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Statistical analysis of dislocation dynamics during viscoplastic deformation from acoustic emission

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Abstract. We present experimental data of acoustic emission (AE) induced by dislocation motion during "pure" viscoplastic (ductile) deformation of singlecrystals and polycrystals of ice which provide opportunity to revisit collective dislocation dynamics as a critical phenomenon, as recently proposed for brittle fracturing. The data were recorded during compression and torsion creep experiments. AE statistics of power law type were systematically obtained under different experimental conditions. Among the possible candidates for such a system with threshold dynamics exhibiting power law statistics, critical points, disordered first-order transitions, and self-organized criticality should be considered. The revisitation of dislocation dynamics as a critical phenomenon allows rationalization of collective effects as well as of the heterogeneity and complexity of viscoplastic deformation of crystalline materials. Such critical behavior implies that dislocation avalanches and strain localizations are unpredictible, in a deterministic sense, in space, time, and energy domains and that large plastic instabilities account for most of the viscoplastic deformation.

1. Introduction

Within a material-dependent range of temperature and stress [*Ashby*, 1972], the viscoplastic deformation of crystalline materials involves the motion of a large number of dislocations. Dislocations are linear defects which interact through their associated stress fields. The interaction can be attractive or repulsive, and mutual annihilation is possible [see, e.g., *Friedel*, 1964]. The nature of the dynamics of an individual dislocation [*Weertmann and Weertmann*, 1980], as well as the interaction between a couple of dislocations [*Friedel*, 1964] are well established. However, the global dynamics of a system containing a large number of interacting dislocations, as during the viscoplastic deformation of crystalline materials, is poorly understood [*Neuhauser*, 1983]. Under conditions where dislocation motion is the dominant mechanism for viscoplastic deformation, when a material is deformed under constant load (creep test), a constant global strain rate regime usually appears after a transient stage. One traditionally explains this so-called secondary creep or viscoplastic steady state behavior by an equilibrium between the production (at dislocation sources like Frank-Read sources [*Friedel*, 1964]) and the elimination (at dislocation sinks like free surface or grain boundaries, or by mutual annihilation) of dislocations [*Poirier*, 1976]. In such a situation, the Orowan's relation predicts a constant strain-rate for the involved system:

$$\frac{d\varepsilon}{dt} = \rho_m \, b \, v \qquad (1)$$

where b is the Burger's vector, ρ_m is the density of mobile dislocations, and v is the stress-dependent dislocation velocity. Relation (1), as well as the term "steady state," implicitely neglects a possible spatial and temporal variability of both dislocation velocity and dislocation density. However, the heterogeneous nature of dislocation slip process has been recognized [*Neuhauser*, 1983; *Hähner et al.*, 1998]. As a result of their interactions, dislocations tend to move cooperatively in groups to form slip lines rather than individually and independently. Moreover, moving dislocations can pile up against stable dislocation walls or boundaries. During the breakaway of a pileup or the activation of a source, theoretical calculations [*Campbell and Taylor*, 1963; *Neuhauser*, 1983] show that dislocation velocities vary by orders of magnitude through time and space. More generally, *Neuhauser* [1983] stressed the fact that at any moment, only a very small fraction of the potentially mobile dislocations ρ_m is indeed moving. Therefore (1), which is based on a mean field approach, strongly underestimates the genuine dislocation velocities. In some alloys, under specific loading-temperature conditions, strain localization is strong enough to be measurable as stress drops on a loading curve [*Estrin et al.*, 1993; *Hähner*, 1993]. This phenomenon is traced back to the diffusion of solute atoms, which act as moving obstacles to slip band propagation, leading to "macroscopic" plastic instabilities. This is the well-documented Portevin-Le Chatelier (PLC) effect [*Estrin et al.*, 1993; *Hähner*, 1993]. Therefore viscoplastic deformation driven by dislocation motion appears as heteregeneous in size, space and time domains, which is not accounted for in the mean field description of (1). Here we reveal further the heterogeneous character of collective dislocation dynamics by using experimental data from acoustic emission (AE) recorded during pure viscoplastic deformation of ice. The so-called steady state viscoplastic deformation is, in fact, shown to occur in bursts of relaxation following a power law distribution of energy and time separation. Such power law behavior is suggestive

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of a critical dynamics of dislocations, similar to those argued for microfracturing [*Petri et al.*, 1994; *Guarino et al.*, 1998].

Attempts have been made to simulate the collective behavior of dislocations [*Lépinoux and Kubin*, 1987; *Kubin and Canova*, 1992; *Groma and Pawley*, 1994]. However, these numerical approaches, which succeeded in capturing some aspects of the collective behavior of dislocations, especially the spatial patterning of dislocations, did not rely on a general framework to explain the observed heterogeneous dynamics. In the present paper, we propose to embed these earlier results in the more general framework of critical systems. Such a critical framework has been recently proposed to describe brittle fracturing [e.g., *Hermann and Roux*, 1990; *Andersen et al.*, 1997], from the laboratory sample scale [*Petri et al.*, 1994; *Guarino et al.*, 1998] to the earth crust scale [*Main*, 1996].

2. Experimental Procedure

As a model material to study dislocation dynamics from acoustic emission, ice provides the following advantages: single crystals or polycrystals with various microstructures can be easily grown in the laboratory; transparency allows verification that AE activity is not related to microcracking; and an excellent coupling between the ice and the AE transducer can be obtained by fusion/freezing. Within the range of temperature and stress corresponding to our experimental conditions, diffusional flow is not a significant mechanism of deformation in ice, and viscoplastic deformation of hexagonal ice Ih occurs by dislocation motion [*Duval et al.*, 1983]. Hexagonal ice Ih presents a very strong plastic anisotropy of the single crystal [*Duval et al.*, 1983]. The resistance to shear on nonbasal planes is at least 60 times larger than that on the basal plane. Therefore viscoplastic deformation of single crystals occurs essentially by basal glide. In polycrystals, basal glide within neighboring grains with different crystallographic orientations leads to strain incompatibilities. By accomodation of these incompatibilities, dislocation climb on prismatic planes and possible glide on nonbasal planes [*Castelnau et al.*, 1996], allow extensive viscoplasticity of the polycrystals.

Uniaxial compression creep tests, each of them constituted by several steps of stress, were performed at -10°C on different types of artificial ice samples, including single crystals, one bicrystal, and polycrystals with different grain sizes. One torsion creep test, with steps of constant momentum, was also performed on a single crystal. Note that the duration of the stress steps varied arbitrarily from step to step and test to test, ranging from 10 min to ~ 2 hours. The characteristics of each test, including the type of loading, the type of ice, the *c* axis orientation (for single crystals) or the mean grain size (for polycrystals), are summarized in table 1. Ice samples were prepared from distilled, deionized, and degassed water. Single crystals grew in about 1 month, within a cylindrical mold frozen from the bottom, from a unique seed selected for the desired *c* axis orientation. For our artificial polycrystals the mold was filled with presieved fragments of ice, allowing us to control the grain size, then pumped down to 0.1 torr to avoid bubbles, filled with water, and finally, frozen in ~ 24 hours. The *c* axes orientations, on the contrary, were not controlled and so were isotropically distributed, leading to an isotropic macroscopic mechanical behavior for polycrystals.

During each mechanical test a piezoelectric transducer with a frequency band width of 0.1-1 Mhz was fixed by fusion/freezing to the side of the cylindrical samples. The amplitudes of AE events were recorded during each loading step. With the transducer fixed to an ice sample, without any loading, we recorded significant acoustic emission up to an amplitude threshold of 25 dB. During an experiment the event amplitude threshold was adjusted to 30 dB, or 3×10^{-3} Volts, i.e. about 5 dB above the noise level, and the envelope "dead time" (the minimum time seperation between two successive events to be recorded as individual events) was 50 μs. The dynamic range between the amplitude threshold (3×10^{-3} V) and the maximum recordable amplitude (10 V, or 100 dB) was 70 dB, i.e., 3.5 orders of magnitude. The calibration of the experimental device was performed previously using the Nielsen test. A linear relationship between the input and the output signals was verified [*Amitrano*, 1999].

Two different mechanisms can account for microseismic activity during the creep deformation of ice: high-velocity motion of dislocations (plastic instabilities) and crack nucleation and propagation. Thanks to the perfect transparency, it was easily verified that no cracks nucleated within any of the ice single crystals for all the creep stresses we applied. Rigorously, an absence of visual detection

Table 1. Characteristics of the Experimental Tests

Test	Type of Ice	Type of Test	*c* Axis Orientation (Relative to Loading Axis)	Mean Grain Size, mm	Number of Loading Steps
1	single crystal	compression	2° compression axis		4
2	single crystal	compression	45° compression axis		4
3	single crystal	torsion	parallel torsion axis		3
4	bi crystal	compression	3° compression axis		3
5	polycrystal	compression		1.5	2
6	polycrystal	compression		0.5	2
7	polycrystal	compression		0.5	1

ensures that no feaures are present with an opening > 0.3 μm, i.e., the lower bound for natural light wavelength. Owing to this very small detection limit (about 650 atomic spacings), crack nucleation is easily detected in fresh water ice. For polycrystals, depending on grain size and ice samples, microcracking was observed above a threshold load. Occurence of microcracking was clearly visible to the eye and correlated with the change of the shape of the AE amplitude distribution (breaking slope; see *Weiss et al.* [1996]). Since we only focused on dislocation dynamics as a source of AE, the loading steps during which cracking was observed were discarded for the present analysis. Moreover, experimental evidence for the recorded AE to be, indeed, related to dislocation motion in our experiments was provided as follows. By varying the orientation of the single-crystal *c* axis relative to the compression axis in the case of uniaxial compression tests on single crystals, for the same uniaxial compression creep stress, we observed an AE activity (defined in section 3 as $\mathring{A}$) at least 2 orders of magnitude larger for a single crystal with *the c* axis inclined at 45° (test 2) to the compression axis than for a crystal with a quasi-vertical *c* axis (test 1). This agrees with an AE activity that highlights dislocation motion driven by the shear stress acting on the basal planes [*Weiss and Grasso*, 1997].

3. AE Source Model and Validation

One difficulty with AE is in relating the characteristics of the generated AE wave to physical processes. Usually, for AE induced by microcracking the assumption is made that the squared amplitude A^2 of the wave is proportional to the inelastic energy E liberated during the acoustic event [see, e.g., *Lockner et al.*, 1991; *Petri et al.*, 1994]. Here we base our analysis on a specific AE source model developed for dislocation dynamics, which relates the wave's characteristics to the characteristics of the plastic instability. This model has been proposed and detailed by *Weiss and Grasso* [1997] and validated from a comparison between global AE activity and global strain rate. We will summarize here the main features of this model and its validation.

In solid materials, sudden local changes of inelastic strain generate AE waves [*Malen and Bolin*, 1974]. In our experiments, given the amplitude threshold and the frequency range of our transducer, the detected AE are unlikely to be the result of a single moving dislocation but most probably are related to synchronized accelerations of dislocations, such as the activation of a dislocation source or a pileup breakaway [*Weiss and Grasso*, 1997]. From the theoretical analysis of *Rouby et al.* [1983] one can relate the maximum amplitude of the acoustic wave A resulting from a plastic instability, to the number of involved dislocations n and their velocity v [*Weiss and Grasso*, 1997]:

$$A = k\frac{nLbvt_0}{d} \qquad (2)$$

where k is a coefficient related to material properties and the piezoelectric constant of the transducer, b is the Burger' s vector, L is the length of the n moving dislocations, t_0 isthe travel time of the acoustic wave through the transducer (considered to be constant), and d is the source/transducer distance (supposed to be large compared to L). In this crude model, L and v are supposed to be identical for all the involved moving dislocations. The dislocation velocity v is considered to be zero before and after the event and constant during the event. The term $1/d$ represents the geometrical attenuation of the acoustic waves.

By comparing (1) and (2), *Weiss and Grasso* [1997] showed that the AE amplitude A is a measure of the local strain associated with the plastic instability. Therefore the rate of global AE activity $\mathring{A}$, defined as the summation of the amplitudes of all the acoustic events recorded during a given time interval divided by this duration, should be proportional to the global strain rate of the sample, provided that (1) the nonrecordable part of AE (below the amplitude threshold of 3×10^{-3} V) is negligible or at least proportional to the recordeable part and (2) the dislocation dynamics within the volume of matter sampled by our single AE transducer is representative of the response of the full sample. The proportionality between global AE activity $\mathring{A}$ and global strain rate has been verified on single crystals for uniaxial compression tests as well as for a torsion test, each of them containing several steps of stress [see *Weiss and Grasso*, 1997, Figure 3], thereby validating our AE source model (relation (2)) as well as points (1) and (2). Note that an independent validation of point (1) is given in the appendix and discussed further in section 4.

4. Statistical Distributions of AE Amplitudes and Time Intervals Between Events

As shown above, the AE amplitude A depends on the number of dislocations involved in the plastic instability, their length, and their velocity. The AE energy radiated by the acoustic wave is proportional to A^2. According to *Kiesewitter and Schiller* [1976], the energy dissipated by viscoplastic deformation during an event also scales with A^2. This results from an expression given by *Eshelby* [1962] for the energy dissipated at the source by a single screw dislocation of length L moving at a velocity v:

$$E = KL^2b^2v^2 \qquad (3)$$

where K is a coefficient depending on material constants, including the shear modulus and the velocity of acoustic transverse waves. A comparison of (2) and (3) with n=1 shows that $E \sim A^2$. This scaling between E and A^2 is similar to that assumed by *Lockner et al.* [1991] or *Petri et al.* [1994] for AE related to microcracking. In other words, A^2 expresses the energy liberated during an avalanche of dislocations. Therefore AE allows to study during deformation the dislocation dynamics in energy, time, and, possibly, space (if AE sources locations are determined with the help of multiple transducers) domains. In the present study, only one transducer was used, and so source locations were not accessible.

For each loading step of each test the distribution of AE amplitudes was recorded. Figures 1-3 show, for two compression tests (tests 1 and 2, see Table 1) and one torsion test (test 3) on single crystals, respectively the cumulative distributions of AE amplitudes for different resolved shear stresses on the basal planes. Reported distributions correspond to all the events recorded during a given loading step. Figure 4 shows a similar distribution for a polycrystal under uniaxial compression (test 7), for which only one loading step without microcracking was available. Figure 5 corresponds to one loading step of a bicrystal under uniaxial compression (test 4). The two distributions displayed in Figure 5 were recorded during the same loading step but for completely separated time intervals. Note that the large number of events recorded for the

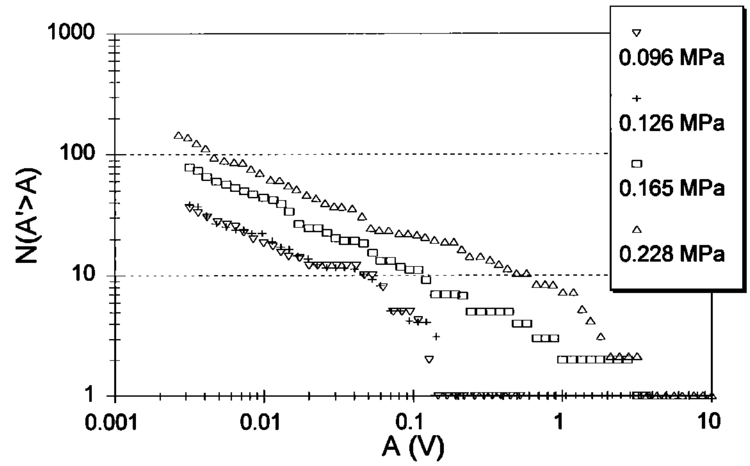

Figure 1. AE amplitude cumulative distributions for a uniaxial compression creep test (T=-10°C) on a quasi-vertical c axis single crystal of ice (test 1; see Table 1). The different sets of data correspond to different loading steps resulting in different resolved shear stresses on the glide (basal) plane.

bicrystal (Figure 5) compared with single crystals (Figures 1 and 2) is very likely the result of the grain boundary as a very active dislocation source. Power law statistics $N(A'>A) \sim A^{-\delta}$ are systematically observed for the different stress steps of the different tests, whatever the kind of ice (single crystals, bicrystal, or polycrystals) or the type of loading (torsion or compression). For some distributions the power law seems to be affected by a cutoff at high amplitudes which possibly depends on the shear stress (see Figure 1). However, this cutoff is far from being systematic (see, e.g., Figure 1, τ=0.165 MPa; and Figures 2-5) and has to be taken with caution owing to the limited number of recorded high amplitudes events. For all the tests performed, δ ranged between 0.2 and 1.2, with most of the δ values close to 0.6-0.7 (Figure 6). The error in the estimation of δ ranged between ±0.17 for large δ values and less than ±0.07 for low δ values. The δ values were estimated by a least squares fit on the linear part of the distributions below the cutoff (if any). Standard deviations of the δ values were estimated by using an empirical formula derived by *Pickering et al.* [1995] from a Monte Carlo simulation of the sampling effect on the exponent of a power law distribution. Considering that A^2 scales with the energy of the dislocation avalanche, $N(A'>A) \sim A^{-\delta}$ is equivalent to $N(E'>E) \sim E^{-\beta}$ with $\beta=\delta/2$. Therefore δ=0.6-0.7 implies β=0.3-0.35. From the source to the transducer the acoustic waves are attenuated (term $1/d$ in (2)). Because we used a single transducer, we were unable to correct this attenuation of the amplitudes. However, *Weiss* [1997] showed that for δ values < 3, as observed for all the present experiments, this attenuation modifies neither the shape of the distributions nor the δ values. Here δ decreased with increasing shear stress (Figure 6), except for one test (1) for which δ remained constant and equal to 0.6. A general tendency for decreasing δ with increasing shear stress is also observed when the δ values for all the experiments are compiled (Figure 6). During a given loading step the statistical properties of the system remained stationary through time, i.e. δ was constant (see, e.g., Figure 5).

For one loading step of one test (2; shear stress: 0.581 MPa) the time intervals t between two successive events of any

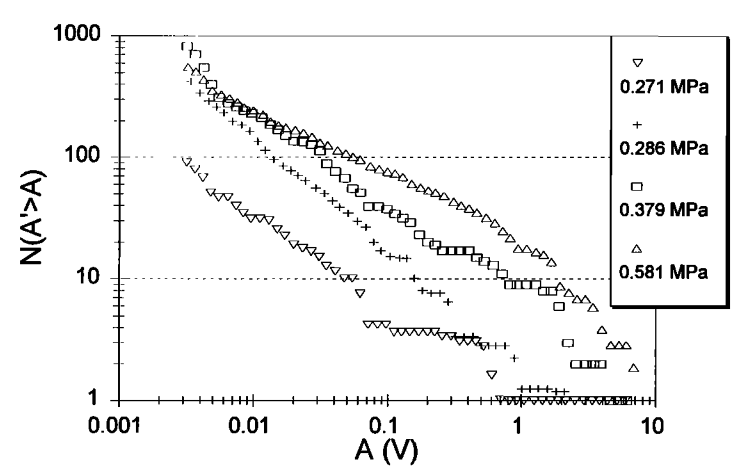

Figure 2. Similar to Figure 1, for a single crystal with an inclined (45°) c axis (test 2; see Table 1).

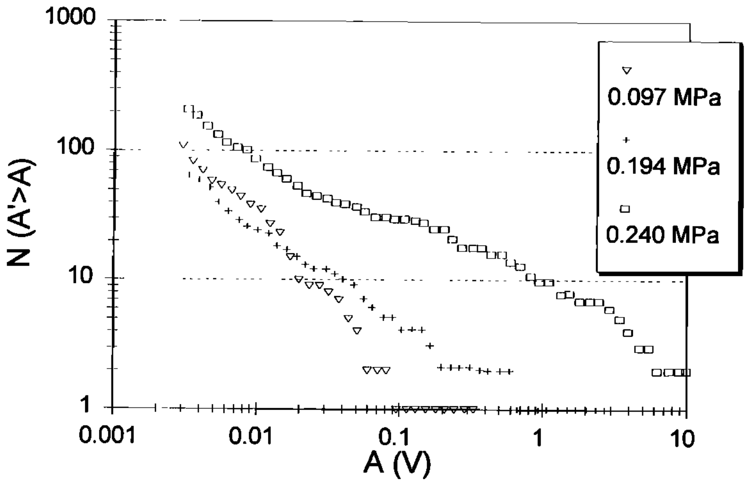

Figure 3. Similar to Figure 1, for a torsion creep test (test 3).

amplitude were recorded. The corresponding cumulative distribution is shown on Figure 7. A power law $N(t'>t) \sim t^{-\gamma}$ is observed with γ=1.0±0.34.

An important question concerns the contribution of the recordable plastic instabilities to the global viscoplastic strain (as noted above, under the applied testing conditions, dislocation creep is the unique mechanism which accounts for viscoplastic deformation of ice). Our investigation is experimentally limited toward small amplitudes by the detection threshold, and one can wonder whether the contribution of the nonrecordable part of the process is negligible or at least proportional to the recordable part. The proportionality observed between the rate of global AE activity $\dot{A}$ and the global strain rate [*Weiss and Grasso*, 1997] not only implies that the volume of matter sampled by the transducer is "representative" of the whole system (see above) but also that the viscoplastic strain corresponding to the recorded plastic instabilities is proportional to the global viscoplastic strain. The knowledge of the analytical form of the AE amplitude distribution (power law), supposing that smaller undetected events follow the same distribution, allows one to estimate the relative contribution of recordable and nonrecordable events. Calculations detailed in the appendix strongly suggest that the nonrecordable part is, indeed, negligible in terms of strain, as well as in terms of dissipated energy.

5. Discussion

We report here AE measurements that give insight into the collective dynamics of dislocations. Previous attempts to study dislocation dynamics from AE mainly focussed on continuous acoustic emission, i.e., the gross background noise level of AE during the loading of metallic samples [see, e.g., *Kiesewitter and Schiller*, 1976]. Here we examine the statistics of individual AE bursts, which show power law distributions for the amplitudes (Figures 1-5), as well as the time separation (Figure 7) of acoustic emissions. This pattern is recurrent, whatever the type of test (compression or torsion), the type of ice (single crystals or polycrystals), and the applied stress on the basal plane. This reveals a strong heterogeneity of dislocation

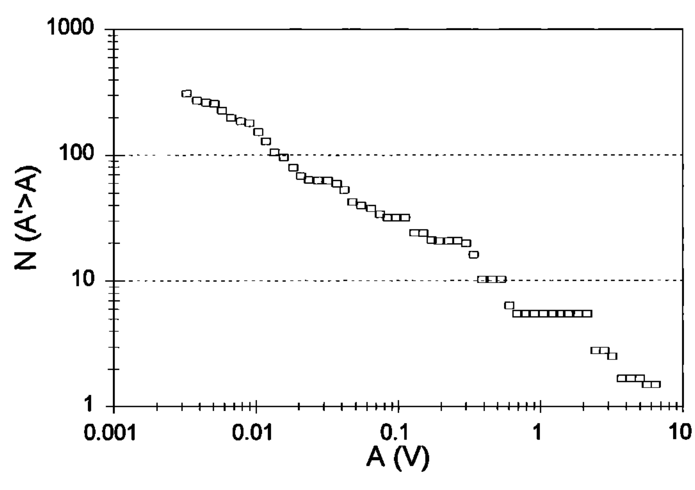

Figure 4. AE amplitude cumulative distribution for a uniaxial compression creep test (T=-10°C;σ_1=1.75 MPa) on a polycrystal of ice (test 7).

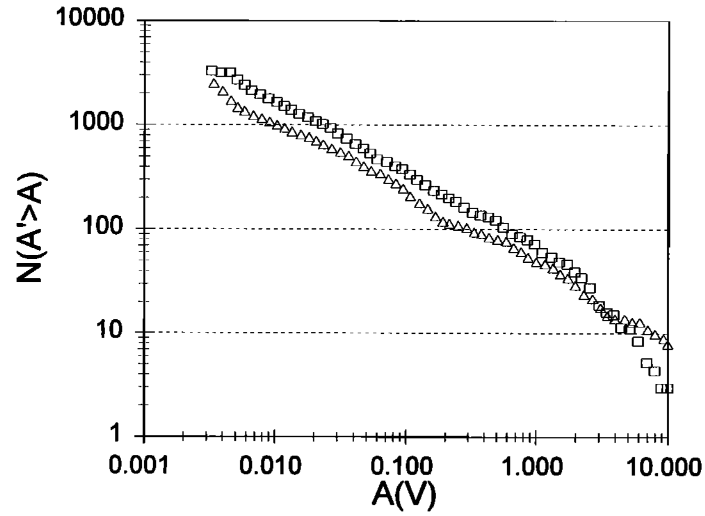

Figure 5. AE amplitude cumulative distributions recorded during the same loading step of test 4 but corresponding to two completely separated time intervals. The two distributions give the same δ value of 0.70 ± 0.12.

dynamics in time and energy domains. Such scale-invariant behavior is strongly suggestive of a system near (or in) a critical state, i.e., in a situation where correlations between different parts of the system become long ranged, such that any small perturbation may cascade into large events. Other positive evidences for a critical state of crystalline solids during dislocation-driven viscoplastic deformation exist. First, a common feature of systems displaying criticality is to contain many interacting entities and to be ruled by threshold dynamics [e.g., *Lesne*, 1996]. Dislocations are known to be numerous and to interact through their associated stress fields, which decreases in $1/r$ [*Friedel*, 1964]. The activation of a dislocation source or any plastic instability is triggered above a threshold stress [*Friedel*, 1964; *Weiss and Grasso*, 1997]. For the smallest possible event, i.e., a single dislocation kink moving by a single atomic spacing, this threshold stress is the Peierls stress. Second, although an analysis of dislocation activation in the space domain was not accessible, other studies have documented a fractal patterning of dislocations that attest for scale invariance of dislocation dynamics in the space domain. *Sprusil and Hnilica* [1992] showed that slip line patterns of Cd single crystals were fractal. More recently, *Hähner et al.* [1998] reported fractal cellular dislocation patterning during plastic deformation of Cu single crystals. Third, in the energy domain, power law statistics were

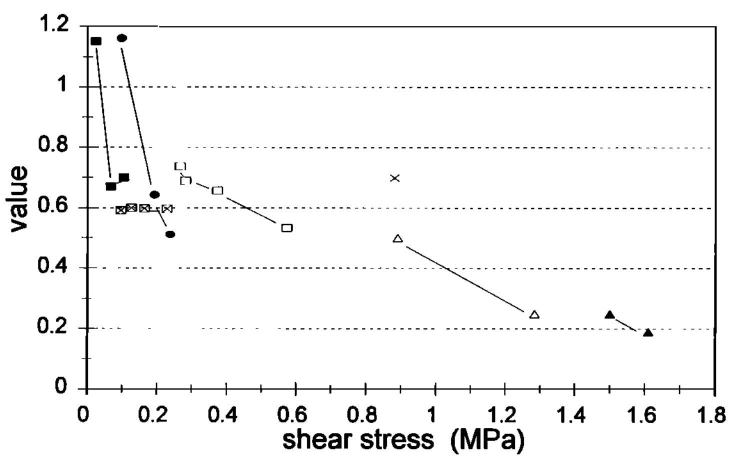

Figure 6. Evolution of the exponent δ with the resolved shear stress on the basal plane. The error on the estimation of δ ranged between ±0.17 (for large δ values, or low shear stresses) and less than ±0.07 (for low δ values, i.e., large shear stresses). The resolved shear stress reported for polycrystals was taken to be half the compression stress, implicitely assuming that most of the AE activity arose from crystals well oriented for basal glide. Crossed squares, test 1; Open squares, test 2; Circles, test 3; Closed squares, test 4; Open triangles, test 5; Closed triangles, test 6; Cross, test 7. Although a large amount of literature reports possible δ value change with mechanical parameters, to our knowledge, no definitive explanation of such anticorrelation between the exponent δ and the shear stress can be proposed so far.

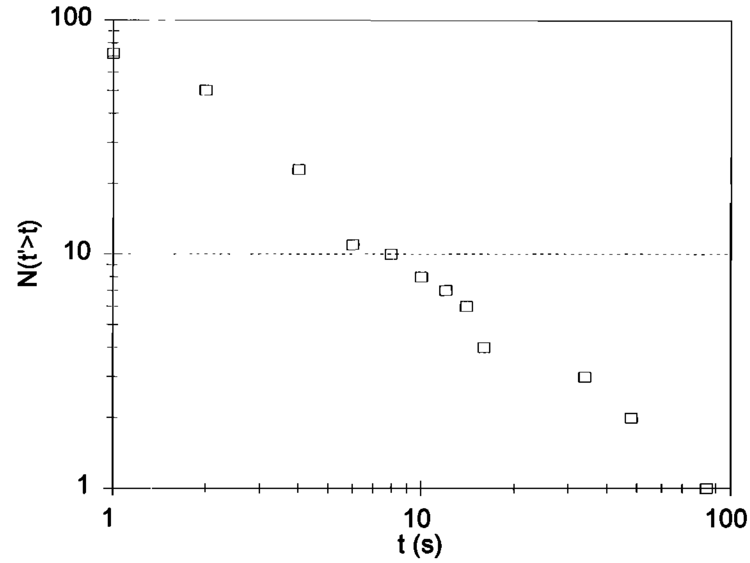

Figure 7. Cumulative distribution of the time interval t between two successive events of any amplitude for a uniaxial compression creep test on a single crystal of ice (test 2; T=-10°C; resolved shear stress on the glide plane: 0.581 MPa). For technical reasons it was impossible to record similar time distributions for each test performed.

also reported for the stress drops resulting from "macroscopic" instabilities associated with the PLC effect during strain rate controlled tests on Al-Mg alloys [*Lebyodkin et al.*, 1995].

From this evidence of scale invariance in space, time, and energy domains, coupled with the intrinsic properties of dislocations, we argue for the collective dislocation dynamics to display criticality not only in ice but more generally in crystalline materials experiencing dislocation-driven viscoplastic deformation.

One of the consequences of the critical state of dislocation-driven viscoplastic deformation is that dislocation avalanches and strain localizations are unpredictible, in a deterministic sense, in space, time, and energy domains; that is, one single event is not predictible. However, the power law scaling of time intervals (Figure 7) implies some kind of statistical predictability. The longer (shorter) it has been since the last event, the longer (shorter) the expected time till the next [*Davis et al.*, 1989; *Sornette and Knopoff*, 1997]. This comes from the correlation between events. Note that random dislocation dynamics would not lead to any kind of predictability, either deterministic or statistical [*Sornette and Knopoff*, 1997]. Another consequence of criticality is that most of the energy dissipated by the system is dissipated through major events/avalanches (see appendix). In the present situation this means that large plastic instabilities account for most of the viscoplastic deformation rather than independent movements of individual dislocations.

The next question remains the origin of such criticality. Different recognized mechanisms can lead to critical behavior. Among these, second-order (continuous) phase transitions and the self-organized criticality (SOC) concept [*Bak et al.*, 1987, 1988; *Vespignani and Zapperi*, 1998] should be considered. To definitively identify one of these possible mechanisms is beyond the scope of this paper. Moreover, observable standards for each of these critical processes remain partly unidentified, and the theoretical frameworks themselves are not completely "quenched" so far, especially for SOC [*Vespignani and Zapperi*, 1998; *Grasso and Sornette*, 1998]. Here we just review the observables that argue for (or disagree with) each critical mechanism. We also discuss alternative mechanisms which are proposed to display power law distributions, without strict reference to criticality, including disordered first-order transition [*Sethna et al.*, 1993; *Zapperi et al.*, 1997a], multiplicative noise [*Sornette and Cont*, 1997; *Sornette*, 1998], and the sweeping of an instability [*Sornette*, 1994].

The usual route toward criticality is second-order, or continuous, phase transitions, illustrated by the Ising model for ferromagnetic transition [e.g., *Goldenfeld*, 1993]. For the fracturing process, this mechanism is usually rejected [*Zapperi et al.*, 1997a] because of the final breakdown of the system. Such discontinuity is typical of a first-order phase transition. For dislocation dynamics during viscoplastic deformation, final breakdown never occurs. This allows us to consider second-order phase transition as a possible process to describe our observations. For second-order phase transition, criticality is obtained by fine tuning a control parameter (e.g., temperature). The system exhibits power law size distributions with an upper cutoff that is rejected toward larger values as the critical point is approached. The cutoffs on Figure 1, which apparently depend on the applied stress, are possible signatures of such a progressive approach to criticality, with the applied stress as the control parameter. Considering the relevance of self-organized criticality for dislocation dynamics, one positive argument is that the statistical properties of the system appear stationary through time, with a constant power law exponent δ (see Figure 5). As noted by many authors [e.g., *Grasso and Sornette*, 1998; *Zapperi et al.*, 1997b], this is an essential ingredient for SOC identification. One can also notice that the γ exponent (equal to 1; see above) observed for the distribution of time intervals between successive events is equal to the mean field exponent for SOC derived by *Sornette and Sornette* [1989] for earthquakes dynamics, while the theoretical mean field exponent for energy distribution is 0.5 [*Vespignani and Zapperi*, 1998], a value slightly larger than the β exponent of ~ 0.3-0.35

observed for most of the present experiments. In terms of atomic-scale physical mechanisms, dislocations display instantaneous healing and reversibility, which favor the stationnarity condition for SOC. However, if the upper cutoffs on energy (or amplitude) distributions were confirmed (far from clear on the present experimental basis), they would contradict the completely scale-free behavior admitted to characterize SOC below the finite length of the system. Moreover, one could notice that in numerical models of microfracturing, constant stress (creep) boundary conditions are not compatible with SOC, whereas constant strain rate conditions could be [*Zapperi et al.*, 1997b].

Alternative mechanisms to strict critical processes, which display power laws and truncated power laws, exist. First, some types of first-order phase transitions were recently shown to exhibit power law distributions, provided that a given amount of disorder is introduced in the system [*Sethna et al.*, 1993]. One central property of first-order phase transitions is the presence of a macroscopic instability (discontinuity of the order parameter) at the transition point. This framework was thus proposed to describe the global breakdown of a system in fracturing phenomena [*Andersen et al.*, 1997; *Zapperi et al.*, 1997a]. However, dislocation-driven viscoplastic deformation during viscoplastic steady state behavior does not lead to a breakdown (or macroscopic instability) of the system. This lack of breakdown is a negative argument for a disordered first-order transition to drive the power law dynamics of dislocations. Second, the mechanism of sweeping of an instability also provides robust power laws [*Sornette*, 1994]. This corresponds to an ordinary phase transition (first or second order) in which the control parameter is swept toward the transition point. In the case of a second-order phase transition this model predicts apparent nontruncated power law distributions. This is not supported by the possible truncations observed on Figure 1. Moreover, if we identify the applied stress as the control parameter for dislocation dynamics (see previous discussion), our experimental creep conditions (i.e., constant applied stress) preclude the sweeping of this control parameter during a given loading phase. Third, multiplicative noise generates power law distributions by product of random variables [*Sornette and Cont*, 1997]. In the case of dislocation dynamics we are unable to properly identify the possible relevant variables for such a process.

Therefore a definitive identification of the critical process implied in dislocation dynamics during creep of materials cannot be proposed at this stage. This stresses the need for more experimental as well as theoretical work, in order to determine the very nature of critical dislocation dynamics, to compare it with the critical fracturing behavior of materials, and to explain the evolution of δ with increasing shear stress (Figure 6).

6. Conclusion

In 1983, as a conclusion of his review on collective dislocation motion, *Neuhauser* [1983] stressed that at that time, it was not yet possible to explain all the collective effects of dislocations and the associated global deformation dynamics from the basic principles of dislocation theory, e.g. the knowledge of the dynamics of a single dislocation. A decade later, *Kubin and Canova* [1992] pointed out that understanding how dislocation dynamics and interactions could lead to an heterogeneous, constantly evolving but "organized" distribution of dislocations was one of the most fundamental challenges in dislocation theory.

Here we reported experimental results of acoustic emission (AE) generated by dislocation motions during viscoplastic deformation in crystalline materials. The data were recorded during compression and torsion creep experiments on single crystals, bicrystal and polycrystals of ice Ih. AE statistics of power law type were systematically obtained under different loading conditions, arguing for criticality. The revisitation of dislocation dynamics as a critical phenomenon allows the rationalization of collective effects as well as the heterogeneity and the complexity of viscoplastic deformation of crystalline materials, especially in terms of predictability and strain localization.

Appendix: Contribution of the Recordable Plastic Instabilities to the Global Viscoplastic Deformation

Power law distributions, $N(A'>A) \sim A^{-\delta}$, of AE amplitudes have been observed above a detection threshold of $A_{th} \approx 3\times10^{-3}$ V, with δ centered around 0.6-0.7. The question is, What portion of the global viscoplastic deformation corresponds to the plastic instabilities detected by AE events above A_{th}?

First, we assume that the power law distribution of AE amplitudes holds below A_{th}, down to infinitely low amplitudes, without lower cutoff. Because A is a measure of the local strain associated with the plastic instability, one can estimate the relative portion of the global viscoplastic deformation related to amplitudes larger than A_{th} (the recordable part $\gamma_>$), and the portion related to amplitudes smaller than A_{th} (the nonrecordable part $\gamma_<$).

$$\gamma_< \sim \int_0^{A_{th}} N(A+dA>A'>A)\,A\,dA \qquad \text{(A1)}$$

$$\gamma_> \sim \int_{A_{th}}^{A_{max}} N(A+dA>A'>A)\,A\,dA, \qquad \text{(A2)}$$

where $N(A+dA>A'>A)$ is the number of AE events with amplitudes between A and $A+dA$. During our experiments, the maximum recorded amplitude A_{max} ranged between 0.7 and 10 V (see Figures 1-5). Because $N(A'>A)$ scales with $A^{-\delta}$, $N(A+dA>A'>A)$ scales with $\delta\times A^{-\delta-1}$. Therefore

$$\gamma_< \sim \int_0^{A_{th}} A^{-\delta}\,dA = \frac{1}{-\delta+1}\left(A^{-\delta+1}\right)_0^{A_{th}} \qquad \text{(A3)}$$

$$\gamma_> \sim \int_{A_{th}}^{A_{max}} A^{-\delta}\,dA = \frac{1}{-\delta+1}\left(A^{-\delta+1}\right)_{A_{th}}^{A_{max}} \qquad \text{(A4)}$$

For δ values < 1, as observed in most of the experiments (see Figure 6), $\gamma_<$ is finite, and the relative portion of recordable viscoplastic deformation is given by

$$R = \frac{\gamma_>}{\gamma_< + \gamma_>} = \frac{A_{max}^{-\delta+1} - A_{th}^{-\delta+1}}{A_{max}^{-\delta+1}}. \qquad \text{(A5)}$$

For typical values A_{max}=10 V, $A_{th}=3\times10^{-3}$ V, and δ=0.6, one finds R=96%.

For δ values > 1, a situation observed twice under low applied shear stress (Figure 6), $\gamma_<$ calculated from (A3) diverges. However, this results from the assumption of the absence of lower cutoff, which is physically wrong. Indeed, a lower cutoff for AE amplitude distribution exists, which would correspond to the most elementary step in the process of dislocation glide, i.e., the motion of a kink along a dislocation by one lattice spacing. In (2), this would be expressed by n=1 and L=b. Note, however, that this lower cutoff A_{min}, which also depends on the distance between the source and the transducer, d, cannot be quantitatively estimated (k and t_0 are unkown constants). For δ values < 1 a lower cutoff implies that (A5) gives a lower estimate of R. Relation (A5) could overestimate R only if the AE amplitude distribution decays faster below A_{th} than above, for instance, like a power law distribution with an exponent δ'>δ. However, such a distribution below the detection threshold has neither experimental nor physical basis and would contradict with the linear relationship observed between the rate of global AE activity $\dot{A}$ and the global strain rate [*Weiss and Grasso*, 1997].

In terms of dissipated energy the negligibility of the nonrecordable part is even more obvious. Because this energy scales with A^2 (see section 4), the energy dissipated by the nonrecordable part $E_<$ and the recordable part $E_>$ are given by (neglecting a lower cutoff):

$$E_< \sim \int_0^{A_{th}} N(A+dA>A'>A)A^2 dA \sim \int_0^{A_{th}} A^{-\delta+1} dA = \frac{1}{-\delta+2}\left(A^{-\delta+2}\right)_0^{A_{th}} \quad (A6)$$

$$E_> \sim \int_{A_{th}}^{A_{max}} N(A+dA>A'>A)A^2 dA \sim \int_{A_{th}}^{A_{max}} A^{-\delta+1} dA = \frac{1}{-\delta+2}\left(A^{-\delta+2}\right)_{A_{th}}^{A_{max}} . \quad (A7)$$

$E_<$ estimated in such a way (no lower cutoff) is finite for δ values < 2, i.e., for all the experiments of the present work, and for the typical values A_{max}=10 V, A_{th}=3×10^{-3} V, and δ=0.6 the recordable energy $E_>$ represents > 99.99% of the total dissipated energy. For the most unfavorable case (A_{max}=0.7 V; δ=1.2) a lower estimate is 98.7%.

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