THE AMERICAN MINERALOGIST
JOURNAL OF THE MINERALOGICAL SOCIETY OF AMERICA

Vol. 24 JUNE, 1939 No. 6

CORRELATION OF QUARTZ DEFORMATION WITH ITS CRYSTAL STRUCTURE

H. W. FAIRBAIRN, *Massachusetts Institute of Technology, Cambridge, Massachusetts*

ABSTRACT

Although it is well known that the manner in which a crystal deforms is governed by its structure, few correlations have been made. The results of an analysis of this type are given here for quartz and are summarized in Table 2. The table is incomplete in many respects and further investigation is required. The need for correlation studies of this kind in interpreting mineral orientation in tectonites is unquestioned and will serve to stabilize the tottering hypotheses used at present.

TABLE OF CONTENTS

INTRODUCTION

The task indicated by the title of this paper may seem futile to those familiar with the structure of silicates and with the structural relation which quartz bears to this group. It may likewise appear hopeless to others unfamiliar with silicate and quartz structures, but who recall from student days the conchoidal fracture and difficult cleavage of quartz. Neither point of view is entirely valid, however, for quartz shows a capacity to deform which is a revelation to those unacquainted with this phase of its behaviour. It is the purpose of this paper to correlate

the scattered literature on quartz deformation and to expand the problem through a qualitative analysis of the structure. There is abundant evidence of different types of quartz deformation, all of which must eventually find their explanations in the crystal structure. The importance of this type of analysis is obvious in any petrotectonic analysis, since quartz has been the chief mineral studied, and it has long been apparent that interpretations were impeded by the lack of correlation with experimental and structural data. Griggs and Bell (1) have made a promising beginning in remedying this situation, and their contribution is well worth studying.

Types of Deformation

A summary of the different ways in which crystalline substances may deform when stressed beyond the elastic limit will help in the discussion of quartz deformation which follows. Beyond the elastic limit either *gliding* or *rupture* may occur. Gliding is a relative movement between certain sheets[1] of atoms which at no stage during the movement causes rupture of the structure. Rupture, on the other hand, arises from conditions which result in loss of continuity of the structure.

Gliding is of two principal kinds. Briefly, *twin-gliding* is a relative movement between two portions of a crystal which involves a change in mutual orientation of the two parts. The amount and kind of movement along neighboring gliding units necessary to bring about this change are governed by definite twinning laws. *Translation-gliding* is a relative movement between two portions of a crystal which does not involve a change in mutual orientation of the two parts. The amount of movement along neighboring gliding units is indefinite, although influenced strongly by the character of the crystal structure and its imperfections.

There are three types of rupture in crystalline substances. If a crystal breaks in such a way that its structure has little or no control over the form of the rupture, we call the break a *fracture*. If the form of the rupture is closely controlled by the structure, we designate it as *parting* and *cleavage*. Parting is a rupture on the composition plane between two twinned portions of a crystal. Cleavage is a structurally-controlled rupture which is independent of twinning.

In the following pages quartz will be analyzed in terms of these types of deformation. Although the treatment is most complete for cleavage and fracture, the problems connected with gliding are stated as fully as is consistent with the information available.

[1] A sheet, as used here, comprises all the atoms between two successive, potential, glide-surfaces.

Twin-gliding

The common quartz twins follow the Dauphiné and Brazil laws. In both, the vertical axis is the twin axis. The Dauphiné twin is composed of interpenetrating parts which are either all right-handed, or all left-handed, and cannot be identified by optical means. The Brazil twin is composed of interpenetrating right- and left-handed parts. A thick, basal section will show in its interference figure the phenomena of Airy's spirals. Except on basal sections, both types may be identified by suitable etching with HF, and usually consist of alternating rhombohedral lamellae, the orientation of the etch figure on alternating lamellae determining the twin law as Dauphiné or Brazil.

Experimental evidence of Dauphiné twinning has been obtained by Zinserling and Shubnikow (2) at room temperature and also near the inversion point. At the higher temperatures the twins formed under pressures as low as 1000 kg/cm^2. At lower temperatures they developed less easily. The authors consider quartz twinning to differ sharply from that represented by calcite twinning, but do not give an adequate interpretation. Twinning has not been thoroughly correlated with crystal structure for any mineral, and since it is not yet proven to be a factor in the formation of quartz tectonites, I have not attempted a correlation. Nothing would be gained by hazarding a correlation for a unique structure like that of quartz when the correlation for simpler structures has not yet been made.

The reason for development of Dauphiné or Brazil twins is a matter of some interest. The inversion of high-quartz to low-quartz results in a 2% decrease in volume, and in formation of irregular patches of Dauphiné twins. As this has the character of a deformation it may possibly be correlated with the Dauphiné twins produced by the Zinserling and Shubnikow experiments. Brazil twins are believed to be growth twins in quartz which have formed at temperatures below the inversion point. The rhombohedral lamellae forming the twins are commonly regular and extend throughout the whole crystal in contrast to the irregular, interrupted areas of Dauphiné twins.

Judd's opinion (3) from a study of a large twinned crystal runs counter to this idea. He found Brazil twins particularly well developed in those parts of a basal section which were highly fractured, and concluded that deformation was the chief factor in their formation.

The importance of twinning in the deformation of tectonite quartz is unknown. Neither Brazil nor Dauphiné twins can be identified optically in the ordinary thin section, and etching is rarely feasible because of the relatively fine grain. Sander has mentioned the possibility of twinning (4, p. 192, D.43) to explain the orientation of quartz in one example.

Although he has not directly stated the type of twin involved, it would necessarily be of the rare type represented by Japanese twins, in which the twin plane is a rhombohedral plane and the angle between the two vertical axes is 84° 33′. The evidence, however, is unconvincing and the orientation may be explained in other ways. Since there is experimental evidence that the commoner Dauphiné twin may be due to deformation, the problem should be explored further with respect to tectonites.

Translation-gliding

Muscovite—Translation-gliding has not yet been produced experimentally in quartz and it is advisable therefore to describe a related silicate structure in which translation does occur. All silicates are built

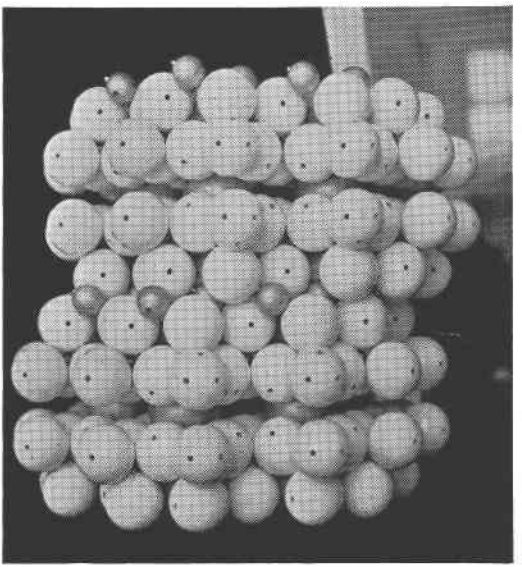

Fig. 1. Packing model of muscovite (14), looking approximately parallel to *b*. The linking of the SiO_4 tetrahedra to each other is clearly seen at the level in the structure where the small *Al* atoms lie. The absence of tetrahedral bonding at the level (locus of *K* atoms) where the bases of the tetrahedra face each other is also conspicuous. This is the translation and cleavage plane as explained in the text. The *OH* atoms (not seen in the photograph) are embedded between the tetrahedra at approximately the same level as *Al*. (Photo by William Parrish. Model constructed by Clifford Frondel.)

up on the fundamental SiO_4 unit in which one *Si* atom is bonded to four *O* atoms in tetrahedral arrangement. Quartz is one of these SiO_4 structures. The various arrangements of these tetrahedra and their associated cations give rise to entirely different behaviour under deforming stresses.

Silicates are distinguished structurally by the degree of sharing of the *O* of one tetrahedron with those of adjacent tetrahedra. In olivine, for example, none is shared, in pyroxene two are shared, in mica three are shared, in quartz all are shared. As will be seen, this distinction is of first importance in the production of gliding or rupture.

Taking muscovite as an example (Fig. 1), single layers of tetrahedra are linked together by *Al* atoms, forming a double sheet. The structure

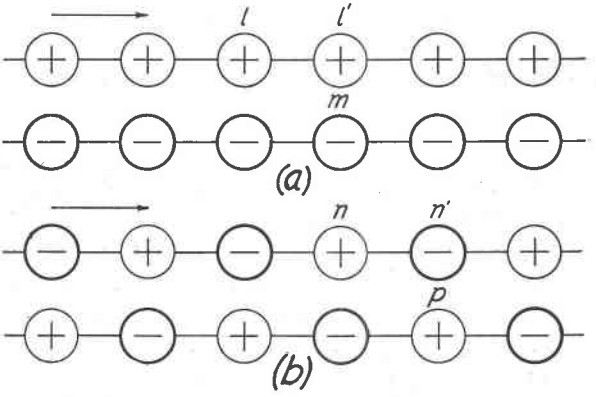

FIG. 2(*a*). To illustrate the essential feature of translation-gliding. The upper row of positive atoms can move over the lower row of negative atoms without development of rupture. Thus if *l* moves to *l'*, directly over *m*, the final disposition of atoms is identical with the original configuration. During the movement from *l* to *l'* no unstable condition is approached, since the attractive forces between the adjacent unlike atoms maintain the continuity of the structure.

FIG. 2(*b*). To illustrate the essential feature of cleavage. The upper row of positive and negative atoms cannot move relative to the lower row of similar positive and negative atoms without development of rupture. Thus if *n* should move to *n'*, directly over *p*, the final disposition of atoms is unlike the original configuration. At the commencement of the movement from *n* to *n'* an unstable condition develops because of the approach of *n* to a like atom *p*. Repulsive forces are thus set up which result in rupture.

is a succession of these double sheets, placed so that the bases of the tetrahedra face each other. The double sheets are linked by *K* atoms.

In the following analysis of translation I am guided by the clear statement of its fundamentals given by Buerger (5).

The fundamental element of translation-gliding is the glide-line *t*. The glide plane is of secondary importance. The glide line is determined by the direction taken by rows of consecutive, like-charged atoms. Figure 2 shows the relation between two adjacent lines of atoms, in one of which gliding is possible, in the other impossible. The definition of gliding states that rupture does not occur at any stage of the relative movement. Thus

at all positions in the gliding structure the forces of attraction must be stronger than the forces of repulsion. This condition is fulfilled for Fig. 2(*a*).

Possible glide-lines in muscovite (rows of consecutive, like-charged atoms) are to be found parallel to [100], [010], and [110]. These indices all refer to directions in the basal plane. In order, they are parallel to *b*, *a*, and the prism-base edge. Inspection of the model shown in Fig. 1 indicates that the gliding might occur between rows of *Al* and *O–OH* atoms, or between *K* and *O* atoms. Since large cations of low valence (e.g., *K*) have much weaker bonds than smaller ones of higher valence (e.g., *Al*), it is likely that the adjacent rows of *K-O* atoms will function as glide-lines in preference to the others. The order of preference for the possible glide-lines is probably [100], [110], [010], listed in order of increasing distance between equilibrium positions.

The plane *T* along which translation takes place is one of the zone of planes which contains the glide-line. The favoured plane is the one which has the least resistance to slip. Resistance to slip is due to (1) the bonding forces between the atoms, and (2) the character of the path along which the movement takes place.

The glide-plane, or more correctly, surface, is determined therefore only by proper evaluation of these factors. In a silicate structure it must first of all be one which does not break the tetrahedra, since there is greater resistance to gliding between *Si-O* atoms than between any other combination in the structure.[2] Since in muscovite three *O* in each tetrahedron are shared by neighboring tetrahedra, it is seen from Fig. 1 that the only possible glide-plane is parallel to [001], passing between the double sheets of linked tetrahedra.

These gliding elements were tested experimentally many years before it was possible to predict them from the structure. Mügge (6) determined the glide-lines [100] and [110] and glide-plane (001). From later petrofabric analyses Sander (4, p. 207 et seq.) also obtained indirect evidence of [100] and (001).

Quartz—The example of translation-gliding in muscovite is given in some detail in order to contrast it with quartz. In quartz the same tetrahedral arrangement of *Si* and *O* occurs, but, since every *O* in the tetrahedra is shared by a neighboring tetrahedron, there can be no sheet-like arrangement as in muscovite. The tetrahedra form a three-dimensional net, and since there are no weaker interstitial cations linked to *O*, the structure is bonded together very strongly and uniformly. Figure 3 shows a packing model constructed by Butler and Buerger which indicates

[2] Strength of bonding increases, in first approximation, with valence. *Si* is in most silicates the element with the highest valence, so that the *Si-O* tetrahedra are the most stable units.

something of the arrangement of the atoms. It is obvious from the *Si-O* relations described above that no glide-line is possible which does not break through one or more tetrahedral bonds. Thus translation-gliding, if it occurs at all, would be immensely more difficult to produce on the

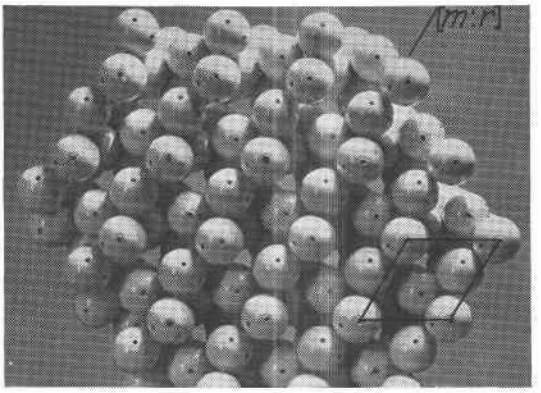

FIG. 3. Packing model of low-quartz (16) looking in the direction of the vertical axis. The *Si* atoms at the centers of the tetrahedra are not visible in the photograph. The sharing of each *O* between two tetrahedra is clearly seen, and emphasizes the great strength of the structure as compared with muscovite. The relative size of the model compared with a unit cell is shown by the parallelogram in the lower right corner. Line [*m* : *r*], lying in the plane of the photograph, shows the direction of a possible glide-line. The "holes" in the structure parallel to the vertical axis reflect a "columnar" bonding in this direction and are associated with a linear type of rupture as described in the text. (Model constructed by Butler and Buerger.)

basis of the usual interpretation. Glide-lines might be expected, therefore, parallel to those rows of consecutive, like-charged atoms which produce the *minimum disturbance* of the tetrahedral bonds. Examination of the packing model of Fig. 3 shows that only one direction fulfills this requirement, and is parallel to the horizontal edges [*m*:*r*].[3]

[3] The nomenclature to describe the quartz planes referred to in this paper is as follows:

c is the basal pinacoid (0001)
m is the unit prism $(10\bar{1}0)$
a is the second-order prism $(11\bar{2}0)$
r is the positive rhombohedron $(10\bar{1}1)$
z is the negative rhombohedron $(01\bar{1}1)$
s is the second-order trigonal pyramid $(11\bar{2}1)$
x is the trigonal trapezohedron $(51\bar{6}1)$

The disposition of these planes on a right-handed crystal is shown in Fig. 4 (with the exception of *a* and *c*). *a* is uncommon as a crystal face, and *c* is unknown.

Directions in the lattice are referred to by combining the letters for two planes whose line of intersection represents this direction—thus, horizontal edges are [*m* : *r*] or [*m* : *c*], vertical edges are [*m* : *m*] or [*m* : *a*].

The attempt to assign a preferred glide-*plane* to it, however, would require more than a qualitative study such as is made here. Assuming that gliding can occur, it is quite possible that resistance to slip on all planes containing these horizontal edges is so great that a linear gliding alone occurs. In this case the glide-line would be the only element which controls the deformation.

There are no experimental data of translation-gliding in quartz. The statement in Sosman's memoir (7) that gliding takes place parallel to *m*, *r*, and *z* is not based on experimental evidence.[4] Griggs and Bell have surveyed the literature of quartz deformation in tectonites and find no unanimous opinion regarding translation-gliding. Possibly the wavy, high-refracting, parallel lamellae[5] in the quartz grains of many strongly deformed rocks may be caused in part by translation, but there is no proof as yet. These lamellae are uniformly sub-parallel to the base but

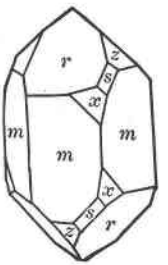

FIG. 4. Right-handed quartz crystal showing faces corresponding to the principal planes referred to in the text. (Reprinted by permission from "Textbook of Mineralogy" by Dana and Ford, published by John Wiley and Sons, Inc.)

do not have a fixed crystallographic orientation. Recrystallization obliterates all trace of them except in certain cases where they contain inclusions. No adequate explanation of their relation to the atomic structure is known at present.

RUPTURE

There is probably no crystalline solid whose rupture surfaces are not controlled, at least to some extent, by its structure. Strictly speaking, therefore, the terms cleavage and fracture have no precise meaning.

[4] Written communication of Sosman to J. F. Bell.

[5] These lamellae are commonly referred to, erroneously in most cases, as Boehm lamellae. The original description by Boehm (see Griggs and Bell (1), p. 1726) refers to *lines of inclusions in recrystallized rocks* which may or may not be relicts of lamellae. They are most certainly unrelated to lamellae in those examples where they cross from one grain into another. Due to this confusion in use of the term "Boehm," I prefer to drop it entirely, except in a historical sense.

Common usage defines cleavage as a rupture which is closely controlled by the structure, and fracture as a rupture in which the structural control is weak. Since parting planes are dependent on a previously developed twinning, they do not show this gradation.

Figures 2(*a*) and 2(*b*) illustrate the contrasting conditions necessary to produce translation and cleavage. Fundamentally, the latter is a result of repulsion of like atoms when the relative movement between two lines of atoms tends to bring like atoms opposite one another.

Cleavage in Muscovite—The same example has been selected to contrast with quartz as was used to illustrate translation. There is a considerable literature dealing with the cleavage of minerals, and various rules have been formulated. The most recent and informative paper is that of Wooster (8), in which the various structural types are discussed in terms of their ability to cleave.

For silicates the following rules are given:

(1) The cleavage leaves the tetrahedra intact.

(2) In general, the cleavage exposes anions only (e.g. *O*, *OH*), but where no such plane exists, large cations (e.g., *K*, *Na*) may also be present.

(3) Where several cleavages are possible two cases arise—(*a*) If the distance between the anions in the different planes varies greatly, only the cleavages corresponding to the greatest distance will occur. (*b*) If the distances are nearly the same, they will all be cleavage planes.

Applying these rules to muscovite (Fig. 1), (1) the only plane which does not break the tetrahedra is parallel to (001), and is located at the level in the unit cell where the tetrahedra are back to back. (2) Cleavage in this plane exposes anions (*O*) and large cations (*K*). This plane corresponds to the excellent cleavage of mica. Although cleavage and translation follow the same plane in muscovite, this coincidence is not at all necessary.

Cleavage in Quartz—Strict application of the same set of rules to quartz fails. Since each *O* is shared by two tetrahedra, there is no plane in the structure which could leave these *Si-O* bonds intact should rupture occur. There would seem, therefore, to be no predictable cleavage in quartz. Since imperfect cleavages are well-established, however, the structure will now be examined for the most likely planes, and correlation attempted with the ruptures known to occur.

Figure 5 shows the edges of a series of planes of atoms parallel to *c*, *m*, *r*, and *a*. The arrows show the *Si-O* bonds, and also the positions of the atoms in each plane. These figures are for high-quartz and are thus simpler than the corresponding figures for low-quartz. For low-quartz the tetrahedra occupy slightly different positions which would complicate the figures without leading to any different conclusion.

These sets of planes have been selected because preliminary analysis

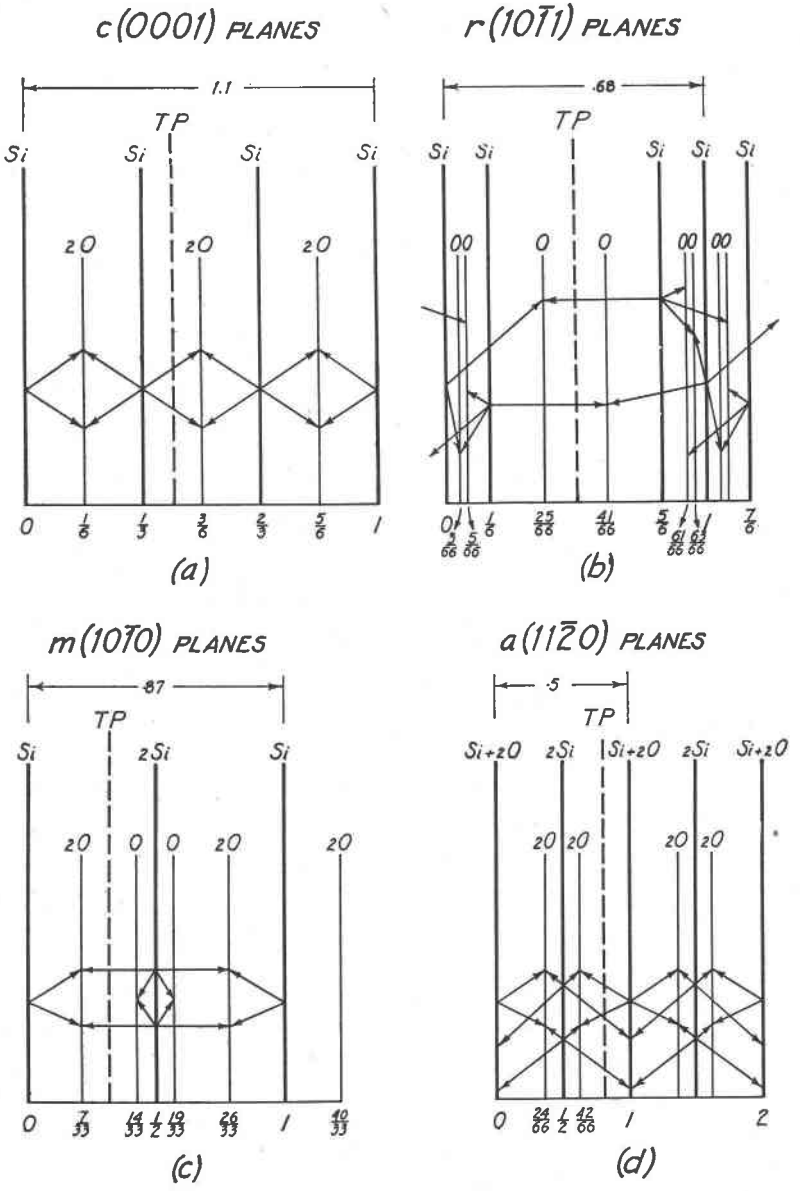

FIG. 5. Sets of atomic planes parallel to *c*, *r*, *m*, and *a*, as drawn for high-quartz by Niggli (13). Across the top of each set of planes is a number corresponding to an axial ratio in which each horizontal axis equals 1. The limits of a unit cell lie between 0 and 1, marked across the base of each set of planes. The positions of the SiO_4 units are shown by the bonding arrows. *TP* on each set of planes indicates a test plane for possible cleavage. The number of bonding arrows intersected by a test plane shows the unit rupture of tetrahedra for that position of the test plane. These planes are located to show the *minimum* rupture in each case. The four sets of atomic planes may then be directly compared as to cleavage possibilities.

showed that they offered the best prospects for cleavage. They are easily tested for cleavage possibilities by passing imaginary planes *TP* between adjacent atomic planes, noting the number of tetrahedral bonds which are intersected, and the number of *O* separated from each tetrahedron by this operation. The following table summarizes the results of such testing for those positions of the imaginary planes involving the least rupture of the bonds.

TABLE 1 (see Fig. 5)

I Plane series	II Area in sq. Å occupied by *TP* within limits of unit cell	III No. of tetrahedra broken per *TP*	IV No. of *O* broken from each tetrahedron	V Total *O* broken by each *TP*	VI Total *O* area of *TP* = bonding per sq. Å	VII % increase in bonding of *m*, *c*, *a*, over *r*, *z*
r	35.733	2	1	2	.056	
z	35.733	2	1	2	.056	
m	26.442	1	2	2	.076	36
c	24.040	1	2	2	.083	48
a	45.797	3	2 from one tetrahedron. 1 each from other two tetrahedra.	4	.087	55

Unit cell parameters $a=4.903$ Å, $c=5.393$ Å

Since ease of cleavage is dependent primarily on the bonding per sq. Å (for quartz the number of *O* broken from the tetrahedra per sq. Å), column V must be divided by column II for each set of planes. The result is tabulated in column VI and gives directly the relative ease of cleavage parallel to the planes considered. Column VII shows in per cent the increase in bonding for *m*, *c*, and *a* over *r* and *z*. It is obvious that the best cleavage should be parallel to *r* and *z*.[6]

[6] A striking feature of the packing model of quartz is the occurrence of numerous sets of openings passing between the tetrahedra. The most conspicuous ones coincide with the horizontal edges [*r* : *m*], the rhombohedral edges [*r* : *r*] and [*r* : *z*], and the vertical edges [*m* : *m*]. The latter are the largest and are easily seen in Fig. 3. As far as known, these holes have no actual significance in an analysis of rupture, since the bonding would not be affected in any way if the tetrahedra were so oriented that these openings did not exist. It is significant, however, that the *r* planes contain more of these sets of openings than any other planes, indicating in a superficial way the weaker bonding already mentioned.

These calculations must not be used in a strictly quantitative sense, since factors such as the resolution of forces necessary to break the tetrahedra have not been taken into consideration. A precise quantitative study of this kind would be difficult for a structure such as quartz and is unnecessary for the problem at hand.

On the experimental side, considerable correlation is possible. Sosman (7) has summarized the older data. The positive rhombohedron r is conceded by all investigators to show the best cleavage. The negative

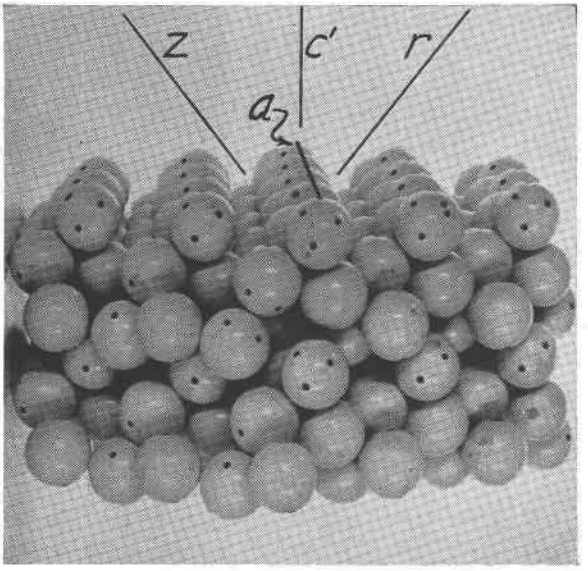

FIG. 6. Side view of quartz model of Fig. 3 tilted down at the front to give sufficient perspective. The close-knit, three-dimensional character of the structure is clearly seen in this view also; a is the line of strike of the rhombohedrons r and z, whose dips are indicated by the inclined lines. Although the identical bonding per sq. Å on these two planes cannot be seen from the figure, the greater "smoothness" of r as compared with z is easily appreciated from the arrangement of the O rows along the top of the model.

rhombohedron z gives a poorer, but distinct, cleavage. Others reported are parallel to m, c, a, s, and x. Mallard (9) found that the rupture surfaces parallel to m and c were really composed of alternating r and z cleavages. Wright and Larsen (10) report on the abundance of rhombohedral ruptures in low-quartz which has passed through the high-low inversion point. In the preparation of thin sections rhombohedral cleavage may likewise develop in grains at the edges of the rock-slice.

The superiority of r cleavage over z cleavage is probably due to the greater "smoothness" of the former planes. This is easily seen from Fig.

6, on which one rhombohedron of each type is marked for reference. Although the bonding is equal parallel to both surfaces, the *z* planes of atoms are not conspicuous in the figure. Close examination of the model reveals a very ragged surface. This inequality in the two rhombohedrons is probably one of degree, not of abundance, as the bonding strengths indicate an equal tendency to rupture. In high-quartz, having hexagonal symmetry, there is no difference in the "smoothness" of the pyramidal planes corresponding to the low-quartz rhombohedra. The pyramidal cleavages of high-quartz should be equally well developed. No experimental data are available to check this point.

Rupture parallel to *m*, composed of alternating *r* and *z* cleavages, as Mallard describes, should be easier to produce than ruptures of similar origin parallel to *c*. This is because the rhombohedral surfaces are more nearly parallel to the prism than they are to the base. The wide experience of the Japanese quartz workers seems to confirm this (11), as they have found that crystals are easiest to work on surfaces cut parallel to *c*. As an illustration, quartz vases are always hollowed out parallel to the vertical axis of the crystal, and engraving is also done on such sections.

Although a rupture of the type just described is very probable, there are at present too few observational data to warrant a statement that this is a general rule. Independent prismatic cleavage does occur, as shown by a crystal brought to my attention by Dr. Harry Berman.[7] This crystal is bounded on one side throughout its entire length of three inches by a fairly smooth cleavage face parallel to *m*. Structurally, however, there appear to be greater possibilities in this zone for a linear rupture than for the planar type observed in this crystal. The *m* and *a* prismatic planes give a total of six intersecting planes and, if *r* and *z* are included, six rhombohedral planes could also aid in the production of ruptures essentially parallel to the vertical axis. Participation of even a few of these twelve possible planes would give a linear character to the resulting composite rupture.[8] This may be the case in tectonite quartz showing parallel orientation of strain shadows under crossed nicols. These oriented shadows are seldom exactly parallel to the vertical axis and show irregularities within individual grains which point to an origin by rupture rather than by gliding.[9]

[7] Specimen in Harvard Mineralogical Collection from Goyaz, Brazil.

[8] Since completion of the manuscript another example of prismatic cleavage has been described by Drugman (*Mineral. Mag.*, **25**, 259, 1939), in which three intersecting sets are shown in an excellent photograph. This illustrates the linear character of ruptures in the vertical zone.

[9] By certain writers these oriented shadows in tectonite quartz have been considered to represent translation-gliding. Griggs and Bell (1) have reviewed the printed evidence and find it inconclusive.

Ichikawa (11) reports imperfect ruptures parallel to *a*, *s*, and *x*, which may represent special combinations of rhombohedral ruptures. As already shown in table 1, *a* is less probable as an independent cleavage than *r*, *z*, *m*, and *c*, and it could be shown that *s* and *x* are even less probable. As a composite rupture, *a* might be explained as follows. Examination of any quartz crystal shows that *a* is symmetrically placed, and is sub-parallel, to two positive rhombohedrons at one end of the crystal, and to two negative rhombohedrons at the other end. Thus rupture parallel to all four rhombohedrons could result in a cleavage essentially parallel to *a*. However, as with *m*, independent cleavage can not yet be ruled out as a possibility.

The most recent experimental data on cleavage of quartz are given by Griggs and Bell (1). In a series of experiments performed on cylinders of differing orientation, immersed in Na_2CO_3 solution and subjected to 4000 atmospheres differential pressure at 400°C., it was found that the ruptured fragments took the form of needles. Measurement of the optic orientation of these needles showed further that the bounding faces were rhombohedral, prismatic, and basal, the predominating face depending on the orientation of the cylinder used. No estimate of the relative ease of separation parallel to these planes could be made from these particular experiments. The hypothesis of quartz orientation which Griggs and Bell have developed on the basis of these experiments will be discussed by me in a later paper.

Parting—Since parting is entirely dependent on the previous development of twins, it has importance in outlining the twin boundaries. As already pointed out, optical tests fail to indicate twinning in ordinary thin sections, and etching requires specially prepared material. Parting planes, where developed, are thus of great assistance. They represent rupture along planes whose atoms have been mutually rearranged by twinning, but, for reasons already stated for twin-gliding, no attempt is made here to correlate the crystal structure with the parting.

I know of no experimental evidence of parting planes developed in deformed quartz. In tectonites likewise they have not been reported to my knowledge. Some information is available, however, from veins and pegmatite dikes. Rogers (15) has described well developed parting parallel to the positive unit rhombohedron in vein quartz from California. It is never developed parallel to more than two rhombohedral directions in any one grain and is believed to be a result of the twinning produced by inversion. In pegmatite quartz from Sudbury, Ontario, I have seen grains composed of plates which probably are rhombohedral parting planes similar to those described by Rogers.

Parting planes parallel to other crystallographic planes have not been

reported as far as I know. An interesting possibility which might be investigated concerns the *a* ruptures described by Mallard as cleavage. Parallel to this plane cleavage is less probable than for the unit forms, yet rupture was apparently easy to obtain. It is known that the twin plane for the Brazil law is *a* and, if *a* could also function as the composition plane under certain conditions, the *a* ruptures obtained by Mallard could be explained as parting planes.

TABLE 2. SUMMARY OF GLIDING AND RUPTURE IN QUARTZ[1]

Type of deformation	Predictable from structure	Experimental evidence
Twinning	Mechanism not investigated	Dauphiné twins
Translation	$t=[m:r]$ (possibly) $T=?$	No unquestioned data
Cleavage	*r*—best developed *z*—equally as abundant, but less perfect *m*—poorer than *r* or *z*, linear character *c*—slightly less probable than *m* *a*—slightly less probable than *c* *s* and *x*—improbable as independent cleavages	*r*—best developed *z*—less perfect *m* and *c*—poorer than *r* or *z*, may be composed of alternating *r* and *z* cleavages *a*, *s*, and *x* reported but may not be independent cleavages
Parting	Mechanism not investigated	None reported
Fracture	Best conchoidal fracture perpendicular to *m* —	Best conchoidal fracture perpendicular to *m* Unoriented fractures

[1] Quartz lamellae are not listed here as they have not been obtained experimentally and are not predictable from the structure.

Fracture—As already pointed out, even the most irregular fracture is probably controlled to some degree by the crystal structure it intersects. This is as true of quartz as of other minerals. Its conchoidal fracture, for example, is better known than the imperfect cleavages which have just been discussed. Even this fracture, however, has a vectorial character which is utilized by quartz sculptors (11). From long experience they know that conchoidal ruptures are much more regular perpendicular to the vertical axis than parallel to it, and spheres, for example, are always fashioned from a crystal by working in this way. The structural reason for the more regular fracturing perpendicular to the vertical

axis is obvious from the preceding analysis of cleavage. Parallel to the vertical axis fracture would be splintery and probably interrupted by rhombohedral cleavages, since the unit rhombs are more nearly parallel to the vertical axis than to the base. Perpendicular to the vertical axis there is no linear cleavage and at best a very imperfect planar cleavage, so that there is less structural control of the fractures.

Sander (4, p. 311, D. 55) has described microscopic fractures in tectonites which pass through quartz grains *independently* of the orientation of the crystals. The fractures are straight, parallel, and are assumed to be tensional in origin. Many of the anomalous fractures obtained in experimental deformation are probably of this character. This is to be expected in a mineral whose structure is so closely-knit as that of quartz. Although I have been emphasizing the anisotropic side of its deformation in this analysis, isotropic deformation is not uncommon and interferes with the predicted anisotropic behavior.

Influence of Lineage Structures

In the foregoing discussion the possible influence of crystal imperfections has not been considered. This was intentional, as I wished first to focus attention on the relation between the ideal quartz structure and its deformation. Deviations from predictable behaviour are not rare, however, and may be due to *lineage* structures. Buerger (12) has recently summarized much important data concerning such crystal imperfections and has discussed their influence on crystal behaviours. Crystals are, in general, imperfect, and are divided into branches, or lineages, which have slightly different orientations. The partitions between lineages are lineage boundaries. Under deformation these boundaries may act as gliding or rupture planes and their distribution and degree of disorientation may be controlling factors of the deformation. For example, the distance between successive glide planes in crystals is many times the distance between the planes parallel to which gliding should be possible. In an ideal crystal, however, in which there is uniform distribution of the stress, no one plane of atoms should have preference over another. Lineage structure could explain this anomaly through concentration of the movements in the boundaries. The slight disorientation of the lineages acts further as a brake on unlimited translation and is thought by Buerger to explain the "hardening" of metals brought about by cold-working.

Lineages are probably common in quartz, and are likely to have a longitudinal character parallel to the vertical axis (Fig. 7). Undeformed vein quartz showing "flamboyant" structure in thin section is possibly a manifestation of lineage structure. In tectonite quartz the rodded

character of the strain shadows subparallel to the vertical axis may also be due primarily to lineages, altered by subsequent deformation. That is, in addition to purely structural reasons for rupture of quartz approximately parallel to the vertical axis, imperfections in the form of lineages possibly influence the spacing and ease of rupture in this zone. The interrelations involved here are beyond the scope of this paper. It is my purpose only to call renewed attention to lineage structure in quartz and to point out its possible significance.

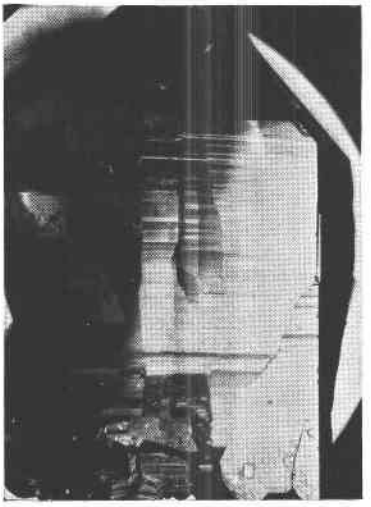

FIG. 7. Prismatic surface of a quartz crystal ($\times\frac{1}{3}$). The prism shows irregular elongate lineages approximately perpendicular to the horizontal oscillation striae. The orientation differences are exaggerated by use of oblique illumination. These disoriented branches, or lineages, may be important factors in certain types of quartz deformation. (Photo by Buerger.)

CONCLUSION

Although quartz has long been the despair of students of mineral deformation and is still more or less of an "enfant terrible," the foregoing analysis shows that its behaviour may be rationalized in terms of crystal structure, at least to some extent. There is essential agreement between experiment and prediction for most of the known cleavages and fractures; for parting, twinning, and translation the data are incomplete. Discrepancies may possibly find their explanation in lineage structures. In a succeeding paper quartz deformation in tectonites will be discussed in terms of possible hypotheses based on gliding and rupture. Although the present paper is admittedly qualitative, and therefore tentative

only, its purpose will have been served if it stimulates criticism and further investigation.

Acknowledgments

The inspiration to carry out this analysis of quartz was due primarily to the initiative of M. J. Buerger of this department in building packing models of various crystalline substances. The co-operation and assistance of Professor Buerger are gratefully acknowledged. J. F. Bell and W. J. Mead have given valuable advice from time to time and have criticized the finished paper. Other members of this department and of the Harvard Mineralogy department have likewise been helpful. To all of these I wish to express my appreciation.

Bibliography

1. Griggs and Bell, Experiments bearing on the orientation of quartz in deformed rocks: *Bull. Geol. Soc. Amer.*, **49,** 1723 (1938).
2. Zinserling and Shubnikow, On the plasticity of quartz: *Trans. Lomonosoff Inst., Leningrad,* **3,** 67 (1933).
3. Judd, J. W., Lamellar structure in quartz: *Mineral. Mag.*, **8,** 1 (1888).
4. Sander, Bruno, Gefügekunde der Gesteine, *Julius Springer*, Wien, **1930.**
5. Buerger, M. J., Plastic deformation of ore minerals: *Am. Mineral.*, **13,** 14 (1928).
6. Mügge, O., Ueber Plasticität und verwandte Erscheinungen in Kristallen: *Neues Jahrb.*, **1,** 102–108 (1898).
7. Sosman, Robert, The Properties of Silica, *Chem. Catalogue Co.*, 487, **1927.**
8. Wooster, Nora, The correlation of cleavage and structure: *Sci. Prog.*, **103,** 462 (1932).
9. Mallard, E., Sur les clivages de quartz: *Bull. Soc. Min. France,* **13,** 62 (1890).
10. Wright and Larson, Quartz as a geologic thermometer: *Am. Jour. Sci.*, **27,** 433 (1909).
11. Ichikawa, S., Appendix to etched figures of Japanese quartz: *Am. Jour. Sci.*, **39,** 472 (1915).
12. Buerger, M. J., Lineage structure of crystals: *Zeits Krist.*, (A) **89,** 195 (1934).
13. Niggli, P., *Zeits. Krist.*, **63,** 306 (1926).
14. Frondel, Clifford, in composite paper—Atomic packing models of some silicate structures: *Am. Mineral.*, **23,** 76 (1938).
15. Rogers, A. F., Unique occurrence of vein quartz in Mariposa Co., California: *Proc. Geol. Soc. Amer.* (abstr.), 347, **1934.**
16. Buerger and Butler, Data for the construction of models, etc., *Am. Mineral.*, **23,** 487 (1938).