Plastic Faulting in Ice

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Abstract Plastic faulting is a brittle-like failure phenomenon exhibited by water ice and several other rock types under confinement. It is suspected to be the mechanism of deep earthquakes and extreme cases of shear localization in shallow rocks. Unlike ordinary Coulombic failure, plastic faulting is characterized by a pressure-independent failure strength and fault plane oriented 45° to maximum principal stress. To research the question of how the instability initiates, we conducted over 50 constant-displacement-rate experiments on polycrystalline ice (phases Ih and II) near the brittle-to-ductile (B-D) transition, at confining pressures P = 0–300 MPa, applied strain rates $\dot{\varepsilon} = 5 \times 10^{-5} - 7 \times 10^{-3}$ s$^{-1}$, temperatures $T = 105$–233 K, and mean grain sizes $d = 0.25$–1.18 mm. We find that (1) the width of the B-D transition in variable space is vanishingly narrow, to the point of appearing as a crossover, (2) a plastic fault plane, once formed, is not a zone of subsequent weakness, (3) distributed ice I→II phase transformation in small amounts (<1 vol%) shows no causal relationship to subsequent failure, and (4) plastic faulting also occurs in ice II. We hypothesize that the elusive nucleating “trigger” parallels that of metals and ceramics undergoing severe plastic deformation, wherein transient local structural rearrangement occurs, in turn causing material strength to drop to a level sufficiently low, in a volume sufficiently large, that adiabatic instability is nucleated. Our results do not require and often are inconsistent with phase transformation. Plastic faulting may therefore be available to all solids undergoing severe deformation, and its appearance in so few is simply the result of insufficiently extreme conditions.

1. Introduction and Background

Ice Ih exhibits two distinct modes of brittle failure when loaded in triaxial compression (Durham et al., 1983; Kirby et al., 1991; Renshaw & Schulson, 2004; Schulson, 2002). Under low but nonzero levels of confining pressure, brittle failure is characterized by the development of a macroscopic shear fault composed of gouge material and a wide zone of coalesced microcracks, oriented following the dictates of the Mohr-Coulomb relationship at a steep angle (often within 30°) to the direction of maximum compression. This mode of failure, called Coulombic or frictional faulting, is associated with pressure strengthening, increased dilatancy near failure, and a low degree of cohesion. The mechanism governing this mode of failure in ice has previously been discussed in terms of crack mechanics, where frictional sliding on primary inclined cracks drives a process zone at crack tips, with that zone involving out-of-plane initiation, growth, and interaction of secondary cracks via the comb-crack mechanism (Renshaw & Schulson, 2001; Schulson, 1999). Coulombic faulting is the most common mechanism of brittle failure of most crystalline rock types in Earth’s shallow crust (e.g., Paterson, 1978).

At pressures above a few tens of MPa, however, hexagonal ice Ih (hereafter simply ice I) exhibits a mode of brittle failure called plastic faulting, which has been seen in only a few other rock types (Durham et al., 1983). Plastic faulting involves the same sudden and substantial loss of strength that characterizes Coulombic faulting but differs in that pressure strengthening and dilatancy, so prominent in the Coulombic process, are absent; and the fault plane, when it is possible to observe, is oriented at ~45° to the direction of maximum compression, on a plane of maximum shear stress. The absence of dilatancy means that microfracturing is absent, that is, that the plastic faulting mechanism is fundamentally a shearing process. In ice, where the process has been studied most thoroughly, the fault is observed to retain a high degree of cohesion, and the material within the fault is highly strained and usually composed of recrystallized grains, often of very fine grain size (Golding et al., 2012; Kirby et al., 1991; Rist & Murrell, 1994).
Adapting an already ambiguous geomatials science lexicon to the discussion of plastic faulting, a process with an oxymoronic name that is seemingly inconsistent with the norms of rock mechanics, requires clarification of two potentially ambiguous terms important to this paper: “brittle” and “failure.” We use “brittle” to describe a mode of stress-strain behavior characterized by sudden or catastrophic loss in strength accompanied by inelastic displacement localized on a narrow fault plane or planes, and “failure” as the inability to support a load without deforming inelastically. Importantly, as used here, neither term is meant to imply a physical deformation mechanism such as localized cracking or distributed ductility. Thus, we can say that plastic faulting is a mode of brittle failure and that rocks can fail in either brittle or ductile fashion.

Plastic faulting appears in both warm ice, \( T = 233–263 \text{ K} \) (Rist et al., 1994; Rist & Murrell, 1994; Sammonds et al., 1998), and cold ice, \( T = 77–158 \text{ K} \) (Durham et al., 1983; Kirby et al., 1987). The plastic faulting phenomenon occurs during working of certain metals and ceramics, even at cryogenic temperatures (e.g., Rogers, 1979), and in laboratory testing of certain materials other than ice, including the germanate analog to olivine, \( \text{Mg}_2\text{GeO}_4 \) (Burnley et al., 1991; Schubnel et al., 2013), and the hydrous mineral serpentine (Meade, 1979), and in laboratory testing of certain materials other than ice, including the germanate analog to olivine, \( \text{Mg}_2\text{GeO}_4 \) (Burnley et al., 1991; Schubnel et al., 2013), and the hydrous mineral serpentine (Meade & Jeanloz, 1991; Renshaw & Schulson, 2017). It is an important geological process in that it is widely speculated to be the mechanism of deep earthquakes (e.g., Hobbs & Ord, 1988; Regenauer-Lieb & Yuen, 2003; Schubert et al., 1975) and of certain shallow crustal earthquakes (Duretz et al., 2015).

Schulson (2002) showed that localization of displacement on a single narrow plane in ice I by mechanisms that are entirely ductile can be described by general relationships governing adiabatic shear instability. Localization of shear strain ("shear zones") is an expression of deformation common in systems containing feedback loops (e.g., Regenauer-Lieb & Yuen, 2003). In particular, feedbacks between temperature, material strength, and plastic work can cause temperature and strain rate to rise virtually without limit if the heat of plastic work cannot be dissipated faster than it is generated (Golding et al., 2012; Karato et al., 2001; J. P. Poirier, 1980; Rogers, 1979). Strain softening following a maximum in the stress-strain curve can also cause localization and thus has the potential to catalyze adiabatic shear instability (Schulson, 2002; Semiatin et al., 1984).

Examples of localization in geologic systems grade from distributed deformation to narrow shear bands. In most such settings strain rates are low and strains high, and the development of localization can be plausibly rationalized in terms of feedback coupling of known (or approximately known) physical properties and processes (e.g., Duretz et al., 2015; Regenauer-Lieb & Yuen, 2003; Warren & Hirth, 2006). Tracing the physical origins of catastrophic adiabatic instability, however, is more problematic because of the short time scales involved. There has been some success in metals. Adiabatic shear instability is widely recognized in metals deformed under extreme conditions (often called "severe plastic deformation") in serrated yielding, equal channel angular processing, high-speed penetration, etc. The nuclei of instability have been established to be zones of microstructural refinement, usually by recrystallization to nanosize grains, with resultant rheological weakness and focusing of plastic flow (Kula & DeSisto, 1966; Meyers et al., 2006; Murr et al., 2002; Rittel et al., 2008). Rist et al. (1994) reasonably concluded that the nucleating process for plastic faulting in ice I must involve localized plasticity but could only speculate about the origin of such weakness.

Leading hypotheses for the triggering mechanism of earthquakes deeper than the shallow crust include “transformational faulting” under phase-metastable conditions, wherein the volume collapse of the olivine-spinel transformation creates local conditions of severe plastic deformation (Kirby et al., 1991), whose grain-size reduction may be facilitated by the reconstructive phase transformation (Green & Burnley, 1989); dehydration and the reduction of effective pressure by the release of water (Meade & Jeanloz, 1991); adiabatic transformational faulting under phase-stable conditions induced by local shear heating across an equilibrium phase boundary (Renshaw & Schulson, 2017); and local melting (Griggs & Handin, 1960; Li et al., 2018). Importantly, for this paper, transformational faulting has also been hypothesized as the mechanism behind plastic faulting in ice observed in the laboratory (Kirby et al., 1991, 1992), given the proximity of test conditions to the ice I/II univariant phase boundary, the large volume decrease accompanying transformation (>25%), and the direct observation of ice II in samples after testing. The olivine→spinel and ice I→II phase transformations share one other important property that makes the transformational faulting hypothesis attractive, namely, significant kinetic inhibition, allowing pressurization without phase change well beyond the equilibrium phase boundary and the possibility of...
catastrophic release of stored elastic energy when phase change does occur. The low- to high-pressure phase transformation induced by overpressurization in olivine at cool temperatures has high nucleation rates and low growth rates, creating a fine-grained and therefore rheologically weak daughter phase (Rubie & Ross, 1994) that can shear at explosive rates (Burnley et al., 1991; Green & Burnley, 1989). Renshaw and Schulson (2017) speculated that during adiabatic transformational faulting, fault propagation is effected through transformational superplasticity, that is, transient structural weakness in the volume currently undergoing phase transformation, which leads to repeated cycles of local heating and operation of the adiabatic trigger.

Early experimental studies of the flow behavior of individual high-pressure ice phases and of ice undergoing high-pressure phase transformation, which eventually led to the discovery of the plastic faulting phenomenon in ice, were originally motivated by planetary interests (Durham et al., 1983; Echelmeyer & Kamb, 1986; J.-P. Poirier et al., 1981). Phase transformation even under geologic strain rates is likely to influence the internal dynamics and structure of the several large icy moons in the outer solar system (e.g., McKinnon, 1998) and of putative super-Earth “water planets” (e.g., Fu et al., 2010). However, the planetary application of plastic faulting may be tenuous. Stresses required for plastic faulting in ice are generally far higher than can be supported in most natural settings, so widespread occurrence of the phenomenon in nature might not be expected. Application to meteoritic impact events cannot be discounted, however, where flow and fracture properties of ice may influence the character of ejecta deposits, among other observables (Melosh, 1989; Singer et al., 2013).

Here we present experimental results on the mechanical and structural characteristics of plastic faulting in ice at intermediate temperatures, \( T = 105\)–\( 220 \) K, thus bridging a gap between previous low- and high-temperature observations. Our aim is to understand in more detail the physics of plastic faulting in ice. Our strategy is to focus on behavior near the transition from unstable failure by plastic faulting to stable failure by distributed ductility (i.e., creep), akin to the brittle-to-ductile transition in crustal rocks (see review by Evans et al., 1990). Although plastic faulting in ice is probably not widespread in nature, given the high levels of deviatoric stress involved, such conditions are easily accessed in the laboratory, making ice ideal for laboratory study of the process because of its availability and the ease with which samples of desired initial grain textures can be fabricated.

2. Methods

The procedures summarized here build on those described in Durham et al. (1983) and Stern et al. (1997) for experimental deformation and for sample fabrication, respectively.

2.1. The Ice

Cylindrical specimens of polycrystalline ice I with diameter 25.4 mm and length 50–65 mm were fabricated as follows: Sieved ice grains ground from frozen, bubble-free, deionized water were packed into cylindrical stainless-steel molds to a pore volume of 40%. Three sizes of sieved grains were used in the present work: 0.18–0.25, 0.50–1.00, and 1.00–2.00 mm. The molds were then evacuated to approximately 100 Pa and then submerged in an agitated ice-water bath at \( T = 273 \) K for 45 min. While still under vacuum, the molds were then flooded with deionized, deaerated water, also at \( T = 273 \) K. After flooding, the ice-water molds were subjected to unidirectional solidification from the bottom upward at \( T = 243 \) K. The resulting ice I was free from cracks and semitransparent, with a porosity of less than 0.5% (based on measured weight and dimensions, using a grain density of 920.0 kg·m\(^{-3}\) at \( T = 243 \) K; Petrenko & Whitworth, 1999). Using scanning electron microscope electron backscatter diffraction (SEM-EBSD) and optical thin sections, final grain size was determined to be \( d = 0.25 \pm 0.10 \) mm, \( d = 0.68 \pm 0.23 \) mm, and \( d = 1.18 \pm 0.41 \) mm, respectively, for the three seed sizes used here, where grain size is the diameter of a circle of equivalent area as measured by EBSD and grains are segmented using a threshold misorientation of 10° using the MTEX code of Bachmann et al. (2011). EBSD imaging also confirmed that the grains exhibited no preferential orientation and were free from internal strain.

Prior to testing, specimens were encapsulated and sealed in pressure-tight, thin-walled (0.5 mm) indium jackets, which conform tightly to the underlying sample surface once the assembly is pressurized (Figure 1). Jacketed assemblies included 12.7-mm-long stainless-steel end caps at either end and a 19-
mm-long zirconia disc between ice and end cap at one of the ends, which served as a thermal insulator during assembly (see Figure S1 in the supporting information). Care was taken during assembly to prevent sudden changes in temperature to avoid thermal fractures in the ice. Assembly ends were maintained parallel within 0.1°.

Polycrystalline ice II was fabricated through high-pressure phase transformation from ice I to ice II. Specimens of ice I with starting grain size $d = 0.68$ mm were loaded at $T = 200$ K to a hydrostatic confining pressure of $P \approx 300$ MPa at a rate of 20 to 30 MPa min$^{-1}$ (note that the symbol $P$ in this paper refers strictly to gas pressure and is different from mean stress, the trace of the stress tensor, when the state of stress includes a nonzero deviatoric component). Under these conditions, the ice I→II transformation occurred at a confining pressure of $P \approx 240$ MPa. X-ray diffraction of earlier samples transformed in similar manner reveals that the I→II transformation runs to near completion, with no recognizable ice I diffraction peaks, with a resolution of ~2 vol% (Durham et al., 1988). To realign specimen ends after the phase transformation, an axial differential stress of $\sigma \approx 20$ MPa was applied for ~10 min at $T = 200$ K. After transformation, the temperature was reduced to $T = 105$–110 K over a period of ~6 hr before mechanical testing. At all times, $P$ was maintained within the ice II stability field. Based on prior analysis by Kubo et al. (2006), the resulting ice II grain size is expected to be on the order of $d = 25$–50 $\mu$m.

### 2.2. Experimental Procedure

Axisymmetric compression tests were performed in our high-pressure cryogenic deformation apparatus (Heard et al., 1990) (see also Figure S1). Axial stress $\sigma_1$ was applied using a screw-driven piston advancing at constant displacement rate. Differential stress, the difference between the maximum and minimum principal compressive stresses, $\sigma = \sigma_1 - P$ (since $\sigma_2 = \sigma_3 = P$), was determined from the piston load, measured by a force gage internal to the pressure vessel (Figure S1), normalized by specimen cross-sectional area. Axial load and piston displacement were recorded digitally at coarse time interval (~7 s) and with an analog chart.
Table 1
Summary of Ductile Runs, Ice I

| Run  | d (mm) | T (K) | P (MPa) | \( \dot{\varepsilon} \) (s\(^{-1}\)) | \( \sigma_{\text{ult}} \) (MPa) | \( \sigma_{\text{ss}} \) (MPa) | \( \varepsilon \) total | Hyperlink to |
|------|--------|-------|---------|----------------------------|------------------|------------------|------------------|--------------|
| 672  | 0.25   | 200   | 28      | \( 3.8 \times 10^{-4} \) | 79.9             | 49.2             | 0.26             | 672p         |
| 675  | 0.25   | 200   | 30      | \( 3.3 \times 10^{-3} \) | 92.1             | 0.142            |                 | 675p         |
| 677  | 0.25   | 195   | 25      | \( 5.0 \times 10^{-4} \) | 93.2             | 59.0             | 0.054            | 677p         |
| 681  | 0.68   | 233   | 18      | \( 6.2 \times 10^{-4} \) | 53.0             | 35.0             | 0.236            | 681p         |
| 686  | 0.68   | 220   | 20      | \( 5.6 \times 10^{-4} \) | 67.7             | 37.9             | 0.192            | 686p         |
| 699  | 0.68   | 180   | 100     | \( 5.7 \times 10^{-4} \) | 108.0            | 86.8             | 0.071            | 699p         |
| 706  | 0.68   | 180   | 200     | \( 3.5 \times 10^{-3} \) | 86.6             | 56.7             | 0.222            | 706p         |
| 710  | 0.68   | 180   | 200     | \( 2.9 \times 10^{-3} \) | 100.7            | 61.9             | 0.224            | 710p         |
| 711  | 0.68   | 180   | 100     | \( 5.4 \times 10^{-5} \) | 82.1             | 63.0             | 0.222            | 711p         |
| 712  | 0.68   | 180   | 100     | \( 7.1 \times 10^{-4} \) | 106.7            | 91.2             | 0.145            | 712p         |
| 716  | 0.25   | 180   | 50      | \( 5.8 \times 10^{-4} \) | 111.0            | 89.8             | 0.133            | 716p         |
| 723  | 1.18   | 180   | 50      | \( 1.0 \times 10^{-4} \) | 93.9             | 71.1             | 0.071            | 723p         |
| 725  | 0.68   | 180   | 50      | \( 5.4 \times 10^{-5} \) | 88.2             | 66.5             | 0.173            | 725p         |
| 727  | 0.68   | 180   | 50      | \( 2.0 \times 10^{-4} \) | 101.3            | 78.9             | 0.149            | 727p         |
| 729  | 0.68   | 180   | 150     | \( 1.0 \times 10^{-3} \) | 104.9            | 86.7             | 0.203            | 729p         |
| 739(i) \(^d\) | 0.68 | 180 | 50  | \( 1.0 \times 10^{-4} \) | 93.4             | 78.1             | 0.045            | 739(i)p      |
| 740(i) \(^d\) | 0.68 | 180 | 50  | \( 1.3 \times 10^{-4} \) | 95.2             | 75.2             | 0.065            | 740(i)p      |

\(^a\)Used vented sample assembly (see Figure S1). \(^b\)Significant phase transformation occurred during run. Value is that of minimum differential stress during transformation. \(^c\)Distinct blip at 91.5 MPa before peak stress. \(^d\)Step (2) in Table 2. \(^e\)Link to guide for reading strip charts.

recorder to capture the point of brittle failure more precisely (0.1 to 1 s, depending on chart speed). At fixed displacement rate, load on a specimen will increase until it can no longer be supported, at which point the specimen fails (in the sense defined in section 1). Failure may be brittle, where the specimen loses all or most of its mechanical integrity very rapidly, or may be controlled (ductile failure), wherein the specimen maintains much or all of its strength as deformation continues. In both cases, the peak value of \( \sigma \) achieved is called the ultimate strength, \( \sigma_{\text{ult}} \). Strain rate \( \dot{\varepsilon} \) was calculated as an engineering strain (or shortening) rate equal to piston displacement rate normalized by initial specimen length. Likewise, the magnitude of inelastic (i.e., nonrecoverable) strain \( \varepsilon \) was measured as piston displacement normalized by initial specimen length less the elastic component, which in turn was calculated from the known compliance of the deformation column and the current load. Differential stress was measured with a sensitivity better than ±0.1 MPa. Hydrostatic confining pressure using nitrogen gas as a confining medium was generated using a conventional oil-gas separator/intensiﬁer system and was measured using a Heise Bourdon tube gage. Compressive stresses and strains are taken here as positive.

For testing at 170 K and above, temperature was maintained by circulating liquid nitrogen in Cu tubing through a 30-L alcohol bath. Because of the large mass of the cryostat and pressure vessel, temperature variations during testing were small, typically less than ±0.1 K. Temperature was measured with type J and type K thermocouples with accuracy of roughly ±1.5 K. For deformation tests at \( T < 170 \) K, liquid nitrogen was released directly into the cryostat without alcohol present. For these tests, a larger temperature gradient existed across the cryostat, corresponding to an accuracy of ±3 K.

3. Experiments: Results and Analysis

We performed over 50 constant displacement rate, axisymmetric compression tests on cylinders of ice of three different grain-size ranges, at temperatures 105 ≤ \( T \) ≤ 230 K, imposed bulk shortening (engineering strain) rates \( 5 \times 10^{-5} \leq \dot{\varepsilon} \leq 7 \times 10^{-3} \) s\(^{-1}\) and confining pressures 0.1 ≤ \( P \) ≤ 300 MPa, with most experiments run at 180 K and 50 MPa. The dependent variable measured was the differential stress \( \sigma \) required to maintain the imposed strain rate. Four of the samples were hydrostatically transformed to ice II before testing; the rest were ice I. Experimental conditions and summary results for all tests are listed in Tables 1–3, in which experiments are grouped according to phase and failure mode: ice I, ductile (Table 1, 15 runs, plus two samples given a ductile “prestrain”); ice I, Coulombic and plastic faulting (Table 2, 34 runs); and ice II, plastic faulting (Table 3, 4 runs). Additionally, we include here as Table 4 the results of an investigation of plastic
Table 2
Summary of Brittle Runs (Coulombic and Plastic Faulting), Ice I

| Run | d (mm) | T (K) | P (MPa) | \(\dot{\varepsilon}\) (s\(^{-1}\)) | \(\sigma_{\text{ult}}\) (MPa) | Fault angle (°) | Fault trace | Photo | Chart | Log|
|-----|--------|-------|---------|------------------|-----------------|---------------|------------|------|------|----|
| 671 | 0.25   | 105   | 50      | 7.4 \times 10^{-5} | 154.9           | 46            | x, e       | 671p | 671c | 671b|
| 679 | 0.68   | 195   | 25      | 5.6 \times 10^{-4} | 86.6            | 40            | s, e       | 679p | n/a  | 679b|
| 680 | 0.68   | 190   | 27      | 6.3 \times 10^{-4} | 95.2            | 45            | s          | 680p | n/a  | 680b|
| 688 | 0.68   | 210   | 20      | 5.7 \times 10^{-3} | 76.6            | 41            | x          | 688p | 688c (poor) | 688b|
| 689 | 0.25   | 175   | 20      | 5.7 \times 10^{-3} | 98.8            | 43            | x, e       | 689p | 689c (poor) | 689b|
| 690 | 0.68   | 175   | 20      | 6.5 \times 10^{-3} | 95.8            | 42            | x, e       | 690p | 690c (poor) | 690b|
| 692 | 0.25   | 180   | 40      | 5.8 \times 10^{-3} | 97.0            | 45            | s          | 692p | 692c | 692b|
| 695 | 0.68   | 180   | 50      | 5.8 \times 10^{-4} | 101.3           | 44            | s, e       | 695p | 695c | 695b|
| 696 | 0.68   | 180   | 10      | 5.7 \times 10^{-4} | 89.3            | 41            | x, e       | 696p | 696c | 696b|
| 697 | 0.68   | 180   | 20      | 5.7 \times 10^{-4} | 95.2            | 45            | s, e       | 697p | 697c | 697b|
| 698 | 0.68   | 180   | 3       | 5.7 \times 10^{-3} | 78.1            | <25           | x, e       | 698p | 698c | 698b|
| 700 | 0.68   | 180   | 100     | 6.9 \times 10^{-3} | 106.7           | 43            | x, e       | 700p | 700c (poor) | 700b|
| 701 | 0.68   | 180   | 40      | 5.8 \times 10^{-3} | 95.8            | 45            | s          | 701p | 701c (poor) | 701b|
| 702 | 0.68   | 180   | 30      | 6.5 \times 10^{-4} | 108.8           | 46/44         | s          | 702p | 702c | 702b|
| 705 | 0.68   | 180   | 100     | 1.1 \times 10^{-3} | 108.1           | 45            | m          | 705p | 705c | 705b|

-\(\sigma_{\text{ult}}\) generally lower chart recordings and sample photographs have otherwise gone unanalyzed. Those experiments emphasized through links in the tables. Comparative load-displacement chart records for the runs in Tables 2 and 4 (excepting those with legibility problems) are provided in Figure S2.
The initial response to loading at constant displacement rate is elastic, with $\sigma$ and $\varepsilon$ increasing linearly with time (e.g., Figure S2). Linear slopes correspond to a column modulus of ~5 GPa per unit strain in the sample but include an elastic contribution from steel column parts (far stiffer but far longer, Figure S1) so is reasonably consistent with the modulus of 9 GPa for polycrystalline ice measured at megahertz frequencies (Gammon et al., 1983; Vaughan et al., 2016). Linearity ceases at the yield point, the first appearance of inelasticity. Yielding and achievement of $\sigma_{\text{ult}}$ are almost simultaneous in brittle failure, and the event is catastrophic and audible, often jolting the entire apparatus. It is typically accompanied by an immediate stress drop of 75% or more from $\sigma_{\text{ult}}$ and a corresponding jump in sample shortening. Under most conditions in these experiments, the fault plane is inclined at approximately 45° to the stress axis (Figures 1a and 1b), consistent with plastic faulting. Where the indium jacket remains intact following the failure event, effective confinement is maintained, and the cycle of elastic loading and faulting can repeat as the loading piston continues inward at the prescribed rate. Virtually all faulting events in this work at $P > 20–30$ MPa maintain the qualitative character of plastic faulting, covering a wide range of temperatures (105–210 K) and strain rates ($\dot{\varepsilon} = 7 \times 10^{-5}$ – $7 \times 10^{-3}$ s$^{-1}$) and including ice II as well (Figure 1b). In the case of ductile failure, the transition from first yield to the achievement of peak stress $\sigma_{\text{ult}}$ and beyond is generally smooth and without sudden change. For previously undeformed polycrystalline ice, strength decreases over a few percent.

### Table 3
Summary of Runs, Ice II (All Plastic Faulting)

| Run | $d$ (mm) | $T$ (K) | $P$ (MPa) | $\dot{\varepsilon}$ (s$^{-1}$)$^a$ | $\sigma_{\text{ult}}$ (MPa) | Fault angle ($^\circ$) | Fault trace$^c$ | Hyperlink to |
|-----|--------|------|--------|----------------|----------------|-----------------|-------------|-----------|
| 737(1) | 0.05 | 110 | 150 | $1.9 \times 10^{-4}$ | 221.6$^b$ | - | - | 737p |
| 737(2) | 0.05 | 110 | 100 | $4.7 \times 10^{-4}$ | 207.2$^b$ | - | - | 737p |
| 737(3) | 0.05 | 110 | 100 | $4.7 \times 10^{-3}$ | 205.0$^b$ | - | - | 737p |
| 737(4) | 0.05 | 110 | 50 | $9.4 \times 10^{-4}$ | 194.0$^b, c$ | 46 | - | 737p |
| 743 | 0.05 | 112 | 150 | $4.7 \times 10^{-3}$ | 153.9$^d$ | 44 | - | 743p |
| 746 | 0.05 | 105 | 150 | $1.8 \times 10^{-4}$ | 288.6 | 45 | - | 746p |
| 781 | 0.05 | 105 | 250 | $1.8 \times 10^{-4}$ | 275.2 | 49 | - | 781p |

$^a$Calculated as bulk shortening rate. $^b$Stop before ultimate failure. $^c$Sample faulted 10 s after stop. $^d$Chart record shows four unusual stress drops before $\sigma_{\text{ult}}$; suspect jacket leak.

### Table 4
Summary of Earlier Runs, Ice I (All Plastic Faulting)

| Run | $d$ (mm) | $T$ (K) | $P$ (MPa) | $\dot{\varepsilon}$ (s$^{-1}$)$^a$ | $\sigma_{\text{ult}}$ (MPa) | Fault angle ($^\circ$)$^b$ | Fault trace$^c$ | Hyperlink to |
|-----|--------|------|--------|----------------|----------------|-----------------|-------------|-----------|
| 261 | 0.68 | 77 | 200 | $3.4 \times 10^{-4}$ | 162.1 | 50 | x | 261p |
| 262 | 0.68 | 77 | 200 | $3.4 \times 10^{-4}$ | 155.2 | 52 | s | 262p |
| 263 | 0.68 | 77 | 100 | $3.4 \times 10^{-4}$ | 164.2 | 44 | s | 263p |
| 265 | 0.68 | 77 | 100 | $3.4 \times 10^{-4}$ | 160.0 | 39 | x | 265p |
| 269 | 0.68 | 77 | 300 | $3.3 \times 10^{-4}$ | 160.5 | $-45$ | s | 269p |
| 270 | 0.68 | 119 | 200 | $3.3 \times 10^{-4}$ | 141.4 | $-45$ | m | 270p |
| 271 | 0.68 | 118 | 100 | $3.3 \times 10^{-4}$ | 140.2 | $-45$ | x | 271p |
| 272 | 0.68 | 171 | 200 | $3.3 \times 10^{-4}$ | 106.3 | 48/49 | x | 272p |
| 273 | 0.68 | 172 | 100 | $3.3 \times 10^{-4}$ | 106.9 | 46 | s | 273p |
| 308 | 0.68 | 159 | 200 | $3.3 \times 10^{-4}$ | 120.5 | 48 | s | 308p |
| 309 | 0.68 | 160 | 300 | $3.3 \times 10^{-4}$ | 111.5 | 46 | s | 309p |

$^a$Calculated as bulk shortening rate. $^b$With respect to vertical. $^c$m = multiple 45° faults, s = single fault, x = complex.

Note. $T$, $P$, and $\sigma_{\text{ult}}$ values published previously (Kirby et al., 1991).
strain to a near steady-state level ($\sigma_{ss}$ in Table 1) typically 10–20% below $\sigma_{ult}$. Spatial distribution of strain across the sample is broadly uniform, although intriguing jacket rumpling at the few millimeter scale (Figure 1c) hints at local heterogeneities in strain rate.

### 3.1. Plastic Faulting

In Figure 2, values of ultimate strength $\sigma_{ult}$ for faulting experiments in this study (Table 2) and those published by others are plotted as a function of $P$ for a range of $T$ values. Our concentration here at 180 K (solid red figures) is apparent. The domain of plastic faulting exists above $P \approx 30$ MPa, where the isotherms are horizontal (i.e., $P$ independent) and shear fault inclinations are approximately 45°. Actual fault inclinations for the 34 faulted ice I samples tested here at $P \geq 30$ MPa are 45.4° ± 2.3° (1 SD) (Table 2), as derived from photographs (e.g., Figure 1a) and polished sections, which were made of several samples in the sequence of runs 688–702. The latter can be viewed by following hyperlinks in the first column of Table 2. In the three lowest pressure runs ($P \leq 10$ MPa), $\sigma_{ult}$ is strongly $P$ dependent, and fault planes are irregular and generally steeply inclined (Figure 1d), consistent with Coulombic faulting. The nature of the transition from Coulombic to plastic faulting at 10–30 MPa at 180 K is addressed in more detail in section 3.4. It is worth noting that the scatter in values of $\sigma_{ult}$ in the plastic faulting regime is 10% or less. There are too few data for ice in the Coulombic regime for comparison, but for crustal rocks, scatter in $\sigma_{ult}$ in the Coulombic regime is considerably more than 10% (Byerlee, 1967; Lockner, 1995; Lockner et al., 1982).

A monotonic increase in $\sigma_{ult}$ with decreasing temperature is evident in Figure 2. Plotting the mean $\sigma_{ult}$ ($P$) values against $T$ (Figure 3) shows that the temperature trend is approximately linear, suggesting commonality to the mechanism of plastic faulting over a broad range of temperatures. Being linear in $T$, such a common mechanism, should it exist, would probably not derive its $T$ dependence from Arrhenius-type thermal activation. We note that the data do support a model of two or three different thermally activated processes at different intervals along the $T$ axis (Figure 3 inset). Also, regarding $T$ dependence, overlain in Figure 3 is the flow law for polycrystalline ice I in the steady-state ductile regime at typical laboratory strain rates illustrating why, when studying the transition from plastic faulting to ductile flow in the lab, the accessible temperature range centered at ~180 K is decidedly narrow.

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Peak differential stress (=ultimate strength $\sigma_{ult}$) versus confining pressure for brittle failure of ice I and ice II at $T = 77$–233 K. Points in this study from Table 2 (ice I) are restricted to those of grain size 0.68 mm. Temperatures are indicated by color, as labeled. Horizontal lines indicate average strength in plastic faulting (solid symbols) at each temperature. Dashed lines are best-fit linear regressions to the observed pressure-dependent failure strength in Coulombic faulting (open symbols) at 77 and 233 K. Points from Table 4 are plotted with “others” since the $\sigma_{ult}$ values themselves have already been published. Data for the first two ice II runs (Table 3) are not plotted.
3.2. Multiple Events

Of the 38 plastically faulted samples in Tables 2 and 4 (27 runs for which \( P > 20 \text{ MPa} \), that is, those that plastically faulted according to Figure 2) and (11 runs), integrity of the indium jacket was apparently maintained after initial brittle failure in eight of the runs, and subsequent cycles of loading and brittle failure were recorded. Severe jarring of the apparatus, as sometimes occurs, can mechanically displace the zero setting of the force gage transducer, thus degrading stress resolution following the first event. However, despite the loss of resolution, the appearance of load-displacement curves for subsequent events is at least consistent with a significant, if not complete, recovery of sample strength. Good examples are records of the four multiple-event runs in Figure S2 (705, 724, 726, and 728), where shapes of load-displacement curves for subsequent events generally parallel those of the first events in their linear slope, slight curvature, and sudden dropoff, although sometimes with considerable vertical offset (up or down).

Examination of fault traces on the indium jackets from these samples suggests that multiple failure events and multiple 45° fault traces are correlated (Figure 4). The fault traces are usually parallel and close together, although for run 709, the faults are conjugate but not intersecting. Of the eight multiple-event runs (Figure 4b), three (265, 271, and 726) show no clear sign of multiple fault traces, although in two of those (265 and 271), the tendency for multiple fault formation may have been mitigated by the intersection of fault and steel end cap. A plastic fault thus remains cohesive, a sign that fault displacement is the result of plastic rather than crack-related deformation as in Coulombic faulting. For run 709, with planes in conjugate orientations that do not intersect, the conclusion is compelling: It is difficult to envision how two faults so far apart (~5 mm at closest approach) could have initiated simultaneously. Multiple fault planes and fault bifurcations do occur in some single-event runs, but the proportion of such samples is small.

3.3. Prestrain Experiments

Four runs in Table 2, numbered 739–742, were “prestrain” experiments at fixed \( P = 50 \text{ MPa} \) and \( T = 180 \text{ K} \), wherein we imposed a ductile strain step prior to the plastic faulting step as a probe of possible microstructural origins for the phenomenon. Ductile prestrains of neither \( \varepsilon \approx 0.05 \) at low strain rate to 80% of expected...
faulting strength nor $\varepsilon \approx 0.004$ at 90% had a detectable effect on the peak stress at plastic faulting. The value of peak stress for the four prestrained samples is all in the range of $105 \pm 5$ MPa, which compares well to the value $\sigma_{\text{ult}} = 106.8 \pm 4.8$ MPa of six nonprestrained brittle runs at similar conditions. Thus, we cannot detect any effect on plastic faulting of processes that occur at low strain, processes that are likely to include a substantial increase in dislocation density, partial recrystallization, and phase change. The related matter of an unavoidable inelastic strain before faulting is discussed in more detail in section 3.5 below.

3.4. Crossover From Plastic Faulting to Ductile Flow

In rocks, where brittle behavior is typically Coulombic, the so-called brittle-to-ductile (B-D) transition typically extends over many tens of MPa in pressure, as pressure-insensitive ductile processes account for an increasing proportion of imposed strain with increasing confining pressure (Byerlee, 1968; Evans et al., 1990; Kohlstedt et al., 1995). In this respect ice is very unrock like: Apart from the precursor phenomenon discussed in the next section, the B-D transition in ice with changing pressure, where the brittle process is plastic faulting rather than Coulombic, is vanishingly narrow within resolution limits (Figure 2). The maximum widths of the B-D transition allowed by the data as plotted on axes of $\sigma_{\text{ult}}$ versus $\varepsilon$ for several grain sizes (Figure 5) and pressures (Figure 6) are shown as colored parallelograms for runs at 180 K. Also, plotted as dashed lines in Figures 5 and 6 are the trends for peak stress, $\sigma_{\text{ult}}$, in the ductile field, which follows a power-law relationship $\sigma_{\text{ult}} = \varepsilon^{1/n}$ where $n \approx 6$ on the basis of our sparse data set. This is a somewhat higher value than the $n = 4$ value for steady-state dislocation creep (e.g., Durham et al., 1997). Similar to the steady state, however, there is no dependence on grain size (Figure 5) at these grain sizes, and there is a negative dependence of strength upon pressure (Figure 6) (Durham et al., 1983).

Figure 4. Photographs of fault traces expressed on indium jackets for all samples in Tables 2 and 4 for which $P > 20$ MPa, separated into two groups according to whether the run had (a) a single faulting event or (b) multiple events with strength recovery. Run numbers labeled. Note the apparent correlation of multiple events with multiple faults. Jacket photos of runs 308 and 309 were taken after removal of the sample from inside. A portion of the inner surface of jacket 308 (white outlined box) is enlarged in Figure 11a.
The sample-to-sample precision in location of the B-D transition across all experiments is striking: The width of the colored parallelograms indicates that the transition is constrained to lie within a range of a factor of $\leq 2$ in strain rate. For $n = 6$, that width is roughly the equivalent of a $\pm 10\%$ scatter in $\sigma_{\text{ult}}$ (Figure 2). The minimum widths cannot be distinguished from a point-like crossover. Furthermore, among the roughly 16 ductile and brittle data points concentrated near the transition at each condition, only one is on the “wrong” side of the transition, that of a ductile run in the brittle field at 50 MPa and $d = 0.68$ mm (thus visible in both Figures 5 and 6).

Grain-size dependence of strength (Figure 5) is largely absent in the ductile field, consistent with the high $n$ value, but is distinct in the brittle field, with $\sigma_{\text{ult}}$ increasing with decreasing grain size. The B-D crossover thus shifts to higher stress and higher strain rate with decreasing grain size roughly following the $n = 6$ ductile flow law. The behavior can be rationalized in terms of grain size effects in either the ductile or brittle fields. A small amount of grain-size-sensitive ductile deformation at lower grain size, too little to deflect the dashed line in Figure 5, could be sufficient to relieve high local stresses that might otherwise trigger brittle instability. Alternately, if flaw size in the brittle field is related to grain size, the finer-grain material should require higher stress to reach criticality, in the manner of classic materials toughening by crack blunting (Schulson, 1990).

By contrast, the pronounced influence of pressure on the location of the B-D crossover (Figure 6), an increase by nearly an order of magnitude in strain rate as $P$ increases from 50 to 150 MPa, is well in excess of the well-known $P$-dependent weakening in the ductile field (Durham et al., 1983). The strain-rate enhancement is, however, easily explained by a small amount of bulk (i.e., distributed) phase transformation of ice I to ice II, which can occur at conditions near those of these tests (Durham et al., 1983). As an example, bulk transformation is manifest in the load-time curves of the two highest-pressure ice I runs here: 706 and 710 (Table 1). Details are provided in Figure S3. Since conditions in the brittle and ductile fields are essentially indistinguishable at the B-D crossover, we must therefore consider the possibility that brittle failure near the crossover is also preceded by some amount of phase transformation.

Figure 5. Plastic faulting-to-ductile (B-D) transition for three different grain sizes (coded by color and symbol shape) at fixed conditions of pressure and temperature as labeled. Dashed line is an estimated fit to the peak stresses of the six ductile runs (open symbols) of strain rate $<1e-4$/s. The slope of the dashed line is approximately $1/6$ ($n = 6$), significantly less than the $n = 4$ value applicable to steady-state flow. Horizontal lines indicate average strength of plastic faulting (solid symbols) by grain size. Shaded parallelograms enclose the three pairs of runs constraining the width of the B-D transition at each of three different grain sizes. Chart records for the three pairs of runs (run numbers are labeled) constitute the top row of Figure 7.
3.5. Inelastic Precursors and Phase Transformation

Consistent with the strain-rate enhancement apparent in Figure 6, among all the available chart records for the runs in Tables 2 and 4 (Figure S2), many of the load versus time traces show a slight curvature away from elastic linearity in the moments leading up to brittle failure. The same is true by definition for the ductile runs (Table 1). Remarkably, the two sets of precursors, those preceding ultimate failure by brittle and by ductile mechanisms, are difficult to distinguish. Figure 7 shows side-by-side comparisons of prefailure load-time records for the five pairs of runs that most tightly constrain the B-D crossover locations in Figures 5 and 6, where test conditions are identical except for the slight difference in strain rate (the pair 715–727, \(d = 0.68\) mm, \(P = 50\) MPa appear in both figures). Prefailure, apart from subtle differences in imposed displacement rate, there is little in the way of distinguishing features of the load-time curves and little upon which to anticipate whether the ensuing failure would be violent or controlled.

It is improbable that brittle and ductile failure mechanisms produce essentially identical load-time records prior to ultimate failure, even versus changes in grain size and pressure. If the precursive mechanisms are the same and prefailure strain in ductile samples includes some amount of bulk phase transformation, as suggested two paragraphs above, then the inelastic precursor to brittle failure must also include some phase transformation. That conclusion is singularly impactful, given the widely hypothesized role of phase transformation in plastic faulting in geologic materials. It would therefore be useful to determine whether bulk phase transformation in our experiments plays a causal role in plastic faulting or if it is entirely passive. Other than Figure 7, which suggests the latter, are there any characteristics or dependencies of precursive phase transformation that might suggest a link to plastic faulting?

It is possible to estimate the proportions of ordinary plastic strain, \(\varepsilon_{\text{creep}}\), and strain due to phase transformation, \(\varepsilon_{I \rightarrow II}\), in the inelastic precursors. Total precursive strain, \(\varepsilon_{\text{tot}}\), is calculable from the load-time record, starting sample length, and piston displacement rate. We can also estimate \(\varepsilon_{\text{creep}}\) based on the flow law for steady-state, grain-size-independent creep of ice I under essentially identical laboratory circumstances and test conditions (Durham et al., 1997), which surely underestimates the strength (and overestimates strain rate) in ice that has not yet yielded (were undeformed ice weaker than ice in the steady state, it would by definition be impossible to achieve any stress above steady-state level). The difference, \(\varepsilon_{\text{tot}} - \varepsilon_{\text{creep}}\), should be a conservative (i.e., under-) estimate of transformational strain, \(\varepsilon_{I \rightarrow II}\) in the precursor.
Results of the calculation are tabulated in Tables 5 and 6 (a more detailed description of the calculation is provided in Text S1; all three tables [Tables 5, 6, and S1] include links to graphical calculations). The magnitudes of precursive strain are generally very low, with only eight of 29 runs exhibiting $\varepsilon_{\text{tot}} > 0.002$.

Because the durations of the precursors are typically short in time (Table S1), values of $\varepsilon_{\text{creep}}$ tend to be small, leaving $\varepsilon_{I \rightarrow II}$ to predominate. It is also important to note that because of the large volume decrease associated with ice I $\rightarrow$ II and because the contraction under nonhydrostatic stress is highly anisotropic, being accommodated almost entirely by shortening in the direction of maximum stress (Kirby et al., 1991), the extent of implied bulk phase transformation in Table 5 is subtle. Most values of $\varepsilon_{I \rightarrow II}$ in Table 5 require $<1\%$ of the ice I in a sample to transform to ice II. Dependence of $\varepsilon_{I \rightarrow II}$ on environmental variables is illustrated in Figure S4. Systematics are elusive given the sparse sampling. The clearest signal is a positive dependence of $\varepsilon_{I \rightarrow II}$ on confining pressure $P$ above 100 MPa (Text S2 and Figure S4a).

Figure 7. Differential stress versus time chart traces for pairs of brittle and ductile runs most tightly straddling the B-D crossover at 180 K, the members of each pair differing only in applied strain rate, for five different sets of grain size and pressure conditions (panel (a) has an additional brittle run; panels (b) and (d) are identical). Brittle runs are those whose trace terminates abruptly during loading; ductile runs are those whose strength rises to its ultimate level and then drops smoothly to a nonzero steady-state level. Traces for all five ductile runs continue to the right and are truncated here for presentational purposes. Note that curved portions of records prior to failure for brittle versus ductile are difficult to distinguish in any given panel. Among the ductile curves, there are a number of small “blips” (runs 723 and 712) or breaks in slope (712, 723, 727, and 729), which may be hints of incipient plastic faulting that failed to propagate. In brittle run 728 a subtle blip can be seen just prior to failure. Top row (a–c) grain-size dependence, corresponding to Figure 5; bottom row (d–f) pressure dependence, corresponding to Figure 6. For multiple brittle events (c and f), the absolute vertical position of the curve is known only for the first event.
Ductile Precursors in Table 2a

| Run | d (mm) | T (K) | P (MPa) | σ_{ult} (MPa) | σ_{tot} × 1,000 | σ_{creep} × 1,000 | ε_{I→II} × 1,000 |
|-----|--------|-------|---------|---------------|-----------------|------------------|-----------------|
| 671 | 0.25   | 105   | 50      | 154.9         | 0.30            | 2.5 × 10^{-12}   | 0.30            |
| 692 | 0.25   | 180   | 40      | 97.0          | 0.00            | 0.01             |                 |
| 693 | 0.68   | 180   | 50      | 101.3         | 0.43            | 0.12             | 0.31            |
| 696 | 0.68   | 180   | 10      | 95.2          | 0.00            | 0.00             |                 |
| 697 | 0.68   | 180   | 20      | 78.1          | 0.17            | 0.08             | 0.09            |
| 698 | 0.68   | 180   | 3       | 89.3          | 0.00            | 0.02             | 0.00            |
| 702 | 0.68   | 180   | 30      | 108.8         | 0.97            | 0.19             | 0.78            |
| 705 | 0.68   | 180   | 10      | 101.8         | 0.75            | 0.21             | 0.54            |
| 706 | 0.68   | 180   | 0.1     | 87.8          | 2.14            | 0.10             | 2.04            |
| 708 | 0.68   | 180   | 10      | 129.3         | 1.50            | 0.53             | 0.96            |
| 713 | 0.68   | 180   | 50      | 106.1         | 1.37            | 0.28             | 0.60            |
| 714 | 0.68   | 180   | 100     | 102.5         | 1.65            | 0.52             | 1.14            |
| 715 | 0.25   | 180   | 50      | 114.0         | 1.71            | 0.26             | 1.45            |
| 717 | 0.25   | 180   | 3       | 115.3         | 1.91            | 0.37             | 1.54            |
| 724 | 1.18   | 180   | 50      | 95.2          | 0.48            | 0.21             | 0.27            |
| 725 | 1.18   | 180   | 3       | 64.7          | 0.45            | 0.03             | 0.42            |
| 726 | 1.18   | 180   | 30      | 83.0          | 0.20            | 0.16             | 0.04            |
| 728 | 0.68   | 180   | 150     | 111.0         | 3.55            | 0.63             | 2.92            |
| 730 | 0.68   | 185   | 50      | 95.2          | 0.88            | 0.58             | 0.30            |
| 735p b | 0.68 | 180   | 50      | 89.1          | 0.16            | 0.07             | 0.09            |
| 735 | 0.68   | 180   | 90      | 90.9          | 0.00            | 0.05             |                 |
| 736 | 0.68   | 195   | 75      | 96.4          | 3.15            | 1.09             | 2.07            |
| 739 | 0.68   | 180   | 50      | 107.4         | 0.63            | 0.04             | 0.59            |
| 740 | 0.68   | 180   | 50      | 98.0          | 0.63            | 0.03             | 0.60            |
| 741 | 0.68   | 180   | 100     | 104.3         | 1.10            | 0.23             | 0.87            |
| 742 | 0.68   | 180   | 50      | 104.9         | 2.47            | 0.35             | 2.12            |
| 786p b | 0.68 | 113   | 100     | 135.4         | 0.45            | 2.0 × 10^{-11}   | 0.45            |

*Excluding nine runs with entries in “chart” column of Table 1b labeled “(poor)” or “n/a.” Precursory “lip” occurred before ultimate failure.

### 3.6. Maximum Normal Stress

To return to the question of a causal or passive role of bulk phase transformation in the context of plastic faulting, in Figure 8, we map the two phenomena on the equilibrium phase diagram for ice. As indicated in section 1, ice I→II is kinetically inhibited, as are most of the reconstructive phase transformations in ice (Bridgman, 1912), requiring a T-dependent overpressure to proceed on the laboratory time scale. As observed in our experiments, the kinetic limit, that is, the overpressure boundary of the kinetically inhibited zone, is defined by the red crosses in Figure 8 for the case of hydrostatic pressurization. As can be seen in Figure 8, the overpressure required at 180 K for the I→II transformation exceeds 100 MPa. Nonhydrostatic stress often assists phase transformation (Wheeler, 2014), and ice I→II is no exception: We have observed that the kinetic limit under nonhydrostatic stress is better correlated to the maximum normal stress (σ_{I} = σ + P) (blue dots in Figure 8) than to either P or mean stress (σ_{I} + 2P)/3 (Kirby et al., 1991). Using a maximum normal stress axis in Figure 8 thus allows us to compare directly the kinetic limit for bulk transformation under nonhydrostatic stress to the conditions for plastic faulting from Figure 2.

Looking at the range of conditions under which plastic faulting occurred, along the broad horizontal lines in Figure 8, one difficulty with a link to phase transformation becomes apparent: Most occurrences of plastic faulting fall well short of the I→II kinetic limit, many by >100 MPa. Moreover, the broad spread of σ_{I} values over which faulting occurs at any temperature means that the variable that exerts primary control over bulk phase transformation, namely, σ_{I}, has little control over plastic faulting.

Although we have equated precursive bulk transformation, σ_{I→II}, to macroscopic bulk transformation in the sense that both are nonlocalized phenomena, recall that while macroscopic bulk transformation occurs at the kinetic limit in Figure 8, finite precursive σ_{I→II} was inferred at virtually every location in this study where plastic faulting occurred (Tables 5 and 6), and many of those locations are distant from the kinetic limit, as just discussed. Note also that of the four plastically faulted samples with the highest amounts of σ_{I→II} (272, 273, 309, and 728, locations labeled in Figure 8), three failed actually at the highest normal stress levels. We suspect that this is a manifestation of stress concentrations in a limited volume (<1%) of material. Local stresses far in excess of applied stress have been observed by SEM-EBSD near grain boundaries in deformed copper (Jiang et al., 2013), marble (Mariani et al., 2018), and olivine (Wallis et al., 2019). A similar argument relating local stress concentrations to plastic faulting is deferred to section 4 below.

### 3.7. Plastic Faulting in Ice II

Figure 2 also includes the first observations of plastic faulting in ice II, in two experiments at 105–110 K, not otherwise invalidated by circumstances of testing (Table 3). Fault inclinations are near 45° (Table 3, Figure 1b), and σ_{ult} levels are consistent with no P dependence, being nearly indistinguishable despite a difference in P of 100 MPa. Plastic faulting has been identified in only a limited number of rock types, so it is intriguing that two polymorphic crystalline phases of the same component are on that short list. Mapped onto Figure 8, the conditions for plastic faulting in ice II lie 100–200 MPa below a dashed line extension of the ice II/VI equilibrium phase boundary. Given the II→VI volume reduction of ~12%, there may be a first impression of parallel behaviors in plastic faulting in ice I and ice II. However, not only is the comparison with respect to a kinetic limit for ice I and an equilibrium boundary for ice II, but also as with I→II, the II→VI transformation is also kinetically inhibited and to a far
Table 6  
Ductile Precursors in Table 4  

| Run  | \(d\) (mm) | \(T\) (K) | \(P\) (MPa) | \(\sigma_\text{ult}\) (MPa) | \(\varepsilon_\text{tot} \times 1,000\) | \(\varepsilon_\text{creep} \times 1,000\) | \(\varepsilon_\text{I-II} \times 1,000\) |
|------|-------------|-----------|-------------|----------------|----------------|----------------|----------------|
| 261  | 0.68        | 77        | 200         | 162.1          | 106.3          | 6.65           | 0.77           | 7.88           |
| 262  | 0.68        | 77        | 200         | 155.2          | 106.3          | 6.65           | 0.77           | 7.88           |
| 263  | 0.68        | 77        | 100         | 164.2          | 106.3          | 6.65           | 0.77           | 7.88           |
| 265  | 0.68        | 77        | 100         | 160.0          | 116.6          | 97.6           |               |               |
| 269  | 0.68        | 77        | 300         | 160.5          | 110.1          |               |               |               |
| 270  | 0.68        | 119       | 200         | 141.4          | 133.6          |               |               |               |
| 271  | 0.68        | 118       | 100         | 140.2          | 121.4          |               |               |               |
| 272  | 0.68        | 171       | 200         | 106.3          | 120.1          |               |               |               |
| 273  | 0.68        | 172       | 100         | 106.3          | 120.1          |               |               |               |
| 288  | 0.68        | 159.3     | 200         | 120.5          | 120.1          |               |               |               |
| 309  | 0.68        | 159.8     | 300         | 111.5          | 230            | 0.05           |               | 2.25           |

Note. For runs 261–271, at \(T \leq 119\) K, no precursor was observed, that is, \(f_\text{lag} = 0\).

greater degree than that of ice I\(\rightarrow\)II (Mishima & Endo, 1980). In fact, the kinetics of II\(\rightarrow\)VI are so slow that identification of the location of the II/VI equilibrium univariant below 200 K (near 600 MPa) is technically infeasible. The kinetic limit below 200 K is observed to extend rapidly toward higher pressure, reaching \(>1\) GPa at \(170\) K, the lowest \(T\) to which it has been observed (Mishima & Endo, 1980). If there is phase transformation involving the ice II samples at \(110\) K, the equilibrium phase diagram is of little help determining what the daughter phase might be.

3.8. Microstructural Imaging

Sections through three of the plastically faulted samples were also examined by EBSD using a Zeiss SIGMAVP field emission scanning electron microscope following procedures outlined in Prior et al. (2015). All specimens were stored at \(T = 77\) K between loading and imaging but were warmed to \(220\) K for periods of several minutes during preparation and mounting (Prior et al., 2015).

All three faults imaged (Figure 9) show bands of finer grains that define the fault trace. In run 671 (Figure 9a) the thickness of the zone of finer grains is highly variable. The fault in run 724 (Figure 9b), presumably related to one of its multiple failure events, shows a width of \(<0.05\)–\(0.2\) mm and an irregular trace with undulations larger than the width of the fracture. From the morphology of the indium jacket, the total fault displacement in two events was \(~1\) mm (Figure 4). The fault in run 730 (Figure 9c) is better organized, with a fault width \(0.3–0.5\) mm and grain sizes within the fault of \(1–10\) \(\mu\)m. Displacement along the fault is roughly \(2\) mm (Figure 4). There is no sign of liquid formation, for example, fracture or embayment filling, in any of the images. There are many instances of narrow bands and pockets of fine-grained material off the main fracture (Figures 9b and 9c), but the bands are generally tortuous and very uncrack like, being more suggestive of recrystallization along grain boundaries. A particularly good example occurs in sample 730 (Figure 9c: top right inset). This is a conjugate band of fine grains. The band is from a location above and to the left of the main fault figure. Local irregular and lobate boundaries occur in all samples most commonly on the boundaries between the original large grains (e.g., run 730 big grains on the left side; Figure 9c) and more rarely on the margins of bands of small grains (e.g., run 671: Figure 9a inset). Often, the margins bordering small-grain areas contain small subgrains, with low-angle boundaries, and which are similar in size to the small grains. These are most clearly seen in boundary maps (e.g., Figure 9c top right inset). Large (original) grains are often distorted. Where the bands of small grains along faults are thick, there are sufficient small grains to define a crystallographic preferred orientation (CPO). CPOs from such zones in runs 671 and 730 have weak maxima of \(c\)-axes (i.e., [0001]) in a direction close to perpendicular to the fault trace (Figures 9a and 9c). There is considerable evidence of inherited orientations from original grains. In sample 724 narrow bands of small grains have CPOs where the maxima correspond to the larger grains from the same area (Figure 9b), but the small grain CPOs are much more dispersed. In Figure 9c a chain of red grains occurs inside the box outlined in yellow. These have very similar orientations to the large red grain below and left of the box and are interpreted as inherited from that grain.

The small grains are reasonably interpreted as recrystallized grains, and there is microstructural evidence outlined above that is consistent with the operation of deformation, recovery, and subgrain rotation recrystallization and also with strain-induced grain boundary migration. The weak CPOs are consistent with those generated in experimental shear of ice at low temperatures and/or fast rates (Qi et al., 2019) and interpreted by the same authors as being related to coupled operation of rotation due to dislocation motion, recrystallization, and grain boundary sliding. The dispersion of inherited orientations has been interpreted in terms of grain boundary sliding processes being more effective in fine recrystallized grains (Bestmann & Prior, 2003; Craw et al., 2018).

Microstructures can sometimes be complicated by overprinting effects of catastrophic postfailure energy release. We can attempt to reconcile the fault image in run 724 (Figure 9b) with the concept discussed...
above that GSS deformation of material within the faults is responsible for the high strain rates and large displacements of plastic faulting. In the first event in run 724, differential stress $\sigma$ dropped from approximately 100 to 25 MPa (Figure S2), while the sample shortened axially by 1.0 mm, approximately half of the measured shortening of 1.8 mm. Thus, displacement along the fault was 1.4 mm, and total inelastic shear strain in the 0.3-mm-wide fault (Figure 9b) was ~5. Assuming that stress drop versus displacement was linear, the work done on the sample was approximately 30 J. This amount of heat deposited adiabatically into a fault of width 0.3 mm is sufficient to raise its temperature from 180 K to near the melting point but insufficient to cause melting. Arbitrarily, taking the duration of the event as 0.01 s and applying appropriate geometric factors for axisymmetric versus simple shear strain, we find, using the GSS flow law from Goldsby and Kohlstedt (2001), that at $T = 265$ K, the grain size required is roughly 10 nm (the calculations are shown in Table S3 along with a link to the table in worksheet format). This is obviously a rough and not necessarily conservative estimate, and while the calculated grain size is exceedingly small, it is not beyond the realm of possibility (Meyers et al., 2006). Alternatively, by the thermal softening model of Renshaw and Schulson (2017) wherein transformational superplastic weakening accompanies temperature rise to near melting, fault propagation is effected through cyclic episodes of strain concentration and grain size reduction. Whether by GSS or cyclic plastic faults, either mechanism also explains why the sample returns to full strength after faulting, if we assume substantial grain growth from nanometer size occurred in the moments after faulting. The images in Figure 9 cannot resolve this particular question because grain growth during handling at even warmer temperature (to 220 K) would likely have erased any signs of nanometer grains that might have existed.

It is possible to detect signs of ice I→II phase change even at very low concentrations when ice II is expressed as local topographic depressions on the outer surface of samples and is replicated in microscopic detail as local bumps on the inside of the indium jacket. Such topography can be retained when the sample is cooled to <150 K before depressurization, which preserves the ice II in metastable form. Kirby et al. (1991, 1992) were able to show convincingly based on powder X-ray diffraction (Figure 2 in Kirby et al., 1992) and jacket replicas that some ice II was present in at least some of their plastically faulted samples. We have more recently reexamined the jacket replicas of samples run earlier. The jacket from plastically faulted run 273 (Figure 10) shows the fault trace along with numerous broad regions of positive topography, a clear signature of ice II. The quasi-rectilinear shape of the ice II domains, with edges aligned along the maximum shear direction, is perhaps not surprising since bulk transformation is enhanced by shear stress (Figure 8). The association of ice II regions with the fault in Figure 10 clearly suggests a causal relationship. Given the uniaxial symmetry of the state of stress before faulting, if the morphology of ice II inclusions is influenced by shear stress, one might expect to see prefaulting ice II formations aligned along 45° planes of various azimuth around the vertical direction. The fact that most ice II inclusions in Figure 10 are parallel to the same plane that in addition is that of the fault is strong evidence that faulting preceded ice II formation. Ice II regions bordering the fault must have formed after faulting, since matching clipped portions do not appear below the fault. On the other hand, run 273 showed an unusually large inelastic precursor (Table S2), meaning that there must have been extensive ice II formation before faulting.

The paradox is partly explained by the images of plastically faulted run 308 (Figure 11a, a1). Here, dense domains of much smaller point-like ice II inclusions are aligned in various orientations with respect to
Figure 9. Structures observed in SEM-EBSD in the fault zones of three plastically faulted samples. Loading direction is vertical in all images. All EBSD data are shown as inverse pole figures (unless stated) with color indicating the crystal orientation in the loading direction, as shown in the legend at top right of (b). All stereonets are lower hemisphere equal area projections, with colors indicating distribution of grain orientations as a multiple of uniform distribution (MUD).

(a) Run 671, failed at low $T$ (105 K) and relatively high $\sigma_{ult}$ (161 MPa), with macroscopic fault intersecting end cap (Figure 4). Inset shows microstructural detail of the area outlined in red. The contoured c-axis figure is from fine grains in the area outlined in yellow. (b) Run 724, failed at 180 K in multiple events near $\sigma_{ult} = 100$ MPa. External appearance suggests multiple fracture planes (Figure 4) of which this may be one. The ~2.5-mm length of fracture intersected here has a width of 0.05–0.2 mm. Fine grains surrounding some of the large original grains suggest recrystallization of highly strained regions near grain boundaries, a process characteristic of ductile flow. Coarse and fine-grained c-axis figures for the area outlined in yellow are shown. It is impossible to determine if this recrystallization played a role in fracture initiation or if it is a passive result of the violent fault displacement event. (c) Run 730, failed in a single event at 195 K. Inset at top right shows a structure from above and left of the main figure. This is a boundary map with yellow boundaries between 2° and 5°, green between 5° and 10°, blue between 10° and 20°, and purple greater than 20° of misorientation. Inset at center shows the c-axis pattern from fine grains in the yellow boxed area; red grains interpreted as inherited from the host larger grains are excluded from the data in this stereonet.
the fault, more in keeping with a uniaxial stress state and consistent with creation prior to faulting. The lineations themselves indicate interactions between neighboring inclusions that cause subsequent neighbors to form at a favored distance and direction, perhaps influenced by the direction of maximum shear stress. Thus, ice II inclusions that predate faulting and contribute to precursive strain (Figure 11a) and those that form after faulting (Figure 10) may both appear in faulted samples. Similarly to those in Figure 11a, ice II inclusions in arrays at various orientations also appear in unfaulted samples partially transformed under differential stress, such as run 292 from Kirby et al. (1991), shown in Figure 11b. Were several domains of aligned inclusions to develop on common planes of maximum shear, a jacket replica might be expected to show domains of lineations striking at orientations of 0° to 45° from horizontal and perhaps curving or splaying as is seen in Figure 11b.

4. Discussion

Our results reject the hypothesized exclusivity of transformational faulting as the mechanism for plastic faulting. The appearance of plastic faulting in ice II at 110 K, for which no available phase transformation exists, may be the most direct evidence of this. Load-displacement curves preceding brittle (plastic faulting) and ductile failure at $T \geq 160$ K are almost indistinguishable (Figure 7). Common patterns in behavior of plastic faulting and bulk I-II phase transformation are few (Figure 8). One serious inconsistency with the requirement for phase transformation is the absence of a convincing connection to plastic faulting in the one setting where evidence of such a connection would be most expected: when bulk I→II transformation is occurring concurrently. The simplest interpretation of the observations taken together is that bulk phase transformation and plastic faulting run concurrently but independently.

How then is plastic faulting initiated? Assuming that in most instances, it is an expression of adiabatic shear instability, what is the origin of the first point of criticality, the nucleus of soft material that triggers the instability? The question applies whether or not the trigger is a load instability (i.e., the result of strain softening) or a gradually rising temperature (i.e., an insufficient rate of diffusion of heat). The promotion of an atomic-scale heterogeneity to an incipient point of instability (through, e.g., phase transformation, melting, critical grain-size reduction [Renshaw & Schulson, 2017; Semiatin et al., 1984], unblocking of lattice defects [Armstrong et al., 1982; Renshaw & Schulson, 2004; J. Weiss & Marsan, 2003], or other process) is at its...
origin a stochastic process. If that is the case, then the preternaturally (for rocks) small variance of location of the B-D crossover (Figures 5–7) suggests a process that is buffered from the extremes in local stress that can exist in polycrystalline materials under load or, invoking the statistical effect of large sampling on variance, that requires not simply one but many temporally and spatially correlated points of incipient action. The very few number of small faulting events (seen as blips on the load-displacement record, e.g., Figure 7) preceding through-going faulting, and the fact they occur only very close in stress to $\sigma_{\text{ult}}$, is consistent with this precision. Contrast this behavior with Coulombic faulting in rocks, where microfracturing events begin well below $\sigma_{\text{ult}}$ and steadily increase in number up to the point of failure (Lockner et al., 1991).

One way to buffer the effects of local stress concentrations is to relieve those concentrations by local $I \rightarrow II$ phase transformation. An interesting consequence of buffering in this manner is that if transformation and plastic faulting are indeed independent in ice as our observations imply (at least in the region near 180 K), then the precision of the B-D crossover is peculiar to ice (or other materials with accessible phase transformations) and may not be a property of plastic faulting in general. On the other hand, if plastic faulting is triggered by an adiabatic process, since thermal diffusion is inherently less sensitive to local stress or structural heterogeneities, a narrow B-D crossover would be expected no matter what the material. The matter in not likely to be resolved soon. Since the B-D crossover in ice can only be studied near 180 K (Figure 3), it would have to be approached with another material.

Thermally activated high-temperature plastic deformation in crystalline materials is the expression of spatially and temporally correlated stochastic events at the lattice scale, in particular dislocation avalanches and clustering of dislocation networks (e.g., Weiss et al. (2000)), yet sample-to-sample variance in flow stress is typically small. Although we have concluded that plastic faulting can proceed in the absence of phase transformation, we may exploit the images in Figure 11 to show an example of the organization that spontaneous formation of ice II inclusions can produce. As the density of inclusions increases, larger scale heterogeneities develop (e.g., the domains seen in the images) rather more predictably in a manner of so-called self-organized criticality (e.g., Bak et al., 1989). For the present case, the scale at which a soft nucleus of critical size and shape forms is difficult to predict.

It is conceivable that there is a mechanism of heterogeneous phase transformation involved in transformational faulting in ice I that is different from the homogenous (bulk) transformation that has been known since the time of Tammann (1903). However, the distinction between phase transformation and local structural rearrangements occurring during severe plastic deformation probably becomes
blurred at finer and finer scale. The essential difference for the discussion here is that the “phase” created during severe plasticity exists only under conditions of severe plasticity, which then frees up all materials to plastic faulting, not simply those which happen to have a nearby melting curve or phase transformation.

5. Conclusions

Water ice has given us the best opportunity yet to isolate and study the nucleating mechanism of plastic faulting, a process with important links to deep earthquakes and other shear instabilities in crustal rocks. It is fairly well established outside of this work that the narrow shear zone forming a plastic fault is an adiabatic instability (thermal runaway) that results from the combined reduction of grain size caused by recrystallization under high stress and the rheologic weakening that follows grain-size reduction and temperature increase. Plastic faulting is nucleated by a zone of weak material of sufficient volume to become adiabatically unstable. The nucleus forms under increasing stress as the ice I structure breaks down locally (and perhaps briefly) to a weaker structure, eventually at a rate such that local points of breakdown are sufficiently dense to interact mechanically. Unresolved are the scale of the local structural breakdown, the nature of the breakdown, and the time scale of the process. What is clear is that points of potential breakdown are widely distributed, that is, large stress concentrations are not required, and that the breakdown itself is not exclusively a known phase transformation. The results here do not require and in many instances are inconsistent with phase transformation. According to this model, most or all materials should be capable of plastic faulting, yet it has been seen in the laboratory in only a handful of rock types, two of which, interestingly, are ices I and II.

The principal experimental findings informing this model are as follows:

- Plastic faulting in polycrystalline ice I occurs over a broad range of temperature and pressure, at least \(20 \leq P \leq 250\) MPa and \(77 \leq T \leq 235\) K. Ultimate strength at failure is largely independent of pressure (Figure 2) and weakly dependent on temperature (Figure 3) over these ranges. The fault itself is confined to a narrow plane oriented at 45° to the principal normal stress (Figure 1).
- Plastic faulting also occurs in ice II.
- Plastically faulted samples retain their full strength (Figure 4), provided that jacket integrity is maintained.
- The change of failure mode at 180 K from brittle (plastic faulting) to ductile (plastic flow) as mapped against applied strain rate is, within a factor of well under two in strain rate, a sharp changeover (Figures 5–7). Mixed mode failure has not been observed.
- Inelastic precursors appear prior to most instances of plastic faulting (Figure S2); they originate from the combined action of bulk phase transformation from ice I to ice II plus ordinary defect-based plasticity, with the former predominating at \(T < 195\) K in most runs ending in brittle failure.
- Inelastic precursors to brittle failure are virtually indistinguishable from those of ductile failure on the basis of stress-time records (Figure 7).
- The fault zone imaged in EBSD after testing has a width of roughly 0.2 to 0.5 mm and is filled with fine-grained crystalline ice I of roughly 1- to 10-μm diameter (Figure 9).

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