Progressive Rock Failure: Observations, Mechanisms and Interpretations

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1. Deformation

Since all processes responsible for the deformation or rocks must necessarily be applied for some finite time before macroscopic failure ensues, it can be said that all rock failure is inherently progressive. This arises for several fundamental reasons. All rocks, whether sedimentary, metamorphic or igneous, are essentially aggregates. Sedimentary rocks comprise assemblages of grains with more or less intergranular cement, while metamorphic and igneous rocks comprise crystal assemblages of one or more mineral phases. Hence, while a uniform remote stress may be applied to the bulk rock, the local stress at grain contacts and mineral interfaces may be much higher. In this case, the most highly stressed contact will fail first, and the stress will be redistributed to the nearest neighbour contacts. Hence, failure of the bulk rock involves the sequential failure of many individual contacts. By far the most common type of experiment performed to measure rock deformation and failure is the short-term strength test, where rock samples are forced to failure by increasing the applied stress at a constant strain rate. Figure 1 illustrates this by showing the deformation of samples of Darley Dale sandstone under different effective confining pressures from 10 to 50 MPa (Heap et al., 2009). Note that cracking commences in these samples at around 50% of the peak (failure) stress. This is manifested in three ways; (1) the rollover of the stress-strain curve (Fig. 1(a)), the increase in sample porosity (Fig. 1(b)), and the commencement of acoustic emission (AE) output (Fig. 1(c)).

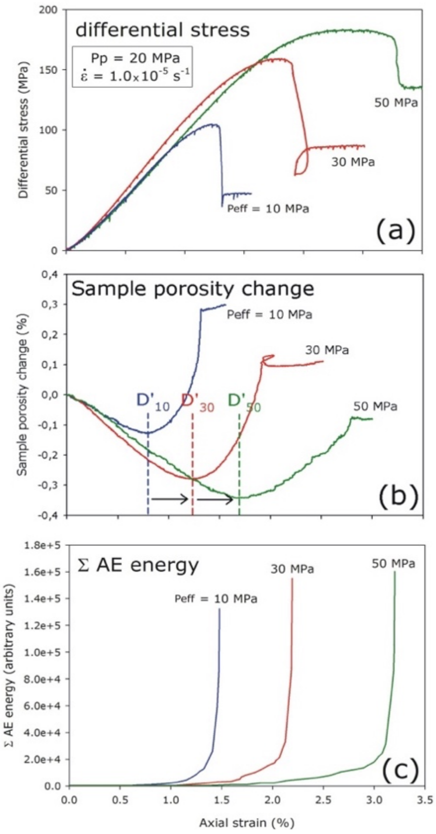

Figure 1. Triaxial deformation of Darley Dale sandstone at a constant strain rate of 10^{-5} s^{-1} and at effective pressures (P_{eff}) from 10 to 50 MPa; (a) stress-strain, (b) porosity change and (c) cumulative acoustic emission (AE) energy. From Heap et al. (2009).

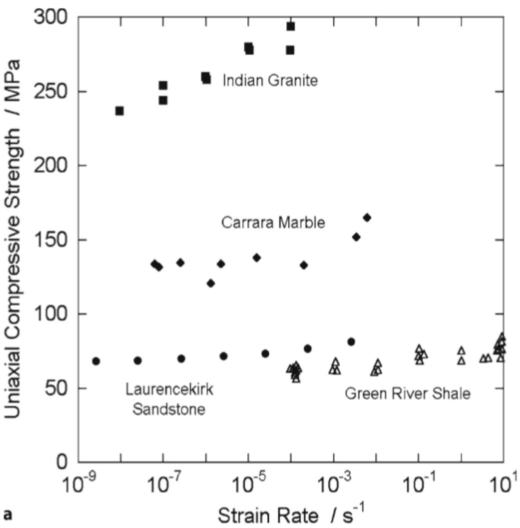

Figure 2. Variation in uniaxial compressive strength (UCS) as a function of strain rate for a range of different rocks. From Paterson & Wong (2005).

Furthermore, it is well-known that the strength of rocks is deformation rate dependent. Figure 2 shows how the uniaxial compressive strength (UCS) of a variety of rocks decreases with decreasing strain rate (Paterson & Wong, 2005). But what is the basis for this dependence? Lankford (1981) and Sano et al. (1981) studied the effect of strain-rate on UCS in limestone and granite, respectively, and found that the dependence follows a relationship where the UCS was proportional to the strain rate raised to the power of $1/(n^* +1)$; where n^* is an environment and material dependent constant. Both authors noted that the value of n^* was identical, within experimental accuracy, to the subcritical crack growth index (n) for the same rocks under the same environmental conditions.

Arguably, therefore, such constant strain rate tests are not the best way to study longer-term, environment-dependent progressive deformation and failure. An alternative approach is to apply a constant stress that is a high percentage of the short-term strength, and simply allow the rock to deform (strain) progressively over time until eventual failure; the so-called *creep* test. Figure 3 shows results from creep tests on four different crustal rocks, plotted as creep strain against time (Brantut et al., 2013). While the absolute numbers are very different for the different rocks, the general mode of deformation is the same; a phase of decelerating strain, an inflexion, and then a phase of accelerating strain to failure. Results from these two end-member approaches can be reconciled through the concept of subcritical crack growth, where the rate of crack propagation is controlled by *stress corrosion* reactions between strained atomic bonds at crack tips and a chemically active pore fluid.

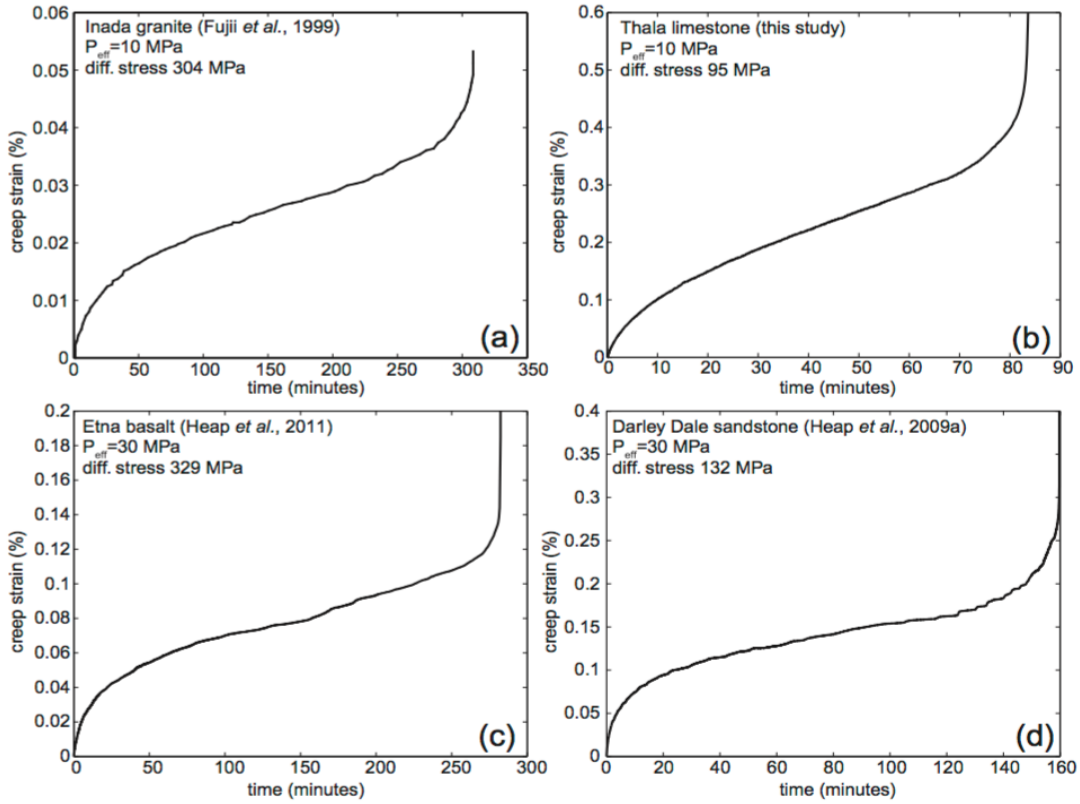

Figure 3. Plots of creep strain against time for a range of different rocks. Note different numerical values but same deformation style. From Brantut et al. (2013).

2. Recovery

Under the temperature and pressure conditions that prevail in the near-surface and the shallow crust, progressive healing and recovery processes can also occur, and these will proceed contemporaneously with fracturing processes. For example, there is now a large body of seismological evidence to show that the co-seismic drop in elastic wave speeds associated with fracture and slip during crustal earthquakes is at least partially recovered over time during the post-seismic phase (see Table 1 of Meyer et al. (2021) and references therein). Just like deformation processes, recovery processes can be purely mechanical or environmentally driven. Meyer et al. (2021) measured post-failure wave speed recovery across faults in laboratory samples of Carrara marble. They found that the wave speed recovered by around 10% in 2 days. Microstructural evidence showed that the recovery was entirely mechanical and driven by time-dependent reduction in crack apertures.

In contrast, Meredith (2013) measured strength recovery in pre-faulted samples of Westerly granite at 400°C and effective confining pressures from 100 to 160MPa over hold periods from 30 minutes to 100 days. His data are shown in Figure 4. For samples that were deformed dry, no strength recovery was observed over any hold period up to the maximum of approximately 40 days. However, significant strength recovery was measured in all water-saturated samples (with a hydrostatic pore pressure to confining pressure ratio of 0.4) where the hold period exceeded about 100 hours (4 days). The experiments were conducted in a closed system, so recovery was achieved chemically through sealing and healing of the fault by local dissolution and re-precipitation processes.

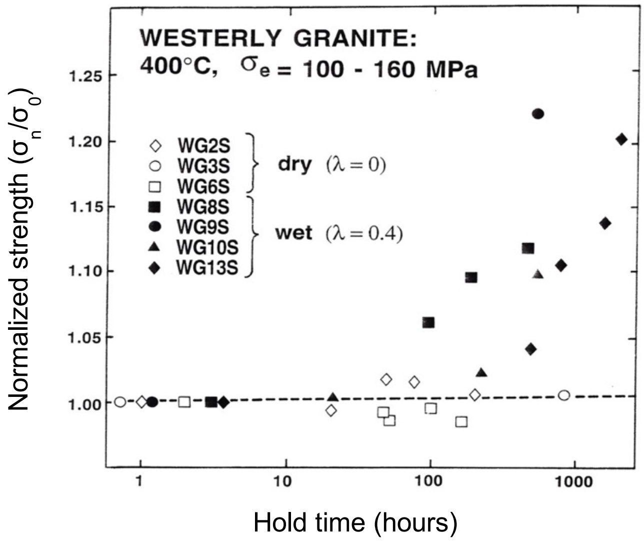

Figure 4. Strength recovery as a function of hydrostatic hold time from cyclic stressing of pre-faulted samples of Westerly granite. Open symbols indicate dry samples, and solid symbols indicate water-saturated samples. From Meredith (2013).

3. Concluding Remarks

In this presentation, we review observations of both progressive failure and progressive recovery, and discuss the possible mechanisms responsible for these processes. We conclude that the resulting time-dependent deformation of rocks under conditions pertaining to Earth's crust will be controlled by the juxtaposition and interplay between all these competing processes.

4. References

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