Fig. 1. Thin sections of cylindrical specimens (2.3 mm in diameter) cored from a synthetic quartz single crystal deformed in compression at a strain of 8×10^{-6} sec^{-1} at a confining pressure of 15 kb. All specimens were cut so that c and a axes are 45 degrees to the axis of the cylinder (direction of compression) and lie in the plane of the thin section with the c-axis trending NW. A, 300°C, 6.2 percent shortening. There are faint NE trending basal lamellae which produce NW kink bands. Strength, 42 kb. B, 400°C, 9.6 percent shortening. Whole central region is a broad NE trending kink band formed by slip on NW trending prismatic lamellae. Strength, 1 kb. C, 600°C, 6.5 percent shortening. No strong lamellae or kink bands. Very fine lamellae throughout of near basal and near prismatic orientation. Strength, 0.4 kb.

untreated natural quartz. This absorption is characteristic of strongly bonded OH in crystals measured at room temperature. Integration of the area between the curves yields, by the method of Bambauer (8), a concentration of 1 atom of H for every 130 atoms of Si, or about 0.1 percent of water equivalent by weight. This concentration of OH is an order of magnitude larger than the maximum reported for natural quartz. It is of the same order as the water available in our earlier experiments with natural crystals.

Nuclear magnetic resonance analysis gave no measurable proton signal: this suggests that the OH is tightly bound and occurs at a variety of sites within the crystal. An x-ray analysis of this crystal by J. Starkey gave the same lattice constants as those published for quartz, ± 0.001 Å (9).

We believe that the water may hydrolyze the Si — O — Si bridges to give two silanol groups, as suggested by Brunner et al. (10) as follows:

$$\text{Si} - \text{O} - \text{Si} \qquad \begin{array}{c} \text{HO} \\ \text{Si} \quad\vdots\quad \text{Si} \\ \text{OH} \end{array}$$

Two adjacent silanol groups would be bound to each other by only the relatively weak hydrogen bonding. Since fewer than 1 percent of the silicon-oxygen bonds would be so weakened, this would not be expected to cause appreciable weakening of the crystal unless these hydrolyzed bridges could catalyze fracture, recrystallization, or plastic deformation.

Fracture seems to have played no part in the deformation. The fractures observed (Fig. 1B, 1C) are of the type formed on release of confining pressure. Evidences of recrystallization are noted (Fig. 1C, Fig. 3) but do not occur in many weak specimens (Fig. 1B). All weak specimens, however, contain abundant lamellae. These lamellae have optical properties similar to those developed in natural quartz in which the lamellae have been shown to be arrays of edge dislocations, whose motion has caused the observed strain (5).

One picture of the way in which water could facilitate such plastic flow is that hydrolysis takes place along preexisting dislocation lines where Si — O — Si bridges are already broken. As the temperature is raised this model would suggest that the silanol groups become sufficiently mobile to move with the dislocations, breaking and re-forming Si — O — Si bridges as they go. If the number of dislocations were 10^9 cm^{-2}, as found in natural quartz (5), then only one one-thousandth of the observed water would take part in this dislocation motion. Whatever the precise mechanism, the process is thermally activated, presumably as the mobility of the silanol groups is increased sufficiently.

Since all silicates have Si — O — Si or Si — O — M bridges (where M is a metal ion) which are susceptible to this type of hydrolysis, this temperature-induced water weakness may apply
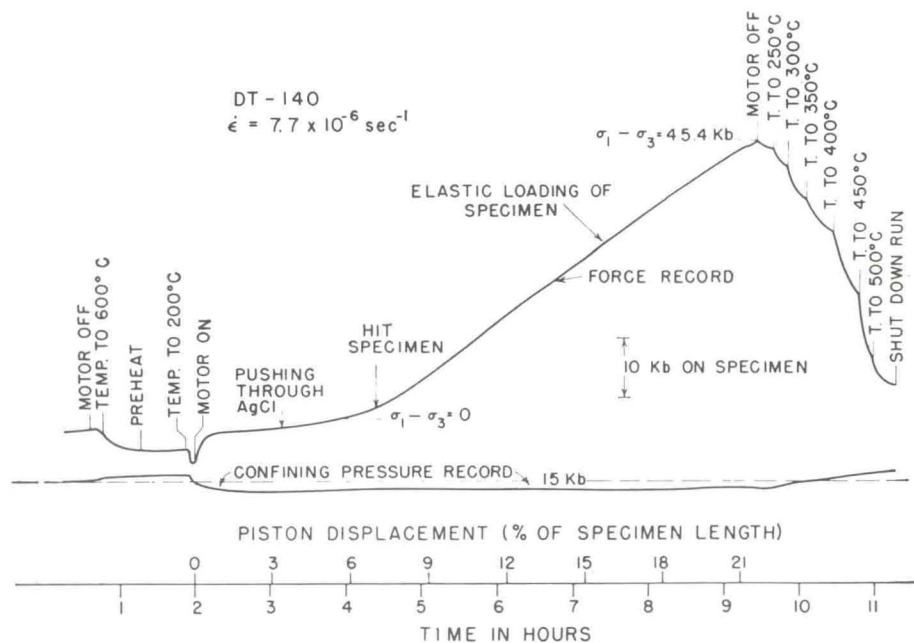

Fig. 2. Tracing of force record of DT-140. Time increases to the right. From left to right: initial heating at 600°C; cooling to 200°C; motor is turned on; force increases slowly while piston is being pushed through AgCl; the piston hits the specimen and the force increases linearly with time during the elastic loading of specimen; the motor is turned off; there is then successive relaxation at 200°, 250°, 300°, 350°, 400°, 450°, and 500°C. The piston displacement during "elastic loading" of the specimen includes apparatus distortion. The elastic strain computed from acoustically determined elastic constants is 4.5 percent at 45 kb.

2

0.1mm

WAVELENGTH (MICRONS)

Natural Quartz Single Crystal (1mm plate)

Synthetic Quartz Single Crystal (1mm plate)

INFRARED TRANSMISSION SPECTRA

ABSORBANCE

FREQUENCY (cm⁻¹)

Fig. 3 (top left). Sepcimen DT-140 photographed in phase contrast illumination between crossed nicols. N-S bands are remnant kink bands subparallel to the *c*-axis. E-W worm-like features are recrystallized basal lamellae. The less prominent NNE trending features are recrystallized lamellae whose traces on the section are inclined 5° to 25° to the *c*-axis. At low temperature, specimen formed prismatic kink bands by basal slip. As the temperature was raised, stress relaxation was accompanied by recrystallization.

Fig. 4 (bottom left). Infrared absorption of natural quartz and synthetic quartz crystals, both 1 mm thick. (Courtesy M. Haugh.) Note essential absence of OH absorption in this natural quartz and large absorption in synthetic crystal, corresponding to 0.1 percent water equivalent (by weight).
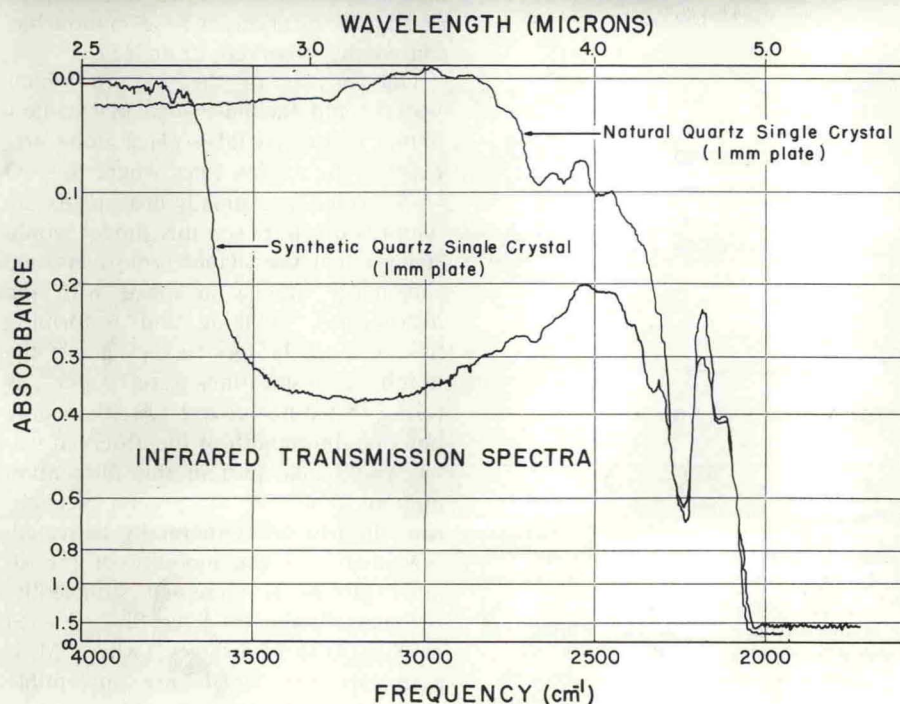
to silicates in general. We have observed such weakness in olivine and feldspar rocks, deformed in a hydrous environment.

These observations raise the possibility of great weakness in the earth's deeper crust and outer mantle at temperatures far below the melting point.

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