength
of quartz is extreme. This subject is reviewed in detail in Griggs
*et al.* (1960b, pp. 65-72) and in *Borg et al.* (1960, p. 181). The strength
of unjacketed quartz single crystals loaded parallel to $c_v$ and confined
under 12 kilobars kerosene pressure is $34$ kilobars. When crystals are
loaded at $45^\circ$ to $c_v$, the strength is lower, and a crystal will break at
a differential stress of $30$ kilobars under the same confining pressure.
The strength reaches $140$ kilobars for a crystal loaded parallel to $c_v$
and confined by lead under $20$ kilobars, and reaches $150$ kilobars for a
similarly oriented specimen under $25$ kilobars liquid pressure. Even at
a temperature of $500^\circ$C, the ultimate strength is of the order of $30$
kilobars under $5$ kilobars confining pressure (*Griggs et al.*, 1960b, p. 70).
These authors point out further that the condition of the surface of quartz
specimens affects their strength, thereby accounting for some of the
variation in the strength data. Griggs and Bell (1938, p. 1735) found that the compressive breaking strength is greatly reduced in the presence of Na₂CO₃ (300 bars pressure, 10 percent solution, 400°C) to 4 kilobars. On the other hand, Borg and Maxwell (1956) and Borg et al. (1960) produced conspicuous fractures in the grains of loose, dry quartz sand aggregates at low confining pressures. 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.

Quartz exhibits a strength anisotropy. This is seldom referred to and may account for some of the observed fracturing mentioned below. According to Brendt (in Sosman, 1927, p. 482), the average crushing strength in air of quartz loaded parallel and normal to \( c_v \) is 24,960 and 23,240 bars, respectively, whereas tensile strengths are only 1100 and 830 bars, respectively. If these average values are real, and there is some doubt, because the reproducibility of the breaking strength of brittle materials is poor, a strength anisotropy does exist in quartz that may affect its modes of deformation; for example, the lower strength normal to \( c_v \) would tend to favor fracturing parallel to planes inclined at low angles to \( c \{0001\} \) or in part explain the characteristic position of deformation lamellae (also inclined at low angles to \( c \{0001\} \)).

Fracture

Fracturing is the most conspicuous deformation mechanism in quartz and in other common detrital grains. Much of the previous work on fractures in quartz has been concerned with the relationship between
fractures and specific crystallographic planes in order to determine whether fractures are related to the structure of quartz. Since quartz does possess "difficult" cleavage parallel to \( r \{10\overline{1}1\} \), \( z \{01\overline{1}1\} \), \( m \{10\overline{1}0\} \), and \( c \{0001\} \), and since cleavage is essentially a tensile fracture closely controlled by crystal structure, whether fractures in quartz aggregates are related primarily to crystal structure or to the principal stresses across the boundaries of the entire specimen must be established. To date, little regard has been paid to the relationship between microfractures and principal stress axes or between the microfractures and the strength anisotropy in quartz.

Griggs and Bell (1938), Fairbairn (1939), Ingerson and Ramisch (1942), Anderson (1945), Rowland (1946), Borg and Maxwell (1956), Bloss (1957), and Borg et al. (1960) have described fractures in a variety of quartz occurrences in both experimentally deformed and naturally deformed environments. Their data indicates a tendency of quartz to fracture primarily parallel to \( r \{10\overline{1}1\} \), \( z \{01\overline{1}1\} \), \( c \{0001\} \), \( m \{10\overline{1}0\} \), and \( a \{11\overline{2}0\} \). Most recently, D. Griggs and J. M. Christie (personal communication, 1960), working at the University of California in Los Angeles, have experimentally deformed single quartz crystals at 25 kilobars confining pressure, in a bismuth medium, and at room temperature. The crystals were loaded parallel to \( c \), and normal to \( m \), \( r \), and \( z \). Results show conclusively that fractures form parallel to \( r \) and \( z \).

Earlier, Griggs and Bell (1938) deformed a number of differently oriented cylinders of quartz single crystals, each exposed to a 10-percent
solution of Na₂CO₃ at 300 bars confining pressure and temperatures up to 400°C. The cylinder axes were oriented at 0°, 22 1/2°, 45°, and 90°, respectively, to cᵥ. Under compression, needle-shaped fragments of quartz were formed regardless of orientation. The fractures bounding the needles were oriented subparallel to the load axis (σ₁). In specimens with cᵥ at 0°, 45°, and 90° to the load axis, the fractures produced were therefore also subparallel to m or a, r or z, and c, respectively. In the cylinder whose axis was at 22 1/2° to the load axis, the fractures parallel to σ₁ are not parallel to any simple crystallographic plane. The number of these fractures is less than in the other specimens. The authors concluded "that the crystallographic zones of separation are of prime importance in the formulation of these needles." It should be emphasized, however, that in all cases, fractures formed parallel to σ₁, i.e., that some were, no doubt, extension fractures. These authors also call attention to the fact that at atmospheric pressure and temperature, quartz fracture is commonly described as conchoidal, but that at elevated pressures and temperatures, the quartz fractures along subplanar surfaces.

Information on the nature of microfractures in detrital grains was gained from studies of experimentally deformed loose, dry sand aggregates by Borg and Maxwell (1956) and by Borg et al. (1960). Borg and Maxwell 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 σ₁. They interpreted these microfractures as "tension" cracks which depart slightly, as ac "joints" frequently do, from the ideal position.
In a study of deformed St. Peter sand aggregates, Borg et al. (1960, pp. 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.

To the writer's knowledge, no studies on dynamic interpretations of microfractures have been published, although similar treatments of macrofractures and faults are well known (Anderson, 1951; Hafner, 1951; Hubbert, 1951; and Odé, 1957).

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. Most specimens exhibit one set of microfractures oriented in the \( ac \)-fabric plane, i.e., perpendicular to the axis of the fold \( (b \)-fabric axis). Some specimens show two sets of microfractures oriented preferentially in planes bisected by the \( ac \)-fabric plane. In addition, Bonham demonstrated that the \( ac \) microfractures are parallel to macroscopic fractures and reflect the plunge of the anticline. He pointed out that in 80 percent of the samples, the attitude of the microfractures could be used to determine the orientation of the fold axis to within 20°.
In summary, 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 Griggs and Christie 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.

Gliding, Undulatory Extinction, and Deformation Lamellae

Undulatory extinction, deformation lamellae, and preferred crystallographic orientations are common features in naturally deformed quartz. They have been ascribed by many workers to one or more gliding systems that are in general poorly understood and not substantiated experimentally. Undulatory extinction and deformation lamellae were not produced in the deformed specimens of the current study.

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\(^1\) and object

\(^1\)A unique determination of a planar element in thin section can be made only on a universal stage. Measurements on a universal stage provide both bearing and inclination of a plane relative to the plane of the thin section, whereas measurements on a conventional stage provide a bearing only.
traverser. The probable error in locating $c_v$ by optical means is $\pm 2^\circ$. Lamellae and microfractures can be located to within $1^\circ$ when they are inclined to the plane of the section at angles greater than $70^\circ$. For inclinations of $30^\circ-70^\circ$, the error may be $\pm 2^\circ$. The total probable error in the position of any fabric element with respect to the known load axes is due to (1) fabrication of the original rock cylinder and end cups, (2) preparation of the oriented thin section, (3) optical measurements, and (4) plotting. The error may be as much as $10^\circ$, but is less than $5^\circ$ in most cases.

Thin sections from sand-crystal specimens are cut parallel to the long axis of each deformed cylinder. Thin sections from calcite-cemented sandstone specimens are cut both parallel and normal to the axis of each cylinder.

The point-count method (Chayes, 1956) is used to obtain modal analyses of experimentally deformed materials. "Point" spacing is 100 $\mu$, and data are recorded for 600 points per specimen.

All measured data (orientation of $c_v$, calcite twin lamellae, and microfracture surfaces in quartz and in other detrital grains) and the derived positions of compression and extension axes are plotted stereographically on a Lambert-Schmidt equal-area net. The lower hemisphere of the projection sphere is projected on the horizontal plane. A review of the stereographic projection and its use in geological problems is given by Tunell and Higgs (1959), and a discussion of the construction of petrofabric diagrams and their interpretation is given by Turner (1948, p. 183).
Technique for Dynamic Interpretation of Calcite Twin Lamellae

This method, which was initiated by Turner (1953), resulted from the determination of gliding mechanisms in calcite. Its application will be demonstrated only for twin gliding on $e\{01\overline{2}\}$, although it holds equally well for other gliding systems (Turner et al., 1954a; Higgs and Handin, 1954 and 1959).

In calcite, twinning occurs on a family of three planes, designated $e\{01\overline{2}\}$, and the direction and direction sense of gliding are fixed (Turner et al., 1954a, p. 887). As the critical resolved shear stress to initiate twinning is low, twin lamellae are the most conspicuous feature in deformed calcite. Furthermore, the greatest amount of twinning occurs on that $e$ plane (designated $e_1$) on which the shear stress, or the resolved shear-stress coefficient ($S_o$), is highest (Turner and Ch'ih, 1951, pp. 899-900). By definition, $S_o$ is a function of the angular relationships between the load axis and the twin plane and between the load axis and the glide direction, as shown in Figure 4. Accordingly, if a maximum $S_o$ value (0.5) for twinning is assumed, the position of the load axis can be uniquely defined, because both $\chi_o$ and $\lambda_o$ must be $45^\circ$.

Figure 5a shows a section through an $e$ plane containing the glide direction and the optic axis ($c_v$). The fixed sense of shear is indicated, and there are two possible directions of loading (compression and extension) that will cause twinning which meet the requirement that $S_o = 0.5$. Accordingly, $\sigma'_1$ and $\sigma'_3$ are fixed for twin gliding when $S_o = 0.5$; $\sigma'_1$ (compression axis) is inclined $45^\circ$ to $e_1$; or to the normal to $e_1$, and $71^\circ$ to $c_v$; and $\sigma'_3$

---

1 For complete exposition, see Handin and Griggs (1951, p. 866).
2 Primes are used to distinguish between derived principal stress axes and those known to exist across the boundaries of the whole specimen.
(extension axis) is inclined 45° to e₁, or to the normal to e₁, and 19° to cᵥ. For any calcite grain, therefore, the positions of σ₁' and σ₃' for S₀ = 0.5 can be determined (Figure 5) by measuring and plotting e₁ and cᵥ.

Technique for Dynamic Interpretation of Microfractures

This technique is based on the assumptions that microfractures are shear or extension fractures and that, statistically, the grains in an aggregate fracture with regard to the principal stresses across the boundaries of the rock as a whole rather than with respect to local stress concentrations at grain boundaries. The orientations of microfractures in experimentally deformed materials discussed in this paper and those in previous studies amply demonstrate the validity of these assumptions. The technique therefore consists of (1) identification of microfractures as shear or extension types from their gross geometrical relationships (orientation patterns) and (2) determination of the principal stress axes that are known from theoretical and experimental evidence to have best produced the shear and extension fractures. It is necessary that the orientations of microfractures in many grains of a specimen be determined in order to identify, statistically, the microfractures as shear or extension fractures. The criterion that shear fractures show offset and extension fractures do not may be inconclusive, because (1) the magnitude of offset may be too small to observe and (2) extension fractures may be offset during later movements unrelated to the pertinent deformation.
Figure 4 - Diagram illustrates that the resolved shear-stress coefficient ($S_0$) is a function of the angles between the glide plane and the load axes ($\chi_o$) and the glide line and the load axis ($\lambda_o$). $S_0$ values range from 0.8 to 0.5.

Figure 5 - Diagrams (a) and (b) illustrating the position of compression ($\sigma_1^c$) and extension ($\sigma_1^e$) axes that would be most effective in causing the observed twin lamellae in a calcite crystal.
SAND CRYSTALS

Undeformed Sand Crystals

A sand crystal (Figure 6) consists of a large single crystal of calcite that poikilitically encloses detrital grains. The undeformed

![Cluster of sand crystals](image)

Figure 6 - Cluster of sand crystals.

sand crystals used in this study are characterized as follows:

1) Mineral composition:      Percent (by volume)
    calcite                38
    quartz                 25
    feldspar               22
    rock fragments         15
    garnet                trace
2) The average number of contacts per detrital grain as measured in thin section is 0.71.

3) The calcite crystal is undeformed; i.e., no twin lamellae are developed.

4) The detrital grains are relatively unfractured: The fracture index is 111 (see footnote 2, Table 1).

5) There is no marked dimensional or crystallographic orientation of the detrital grains.

Deformation Favorable for Twin Gliding

Experimental Deformation

Cylinders 1/2 inch in diameter and 1 inch long were cored from the sand crystals parallel and perpendicular to \( c_v \) of the calcite and were deformed dry under the conditions listed in Table 1, columns 2-5. The ultimate strengths (Table 1, column 6) were taken from the stress-strain curves of Figure 7. Descriptions of the experimental technique and apparatus are given by Handin (1953) and by Handin et al. (1957, and 1958). The cylinders were loaded to promote twin gliding in the calcite crystal, i.e., compressed perpendicular to or extended parallel to \( c_v \), respectively (see Glossary, p. 77).

Petrographic Observations of Deformed Specimens

All deformed specimens are characterized by at least two sets of twin lamellae parallel to \( 01\bar{2} \) in calcite and by relatively planar microfractures in detrital grains. Both the spacing index of twin lamellae and the index of fracturing in grains tend to increase with increased strain (Table 1, columns 8 and 9). In all specimens, the great majority
Table 1
EXPERIMENTAL CONDITIONS AND DATA FOR SAND CRYSTALS
DEFORMED FAVORABLY FOR TWIN GLIDING

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compression or Extension</td>
<td>Confining Pressure bars</td>
<td>Temp. °C</td>
<td>Total Strain percent</td>
<td>Ultimate Strength bars</td>
<td>Remarks</td>
<td>Fracture Index</td>
<td>Twin-Lamellae Spacing Index</td>
<td></td>
</tr>
<tr>
<td>Undeformed</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Sheared 33° to σ₁</td>
<td>111</td>
<td>0</td>
</tr>
<tr>
<td>878</td>
<td>Compression</td>
<td>1000</td>
<td>150</td>
<td>1.7</td>
<td>515</td>
<td>-</td>
<td>Sheared 30° to σ₁</td>
<td>126</td>
<td>99</td>
</tr>
<tr>
<td>915</td>
<td>Extension</td>
<td>5000</td>
<td>300</td>
<td>5.1</td>
<td>3600</td>
<td>Expt. ended before fracture</td>
<td>219</td>
<td>212</td>
<td></td>
</tr>
<tr>
<td>877</td>
<td>Compression</td>
<td>2000</td>
<td>300</td>
<td>8.5</td>
<td>4350</td>
<td>Sheared 30° to σ₁</td>
<td>212</td>
<td>297</td>
<td></td>
</tr>
<tr>
<td>911</td>
<td>Extension</td>
<td>2000</td>
<td>300</td>
<td>13.5</td>
<td>1560</td>
<td>Sheared 30° to σ₁</td>
<td>288</td>
<td>315</td>
<td></td>
</tr>
</tbody>
</table>

1Ultimate strength, as defined by Handin and Hager (1957), is the maximum ordinate of the stress-strain curve.

2Based on fracturing in 400 grains per specimen as follows: Percent unfractured grains x 1, plus percent of grains with 1-5 fractures x 2, plus percent with 6-10 fractures x 3, plus percent with greater than 10 fractures x 4, plus percent of demolished grains (grain shape obliterated) x 5, x 100 (Borg et al., 1960, p. 159). Index may vary from 100 to 500. The method is subjective, but indices determined by one operator can be used to compare relative amounts of fracturing from specimen to specimen. The writer's reproducibility is within 2 percent.

3Based on the number of lamellae per mm when measured along a line normal to twin planes. Values represent an average spacing index for all twin sets developed, as measured in four fields of view in each specimen.

4A macroscopic shear zone, probably containing highly fractured and demolished grains, was destroyed during sectioning. It is reasonable to assume that the index for this specimen would have been higher if grains along this zone could have been counted.
Figure 7 - Stress-strain curves for sand crystals deformed favorably for twin gliding.
of microfractures tend to lie perpendicular to the direction of \( \sigma_3 \) and thus, by definition, are extension fractures (in compression tests \( \sigma_2 = \sigma_3 \) and fractures are distributed radially and parallel to \( \sigma_1 \)). The spacing and orientation of the microfractures are independent of mineralogy and, in quartz grains, are independent of crystallography. In addition, specimens 878, 877, and 915 exhibit microscopic and/or macroscopic shear zones marked by granulation of the detritus and calcite. These zones are inclined from 26° to 38° to \( \sigma_1 \).

Specimen 878. Twin lamellae are developed parallel to two of the three potential twin planes. The average spacing index (99) is low compared to those of the other specimens. A macroscopic shear zone is inclined at 33° to \( \sigma_1 \). Microfractures are inconspicuous, and those that do occur are confined to the shear zone. This is reflected by a low fracture index (126). Although the microfractures are few in number, they are strongly oriented subnormal to \( \sigma_3 \) and nearly parallel to \( \sigma_1 \); i.e., they are extension fractures (Figure 8a).

Specimen 915. Three sets of twin lamellae are developed, with an average spacing index of 212. Fractured detrital grains are found throughout the specimen, and the fracture index (219) is markedly higher than that of specimen 878. Moreover, the microfractures tend to lie perpendicular to \( \sigma_3 \) (Figure 8b). No shear zone is developed.

Specimen 877. Three sets of twin lamellae are developed, with an average spacing index of 297. Microfractures occur throughout the specimen, and again are oriented as extension fractures (Figure 8c). The fracture index (212) probably represents a minimum value (see footnote 4).
Figure 8 - Diagrams illustrating the orientation of microfractures with respect to load axis for specimens 878, 915, and 877. The plane of each diagram is parallel to the long axis of the deformed cylinder. a) Specimen 878. Normals to 63 sets of microfractures in 50 detrital grains. b) Specimen 915. Normals to 64 sets of microfractures in 50 detrital grains. c) Specimen 877. Normals to 69 sets of microfractures in 50 detrital grains.
Table 1). A macroscopic shear zone inclined at 38° to $\sigma_1$ was observed prior to sectioning. Three instances of intragranular internal rotation were observed in this specimen; i.e., the twin lamellae formed early were rotated to irrational positions by twin gliding on another set of lamellae formed later in the deformation. Since the position of $\sigma_1$ is known in the experiment, it is possible to calculate the strain of the specimen (Turner et al., 1954a; Higgs and Handin, 1959). The strains in the three different fields of view are 6.8, 7.6, and 10.6 percent, respectively—average, 8.3 percent. The total strain, measured experimentally, is 8.5 percent.

Specimen 911. The same fabric elements that characterize the other specimens are more strongly developed in specimen 911 (Figure 9). From bottom to top, the specimen can be divided into slightly deformed, moderately deformed, and highly deformed areas. The calcite crystal within the slightly deformed and moderately deformed areas exhibits three sets of twin lamellae. The spacing index of each of these sets varies from one field of view to another, but usually the three sets are equally well developed; the average index is 315. The index increases toward the highly deformed, necked portion of the specimen. In any field of view, the index of a given twin set tends to be greater near detrital-grain boundaries than in the central portion of an interstitial area (Figure 10d). In the highly deformed area, calcite is characterized as follows:

1) Three twin sets are recognizable, although spacing of lamellae is predominantly dense, i.e., $>400$ per mm. Undulatory extinction and bent lamellae are common.
Figure 9 - Specimen 911. Photograph shows thin section cut parallel to the axis of deformed, necked cylinder. $\sigma_2$ is vertical, and $\sigma_1$ is horizontal. Area of thin section is approximately one-half of total specimen; i.e., cylinder broke just above the necked region when removed from its copper jacket. Planar fractures in detrital grains are oriented predominantly perpendicular to $\sigma_2$, and twin lamellae in the calcite crystal are visible. Slightly deformed, moderately deformed, and highly deformed sectors of the cylinder are indicated.

Crossed nicols X 10
Figure 10 - Photomicrographs showing details in specimen 911. The orientation of the principal stresses during the deformation is shown in the center of the figure. In (a), (b), (c), and (d), planar microfractures are illustrated which are developed in parallel sets oriented perpendicular to \( \sigma_3 \) and parallel to \( \sigma_1 \); i.e., they are extension fractures. In (c), a microshear zone in a feldspar grain is shown. The shear zone is inclined at 30° to \( \sigma_1 \). In (b) and (d), twin lamellae in the calcite crystal are visible.

Crossed nicols
2) Narrow areas of very fine grained calcite gouge have developed along shear zones.

3) A very fine to fine grained mosaic of granulated calcite--a deformation mosaic--has developed throughout the area.

This specimen, like the preceding ones, was loaded favorably for twin gliding. The $S_o$ value (0.38) on all three twin planes was the same. It is not surprising, therefore, that the derived compression and extension axes that would most effectively cause twin gliding ($S_o = 0.5$) on each of the three sets of twin planes are in good agreement with the known orientations of $\sigma_1$ and $\sigma_3$ (Figure 11). The center of the triangle made by the three extension axes ($\sigma_3$) lies 7° west of the known position of $\sigma_3$. In addition, the three compression axes lie within 25° of the periphery. In extension experiments, $\sigma_1 = \sigma_2$ and is disposed everywhere.

$\sigma_1 = \sigma_2 > \sigma_3$

Figure 11 - Diagram illustrating positions of compression (X) and extension (\*) axes for three sets of twin lamellae in specimen 911. Known positions of $\sigma_3$ and of $\sigma_2 = \sigma_1$ are shown.
about the circumference of the cylindrical specimens—in this case anywhere on the periphery of the diagram.

The detrital grains are fractured (index 288), except for those in the triangular area at the base of the cylinder in the "shadow" of the end cup (Figure 9). Except for demolished grains, most quartz, feldspar, and garnet grains and rock fragments exhibit one set of many subparallel microfractures. The microfracture surfaces are strikingly planar (Figure 10a, b, and c). The number of microfractures per set increases from the slightly deformed to moderately deformed to highly deformed areas; in the highly deformed portion, "demolished" grains are commonly smeared out along shear zones. Most microfractures completely cross the host grain, but they commonly die out within the grain. A 5°-15° rotation of fragments between microfracture surfaces can sometimes be seen if the host grain is at extinction. This phenomenon and the play of light on the microfracture surfaces cause some grains to exhibit "pseudolamellae" of slightly different optical orientation.

The angular relationship between the normals to microfracture surfaces and the \( c \) of the host quartz grains is illustrated in Figure 12. There is a slight tendency for the surfaces to parallel \( r \) or \( z \). That this relationship is nonrandom may be demonstrated by comparing the histogram with one representing random distribution as shown in Figure 12a (after Bloss, 1957, p. 217).

The microfractures show a strong tendency to lie perpendicular to the known position of \( \sigma_3 \) (Figure 13) and are, by definition, extension fractures. The few microscopic shear zones occur at approximately 30° to \( \sigma_1 \) (Figures 9 and 10c).
Figure 12 - Histograms of the distribution of the angles between the normal to the microfractures and the $c_v$ in host quartz grains.  

a) Random distribution (Bloss, 1957)

$$P = 100 \int_0^{\theta_2} \sin \theta d\theta = 100(\cos \theta_1 - \cos \theta_2)$$

$$\theta_2 - \theta_1 = \text{cell width in degrees.}$$

Angle index shows the angles between $c_v$ and common forms in quartz.  (This index applies to all diagrams of Figure 12.)

b) Specimen 911.  Data are from 111 fracture sets in 100 quartz grains.

c) Specimen 725.  Data are from 348 fracture sets in 200 quartz grains.
Figure 13 - Specimen 911. Diagram of normals to 143 fracture sets in 129 detrital grains, of which 100 are quartz. Contours: 0.7, 3.5, and 10 percent per l-percent area, 40 percent maximum per l-percent area.

Deformation Unfavorable for Twin Gliding

Experimental Deformation

Cylinders 1046 and 1049 were oriented unfavorably for twin gliding during deformation. Accordingly, it is instructive to compare the stress-strain curves and the deformation features produced in these tests with those for specimens 878 and 877, which were oriented favorably for twinning. Experimental conditions for deformation of the four specimens are listed in Table 2, columns 2-6. Thin sections cut parallel to each cylinder axis were studied petrographically for a better understanding of how these specimens deformed.
Table 2

EXPERIMENTAL CONDITIONS AND DATA FOR SAND CRYSTALS
DEFORMED UNFAVORABLY FOR TWIN GLIDING

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Loading Conditions</th>
<th>Confining Pressure, bars</th>
<th>Temp., °C</th>
<th>Ultimate Strength, bars</th>
<th>Total Strain, %</th>
<th>Remarks</th>
<th>Fracture Index</th>
<th>Twin-Lamellae Spacing Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undeformed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>878</td>
<td>Compression (\perp c_v)</td>
<td>1000</td>
<td>150</td>
<td>515</td>
<td>1.7</td>
<td>Sheared 33° to (\sigma_1)</td>
<td>126</td>
<td>99</td>
</tr>
<tr>
<td>1046</td>
<td>Compression (/ c_v)</td>
<td>1000</td>
<td>150</td>
<td>2290</td>
<td>2.9</td>
<td>Sheared 28° to (\sigma_1)</td>
<td>136</td>
<td>22</td>
</tr>
<tr>
<td>877</td>
<td>Compression (\perp c_v)</td>
<td>2000</td>
<td>300</td>
<td>4350</td>
<td>8.5</td>
<td>Sheared 38° to (\sigma_1)</td>
<td>212</td>
<td>297</td>
</tr>
<tr>
<td>1049</td>
<td>Compression (/ c_v)</td>
<td>2000</td>
<td>300</td>
<td>6040</td>
<td>22.1</td>
<td>Incipient shear 35° to (\sigma_1)</td>
<td>300</td>
<td>153</td>
</tr>
</tbody>
</table>
Stress-Strain Relationships

Stress-strain curves for the four experiments are shown in Figure 14. Although the total strain for each specimen is different, it is possible to compare the strengths of the specimens at a given percentage of strain for each set of experimental conditions. Thus, specimens 1046 and 1049 can be compared with specimens 878 and 877, respectively. At 1.7 percent strain, specimen 1046 is 3 times as strong as specimen 878; and at 8.5 percent strain, specimen 1049 is 1.4 times stronger than specimen 877. Both relationships are consistent with the greater strength of a calcite crystal loaded parallel to $c_v$, i.e., in a direction unfavorable for twin gliding.

Figure 14 - Stress-strain curves for specimens 878, 1046, 877, and 1049.
Petrographic Observations and Comparisons

Specimen 1046 exhibits a macroscopic shear zone or fault that is inclined at 26° to the greatest principal stress (σ₁). A fine-grained gouge of highly fractured and demolished detrital grains and pulverized calcite marks the shear zone. Detrital grains are generally slightly fractured. Grains adjacent to the shear zone are more highly fractured. The over-all fracture index is 136 (Table 2, column 8). Nearly all the microfractures are oriented parallel to σ₁ and accordingly are extension fractures (Figure 15a).

The calcite crystal in specimen 1046 contains a few e twin lamellae, traces of r{1011} cleavage planes, and extension fractures. The twin lamellae [spacing index is 22 (Table 2, column 9)] are developed only adjacent to the macroscopic shear zone and adjacent to fractured detrital grains. Where the grains are unfractured, the calcite is untwinned. Cleavage planes (r{1011}) are common throughout the specimen, although they are best developed adjacent to the shear zone. In addition, the calcite crystal contains fractures oriented parallel to σ₁, i.e., extension fractures (Figures 15a, and 16). The fractures are common throughout the specimen but, like the twin lamellae and r planes, are best developed adjacent to the shear zone. Although extension fractures in calcite are not common, they probably developed here because the crystal was loaded unfavorably for twin gliding.

1The possibility of translation gliding parallel to r cannot be excluded. Translation on r with a negative sense of shear is a known mechanism in calcite, and in a calcite crystal compressed parallel to c̅₁, there is a high resolved shear stress parallel to r planes and in the correct sense for translation gliding. However, since translation gliding does not produce visible lamellae, and since there has been no internal rotation caused by gliding on r, it is not possible to substantiate the occurrence of r translation in this specimen.
Figure 15 - Diagrams illustrating orientation of microfractures with respect to load axes for specimens 1046 and 1049. The plane of each diagram is parallel to the long axis of the deformed cylinder. 

a) Specimen 1046. Solid circles represent normals to 23 sets of microfractures in calcite crystal. Open circles represent normals to 15 sets of microfractures in the detrital grains.

b) Specimen 1049. Solid circles are normals to 57 sets of microfractures in 50 detrital grains.
Figure 16 - Photomicrograph of extension fractures in calcite crystal and in detrital grains of specimen 1046. The fractures are oriented with respect to the principal stress axes as shown. Crossed nicols.
It is interesting to compare the fracture indices and twin-lamellae spacing indices for specimens 1046 and 878 (Table 2, columns 8 and 9). The fracture index for specimen 1046 (136) is slightly higher than that for specimen 878 (126). This probably reflects the higher strain (2.9 percent) of specimen 1046. On the other hand, the twin-lamellae spacing index for specimen 878 (99), loaded favorably for twinning, is 4.5 times as high as that for specimen 1046 (22). This no doubt reflects the difference between the orientation of the load axis with respect to the calcite crystal in the two specimens.

Specimen 1049 exhibits an incipient shear zone 0.1 inch wide that is inclined at 35° to σ₁. The zone is marked by a deformation mosaic in the calcite. Detrital grains are highly fractured within the zone, but not more so than outside. Little, if any, shearing movement has taken place along the zone, as is evident from the lack of offset at the cylinder boundaries. In addition, the specimen exhibits a clockwise external rotation of 10°-15° caused by deformation of the steel end cups. The detrital grains are highly fractured throughout the specimens (fracture index is 300). The microfractures are parallel to σ₁; i.e., they are extension fractures (Figure 15b). The microfractures reflect the external rotation of the cylinder and therefore formed prior to the rotation.

The calcite crystal in specimen 1049 exhibits twin lamellae (index is 153), undulatory extinction, a few [1011] planes, and some extension fractures. In areas of the specimen outside the incipient shear zone, the calcite is characterized as follows:
1) Twin lamellae are best developed adjacent to fractured detrital grains and die out into the centers of the interstices.

2) Lamellae are commonly bent about detrital grains. This is accompanied by undulatory extinction in the area of bending so that the rational relationship between lamellae and $c_v$ is maintained. Maximum displacement of the $c_v$ occurs immediately adjacent to detrital grains.

3) Lamellae are best developed on those sides of fractured grains that are subparallel to the microfracture surfaces. Commonly, only a few lamellae are developed on those sides of the grains that are normal to the microfracture surfaces (Figure 17).

4) In the untwinned portions of the crystal, some cleavage planes and extension fractures have developed. The extension fractures are parallel to and sometimes continuous with those in neighboring detrital grains.

![Figure 17](image)

*Figure 17 - Sketch of fractured detrital grains and twin lamellae in calcite crystal. Twin lamellae are best developed on E and W sides of fractured grains and tend to die out into the interstices. Few lamellae are developed N and S of the grains.*
It is also interesting to compare the fracture indices and twin-lamellae spacing indices for specimens 1049 and 877. The fracture index of specimen 1049 (300) is higher than that for specimen 877 (212). This again probably reflects the greater strain of specimen 1049. The twin-lamellae spacing index of specimen 1049 (153) is about half that in specimen 877 (297), even though specimen 1049 has been strained about 2.7 times as much as specimen 877. There is no doubt that this index difference is associated with the fact that specimen 1049 was loaded unfavorably for twin gliding.

Discussion. It is apparent that specimens 1046 and 1049 are stronger and exhibit fewer twin lamellae than specimens 878 and 877. However, if specimens 1046 and 1049 were loaded unfavorably for twin gliding, why should any twin lamellae develop in these specimens? It is clear that in both specimens the twin lamellae are well developed adjacent to fractured detrital grains. As already noted, the fractures in the detrital grains are extension fractures. Theoretically, movement associated with extension fractures is normal to the walls of the fracture. Thus, as schematically illustrated in Figure 18, this movement creates a

![Figure 18 - Schematic explanation of development of twin lamellae in 1046 and 1049. Detrital grain exhibits extension fractures. Movement on extension fractures is normal to fracture surfaces. This sets up a local stress (σ') which produces a high resolved shear stress parallel to the e twin plane and in the correct sense for twin gliding.](image)
local stress in the proper sense for twin gliding parallel to the \( e \) planes in the adjacent calcite crystal. As the critical resolved shear stress to produce twinning in calcite is low, the local stress induces twin gliding despite the orientation of \( \sigma_1 \) on the specimen as a whole.

It is also important to emphasize that in specimens with increased strain (Table 2, columns 6 and 9), the number of microfractures tends to increase independently of the orientation of the load axis with respect to the calcite crystal. Also, in specimen 1046, all deformation features are best developed adjacent to the macroscopic shear zone.

**CALCITE-CEMENTED SANDSTONES**

Undeformed Tensleep Sandstone

Undeformed Tensleep sandstone is well suited for this study because of its simple mineralogy, grain size, undeformed cement, unfractured detrital grains, and low porosity. It is characterized as follows:

1) Simple composition: The rock contains 69 percent detrital grains (62 percent quartz) and 31 percent calcite cement.

2) Suitable crystal size: Half of the cement (15.8 percent of the rock) is ideal for universal-stage study; i.e., crystals are between 0.1 and 0.4 mm in diameter.

3) Undeformed cement: Only 2 percent of the calcite crystals exhibit any twin lamellae; \( _\nu \) of the calcite are randomly oriented.

4) Low porosity: The porosity is 3.4 percent (capillary-pressure determination); the low porosity minimizes the deformation effects caused by the collapse of voids upon application of confining pressure.

5) Lack of visible evidence of strong compaction: Point- and long-grain contacts occur; the average number of contacts per grain is 2.1.
6) Unfractured detrital grains: The fracture index in the quartz grains is 114; $c_v$ of quartz grains are randomly oriented (Figure 19a).

Undeformed Supai Sandstone

Undeformed Supai, which is similar to the Tensleep except for higher porosity and fewer contacts per grain, is characterized as follows:

1) Simple composition: The rock is composed of 55 percent detrital grains (53 percent quartz), 35 percent calcite cement, and 10.5 percent void space.

2) Calcite cement: The cement is almost entirely undeformed; the crystals range from 0.1 to 0.3 mm in diameter; $c_v$ are randomly oriented.

3) Porosity: The porosity is 17.5 percent (capillary-pressure determination).

4) Lack of compaction: The average number of contacts per grain is 1.1.

5) Previous deformation features: The fracture index is 114; small, incipient shear zones occur, with small amounts of gouge; $c_v$ of quartz grains are randomly oriented (Figure 19b).

Experimental Deformation

Cylinders 1/2 inch in diameter and 1 inch long were cored perpendicular to the bedding and with regard to reference markings so that similarly oriented thin sections of undeformed and deformed specimens could be compared. The cylinders were deformed dry under the conditions listed in Table 3, columns 2-5. Specimens 778 and 780 are from the Supai sandstone;
Figure 19 - Diagrams illustrating the random orientation of quartz c<sub>v</sub> in undeformed Tensleep and Supai calcite-cemented sandstones.  

(a) Undeformed Tensleep, 100° c<sub>v</sub>, quartz grains.  
(b) Undeformed Supai, 50° c<sub>v</sub>, quartz grains. The plane of each diagram is parallel to bedding.
Table 3

EXPERIMENTAL CONDITIONS AND DATA FOR CALCITE-CEMENTED SANDSTONES

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Compression or Extension</th>
<th>Confining Pressure bars</th>
<th>Temp. °C</th>
<th>Total Strain percent</th>
<th>Ultimate Strength bars</th>
<th>Remarks</th>
<th>Fracture Index</th>
<th>Twin-Lamellae Spacing Index*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undeformed</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Tensleep</td>
<td>114</td>
<td>0</td>
</tr>
<tr>
<td>Undeformed</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Supai</td>
<td>114</td>
<td>0</td>
</tr>
<tr>
<td>724</td>
<td>-</td>
<td>1000</td>
<td>150</td>
<td>-</td>
<td>-</td>
<td>Confining pressure only</td>
<td>115</td>
<td>0</td>
</tr>
<tr>
<td>763</td>
<td>Extension</td>
<td>1000</td>
<td>150</td>
<td>2.6</td>
<td>1160</td>
<td>Broke near center 10° to σ1</td>
<td>114</td>
<td>0</td>
</tr>
<tr>
<td>745</td>
<td>Extension</td>
<td>2000</td>
<td>150</td>
<td>2.9</td>
<td>1690</td>
<td>Expt. ended before fracture</td>
<td>117</td>
<td>22</td>
</tr>
<tr>
<td>762</td>
<td>Compression</td>
<td>1000</td>
<td>150</td>
<td>3.9</td>
<td>4660</td>
<td>Sheared 29° to σ1</td>
<td>169</td>
<td>212</td>
</tr>
<tr>
<td>725</td>
<td>Compression</td>
<td>1000</td>
<td>150</td>
<td>5.9</td>
<td>4800</td>
<td>Sheared 30°-35° to σ1</td>
<td>184</td>
<td>152</td>
</tr>
<tr>
<td>778</td>
<td>Compression</td>
<td>2000</td>
<td>300</td>
<td>9.2</td>
<td>2040</td>
<td>Sheared 29° to σ1</td>
<td>189</td>
<td>238</td>
</tr>
<tr>
<td>780</td>
<td>Compression</td>
<td>5000</td>
<td>300</td>
<td>10.1</td>
<td>6890</td>
<td>Expt. ended before fracture</td>
<td>203</td>
<td>302</td>
</tr>
</tbody>
</table>

*Values represent the average number of \( e_1 \) lamellae per mm when viewed on edge in all grains measured.
Figure 20 - Stress-strain curves for calcite-cemented sandstone.
all others are from the Tensleep sandstone. Ultimate strengths (Table 3, column 6) were taken from the stress-strain curves of Figure 20.

Petrographic Observations of Deformed Specimens

All specimens, except 724 and 763, are characterized by twin lamellae parallel to $\{0\overline{1}2\}$ in the calcite, by microfractures in the detrital grains, and, by macroscopic shear zones. Both twin-lamellae spacing and microfracture indices tend to increase with increased strain (Table 3, columns 8 and 9). Generally, the microfractures tend to lie perpendicular to $\sigma_3$; i.e., they are extension fractures. The orientation and spacing of the microfractures are independent of mineralogy and, in quartz grains, are independent of crystallography. Macroscopic shear zones are inclined between 29° and 35° to $\sigma_1$ (Figure 21).

Specimen 724. This specimen was subjected to a uniform pressure of 1000 bars, thereby simulating about 15,000 feet of overburden. The cylinder suffered no permanent deformation. Detrital grains are unfractured (index is 115), and the average number of contacts per grain is unchanged (2.1). In addition, the calcite cement is undeformed; the twin-lamellae spacing index is the same as that of the undeformed material (0).

Specimen 763. This specimen was extended 2.6 percent under 1000 bars confining pressure, but no evidence of the strain is apparent in the thin section (i.e., no microfractures or twin lamellae formed).

Specimen 745. This specimen was extended 2.9 percent under 2000 bars confining pressure, and some evidence of the deformation is apparent. Some detrital grains exhibit microfractures (index is 117), and the calcite cement exhibits a few twin lamellae (spacing index is 22).
Figure 21 - Specimen 725. Photograph shows thin section cut parallel to the long axis of the deformed cylinder. The greatest principal stress \( (\sigma_1) \) is N-S. The macroscopic shear zone containing gouge of quartz fragments and calcite cement is inclined at about 30° to \( \sigma_1 \). Fractures in detrital grains are predominantly parallel to \( \sigma_1 \); i.e., they are extension fractures.

Crossed nicols
Specimens 762, 725, 778, and 780. These specimens were compressed 3.9, 5.9, 9.2, and 10.1 percent, respectively, under the conditions listed in Table 3, columns 2-5. They contain similar, pronounced deformation features that are characterized as follows:

1) Macroscopic shear zones occur in specimens 762, 725, and 778; they are inclined at 29-35° to ơ₁ (Table 3, column 7), as shown in Figure 21 for specimen 725. Along these zones, detrital grains have been smeared out to form fine-grained gouge (Figure 22a). In addition, elongate grains along shear zones have been bodily rotated to lie sub-parallel to the zones. Shearing is not as pronounced in specimen 778 as in specimens 725 and 762. This may be due to a combination of the effects of increased confining pressure and temperature in specimen 778.

2) Highly fractured detrital grains occur throughout all four specimens, as illustrated in Figures 21 and 22. The fracture index increases with increased strain (Table 3, column 8). Sets of microfractures are statistically oriented parallel to ơ₁ and normal to ơ₃ (Figures 21, 22, and 23a-e) and, accordingly, are identified as extension fractures. In thin sections cut perpendicular to the ơ₁ axis, the normals to the microfractures form nearly complete peripheral girdles which are inclined at about 90° to ơ₁ (Figure 23a). The microfracture surfaces themselves, therefore, are subparallel to ơ₁. In these experiments, ơ₁ > ơ₂ = ơ₃, and the least principal stress (ơ₂ = ơ₃) is oriented everywhere about the circumference of the deformed cylinder. Therefore, the normals forming the girdle are also everywhere normal to the least principal stress. In thin sections cut parallel to the ơ₁ axis, the orientation of the
Figure 22 - Photomicrographs showing details in specimen 725 (Figure 21).

a) Photomicrograph shows microfractures in the detrital grains and the through-going shear zone. It is oriented such that \( \sigma_1 \) is N-S and \( \sigma_3 \) is E-W. Crossed nicols.

b) and c) Photomicrographs illustrate twin lamellae in deformed calcite cement, located at the center of each field of view. Photomicrographs were taken with the thin section mounted on the universal stage so that the twin lamellae at the center of (c) are tilted on edge. One nicol.
Figure 23 - a) Specimen 725. Normals to 198 sets of fractures in 100 detrital grains. Diagram oriented perpendicular to long axis of deformed cylinder with $\sigma_1$ at the center, at B. b) Specimen 725. Normals to 153 sets of fractures in 100 detrital grains. Diagram oriented parallel to long axis of deformed cylinder with $\sigma_1$ oriented N-S. In both diagrams the microfracture planes are parallel to $\sigma_1$ and are normal to $\sigma_3$; i.e., they are extension fractures.
Figure 23 (cont.) - c) Specimen 762. Normals to 138 sets of microfractures in 100 detrital grains. Diagram is oriented same as in (b). d) Specimen 778. Normals to 125 sets of microfractures in 100 detrital grains. Diagram is oriented same as in (b). e) Specimen 780. Normals to 119 sets of microfractures in 100 detrital grains. Diagram is oriented as in (b). In all diagrams the majority of the microfractures are oriented parallel to $\sigma_1$ and normal to $\sigma_3$; i.e., they are extension fractures.
microfractures is clearly illustrated (Figures 23b-e). It should be remembered that there is a central blind spot in these diagrams. The concentrations of normals at nearly right angles to the direction of \( \sigma_1 \) show that, for the most part, the microfracture surfaces are oriented parallel to \( \sigma_1 \) and normal to \( \sigma_3 \). That all the microfractures are not extension fractures is clear from the number of normals that are not inclined at 90° to \( \sigma_1 \). Those normals inclined between 70° and 50° to \( \sigma_1 \) probably represent shear fractures. The distribution of microfractures in specimen 780 tends to be more diffuse than in specimens 762, 725, and 778, although extension fractures predominate. This is probably due to the bodily rotation of the fracture planes away from their initial positions.

There appears to be a slight tendency for the microfractures to form parallel to \( x \) and \( z \), as shown in Figure 12c, which illustrates the relations between the normals to the microfractures and the \( c_v \) in the host quartz grains for specimen 725. This possible crystallographic control of fractures is, however, greatly overshadowed by the marked relationships between the microfractures and the principal stresses across the boundaries of each specimen.

3) Twin lamellae are profusely developed in the calcite cement (Figures 22b and c). Approximately 85 percent of the grains exhibit at least one set of twin lamellae, and the average spacing indices are generally high---212, 152, 238, and 302 for specimens 762, 725, 778, and 780, respectively. Moreover, it is significant that the spacing index generally increases with increased strain, although one reversal was noted
in comparing specimens 762 and 725. The twin lamellae in specimen 780 are commonly bent, and the calcite grains exhibit undulatory extinction. This indicates that the grains have been externally rotated during deformation. In the four specimens, twin lamellae are preferentially oriented in contrast to random \( \sigma_v \) orientations; normals to the lamellae are clustered within \( \pm 45^\circ \) of \( \sigma_1 \), as illustrated in Figures 24a and b for specimens 725 and 780. This indicates that twin gliding takes place only on those sets of twin planes that are favorably oriented with respect to \( \sigma_1 \).

**DISCUSSION OF RESULTS**

Relationship between Principal Stress Orientations and Observed Twin Lamellae

The preferential arrangement of twin lamellae relative to \( \sigma_1 \) in specimens 762, 725, 778, and 780 is significant. Handin and Griggs (1951) predicted that each calcite grain in a monomineralic aggregate should reflect the loads applied to the specimen as a whole rather than the effects of stress concentrations at grain contacts. This was confirmed for calcite marble by Turner and Ch'ih (1951), who showed statistically that, for each calcite grain in the aggregate, the highest spacing index is correlated with the highest resolved shear-stress-coefficient \( s_o \). That is, of the family of three \( e \) planes, twinning is best developed on that plane for which \( s_o \) is highest. If this obtained for calcite-cemented sandstones, each crystal of cement would respond to over-all loading instead of to local stresses at grain boundaries.

Resolved shear-stress coefficients with respect to the known position of \( \sigma_1 \) were determined for \( e_1, e_2, \) and \( e_3 \) in each calcite crystal
Figure 24 - a) Specimen 725. Composite diagram of normals to 102 $\varepsilon$ twin lamellae. The plane of the diagram is perpendicular to long axis of deformed cylinder, and $\sigma_6$ is at the center. Contours: $1, 3, 5, \text{ and } 7 \text{ percent per 1 percent area.}$ b) Specimen 780. Composite diagram of normals to 61 $\varepsilon$ twin lamellae. The plane of the diagram is perpendicular to long axis of deformed cylinder, and $\sigma_1$ is at the center. Contours: $1.66, 3.33, 5.0, \text{ and } 6.66 \text{ percent per 1 percent area.}$
in specimens 762, 725, 778, and 780, which contained at least one set of twin lamellae. The method is described by Handin and Griggs (1951, pp. 866-869, Figure 3). The results are listed in Table 4. The direction sense for twinning with respect to the load axis is correct in 74 percent of the measured $e_1$ lamellae. Moreover, the $S_0$ values (0.23 to 0.30) are adequate for twinning. Since the direction sense of twinning and $S_0$ correlate significantly with $\sigma_1$ in each specimen, it is reasonable to conclude that, statistically, the individual crystals of calcite cement are twinned in response to the load on each cylinder as a whole rather than to local stress concentrations.

### Table 4

**RESOLVED SHEAR-STRESS COEFFICIENT ($S_0$) DATA**

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Specimen No.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>762</td>
</tr>
<tr>
<td>a) Number of grains measured</td>
<td>50</td>
</tr>
<tr>
<td>b) Number of grains exhibiting twin lamellae</td>
<td>49</td>
</tr>
<tr>
<td>c) Percentage of grains in which the $e_1$ lamellae twinned in the correct sense with respect to $\sigma_1$</td>
<td>76</td>
</tr>
<tr>
<td>d) Average $S_0$ on $e_1$ for the grains in (c)</td>
<td>0.30</td>
</tr>
<tr>
<td>e) Percentage of grains (c) in which $e_1$ lamellae have the highest $S_0$ for the correct sense of gliding when compared to $e_2$ and $e_3$</td>
<td>92</td>
</tr>
</tbody>
</table>
In specimens 762, 725, and 778, the highest values of $S_0$ are for planes other than those designated as $e_1$ in about 10 percent of the cases (Table 4, line e). In specimen 780, true $e_1$ lamellae were not identified in 43 percent of the cases. Either the $e$ plane of highest spacing index is inclined to the thin section at too small an angle to be measured, or the spacing indices of two or more of the planes are too high or too nearly equal to permit proper identification.

The fact that the calcite cement responds to over-all loads leads to the conclusion that it should be possible to determine orientations of principal stresses from measurements of twin lamellae. Following the methods outlined previously, one can plot the compression axes that would be most effective in producing the observed $e_1$ lamellae in specimens 762, 725, 778, and 780 (Figures 25a-d, respectively). In specimen 762, the center of gravity of the highest concentrations marks the deduced position of the greatest principal stress ($\sigma'_1$), which is about 20° southeast of the known position of $\sigma_1$ (i.e., the center of the diagram). For specimen 725, the derived $\sigma'_1$ is 10° north of the known $\sigma_1$, and for specimen 778, $\sigma'_1$ is 10°-15° southeast of the known $\sigma_1$. The effect of almost doubling the strain in specimen 778 is a higher concentration of compression axes about $\sigma'_1$. The distribution of compression axes is more diffuse for specimen 780 than for the other specimens because of the high percentage of incorrectly identified $e_1$ lamellae and because of the external rotations of many of the grains. Even so, there is a definite grouping of compression axes about the known position of $\sigma_1$. Generally, the deduced ($\sigma'_1$) positions agree well with the known $\sigma_1$. 
Figure 25 - Diagrams illustrating orientation of compression axes derived from e, twin lamellae in specimens 762, 725, 778, and 780. The plane of each diagram is oriented normal to the long axis of the deformed cylinder, and \( \sigma_1 \) is at the center. 

a) Specimen 762. Diagram of 50 compression axes. Contours: 2, 4, 6, and 8 percent per 1 percent area, 10 percent maximum. Center of gravity (\( \sigma' \)) is about 20° SE of center.

b) Specimen 725. Composite diagram of 100 compression axes. Contours: 1, 2, 4, and 6 percent per 1 percent area, 10 percent maximum. Center of gravity (\( \sigma_1' \)) is about 10° N of center.

c) Specimen 778. Diagram of 50 compression axes. Contours: 2, 4, 6, and 8 percent per 1 percent area, 10 percent maximum. Center of gravity (\( \sigma_1' \)) is 10°-15° SE of center.

d) Specimen 780. Composite diagram of 50 compression axes. Contours: 2, 4, 6, and 8 percent per 1 percent area, 12 percent maximum. There is a general grouping of the axes about the center.
The lack of deformation effects in specimen 724, which was subjected only to uniform 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, i.e., tectonism.

Relationship between 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. In the cemented materials studied here, however, this is not the case; the microfractures formed during the deformation are, in the main, extension fractures. The microfractures, therefore, formed with regard to the known principal stress axes across the boundaries of the specimen rather than with respect to local stress concentrations at grain contacts. These results hold at least over the 0- to 18-percent porosity range.

Stress-Strain Relationships

At what differential stress will these deformation features begin to develop? Experiments on calcite single crystals have established that the critical resolved shear stress which will induce twinning on \( \mathbf{e} \) at room temperature is 15 ± 5 bars at 1 bar confining pressure, and 60 ± 20 bars at 5000-10,000 bars confining pressure. In heated crystals, the critical resolved shear stress is 30 bars at 150°C and 10,000 bars confining pressure, and 20 ± 5 bars at 300°C and 5000 bars confining
pressure (Turner et al., 1954a, p. 889)—in short, calcite twins at a very low shear stress, even under high confining pressure. On the other hand, the breaking strength of quartz in short-time tests at atmospheric pressure and room temperature is extremely high—24,200 bars (Sosman, 1927, p. 481). 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. However, data from the experimentally deformed sand crystals and Tensleep and Supai sandstones amply demonstrate that this is not true.

In this regard, it is instructive to compare the stress-strain curves for sand crystals (Figure 7) and calcite-cemented sandstones (Figure 20). 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 yield points. The calcite-cemented sandstones exhibit S-shaped curves (Figure 20), which, according to Handin (personal communication), are characteristic of porous rocks deformed under moderate confining pressures. The initial load collapses pore spaces, so that strain at low differential stresses is relatively large. Thereafter, the rock is strained elastically to the yield stress. The fact that little or no permanent deformation is associated with these events is indicated by specimen 763, which exhibits
a typical S-shaped curve, has obtained a maximum differential stress of 1160 bars at 1000 bars confining pressure, and yet exhibits no twin lamellae in the calcite 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 1690 bars at 2000 bars confining pressure. Accordingly, microfeatures develop in these extension experiments at differential stresses of between 1200 and 1700 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 1000 bars confining pressure and 150°C), microfeatures begin to form at differential stresses of 4500 and 4800 bars, respectively. At higher temperatures, the yield stress is lower--1500 and 2000 bars for specimens 778 and 780, respectively. Clearly, the nature of the tectonic environment greatly affects the magnitude of the differential stress at which permanent deformation in the rock begins.

The stress-strain curves for the sand-crystal experiments (Figure 7) 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 does not result. 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 they 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, calcite is unprotected and twins in response to smaller loads. In addition, the detrital grains exhibit fewer contacts per grain, and the stress concentrations per contact are correspondingly increased. 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 significant results are as follows:

1) The most conspicuous feature of deformed calcite is twin
lamellae which develop parallel to 0 112.

2) The twin-lamellae spacing index increases with increased
strain of the specimen (Tables 1 and 3). This effect is clear in comparing
different specimens or differently strained parts of the same specimen
(e.g., specimen 911).

3) Resolved shear-stress coefficient data indicate that (a)
74 percent of the e⊥ lamellae form in response to the load on the specimen
as a whole, (b) the average S₀ value on e⊥ lamellae is 0.27, and (c)
the reliability of correctly identifying e⊥ 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⊥ lamellae is more difficult
(Table 4).

4) Positions of principal stresses deduced from e⊥ lamellae
are in good agreement with the known positions (Figure 25a-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 e; i.e., they are extension fractures (Figures 8, 13,
and 23).
7) Microscopic and macroscopic shear zones are inclined at approximately 30° to $\sigma_1$ (Figures 10c and 21).

8) The fracture index increases with increased strain of the specimen (Tables 1, 2, and 3).

9) The 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 $x$ and $z$. Accordingly, microfractures are little affected by crystallographic control.

11) The consistent preferred orientation of microfractures relative to the principal stresses indicates that although stresses may be transmitted through grain contacts, the points of contact do not control the orientation of the fractures.

12) Uniform pressure alone does not produce twinned calcite or fractured detrital grains. When these features are present, tectonism is most probably indicated.

13) In calcite-cemented sandstones, both the twin lamellae in the calcite and the fractures in the detrital grains develop concomitantly under the same simulated tectonic conditions.
APPENDIX I

CRYSTALLOGRAPHIC NOTATIONS

Intracrystalline gliding occurs on planes and along lines of simple, rational crystallography. As this paper deals with glide planes and glide lines, it is necessary to discuss briefly their terminology.

Forms, Planes, and Letter Symbols

Gliding planes are specified according to forms and individual planes. A form in crystallography includes all planes which have a like position relative to the planes and axes of symmetry; for example, in calcite, twin gliding occurs parallel to the planes (1012), (1102), and/or (0112) of the form {0112}. The form symbol is denoted by braces, and the specific individual planes are denoted by parentheses. To facilitate this kind of specific designation and to allow rapid comparisons among various cases, letter symbols are commonly used instead of the Miller indices. Some of these symbols for frequently referred to axes and forms in calcite and quartz are listed in Tables 5a and b.

Individual planes of a form are differentiated by subscript numbers, e.g., e₁, e₂, and e₃ for the three planes of the form e {0112}. In the study of deformed calcite, the best developed set of e twin lamellae are designated e₁; second best, e₂; least developed, e₃.

Zone Axes

Gliding lines or directions are specified as zone axes; the glide line is thus defined as the intersection of two planes. In calcite, the glide direction for twinning parallel to e is the intersection of an e plane and an r plane. The generalized expression for this glide line
or zone axis is \([e_1:e_2]\), or specifically \([e_1:z_2]\). Zone axes are denoted by brackets.

Table 5a

**SUMMARY OF IMPORTANT FORMS, AXES, AND INTERFACIAL ANGLES IN CALCITE AND IN QUARTZ**

<table>
<thead>
<tr>
<th>Notation</th>
<th>Interfacial Angles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calcite</td>
</tr>
<tr>
<td>(c_v)</td>
<td>(c \wedge e = 26^\circ 15')</td>
</tr>
<tr>
<td>(a_1, a_2,) and (a_3)</td>
<td>crystal axes (horizontal)</td>
</tr>
<tr>
<td>(c\ {0001})</td>
<td>basal pinacoid</td>
</tr>
<tr>
<td>(r\ {10\overline{1}})</td>
<td>1st order rhombohedron</td>
</tr>
<tr>
<td>(z\ {01\overline{1}})</td>
<td>1st order rhombohedron (quartz only)</td>
</tr>
<tr>
<td>(m\ {10\overline{1}0})</td>
<td>1st order hexagonal prism</td>
</tr>
<tr>
<td>(a\ {11\overline{2}})</td>
<td>2nd order hexagonal prism</td>
</tr>
<tr>
<td>(e\ {01\overline{2}})</td>
<td>negative rhombohedron (calcite only)</td>
</tr>
<tr>
<td>(f\ {02\overline{2}1})</td>
<td>negative rhombohedron (calcite only)</td>
</tr>
</tbody>
</table>
Table 5b

NOTATIONS OF INDIVIDUAL PLANES FOR EACH OF THE COMMON CRYSTALLOGRAPHIC FORMS IN CALCITE AND QUARTZ

<table>
<thead>
<tr>
<th></th>
<th>$a_2 = Zone\ Axis$</th>
<th>$a_3 = Zone\ Axis$</th>
<th>$a_4 = Zone\ Axis$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcite</td>
<td>( e_1 ) (1012)</td>
<td>( e_2 ) (1102)</td>
<td>( e_3 ) (0112)</td>
</tr>
<tr>
<td></td>
<td>( f_1 ) (2021)</td>
<td>( f_2 ) (2201)</td>
<td>( f_3 ) (0221)</td>
</tr>
<tr>
<td></td>
<td>( r_1 ) (1011)</td>
<td>( r_2 ) (1101)</td>
<td>( r_3 ) (0111)</td>
</tr>
<tr>
<td></td>
<td>( m_1 ) (10\bar{1}0)</td>
<td>( m_2 ) (1\bar{1}00)</td>
<td>( m_3 ) (0\bar{1}10)</td>
</tr>
<tr>
<td>Quartz</td>
<td>( r_1 ) (10\bar{1}1)</td>
<td>( r_2 ) (1\bar{1}01)</td>
<td>( r_3 ) (0\bar{1}11)</td>
</tr>
<tr>
<td></td>
<td>( z_1 ) (1011)</td>
<td>( z_2 ) (1\bar{1}01)</td>
<td>( z_3 ) (01\bar{1}1)</td>
</tr>
</tbody>
</table>

The crystallography of calcite and of quartz is shown in Figures 26a and b. The interfacial angles useful in identifying crystal planes and axes are listed in Table 5. Letter symbols are used in both projections. All the faces that are coozonal (i.e., those which intersect along a common line) with one another and with \( c \) have the same subscript number appended to the plane designator. Thus, \( f_1, e_1, f_2, r_1, \) and \( m_1 \) are coozonal. In reconstructing the calcite lattice from observed \( e \) twin lamellae and \( c \), one selects \( e_1, e_2, \) and \( e_3 \), as defined above, and sets all other coozonal planes according to the \( e \) numerical subscripts.
Figure 26 - Crystallography of calcite (a) and of quartz (b). Stereographic projection (upper hemisphere) of the common forms, and crystallographic axes. The three glide directions for twinning parallel to \( \{101\} \) are projected on (a).
APPENDIX II

GLOSSARY

Center of Gravity as used in connection with the interpretation of petrofabric diagrams is that location within the diagram that qualitatively represents the mean of the major groupings. Both the areal extent and the density of the major groupings are considered in selecting a center.

Critical resolved shear stress is that resolved shear stress along a specific plane and in a given direction that must be exceeded in order to initiate slip.

Ductility is the total-percent elongation or shortening before fracture (Handin and Hager, 1957, p. 4).

Dynamic pertains to physical forces or stresses. In petrofabrics, it is the approach which attempts to relate the fabric to the stresses in the rock at the time of deformation. By contrast, see kinematic.

Fabric (German, Gefüge) denotes the sum total of all textural and structural features of a rock from constituent ions of the crystal lattice up to and including major features whose large dimensions necessitate field investigation (Turner, 1948, p. 342).

Fault is defined as "a localized offset in a body parallel to a more or less plane surface of nonvanishing shear stress. The surface may be inclined from 45° to a few degrees to the direction of maximum principal (compressive) stress in homogeneous materials. There may or may not be total loss of cohesion, actual separation, release of stored
elastic energy, or loss of resistance to differential stress. In other words, the phenomenon need not involve fracture in the ordinary sense" (Griggs and Handin, 1960a, p. 348).

Fracture. A body under differential stress is said to fracture when it entirely loses cohesion and resistance to differential stress and separates into two or more discrete parts. Fracture is accompanied by release of stored elastic strain energy (Griggs and Handin, 1960a, p. 348). Extension fracture is a separation in a body across a surface oriented normal to the direction of least principal stress. There is no offset parallel to the fracture surface. Extension fracture includes tensile fracture as a special case. Shear fracture is an offset within a body along a surface or zone that is oriented from a few degrees to as much as 45° to the direction of maximum principal (compressive) stress (usually around 30° in rocks).

Glide direction or line is synonymous with slip direction or line. It is the direction in a plane along which shear displacement takes place. The glide direction is defined by rows of closely spaced atoms or ions in the glide plane.

Gliding flow is the "plastic flow" used in metallurgy terminology. It denotes yielding of a solid body, in contrast to viscous flow of a fluid, by intragranular deformations of simple shear--that is, by twin or translation gliding parallel to specific crystallographic planes. Intergranular movements are of minor importance (Handin and Hager, 1957, p. 3).
**Glide plane** is synonymous with slip plane. It is that plane in a glide system along which shear displacement takes place. The plane is generally defined by layers of greatest density of atoms or ions. Accordingly, glide planes are usually planes of some simple crystallographic form.

**Kinematics** pertains to motions considered in themselves, or apart from their causes. In petrofabrics, Professor Bruno Sander (1930) of Innsbruck has emphasized the relation between rock fabric and movement of component parts. Symmetry has emerged as the basic criterion for correlating fabric with movement. The symmetry concept, or kinematic approach, holds that the symmetry of the tectonic fabric reflects the symmetry of the movement plan responsible for the evolution of the fabric.

**Normal stress** is the stress oriented normal to a given plane within a body.

**Plasticity** signifies the ability of a material to undergo large permanent strain without rupturing. Nothing is implied about the mechanism of deformation or the detailed shape of the stress-strain curve (Handin and Hager, 1957, p. 3).

**Principal stresses** are the three normal stresses, σ₁, σ₂, and σ₃, that characterize the state of stress at an infinitesimal cube within a body when the coordinate axes of the cube are directed in such a way that the shear stresses on all faces are zero. This is always possible regardless of the complexity of the stress situation (Barrett, 1943, p. 269). Where the principal stresses are unequal, the following convention is used:
\( \sigma_1 \) is the greatest, \( \sigma_2 \) is the intermediate, and \( \sigma_3 \) is the least principal stress. These stress directions are mutually perpendicular and, unless otherwise noted, are compressive (compression taken positive).

**Resolved shear-stress coefficient** (\( S_o \)) is that numerical coefficient, varying between 0.0 and 0.5, that is equal to the sine of the angle between the stress axis and the glide plane (\( x_o \)) multiplied by the cosine of the angle between the stress axis and the glide direction (\( \lambda_o \)):

\[
S_o = \sin x_o \cos \lambda_o .
\]

The resolved shear stress along a plane and in a given direction parallel to that plane can be determined by

\[
\tau = (\sigma_1 - \sigma_3) S_o .
\]

**Sense of shear** is the direction of relative shear along a plane.

In fabric work, the following arbitrary convention has been used to define the sense of shear along glide planes that intersect \( c_v \) at other than 90°:

**Positive sense** (+): relative displacement of the upper layers of the lattice upward toward the upper end of \( c_v \).

**Negative sense** (-): relative displacement of the upper layers of lattice downward from the upper end of the \( c_v \) (Turner *et al.*, 1954a, p. 887).

**Shear stress** (\( \tau \)) is the stress oriented parallel to and in a specific direction along a given plane in a stressed body.

**State of stress** is the stress condition at any point in a body. It requires six components of stress to specify completely the state of stress—three normal stresses and three shear stresses (Barrett, 1943, p. 269).
Stress-strain curve is a plot of the load per unit area applied to a specimen against the ensuing strain. In this paper, the curves are plots of conventional strain in percent shortening or elongation as the abscissa and differential stress (difference between \( \sigma_1 \) and \( \sigma_3 \) based on the average cross-sectional area of the deformed cylinder) as the ordinate (Handin and Hager, 1957, p. 4).

Stress pattern or system denotes the orientations (not the magnitudes) of the principal-stress trajectories in a rock body. This is obtained from a number of states of stress at points within the body.

Triaxial tests are conducted by axially loading specimens subjected also to a fluid confining pressure. A specimen is initially under hydrostatic pressure with the principal stress across the boundaries of the specimen equal. The axial load is then increased or decreased. Specimens are usually jacketed to deny access of the confining medium to the pores of the rock (Handin and Hager, 1957, p. 4).

Compression tests are made by superposing a compressive load upon the confining pressure, so that two of the principal stresses are equal to the confining pressure, and the third is greater.

Extension tests are made by reducing the axial load while a constant confining pressure is maintained. Two of the principal stresses are equal, and the third is smaller, but greater than zero (i.e., not tensile).

Twin lamellae are portions of a crystal within which the lattice has a twinned relationship to the lattice of the host crystal. The boundaries of the twin lamellae are generally parallel to the twin plane.
Ultimate strength is the maximum ordinate of the stress-strain curve, i.e., the maximum stress achieved during an experiment (Handin and Hager, 1957, p. 4).

Uniform confining pressure is that condition where the specimen is surrounded by equal pressure—i.e., the three principal stresses across the boundaries of the specimen are equal. This condition approximates that of overburden pressure in nature (Rubbert, 1951, p. 358).

Yield strength or yield stress is the stress at the knee of the stress-strain curve. Owing to the lack of a marked break in the curve, it is usually indefinite and so is specified at an arbitrary, small permanent strain (Handin and Hager, 1957, p. 4).
REFERENCES


Fairbairn, H. W., 1939, Correlation of quartz deformation with its crystal structure: Am. Mineralogist, V. 24, p. 351-368.


Deformation of Yule marble: Part VII - development of
oriented fabrics at 300°C-500°C: Geol. Soc. Amer. Bull.,
V. 67, p. 1259-1294.

Weiss, L. E., 1954, A study of tectonic style - structural investigation
of a marble-quartzite complex in southern California: Univ.