Crystal-Plastic Defect Dynamics of Calcite Single Crystals Revealed by Ultrasound Probes and Fast Camera

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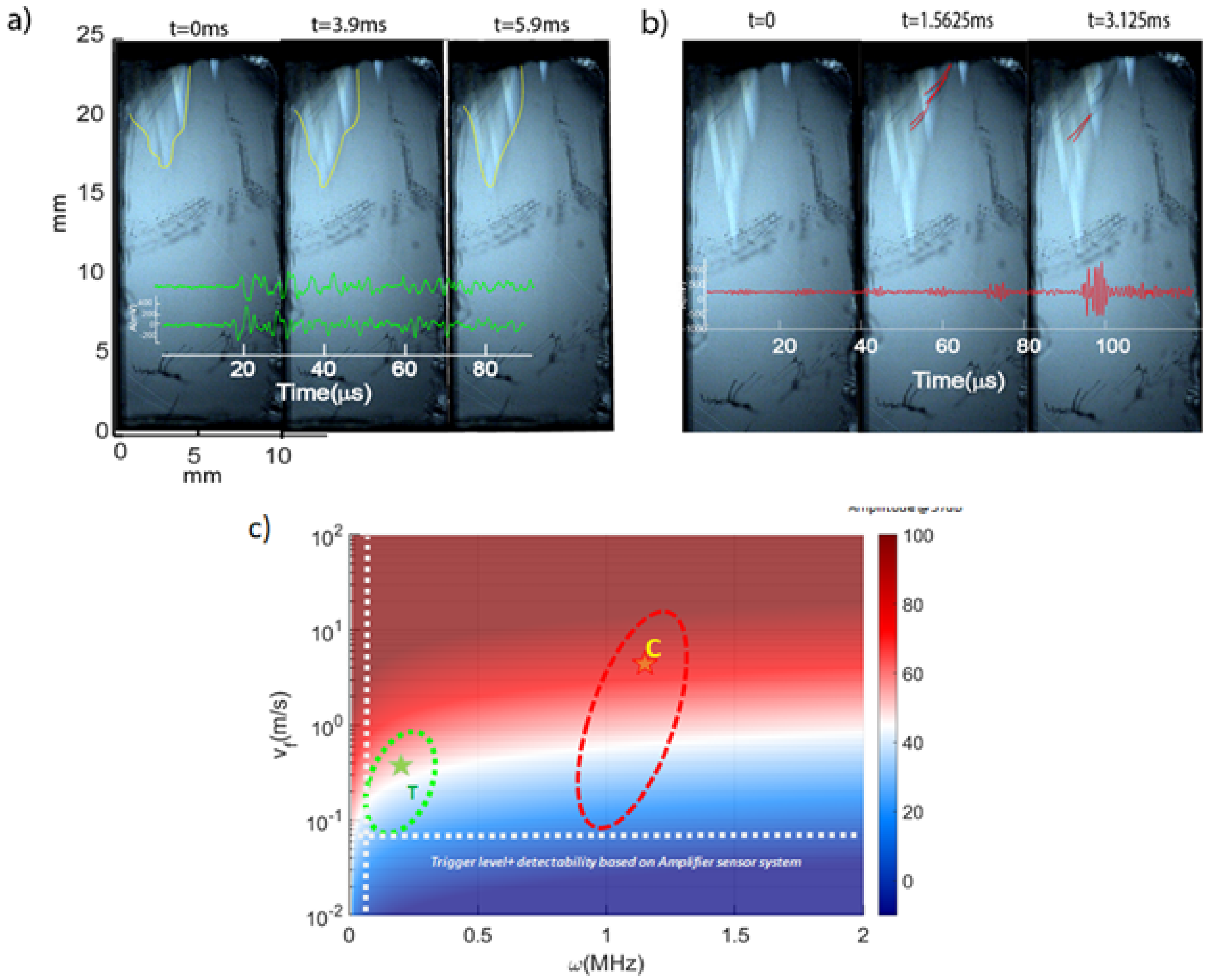
The rheology of Earth materials determines the partitioning of stress and strain, and thus acts as a first order control on solid Earth dynamics ranging from earthquakes to volcanic eruptions to landslides. Thus, understanding the rheology of materials, preferentially at a micro-scale to allow process-based upscaling, has broad applications across multiple Earth science disciplines. Cracks, dislocations and point defects are microscale agents of deformation that govern the macro-scale relaxation response of rocks and minerals under stress. Complexity in deformation behavior arises due to the interplay between these defect types. Here, we deformed calcite single crystals at room temperature and room pressure conditions under uniaxial loading. We study the defect dynamics using an array of piezo-sensors –recording in both triggered and continuous mode –synchronized with fast camera recordings. We show distinct emitted ultrasonic signals due to motion of twins versus cleavage cracks. The recorded signals from cleavage cracking show temporal avalanche-like patterns. Parallel, real-time imaging indicates that such temporal structure is related to river-like propagation of crack fronts as a typical signature of cleavage stepping in calcite. These avalanches of steps are usually observed in the form of monochromatic waves that carry frequencies as high as ~1 MHz. Ultrasonic signals emitted during mechanical twining form three main classes of signals: the first class includes signals with typical "Mexican hat" shaped wiggles correlated with moving twin fronts at average velocities 0.1-10 m/s; the second class of recorded signals are weak and often occur in thickening phase of twining –we detect these latter signals using continuous recording of ultrasonic waves as they are below detectability of classic recordings using triggered system. Lastly, a third class of signals corresponding to much slower evolution of twins (~1-20 mm/s) is well captured by high-speed camera. We interpret these signals to be driven by potential dislocation pile-ups behind the twin tip. These long-standing fronts endure for more than >100ms and are detected with quasiperiodic time scales of ~400 μs giving rise to signals with at least two dominant corner frequencies (>100kHz and ~2.5kHz). Overall, our results help illustrate key microscale processes leading to mineral deformation in calcite and helps towards building an experimentally based, but process driven rheological model. We also highlight the utility of using ultrasonic signals, with detailed time series methods, to help infer in-situ microscale deformation at a range of spatio-temporal scales.

Keywords: Brittle-Ductile transition , Calcite-Marble deformation , Ultrasonic probes , Dislocations-Twin-cracks


a)
t=0ms
t=3.9ms
t=5.9ms
25
20
15
10
5
0
mm
0
5
10
mm
20
40
60
80
Time(μs)
b)
t=0
t=1.5625ms
t=3.125ms
20
40
60
80
100
Time(μs)
c)
10^2
10^1
10^0
10^-1
10^-2
v_f(m/s)
C
T
Trigger level+ detectability based on Amplifier sensor system
0
0.5
1
1.5
2
ω(MHz)
100
80
60
40
20
0