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Microscale characterization of rupture nucleation unravels precursors to faulting in rocks

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Precursory signals, manifestations of microscale damage that precedes dynamic faulting, are key to earthquake forecasting and risk mitigation. Detections of precursors have primarily relied on measurements performed using sensors installed at some distance away from the rupture area in both field and laboratory experiments. Direct observations of continuous microscale damage accumulated during fault nucleation and propagation are scarce. Using an X-ray transparent triaxial deformation apparatus, we show the first quantitative high resolution three-dimensional (3D) information about damage evolution of rocks undergoing brittle failure. The dynamic microtomography images documented a spectrum of damage characteristics and different fault growth patterns. The interplay between various deformation mechanisms can result in either a positive, negative, or constant net volume change. Consequently, changes in rock density and acoustic wave velocities before faulting are expected to vary in different tectonics settings, hence making failure forecasting intrinsically dependent on rock type at depth.

1. Introduction

In the Earth's crust, faulting and fault rupture release a significant part of the elastic strain energy that accumulates due to tectonic loading, gravitational relaxation, and industrial activities such as underground fluid injection and extraction. The existence of precursory signals (Jones and Molnar, 1979; Ellsworth and Beroza, 1995; Bouchon et al., 2011; Kato et al., 2016) to such ruptures is a very old problem and it may provide the key to failure forecasting (de Arcangelis et al., 2016). Variations of geophysical or geochemical signals have been reported before major earthquakes (Ellsworth and Beroza, 1995; Bouchon et al., 2011), volcanic eruptions (Kato et al., 2015), and cliff collapses (Amitrano et al., 2005), however they are not ubiquitous and vary with geological settings (Bouchon et al., 2013). The occurrence of small seismic events weeks to hours before a major earthquake (Kato et al., 2016) has been interpreted in terms of small seismic or aseismic slips along the fault plane (Guglielmi et al., 2015). The distribution of microearthquake magnitudes in the foreshock area may also vary before an earthquake or a volcanic eruption with a change in Gutenberg–Richter frequency–magnitude b-value (Sugan et al., 2014) interpreted as related to high stress concentration, dilatancy in the fault zone, and propagation of fractures. Geochemical proxies, such as the concentration of radon gas in soils (Hauksson, 1981), and sulfate and chloride anions in spring waters (Tsunogai and Wakita, 1995; Toutain et al., 1997) have been observed to increase days before an earthquake (Wakita, 1996). These events are thought to be caused by the opening of cracks preceding dynamic faulting that provide paths for the migration of these chemical species towards the surface. Even when such precursory signals have been detected, their amplitude varies spatially, their existence is not ubiquitous, and the physical processes that enable migration from depth to the surface cannot be observed directly. Here, we present experimental evidence of the nucleation and propagation of such precursory deformations at the microscale. We show how small variations of porosity self-organize prior to a catastrophic failure and how their dynamics varies between different rock types, allowing the identification of different paths to fault initiation.

Small deformations preceding a large rupture are detected in both field and laboratory studies. Field observations are per-

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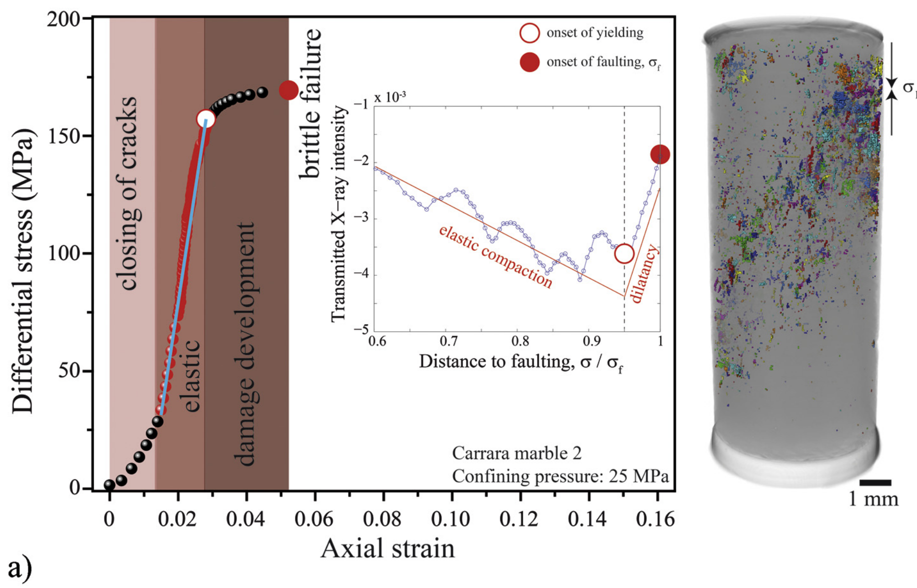

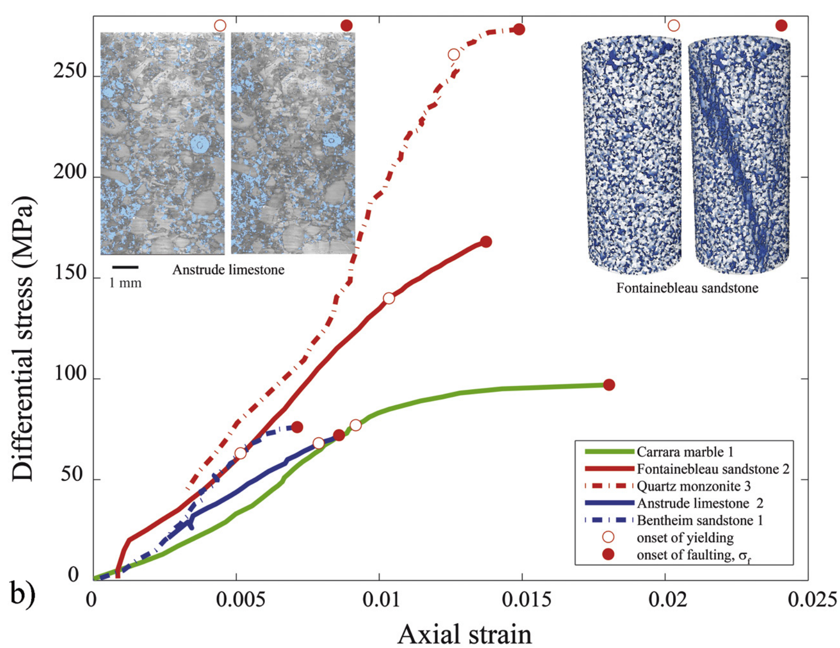

Fig. 1. Stress–strain relationships and damage development prior to faulting. a) Stress–strain curve for a Carrara marble sample deformed at 25 MPa confining pressure. For each differential stress increment a 3D volume was imaged. At low stress, some microfractures initially present in the sample closed. Then, as the axial stress was increased, the sample deformed elastically with a more-or-less linear relationship between strain and stress. At the yield point (empty circle), irreversible deformation occurred, and the curve became non-linear, until faulting occurred (solid circle). The inset shows the corresponding X-ray absorption signal, with an increase of intensity as damage (i.e. porosity) developed towards faulting. On the right hand side, the sample is viewed in 3D with all individual damage events at the onset of faulting. b) Stress–strain curves of representative rocks deformed until faulting. Insets shows 3D views of a Fontainebleau sandstone and 2D views in the middle of an Anstrude limestone at the onset of yielding and onset of faulting, respectively. Void spaces are shown in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

formed using seismometer and GPS networks located at the surface of the Earth, several kilometers away from the earthquakes hypocenters. In laboratory, acoustic emissions of damage prior to failure has been recorded and analyzed (Lockner et al., 1991; Zang et al., 2000; Schubnel et al., 2007; Benson et al., 2008). However, a limitation of acoustic emission damage characterization comes from the low spatial resolution of source location, particularly in heterogeneous rocks. To date, few direct in-situ 3D images of such damage processes have been obtained at the scale of whole rock samples, and most have been obtained under shallow depth stress conditions (Lenoir et al., 2007; Hall, 2013; Zhu et al., 2016).

Using a state-of-the-art triaxial deformation apparatus (Renard et al., 2016) that is transparent to the high flux of X-rays produced by a synchrotron, we studied the microscale damage evolution in rocks as they were driven towards brittle failure by increasing the differential stress at constant pressure confining pressure. Because the adsorption of X-rays depends on the local density of the solid, the evolution of microscale damage in the forms of microfracturing and pore-collapse during deformation can be monitored in 3D in centimeter-size core samples with a spatial resolution of 6.5 μm, as the differential stress is increased under stress conditions at depths of several kilometers (Fig. 1). The time-resolved 3D images document the interplay of a variety of deformation mechanisms and the