American Mineralogist, Volume 66, pages 596–600, 1981

Quartz with rhombohedral cleavage from Madagascar

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Abstract

Anhedral quartz slabs from a vein deposit in Madagascar showing smooth cleavage planes parallel to positive rhombohedra *r* $\{10\bar{1}1\}$ are described. Only two of the three equivalent pairs of the form $\{10\bar{1}1\}$ show cleavage, although of different quality (smoothness). The best developed planes lie parallel to Brazil-twin lamellae; the less well developed planes do not. We presume small tectonically induced thermal shocks to be the releasing mechanism for rhombohedral cleavage fractures. In combination with hydrolytic weakening and directed stress, large smooth cleavage planes were formed. Since the *r*-faces of quartz are F-faces, they have a minimum of free surface energy. We assume this to be the reason for cleavage parallel to positive rhombohedral faces.

Introduction

Many authors describe quartz that, beyond its well-known conchoidal fracturing, under special conditions shows cleavage of decreasing quality (smoothness or perfection) on *r* $\{10\bar{1}1\}$, *z* $\{01\bar{1}1\}$, and *m* $\{10\bar{1}0\}$, respectively. In most cases however no distinction has been made between *r* and *z*. The cleavage parallel to *m* usually is not well developed.

Rose (1844) mentioned that cleavage of quartz may occur to an equal extent parallel to the positive and negative rhombohedra. The 19th century literature on quartz cleavage was reviewed by Hintze (1915), and the literature up to 1960 by Frondel (1962). All authors reported that pronounced platy cleavage or parting occasionally occurs in vein quartz, mostly in the inner parts of vein fillings. Rogers (1934) mentioned huge anhedral blocks of vein quartz from California pegmatites. Since parting was not observed parallel to all three equivalent pairs of rhombohedral faces, Rogers rejected the term cleavage and concluded that parting might be due to polysynthetic Dauphiné twinning, mechanically produced during the high–low transformation of the quartz.

Murdoch and Webb (1938) described quartz with nearly perfect platy parting in pegmatitic veins from another California locality. The slabs showed flat surfaces with pearly luster over areas of 15 to 20 cm². Faint, unevenly spaced, parallel striations indicated a second and a third direction of parting which were not as well developed as the first. Thin sections cut normal to the principal parting plane showed parallel lamellae of varying width. The alternating arrangement of these lamellae resembled albite twinning. Therefore the authors concluded that this peculiar parting might be explained as a pseudomorph of single-crystal quartz after triclinic feldspar, though it was admitted that pseudomorphic replacement by single crystals instead of fine-grained polycrystalline material is very unusual. Jahns (1953) stated that there exists no evidence that large crystals in pegmatites grow by replacement of other minerals.

The production of cleavage in quartz through thermal shock by Kenngott (1844–49) and under directed stress by Judd (1892) was mentioned by Hintze (1915). Borg and Maxwell (1956) subjected quartz sand to a directed stress of about 2 kbar at 300°C, under a confining pressure of about 1 kbar transmitted by alkaline hydrous solutions. They observed a remarkable increase of fracturing parallel to *r* and *z*, but none parallel to *m*. The percentage of grains with deformation lamellae decreased simultaneously. The fractures occurred rarely in parallel sets and occasionally conformed to more than one crystallographic plane. Bloss (1957) crushed quartz crystals both

0003–004X/81/0506–0596$02.00

at room temperature and between 650 and 700°C. He obtained a pronounced cleavage parallel to the rhombohedra *r* and *z* and to a much lesser extent parallel to the prism *m*.

Geological setting and mineralogy

One of us (HK) collected anhedral fragments of large single crystals with almost perfect platy cleavage from quartz veins in NE Madagascar. The hills, bordering D'Antongil Baie (Fig. 1) are part of an old cratonic block of Gondwana. Granites, migmatites and gneisses were cut by a great number of quartz veins and basaltic dikes during the Late Cretaceous. At that time the separation of India from Madagascar caused intense shearing and mylonitization of the basement rocks (Hottin, 1969).

Deep lateritic weathering obscures the attitude and thickness of the quartz veins. Furthermore, frequent landslides have produced accumulations of quartz blocks at the base of the slopes containing the original outcrop.

Our samples come from quartz veins of about 2 m thickness, presumably crystallized from hydrothermal solutions at the expense of the quartz content of the sheared host rocks. The quartz varies from milky or slightly smoky to absolutely transparent in various parts of the vein. Cleavage occurs especially in the inner parts of the vein filling. The remainder exhibits conchoidal fracturing only. The best developed cleavages were observed in blocks of approximately 1 m^3 volume composed of almost clear quartz with only minor trains of inclusions and cloudy schlieren (Fig. 2).

Sample description

Thin sections of various thicknesses proved the samples to be single crystals; however, the microstructure is characterized by twin lamellae following the Brazil law. Neighboring lamellae show differences in extinction position of 2°. The lamellae themselves extinguish homogeneously. Specimens with macroscopically planar cleavages show systems of long linear fractures parallel to the best developed cleavage planes. We refer to this fracture system as R_I. The twin lamellae boundaries are frequently identical with the R_I-fractures. On the universal stage a second system of linear fractures, here termed R_{II}, running parallel to a second pair of rhombohedral faces *r*, could be measured. These fractures are significantly shorter than the R_I type. The angles of intersection between fracture systems R_I and R_{II} in sections perpendicular to the two recognizable cleavage planes were measured to be 87±2°.

A system of short and less linear, healed fissures M also exists (Fig. 2). Angles of intersection between these fissures and R_I or R_{II} are about 130 to 140° in the same sections as above. The M-fissures, which have healed after fracturing, represent characteristic accumulations of aligned fluid inclusions. The R-fractures are unhealed.

Universal-stage measurements proved the R-fractures to be the traces of rhombohedral faces and the M-fissures to be aligned almost parallel to prism faces.

Experimental results

X-ray measurements, according to the orientation method of Keppler (1975), proved that the observed cleavage planes are rhombohedral faces. It is difficult to distinguish between *r*- and *z*-rhombohedra using X-ray methods. Although the intensities of the reflections $10\bar{1}1$ and $01\bar{1}1$ are different (*International Tables for X-ray Crystalography,* 1969, Vol. I, p. 465) their exact determination is nearly impossible, because both reflections are strongly affected by extinction effects. Literature data (*International Tables*, 1962, Vol. III, p. 79; Le Page et al., 1976) are contradictory on the question of which reflection is the more intense.

An unequivocal experimental indication of whether the rhombohedral cleavage planes are positive *r*- or negative *z*-planes (Bravais-set of crystallographic axes, see Dana Frondel, 1962) can be obtained by hydrothermal growth. Prisms measuring 5 × 5 × 15 mm were cut from platy fragments with two natural cleavage planes forming two faces of these prisms. These served as seeds. Growth conditions were: seed temperature 380°C, nutrient temperature 400°C, pressure 1.5 kbar, duration 14 days; nutrient: broken quartz of the same sample, solvent: 1 m Na_2CO_3 in H_2O. After the runs the seed crystals were terminated only by real faces *m*, *r* and *z*, with *r* prominently developed parallel to the original cleavage planes of the seed. The faces *m* and *r* were morphologically dominant, whereas *z*-faces were subordinate due to their higher growth rate. The product crystals exhibited an unusual pseudoorthorhombic-prismatic habit because of the prominent development of the rhombohedral faces. In agreement with literature values, the measured velocities of growth VG were: $VG_m < VG_r \ll VG_z$ (*cf.* Jost, 1955). Our growth experiments at different temperatures (pH 11, pressure 1.5 to 3 kbar) show that in the temperature range up

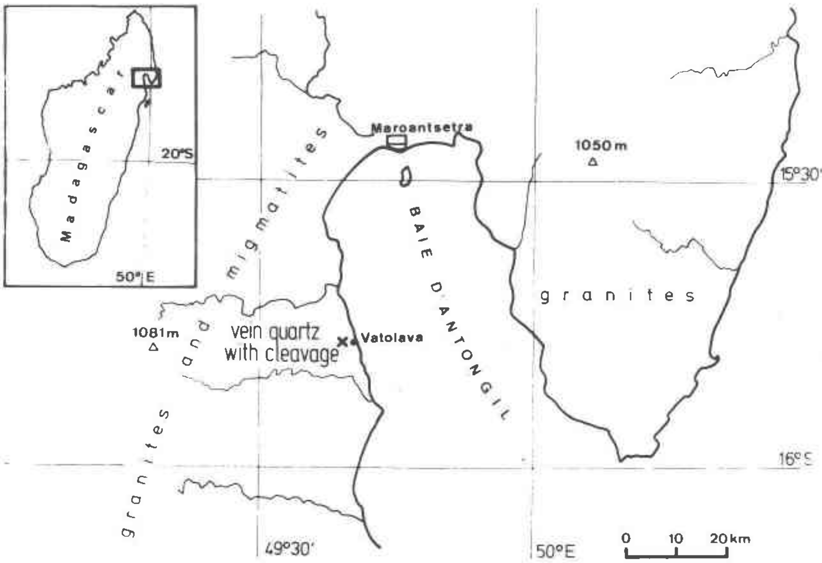

Fig. 1. Sketch of deposit.

to 300°C the free surface energy difference between *r* and *z* is so large that *z* shows much higher growth rates than *r*. With increasing temperature, however, the growth rates of *r* and *z* approach each other and at 500°C there is almost no difference between them.

Twinning was analyzed by etching cuts perpendicular to the *c*-axis (45% HF, 20°C, 30 min), revealing polysynthetic Brazil twinning parallel to only that rhombohedral face *r* which represents the best developed cleavage plane.

Untwinned, single crystal slabs (3–5 cm diameter) of transparent quartz from different localities (Arkansas, Goiaz, Madagascar) were slowly heated (1°/min) in air (1 atm) to 100°C and subsequently quenched in water to room temperature. After this procedure a few linear fractures parallel to the

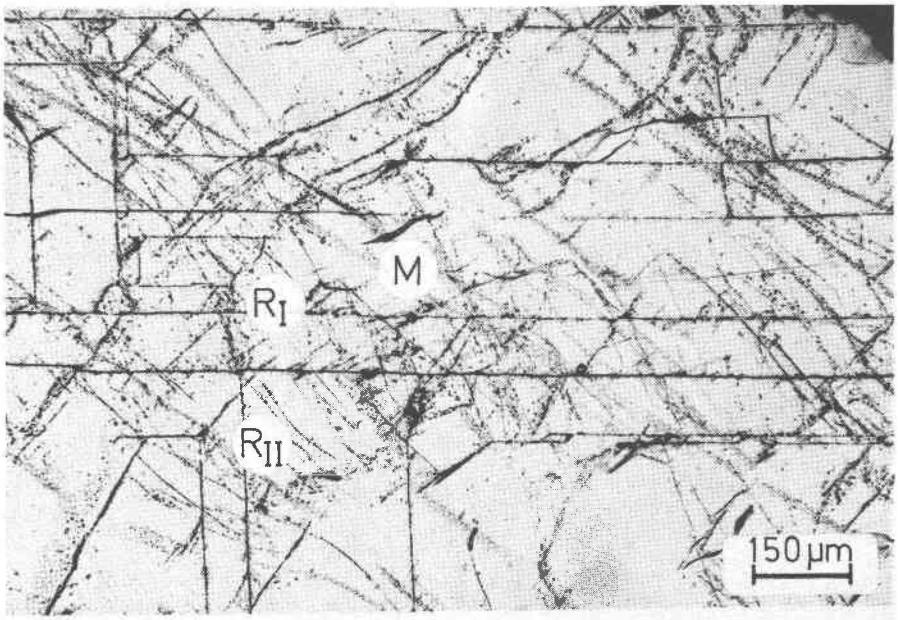

Fig. 2. Photomicrograph of linear rhombohedral cleavage fracture systems R_I and R_{II} and of healed fissures M; thin section cut perpendicular to the two macroscopic cleavage systems.

rhombohedra were observed. When the maximum temperature reached is increased, the fractures became more frequent but less linear. The reverse procedure—shock heating and slow cooling to room temperature—resulted in the same observations.

Completely different fractures were produced by shock heating to temperatures about the low-high-transformation of quartz. In this case the slabs cracked into a fabric of hexagonal, contiguous prisms, elongated parallel to the *c*-axis. Even under hydrothermal conditions, as well as comparatively low rates of heating and cooling the quartz shattered during the low-high-transformation.

Discussion and conclusions

The quartz cleavage parallel to the positive rhombohedron is in all cases observed by us to be of different quality on the three equivalent pairs of the form $\{10\bar{1}1\}$. One pair always shows the best development of cleavage planes and fractures (R_I). A second pair is of poorer cleavage quality (R_{II}). The third possible system R_{III} was never observed in our samples. At standard temperature and pressure (25°C, 1 atm), and in the absence of water, suitably oriented stresses caused samples with R-fractures to disintegrate into thin flakes parallel to these fracture planes, but they do not show any tendency to form new ones.

Under the as yet unknown natural conditions, the huge vein quartz crystals underwent an *in situ* cleaving process without the formation of deformation (Boehm) lamellae or deformation bands. The cleavage described here must be correlated with the structure of quartz. It requires breaking of the strong Si–O–bonds in the tetrahedra-framework. Fairbairn (1939) calculated the number of Si–O–bonds per face unit and showed *r* and *z* to have a minimum, corresponding with a minimum of coherence of the corresponding lattice planes. Though he did not quantitatively discriminate between *r* and *z*, he assumed a decrease of coherence in the sequence:

$$a = \{11\bar{2}0\},\ c = \{0001\},\ m,\ z,\ r.$$

Flörke (1955, 1959) described the positive rhombohedron as the only F-form, according to the PBC theory of Hartman and Perdoc (1955). In order to explain its morphological prominence, it must have the lowest free surface energy, *i.e.*, a minimum of loose Si–O–bonds after cleavage. According to Hartman (1959), however, the *z*- and *m*-faces should be F-faces as well, but these do not show a comparable tendency to cleave. Hartman's method, though excellent, is a qualitative evaluation of surface energies. Especially in complicated structures with a complex bonding character, the results derived from it must be viewed with caution.

The review of literature and our own experiments show that experimentally produced cleavage in quartz, either by directed stress or by thermal shock without a hydrothermal confining pressure, is poor compared to the observed natural cleavage. Therefore we assume, without experimental evidence at present, that the coupled action of a directional stress, with the resolved shear stress RSS exceeding the cleavage stress σ_c $10\bar{1}1$, and a confining hydrothermal pressure high enough to initiate hydrolytic weakening (cf. Griggs, 1967) are necessary to produce cleavage in quartz.

We presume small tectonically induced thermal shocks (cf. Gay *et al.*, 1978) under hydrothermal conditions in comparatively small volumes of the vein-bearing rocks to be the releasing mechanism for cleavage in giant quartz crystals of suitable purity and suitable orientation relative to the stress directions. From our experimental results we assume a rise of temperature on the order of about 100°C to be necessary. We consider the temperature not to have exceeded 300°C. Due to the decreasing surface energy differences of *r* and *z* above 300°C the tendency for cleavage should not show significant differences. At higher temperatures, and especially above the low-high transformation temperature, we expect from our experimental results that even under hydrothermal conditions quartz should shatter rather than cleave.

The cleavage strength σ_c of the positive rhombohedral faces *r* at low temperatures (far below the low-high-transformation) is, from our understanding of the quartz structure, less than it is for any other form and especially for the negative rhombohedron *z*. Thus the explosive transformation of the stored stress energy into surface energy serves to form large, even smooth cleavage planes. Additional hydrolytic weakening moreover specifically lowers the ideal and real cleavage energy for *r* by Si–O–bond breaking and activation of dislocations in the structural framework.

The proposed mechanism of cleavage accounts for both fracture and cleavage systems R_I and R_{II}, but it does not explain the difference in cleavage quality and the absence of the symmetrically equivalent system R_{III}. We assume this to be due to the polysynthetic Brazil twinning parallel to the best rhombohedral plane of cleavage. Brazil twinning along the system R_{II} does not occur. Twin boundaries are two-dimensional areas of structural weakness. This causes cleavage to be more easily achieved and explains the better cleavage of R_I compared to R_{II}. Therefore we assume the polysynthetic Brazil-twinning to have been formed before cleavage. Polysynthetic Brazil-twinning has been frequently observed in vein quartz (Frondel, 1962, p. 87, Figs. 62, 63).

The absence of the third cleavage system R_{III} is due to the orientation of the quartz with regard to the directed stress. According to Schmid's law the shear stress τ reaches a maximum at $\tau_{max} = \sigma/2$, if the angle between stress σ and gliding plane happens to be 45°. The interfacial angle between two symmetrically equivalent rhombohedron faces r is 87°. If the directed stress σ_c bisects the interfacial angle between two equivalent rhombohedron faces r_1 and r_2 the shear stress τ nearly reaches a maximum for two planes at the same time. The analogous orientation with regard to three equivalent rhombohedral faces r_1, r_2 and r_3, is, according to Schmid's law, difficult to realize. For only one single orientation will the directed stress be inclined at 45° to all three faces. The latter case is less probable. Thus usually two rhombohedral cleavage systems are formed.

Our understanding of rupture suggests that the distinction between fracture, parting and cleavage suggested by Fairbairn (1939) cannot be upheld. Even the conchoidal fracture of quartz is controlled by its structure (Hoffer, 1961). The term parting should be preserved for fractures controlled by segregation, zoning of impurities or exsolution (Buckley, 1934; White, 1979), whereas cleavage should be used for all planar fractures of crystals which are intrinsically or primarily controlled by the structure.

Acknowledgments

We gratefully acknowledge the thorough revision of the manuscript by Walter V. Maresch Ph.D., and we would like to express our most sincere thanks to Mrs. Helene Nowara and Mr. Dieter Dettmar for their valuable technical assistance.

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Manuscript received, June 16, 1980;
accepted for publication, January 5, 1981.