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DISLOCATIONS IN QUARTZ CRYSTALS

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In studying a natural transparent quartz crystal that had grown along the basal direction, on the 0001 surface of the growth pyramids the author recorded the presence of a distinctive pattern in the form of a ditrigonal network, shown in Fig. 1 (see insert to p. 81). The conditions under which the crystal was found in the deposit suggest that the appearance of so clear a network pattern is due to natural etching, which contributed to its decoration. On examining the structural details of the individual cells of the network, one can see that each hexagon is characterized by the presence of a distinctive center, often responsible for the appearance of separate growth microaccessories, visible in Fig. 1. Subsequently the microaccessories, as they grow, assume in plan a triangular or quadrangular (trapezoidal) form. With strong growth, the macroaccessories merge, forming a knobby subpinacoidal surface that in many respects resembles the analogous surface of synthetic quartz crystals grown on the pinacoid. In the course of the growth of individual accessories, numerous new centers are formed on their surface, from which the development of new accessories begins; these evolve analogously to the accessories indicated above. Thus it was obvious that the growth centers determine the mechanism of growth of quartz crystals during their growth along the basal direction.

In attempting to determine the causes giving rise to the appearance of microaccessories, the author studied the structure of individual centers with an MBI-6 microscope and with an electron microscope. Analysis of the photographs shown in Figs. 1 and 3, as well as observations by the moiré method, made it possible to conclude that the growth centers are of a dislocation nature. The appearance of single growth centers is due to the presence of many "coalesced" spirals of one sign. The formation of paired growth centers is due to the blocking of two spirals of opposite sign. The growth accessories of paired spirals have a trapezoidal form and grow by means of three steps formed by such paired spirals. The total number of centers on the 0001 surface of quartz amounted to more than 200,000 per 1 cm^2. The most widespread are paired centers. The latter, being formed by a combination of a right-hand spiral with a left-hand one, function as Frank-Read sources ([1], [2], [4]). For illustration, Fig. 3 presents photographs of paired centers at different stages of evolution.

On the basis of the factual material presented, one may suppose that the appearance of dislocations in quartz crystals is due to the capture, during growth, of accessory particles capable of deforming the crystal structure. Having arisen, such a dislocation (Fig. 2), if pinned at points A and B, begins to bow out in a definite direction. When the loop closes at point C, it breaks away, turning into an independent loop. Subsequently the loop, expanding, assumes positions 3, 4, 5, etc., up to its emergence from the crystal. As is evident from the photographs, during expansion the dislocation loops in quartz move not in a circle, but along definite structural directions, which accounts for their trigonal symmetry. We emphasize that, since growth steps are inseparably connected with dislocations, an analogous picture is observed—

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Fig. 1. Ditrigonal network on the 0001 surface of a growth macroaccessory of a quartz crystal. In the central part of the figure a series of elementary growth accessories of trapezoidal form is observed.

Fig. 3. Various stages in the evolution of slip sources in quartz. On the right, explanatory drawings are given. **a** —the position of loop **B** before the first discharge of the loop; **A** and are fixed nodes of dislocation , whose appearance is caused by the capture of a particle (black dot) during crystal growth; —the position of the loop soon after discharge; **a** —a new loop generated by source ; **R** and **r** are rhombohedron faces on an elementary growth accessory; $\mathbf{P}_1$ is the pinacoid face of this same accessory; **P** is a subbasal surface of the quartz crystal; $\mathbf{B}_1$ is the unstudied face of an accretionary growth with a subbasal surface of the crystal; —the position of loops **B** and **I**, caused by their blocking; —a half-loop; —the "initial" position of dislocation after discharge of the loops.

also occurs during the formation of growth steps on the basal surface of quartz. It is interesting to note that, when observed by the moiré method, the loops appear as intricately twisted spirals. Loops naturally etched on the basal surface appear as a diversely spiral-constructed bundle. When etched with HF, individual turns of the loops are etched out with the formation of small triangular etch pits. Single centers generating spirally constructed loops, when observed by the moiré method, appear as characteristic moiré spirals with a central point. When such centers are etched with HF, large triangular etch pits form on the basal surface. In sections parallel to the third-order axis, single centers look like swirls with a spiral structure. The individual turns of such swirls, in turn, have a complex spiral structure caused by the presence not of one but of several spirals gathered into bundles. Thus, it may be assumed that the thickness of the principal spirals of the centers is determined, on the one hand, by the degree of their twisting and, on the other, by the joining of several thin spirals (dislocations) into bundles of various orders. It is probably precisely this circumstance that is responsible for the appearance, on the basal surface, of etch pits of different orders (at the same exposure). Observations show that even the very finest channels, similar to those described by E. V. Tsinzerling (3),

Fig. 2

Figure 1: Fig. 2

Fig. 4

Figure 2: Fig. 4

when observed by the moiré method prove to be very complex, clearly spiral formations. Moreover, in most cases such a "dislocation" is a moiré spiral that disappears when one attempts to examine it at high magnifications.

Fig. 2. Schematic representation of the structure and position of a slip source in a quartz crystal at various stages of evolution (1–8). The bold line indicates the stage often accompanied by the formation of an elementary accessory. Light points are fixed nodes of dislocation AB. The black point is an accessory particle that generated the dislocation.

From the mode of formation of dislocation bundles in quartz crystals follows also the reason for the appearance in them of regularly oriented optical inhomogeneity of various orders. Dislocation bundles of various orders predetermine not only the morphology of the growth surface and the optical inhomogeneity, but also a finer sculpture caused by the presence of disordering boundaries, including twin boundaries. As can be seen from the figures, the pattern on the pinacoid surface is largely predetermined by the interaction of intricately combined screw dislocations (bundles) operating with different signs. As an example, let us consider two cases of dislocation interaction that find their reflection in the sculpture of the 0001 surface of quartz.

Case 1. The interaction of two spiral slip sources (Fig. 4*a*), directed toward each other, leads to the formation of a twin connected with the surrounding quartz structure by a dislocation loop. From this figure it is also easy to notice that, during the interaction, each of the sources shed at least three loops.

Case 2. The interaction of sources directed "away from each other" (Fig. 4*b*) at the moment when the loops meet leads to their "slamming shut." As a result, "clean" hexagons without an internal sub-boundary are formed.

The examples cited, of course, do not exhaust the enormous variety of cases of interaction of dislocations. It is interesting to note that the formation of distinct chains of dislocation centers is almost always observed as a continuation of cracks that have wedged out in crystals. Thus, it may be thought that dislocations also play an important role in the formation of cracks in quartz crystals.

Fig. 4. Interaction of slip sources observed on the 0001 surface of a quartz crystal. **a** –interaction of two sources when half-loops move "toward each other." In the Φ image the movement of half-loops is clearly visible. In the lower part of the figure a diagram is given of the presumed interaction of the sources; **b** – formation of a large "clean" hexagon when half-loops move "toward each other."

An explanatory diagram is given below. The boundary that disappears at the moment the loops meet is shaded with transverse lines.

The study of gas-liquid inclusions, observed in the form of negative crystals, and of other forms also showed their close connection with dislocations. In particular, it was almost always possible to observe that gas-liquid inclusions are connected with the main spirals by the finest dislocations, analogous to those indicated above.

Conclusions

The sculpture on the 0001 surface of natural quartz crystals is of a dislocation nature. The appearance of dislocations in quartz crystals is probably caused by the precipitation of accessory particles during crystal growth. The dislocations that form often combine into bundles of various orders. The interaction of dislocations and dislocation bundles of various orders can lead to the formation in quartz crystals of twins, swirls (optical inhomogeneity), cracks, and other defects. Growth of quartz crystals along the pinacoid occurs by the addition of a step rotating in a spiral around a dislocation center, as well as by the addition of triple steps formed by double spirals.

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Note: Figure translations are in progress. See original paper for figures.

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