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Frictional Behaviour of Carbonates: Defining the Seismogenic Zone in Dolomite

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Motivation

Natural and induced earthquakes have been observed in carbonate formations across various tectonically active regions, often causing fatalities and severe economic losses. The frictional strength of faults can be influenced by factors such as pore fluid pressure build-up, frictional heating, lubrication effects, and chemical alterations, all of which depend on reservoir conditions and subsurface rock characteristics. Understanding the complex relationship between these factors and the frictional stability is crucial, as advancing our knowledge can mitigate earthquake damage and enable safer geothermal energy operations.

Objectives

- Investigate the deformation mechanisms operative in on a laboratory scale (mm to cm).
- Provide insights vital for understanding fault behaviour at regional scales (hundreds of m) and lithospheric scales (tens of km), assuming self-similar fault behaviour.
- Help using laboratory results to make seismic models more realistic, facilitating a shift from empirical to more physics-based approaches.

Approach

- Friction (evolution) experiments in the hydrothermal Rotary Shear Apparatus (RSA) on simulated dolomite gouge at temperatures ranging from RT – 600 ℃ and velocities ranging from 3 $^{nm}/_{s}$ - 300 $^{\mu m}/_{s}$.
- Analyses of velocity stepping test using the Rate and State Friction (RSF) law (Eq. 1).
- Microstructural and microchemical analyses to identify deformation mechanisms.

$$\tau = [\mu_0 + (a-b)\ln(^{v}/_{v_0})]\sigma$$
$$(a-b) = {}^{\Delta\mu}/_{\Delta\ln(v)}$$

Eq. 1. Steady state RSF law where τ is shear stress , σ effective normal stress, v slip velocity, v_0 reference velocity, μ_0 steady state friction and a and b are material properties.

Mechanical results

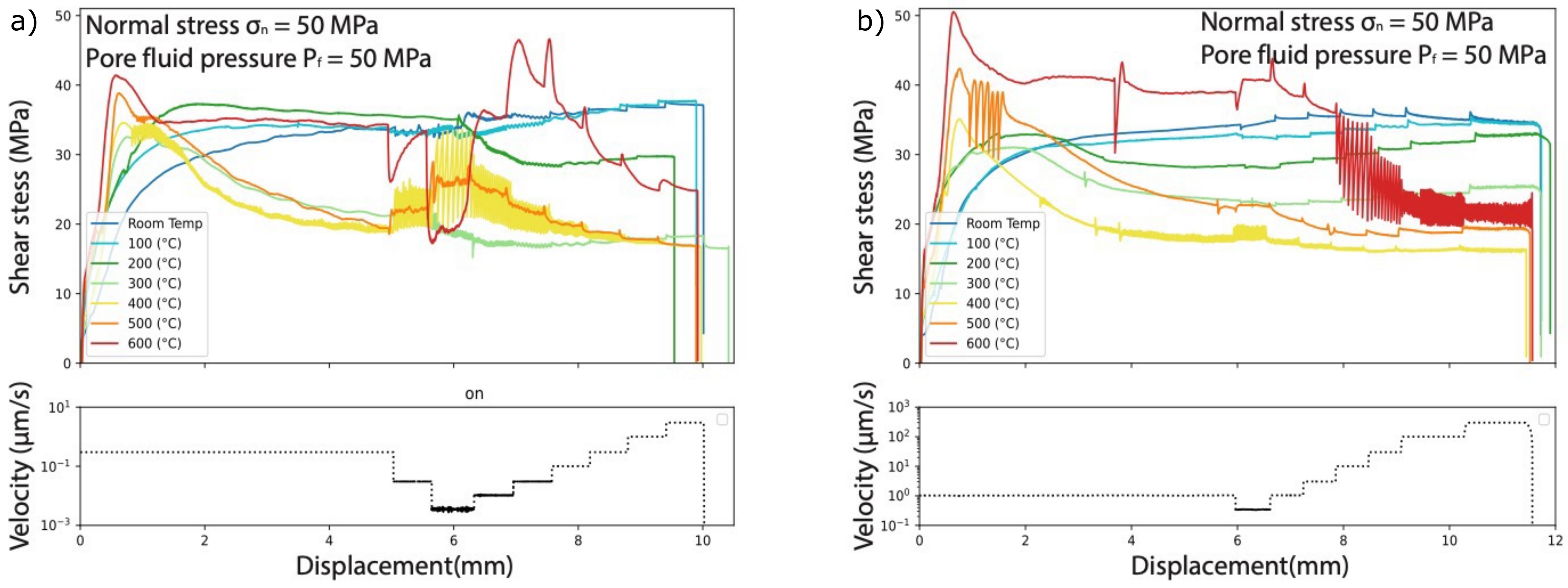

Fig. 1. Shear stress vs. displacement plots for dolomite gouge sheared at a) v = 0.003 – 3 $^{\mu m}/_{s}$ and b) 0.3 – 300 $^{\mu m}/_{s}$. All experiments were conducted at constant σ_n, P_f and T as indicated in the plots. RSF (a-b) values were only analysed for velocity upsteps.

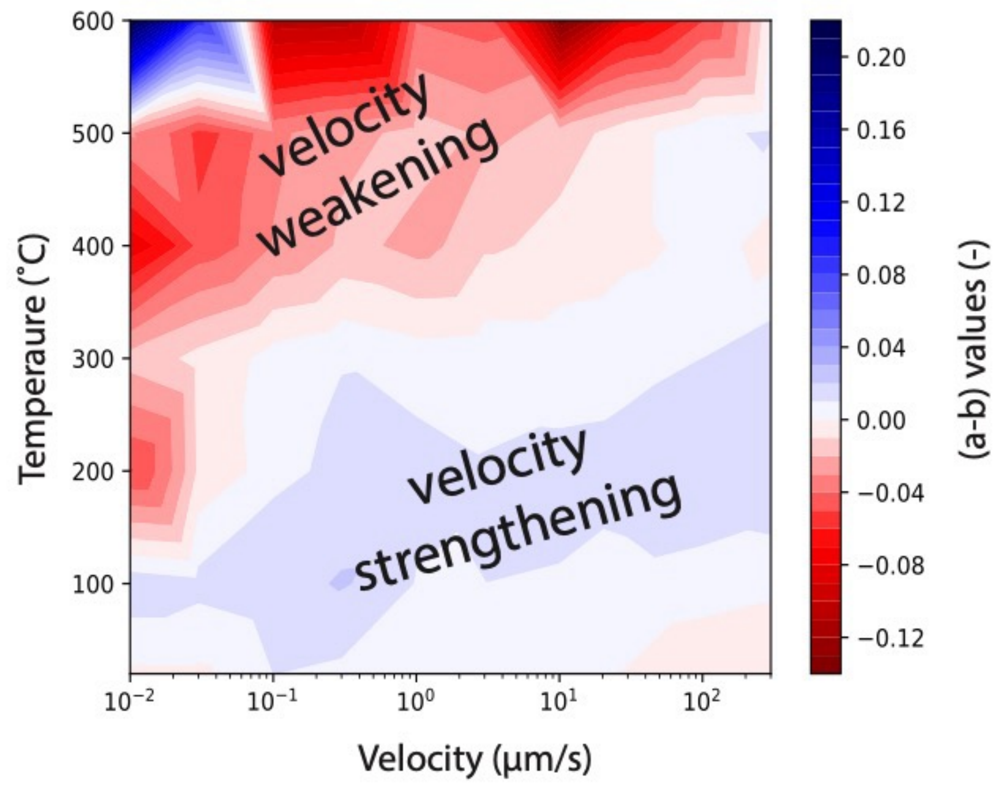

Fig. 2. Contour plot of (a-b) variations with temperature and velocity, where bluish colours represent stable and reddish colours unstable zones.

Microstructural observations

Observation made on experimental samples include scanning electron microscope (SEM): Back Scattered Electron (BSE) imaging, Energy Dispersive X-ray Spectroscopy (EDX) and Raman microscopy.

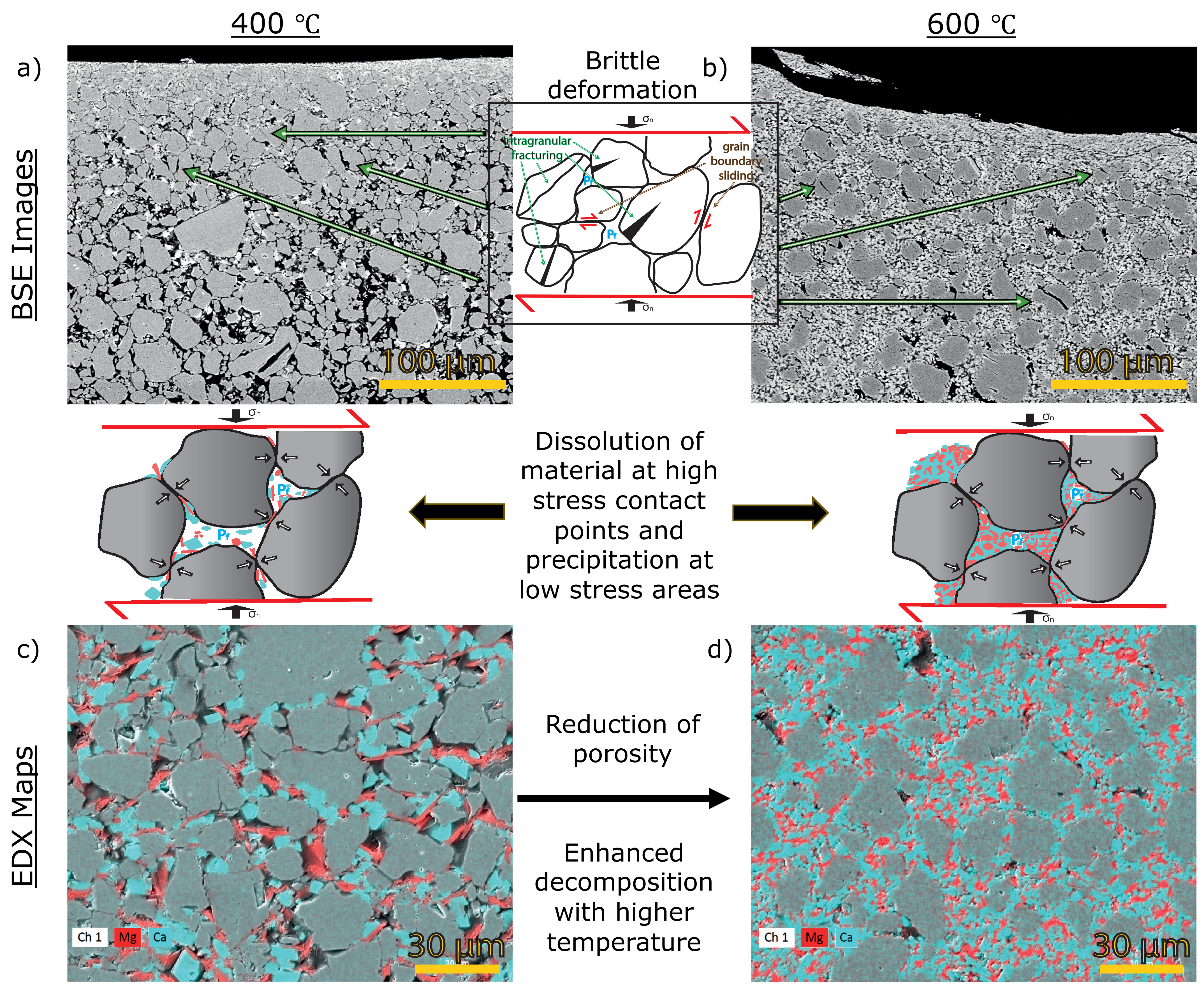

Fig. 3. BSE-SEM a), b) and EDX c), d) images of two post-experimental samples: dolomite gouge sheared at a), c) 400 ℃ and b), d) 600 ℃ at otherwise same conditions and velocity protocols. EDX images show the formation of fibrous Mg-rich mineral at grain boundaries at 400 ℃ which becomes more rounded at 600 ℃.

Raman microscopy

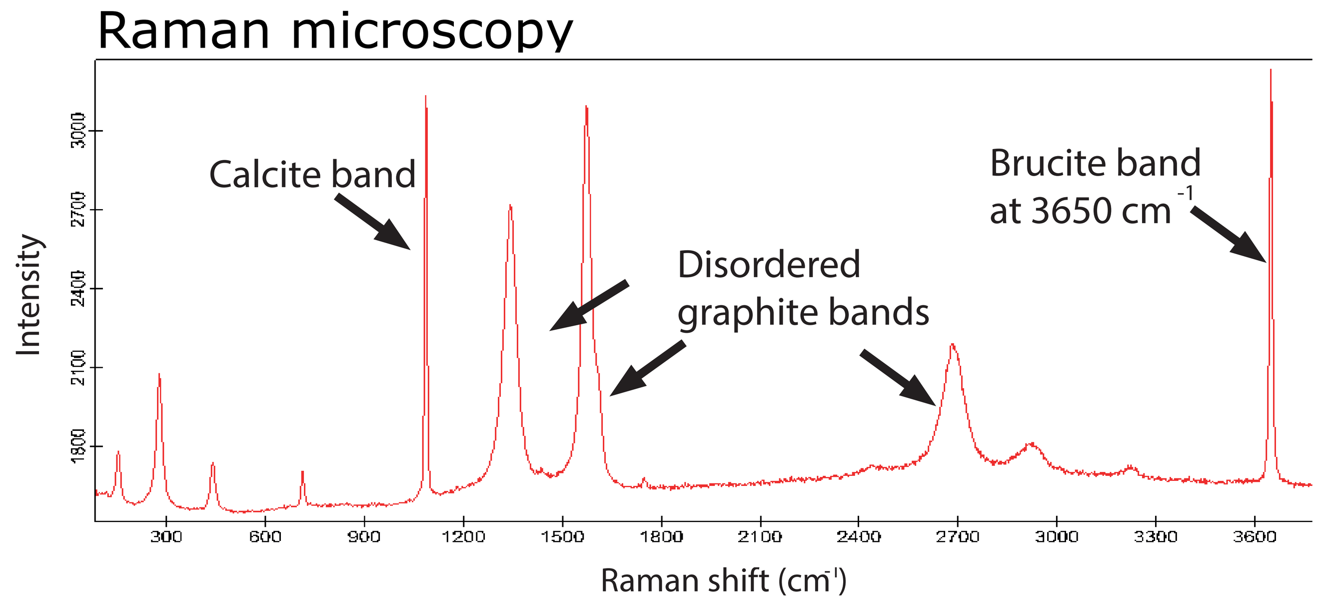

Fig. 4. Typical Raman spectrum for a pore space in samples that showed separation of Magnesium and Calcium in EDX measurement.

Decarbonization of dolomite:

$$CaMg(CO_3)_2 \rightarrow CaCO_3 + MgO + CO_2$$

Reaction of periclase with water:

$$MgO + H_2O \rightarrow Mg(OH)_2$$

Main findings

- The investigated temperatures and velocities show a mostly velocity-strengthening zone at temperatures relevant in geothermal reservoirs (RT – 200 ℃) which transitions to a velocity-weakening zone at higher temperatures (200 – 300 ℃) and low velocities (< 0.1 $^{\mu m}/_{s}$) to a mostly velocity weakening zone at T > 300 ℃. Implying that it is unlikely for earthquakes to nucleate in dolomite reservoirs.
- All investigated samples showed signs of brittle deformation; samples sheared at T > 300 ℃ also showed ductile pressure solution creep.
- Displacement weakening at higher T can be associated with decomposition of dolomite to rel. weak brucite and rel. strong calcite.

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