Reports

Meteoritic Impact and Deformation of Quartz

Abstract. *Quartz deformation lamellae parallel to* c$\{0001\}$ *and planar features parallel to* $\omega\{10\bar{1}3\}$ *appear to be both characteristic of and reliable criteria for quartz deformed by shock due to impact by meteorite or comet. These features are readily distinguished from microstructures, induced during tectonic deformation, by differences in optical properties or spatial and crystallographic orientations of statistically sound populations, or in both.*

Greenwood (*1*) has questioned the validity of certain microstructures in quartz as indicative of shock deformation due to collisions of extraterrestrial bodies with Earth. If borne out, his conclusions will eradicate many intensive efforts during the last 5 years to establish petrographic criteria for distinguishing between meteoritic impact and tectonic deformations; moreover they will seriously challenge recent interpretations of the origin or modification of some major structures of Earth's crust, such as Vredefort Ring (South Africa) and Sudbury structure (Ontario).

Greenwood's discussion is based on limited study of specimens from the Coeur d'Alene district in Idaho, for which there are no indications of meteoritic impact. Although the data are not presented, Greenwood reports the discovery of lamellar structures in 160 quartz grains, of which five are parallel to $\{0001\}$ and 46 are parallel to $\{10\bar{1}3\}$, within the stated ± 4-percent measuring error.

Certain microstructures parallel to these forms have been claimed to be characteristic of and unique to known or supposed sites of meteoritic impact (*2*). Accordingly, the main implications of Greenwood's arguments are that (i) deformation structures parallel to $\{1001\}$ and $\{10\bar{1}3\}$ are not unique to quartz deformed by meteoritic impact, and (ii) "The scarcity of available reports on deformation lamellae makes arguments based on negative evidence rather tenuous." These criticisms are very serious to the impact interpretation and must be evaluated critically in the light of available information.

Deformation lamellae in naturally deformed quartz were described in 1883 (*3*), since when no fewer than 22 published papers have described these features and their orientations. Ten rather detailed studies published during the last decade carefully describe the optical characteristics and crystallographic and spatial orientations of the lamellae. The lamellae are closely spaced planar or lenticular features having very distinctive optical properties; unless decorated by minute brownish cavities or

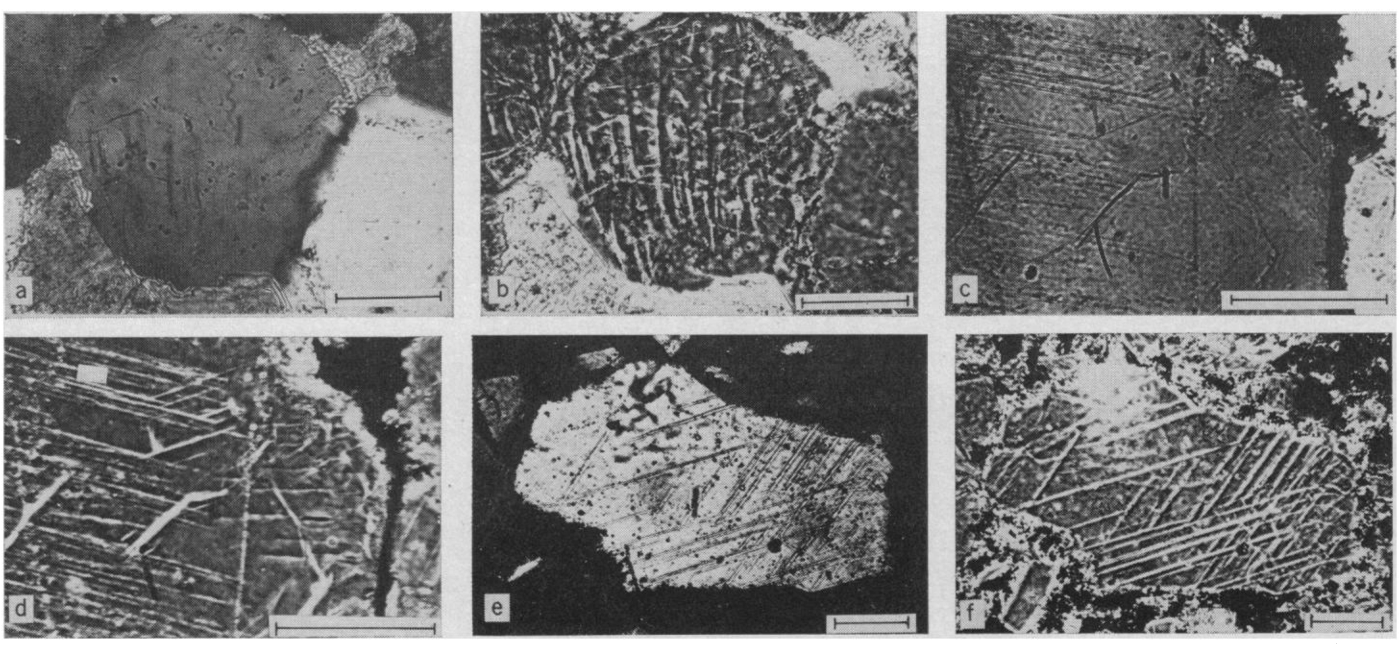

Fig. 1. Photomicrographs of microstructures in quartz taken under bright-field illumination, crossed nicols (a, c, e), and phase-contrast illumination (b, d, f). Scales, 0.1 mm. (a and b) Quartz grain in calcite-cemented sandstone specimen from Montana (*4*). Deformation lamellae are N–S linear features. The lamellae are plainly visible near the bottom of (a) because of decoration but are scarcely visible near the top. In phase contrast (b), the lamellae are sharp and visible throughout and they are asymmetric, being dark on one side of an almost plane discontinuity and light on the other. (c and d) Basal deformation lamellae and planar features parallel to $\{10\bar{1}3\}$ in quartz from Clearwater Lakes, Canada (*2*). The lamellae are the sharp, asymmetric, E–W trending features on the right side of the grain in (d). Note that they are very difficult to detect in (c). The straight, sharp, symmetric, ENE- and WNW-trending planar features are parallel to $\{10\bar{1}3\}$. (e and f) Planar features parallel to $\{10\bar{1}3\}$ in quartz from Clearwater Lakes. Note that the features bear little resemblance to deformation lamellae (a and b) and that they are equally prominent under both types of illumination.

inclusions, they are difficult to detect in bright-field illumination (Fig. 1a) but are easily identified in phase contrast where they appear as sharp asymmetric features (Fig. 1b).

A recently published compilation of the orientations [from seven sources (*2, 4*)], with respect to the quartz *c*-axis, of 3835 sets of deformation lamellae (Fig. 2a) is by no means complete; the number of observations could very likely be doubled by taking into account all measurements, but the result would be similar. With two exceptions (*5*), data from individual studies deviate only slightly from the composite data. With regard to the exceptions, the lamellae show bimodal distributions and are inclined at significantly greater angles to the base than are most of the lamellae represented (Fig. 2a). Thus deformation lamellae in naturally deformed quartz have interested students of rock deformation for 85 years, and there certainly is no paucity of published information concerning their nature and orientations.

Let us now compare the orientations of natural lamellae, as indicated in Fig. 2a, with Greenwood's data. We note that 3.2 percent of all lamellae represented are inclined at less than 5 deg to {0001} (Fig. 2a), compared to 3.1 percent (5 of 160) observed by Greenwood. Moreover, the figure of 29 percent (46 of 160) for the lamellae oriented close to {10$\bar{1}$3} for the Coeur d'Alene specimens compares very well with the frequency shown (Fig. 2a), when account is taken of errors in measurement.

Because of this apparent close correspondence I sought and received Greenwood's data and a representative thin section. A similar plot of his composite data shows no significant differences in orientations from those in Fig. 2a. In addition, careful examination of the thin section revealed that the lamellae are identical with those shown (Fig. 1, a and b) and represented (Fig. 2a); that is to say, they were produced by tectonic deformation, in agreement with Greenwood's conclusions. However, the few lamellae inclined at low angles to {0001}, and the concentration near an angle corresponding to {10$\bar{1}$3}, do not vitiate the conclusion (*2*) that particular microstructures, predominantly parallel to these forms, are characteristic of and virtually unique to impactites, as will become clear in the discussion that follows.

By contrast, cumulative data are shown for quartz deformation lamellae

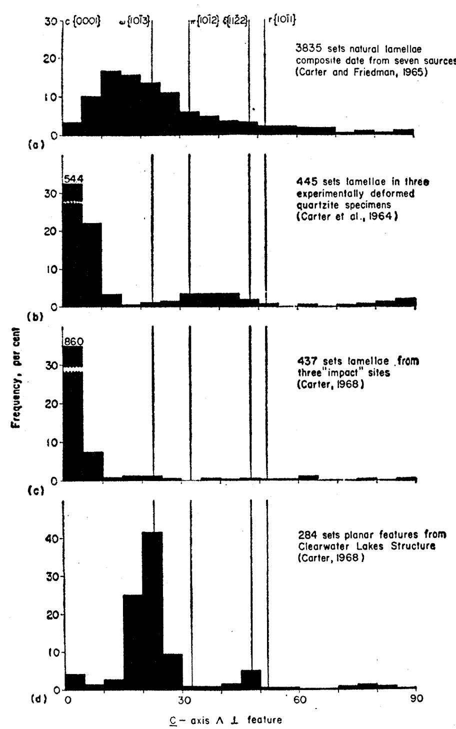

Fig. 2. Histograms showing the variation of orientations of various planar structures in quartz with respect to the quartz *c*-axis.

in three experimentally deformed quartzite specimens (*2, 6*) (Fig. 2b) and impactite specimens from Barringer (meteor) Crater, Vredefort Ring, and Middlesboro structures (*2, 7*) (Fig. 2c). These two histograms (Fig. 2, b and c) are very similar in that most of the lamellae are inclined less than 5 deg from {0001}; 53 percent of the lamellae in the impactite specimens are inclined less than 3 deg from the base. The basal lamellae (right side of grain in Fig. 2d), although possessing the same distinctive optical properties as have lamellae in tectonites, are generally less complex and straighter and sharper, so that the error in measurement is probably ± 2 deg. Basal lamellae, almost to the exclusion of lamellae of other orientations, were discovered in specimens from five other cryptoexplosive structures and in a specimen recovered from the Hardhat nuclear explosion (*2*); they have since been found in many cryptoexplosive structures (*8*).

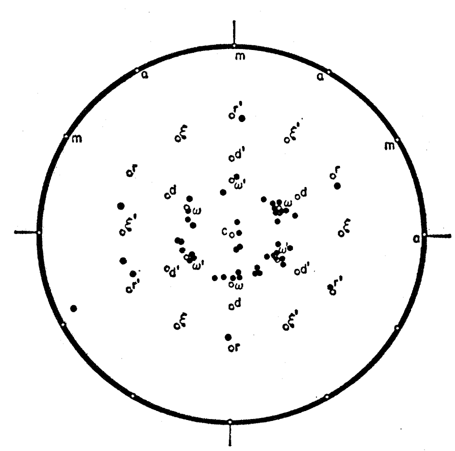

Fig. 3. Orientation, with respect to the crystallography of quartz, of poles to 50 sets of planar features (solid circles) in grains containing faults or cleavages parallel to *r*{10$\bar{1}$1} or *z*{01$\bar{1}$1}.

Basal deformation lamellae in the experiments were shown to be photoelastic effects produced by stresses due to dislocation arrays locked in the basal slip planes (*9*). It seems likely that lamellae in the impactites originate similarly; their profuse development and random spatial orientation in some specimens indicates that they probably originated by some shock mechanism (*2, 7*). If static critical shear data for basal slip (*10*) in quartz are extrapolated to the very high strain rates of impacts or explosions (about 10^6 per second), it is found that the shear stresses required are much too high to be accounted for over large areas by any intraterrestrial source of energy (*2*). Accordingly it was concluded that the basal lamellae originated by shock due to impact of meteorite or comet.

Very distinctive planar features, commonly occurring in multiple sets, were first discovered in quartz from the Clearwater Lakes structure, Ontario (*11*); they (Fig. 1, e and f; left sides of c and d) differ from deformation lamellae in that they are equally prominent under bright-field and phase-contrast illumination and are symmetric; they differ further from deformation lamellae in tectonites in that they are much less complex and straighter. Figure 2d shows the orientation of these structures with respect to the quartz *c*-axis; clearly this histogram is very different from that for natural lamellae (Fig. 2a). A very strong maximum occurs between 20 and 25 deg, at angles corresponding closely to that for ω{10$\bar{1}$3}—a rare morphological form in quartz. This fact does not prove that these planes are indeed parallel to ω, as an infinite number of orientations of planes inclined at 23 deg to the *c*-axis are possible. The ambiguity was removed, however, by measurement of the orientation of faults or cleavages parallel to one of the unit rhombohedrons *r*{10$\bar{1}$1} or *z*{01$\bar{1}$1} present in some of the grains. The unit rhombohedrons intersect the basal plane parallel to an *a*-axis, thus fixing the crystallographic orientation (one necessarily ignores polarity). The orientations so determined (Fig. 3) show a distinct clustering about ω, indicating that most of these features do indeed form parallel {10$\bar{1}$3}. To my knowledge, there is no evidence indicating that deformation lamellae in tectonites form preferentially parallel to ω, and the data in Fig. 2a certainly cannot be interpreted to support this notion. Deformation lamellae, identical with those in tectonites, have recently been produced in static experiments on oriented quartz crystals (*12*), and these clearly are not parallel to ω.

A detailed study with optical and electron microscopes of the planar features parallel to {10$\bar{1}$3} reveal that individual bands commonly comprise several very thin planar features (*7*). Replication electron microscopy of polished surfaces showed no discontinuities, the indication being that the features are not open fractures as was suggested (*13*). Replicas of planar features etched in HF vapor show thin, nearly linear, but discontinuous ridges. Electron micrographs of the area of intersection of two sets of the features (Fig. 1, e and f) show slight mutual offset of the features, indicating small shear displacements along them. Therefore, inasmuch as the shear strength of quartz is very high, these features are probably reliable indicators of intense deformation by shock.

Interferometry (*14*, *15*) and x-ray studies (*15*) have indicated that the material composing the features is silica having a short-range order. Apparently the crystal structure along these planes was severely distorted and partly reduced to glass during small shear deformations accompanying the passage of the shock wave. Planar features parallel to {10$\bar{1}$3} have also been observed in quartz from the Ries Kessel (*16*), Sudbury structure (*17*), and many other cryptoexplosive structures (*8*).

Thus it appears that both deformation lamellae parallel to {0001} and planar features parallel to {10$\bar{1}$3} are reliable criteria for shock due to impact by meteorite or comet. Both the optical characteristics and frequency (distribution of orientations with respect to the *c*-axis) of a statistically sound population serve to distinguish these structures from those produced by tectonic deformation. It seems that studies of microstructures in tectonically deformed quartz have been sufficient to preclude the probability that these structures could be produced during tectonic deformations. The possibility (unlikely, in my opinion) remains, however, that these features could be created by shock due to volcanic explosions. No such features have been reported, but no careful search has been made that I know of.

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Direct High-Temperature Ohmic Heating of Metals as Liquid Pipes

Abstract. *When a sufficiently high electric current is passed through a liquid metal, the electromagnetic pressure pinches off the liquid metal and interrupts the flow of current. For the first time the pinch effect has been overcome by use of centrifugal acceleration. By rotation of a pipe of liquid metal, tin or bismuth or their alloys, at sufficiently high speed, it can be heated electrically without intermission of the electric current. One may now heat liquid metallic substances, by resistive (ohmic) heating, to 5000°K and perhaps higher temperatures.*

The electromagnetic pinch effect was first described by Hering (*1*) in 1907 as a practical limitation for electrical-resistance furnaces. Northrup (*2*) established the simple relation between pinch pressure (P_{el}), current (c), and cross-sectional area (a) of the liquid conductor (in centimeter-gram-second units throughout):

$$P_{\mathrm{el}} = c^2/a \quad (1)$$

If the current is measured in amperes (I),

$$P_{\mathrm{el}}\ (\mathrm{dyne/cm^2}) = I^2/(100 \cdot a) \quad (2)$$

Earlier the pinch effect was overcome in liquid-metal tubes (*3*) by application of hydrostatic pressure to them in a U-tube type of furnace. We shall now show that the pinch pressure can be easily overcome [as was suggested (*4*)] by centrifugal pressure P_{cent}. The centrifugal force F (in dynes), in a liquid tube having an inside radius R (centimeters) and rotating at r revolutions per minute, equals

$$F = 4\pi^2 R \cdot r^2 \cdot M/3600 \quad (3)$$

M being the total mass in grams.

The force per unit area of the tube (P_{cent}) in dynes per square centimeter is

$$P_{\mathrm{cent}} = 4\pi^2 \cdot R \cdot r^2 \cdot M/3600 \cdot 2\pi R \cdot L \quad (4)$$

where L is the length of liquid metal in centimeters. If D is the density of the liquid metal in grams per cubic centimeter and θ is its thickness in centimeters,

$$M = 2\pi R \cdot L \cdot \theta \cdot D \quad (5)$$

Therefore, from Eqs. 4 and 5,

$$P_{\mathrm{cent}} = \frac{4\pi^2 \cdot R \cdot r^2 \cdot \theta \cdot D}{(60)^2} = \frac{1.0966 \cdot R \cdot r^2 \cdot \theta \cdot D}{100} \quad (6)$$

The hydrostatic pressure in a liquid is exerted equally in all directions. In Eq. 2 the cross-sectional area a is

$$a = 2\pi \cdot R \cdot \theta \quad (7)$$

(we ignore the term $\pi\theta^2$ for $R \gg \theta$).

Therefore P_{cent} equals the pinch pressure when (from Eqs. 2 and 6)

$$I = 2.625 \cdot r \cdot R \cdot \theta \cdot D^{\frac{1}{2}} \quad (8)$$

or

$$r = 0.3809 \cdot I/(R \cdot \theta \cdot D^{\frac{1}{2}}) \quad (9)$$