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Formation of Nanocrystalline and Amorphous Materials Causes Parallel Brittle-Viscous Flow of Crustal Rocks: Experiments on Quartz-Feldspar Aggregates

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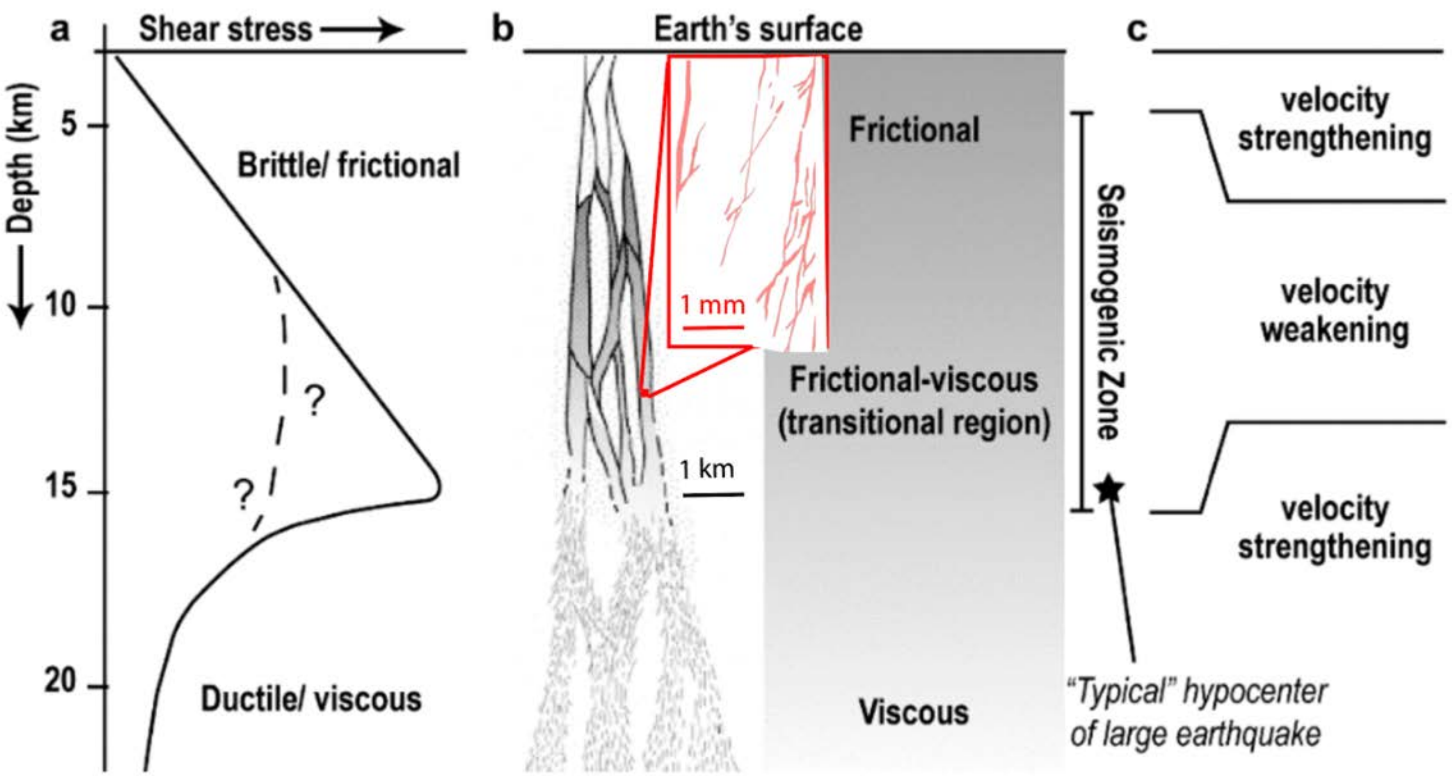
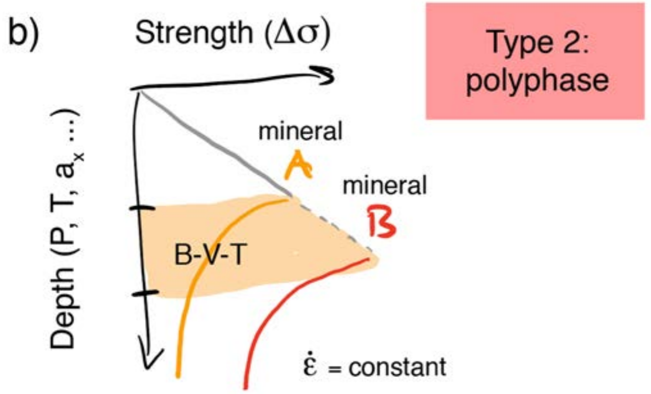
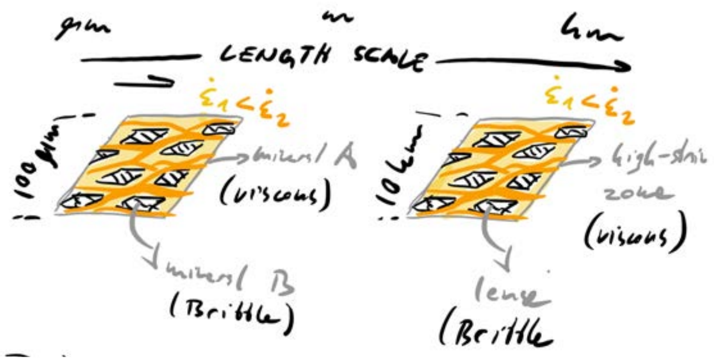
Brittle – Viscous Transition



Sibson-Sholz-model *(modified after Verberne et al. 2020)*

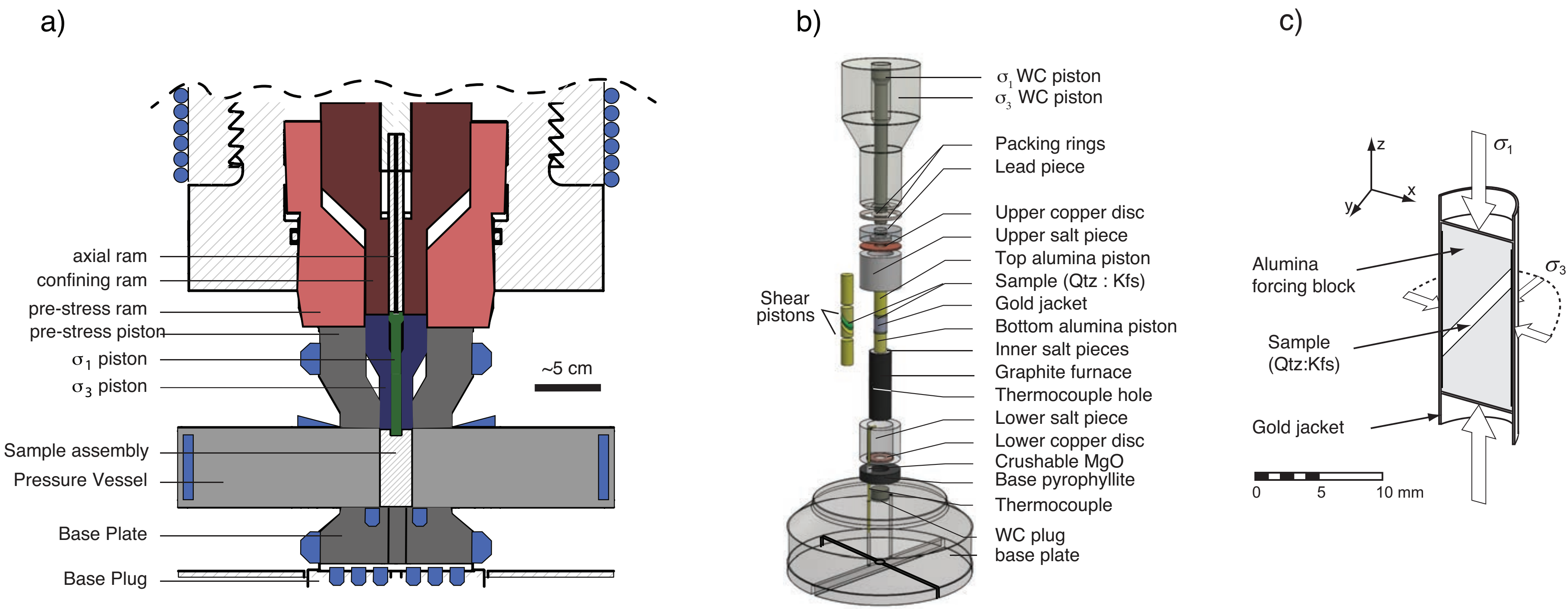
- Sequential & Parallel B-V-T





Experimental set-up & methodology

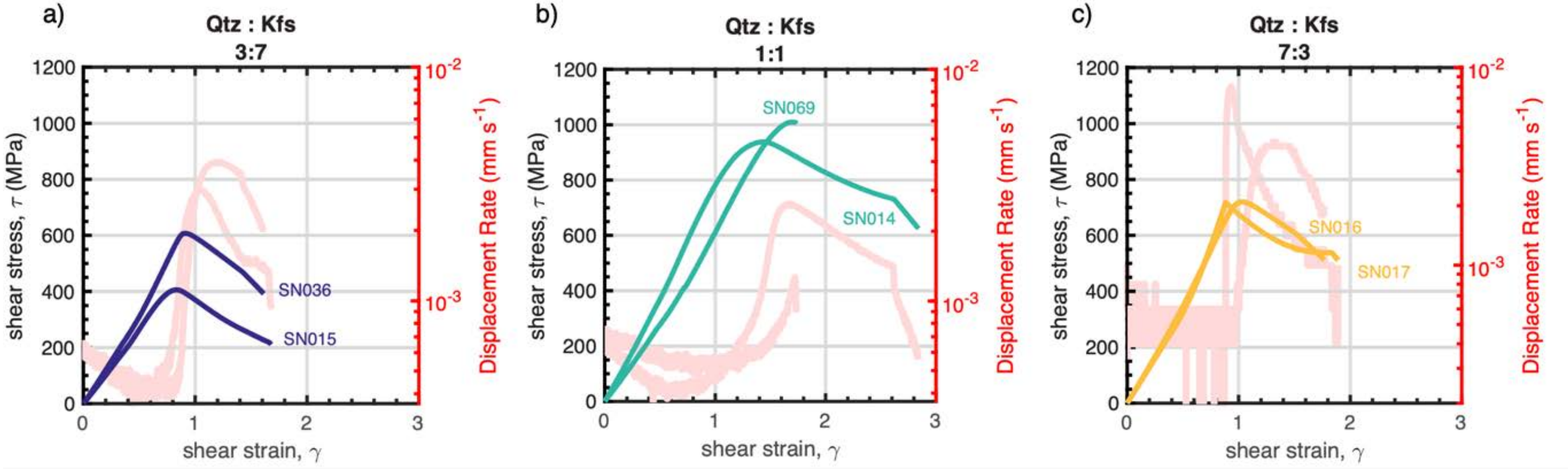
- **Pc** ≈ 800 MPa, **T** = 750˚C
- **Qtz : Kfs** powders + 0.1 wt% H_2O
    - hot-pressed for ≈ 20 h
    - 10-20 μm starting grain size
    - 3:7, 1:1 and 7:3 ratios
- **Constant load** and **constant displacement rate** boundary conditions

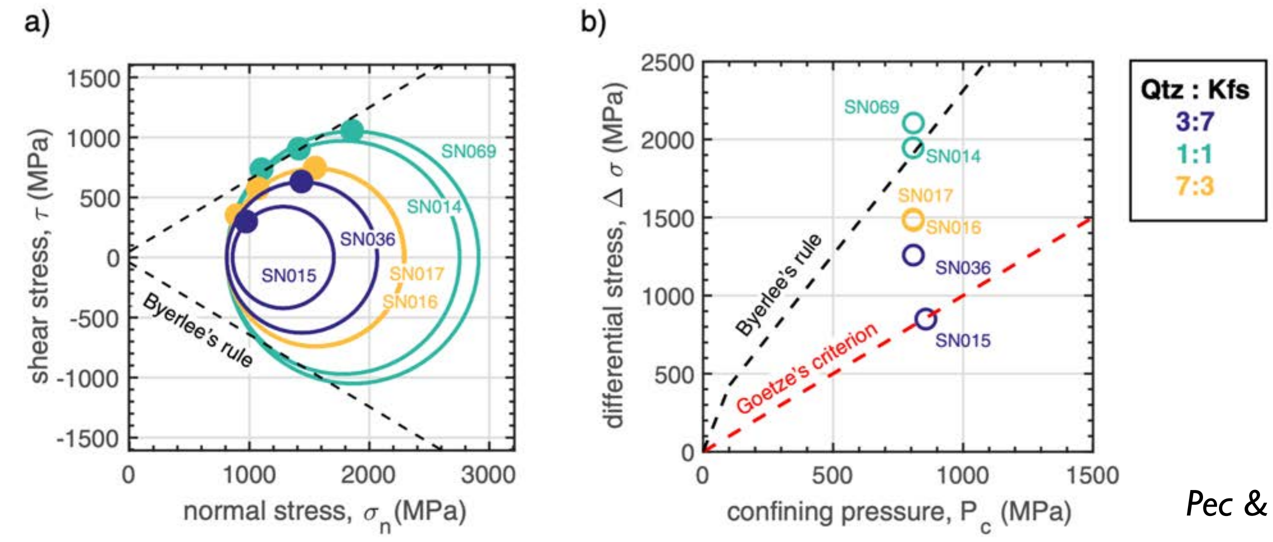


Ghaffari and Pec 2020, Review of Sci. Inst.

Précigout et al. 2018

Mechanical Data: ~ constant displacement rate

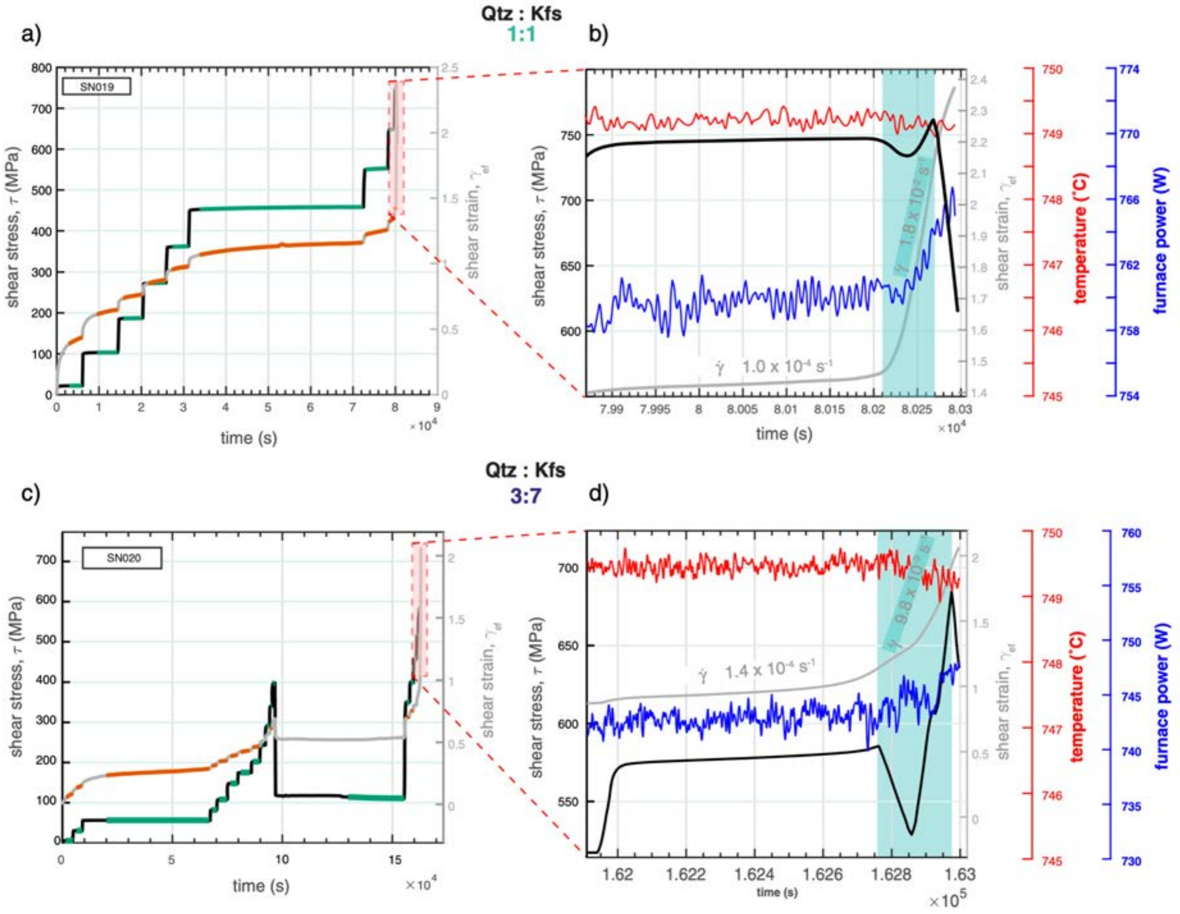


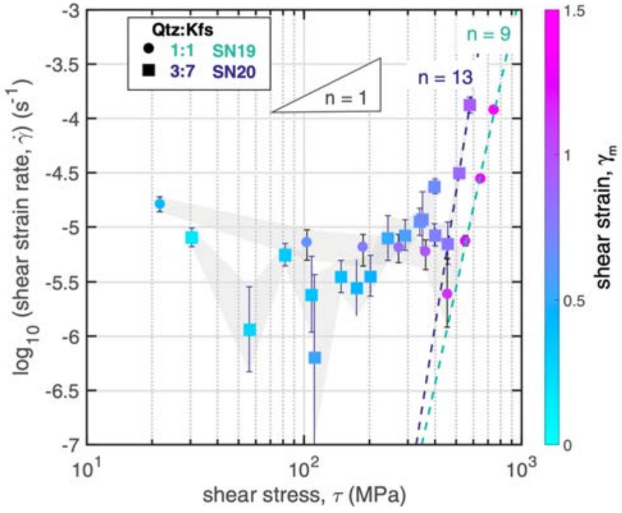


Pec & Al Nasser 2021, JGR

- Strength depends on composition in non-trivial manner (**1:1 mixtures the strongest**)
- Weakening is accompanied by a **transient increase** in displacement rate
- Peak strength between Byerlee's rule and Goetze's criterion as expected for **semi-brittle flow**

Mechanical Data: constant load

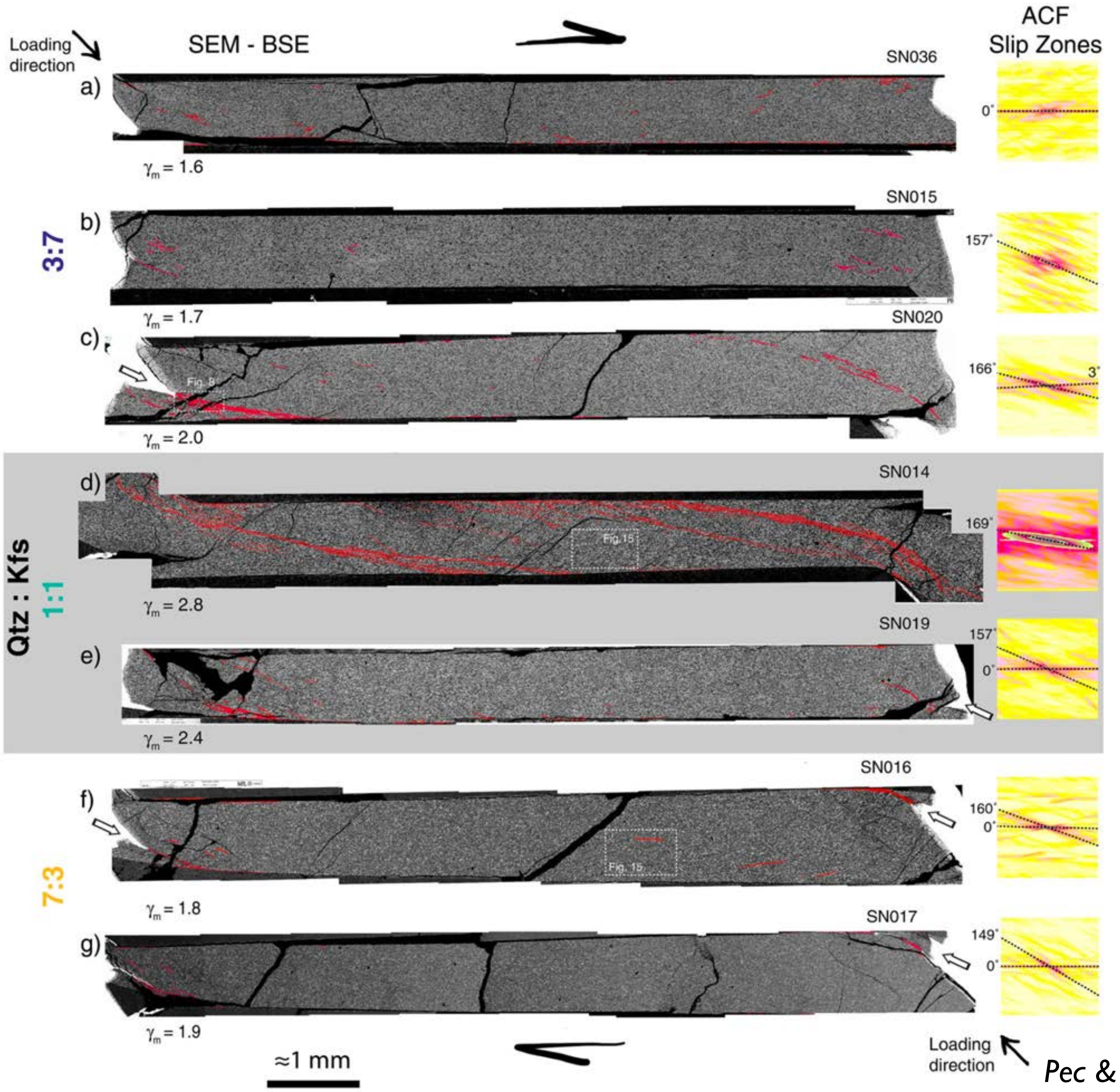


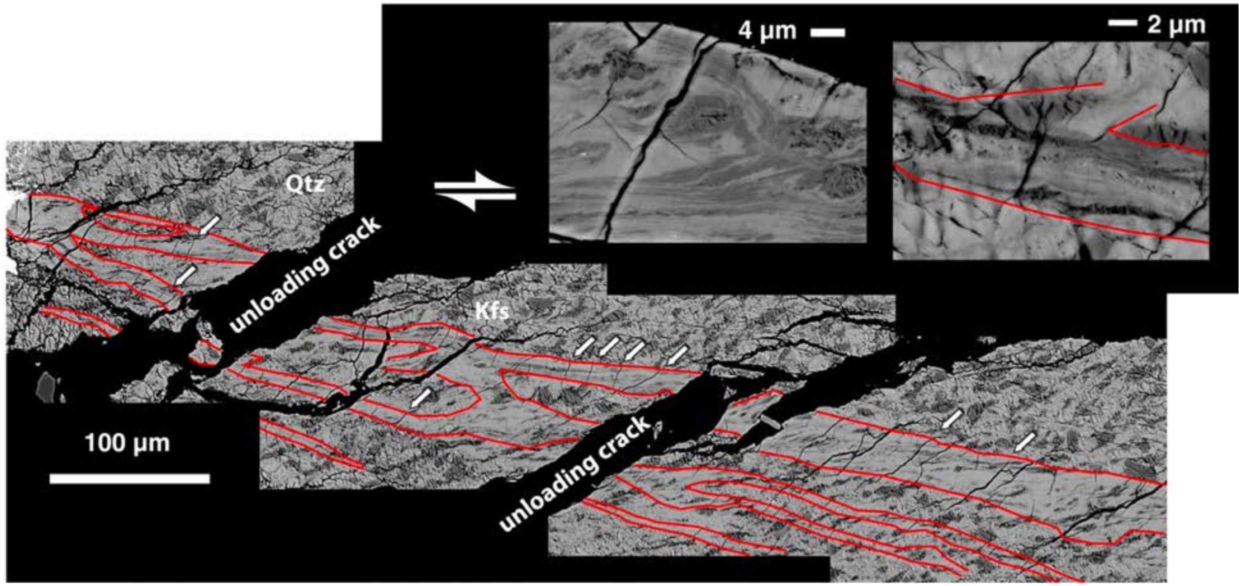


- Low stress sensitivity at low stresses and strain followed by high stress sensitivity (n = 9 – 19 assuming $\dot{\gamma} \propto \tau^n$) at τ >400 MPa & γ > 1
- Failure occurs by abrupt acceleration at constant stress and is **not accompanied** by measurable **thermal anomalies**

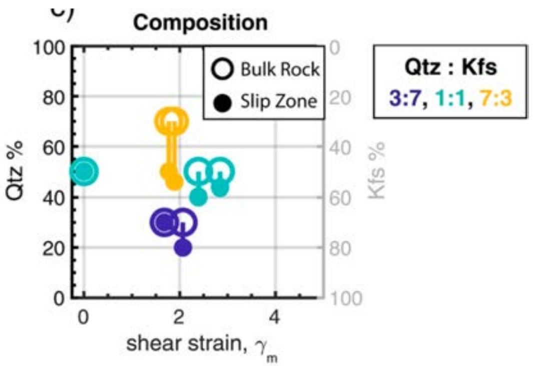
Pec & Al Nasser 2021, JGR

Microstructures



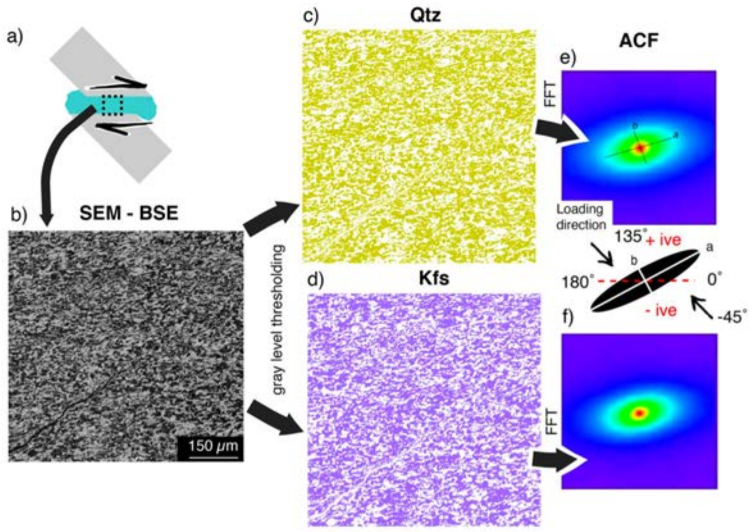


- Strain localizes into **slip zones** (red) in all experiments irrespective of mineral ratio.
- Slip zone material shows **flow features** and no discernible porosity at highest magnifications in FE-SEM.
- Slip zones **depleted in Qtz**

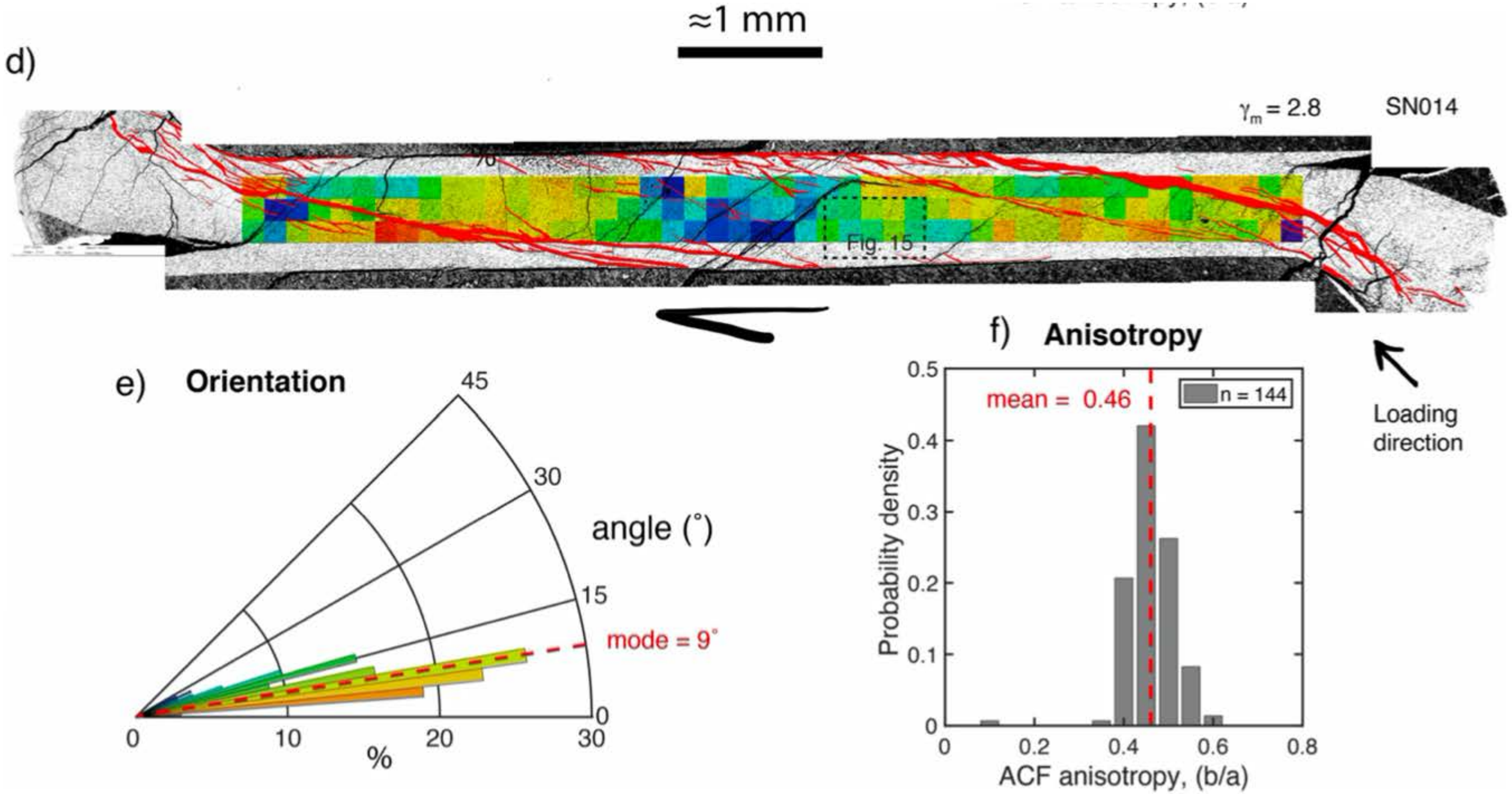


Pec & Al Nasser 2021, JGR

Microstructures



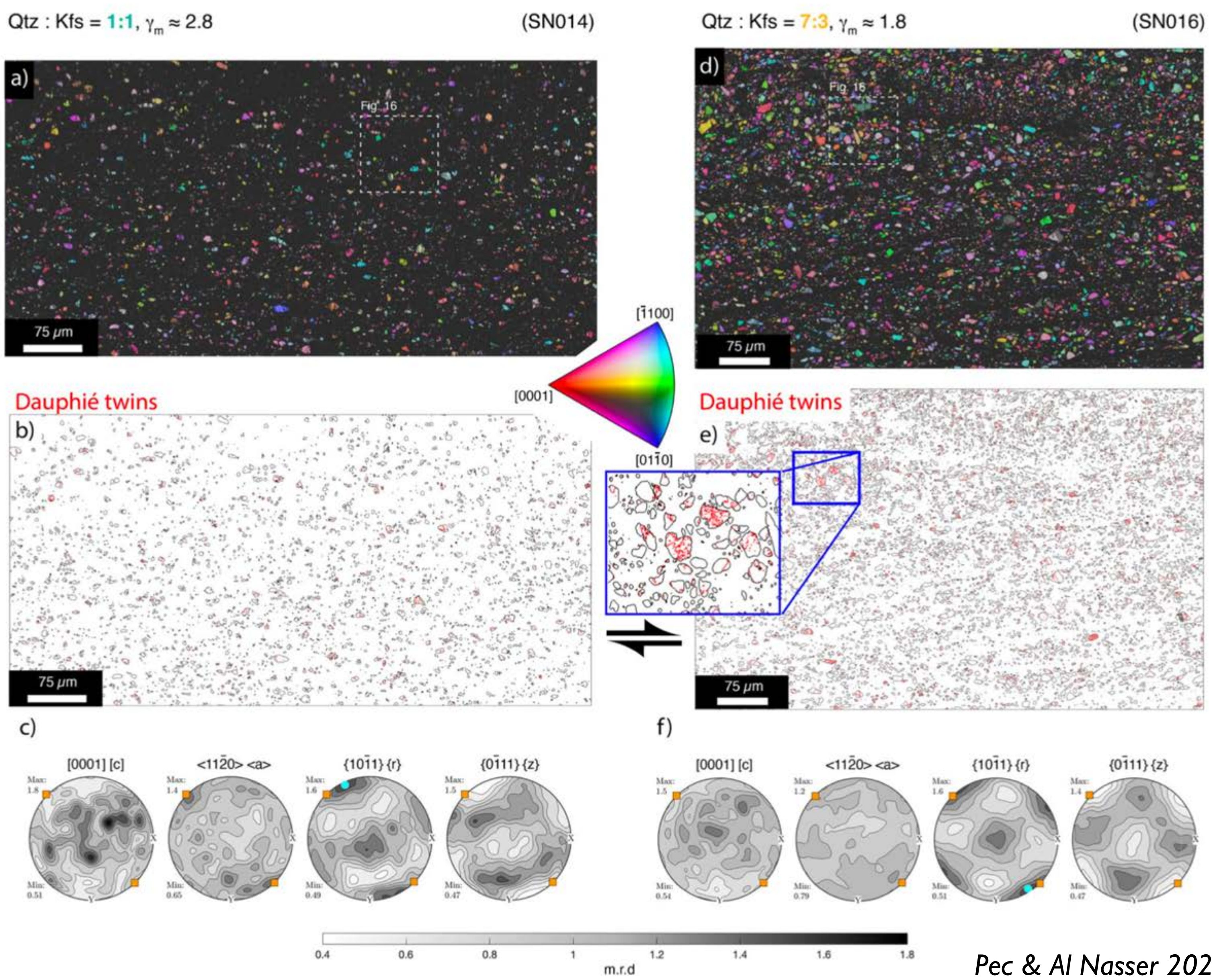
Pec & Al Nasser 2021, JGR

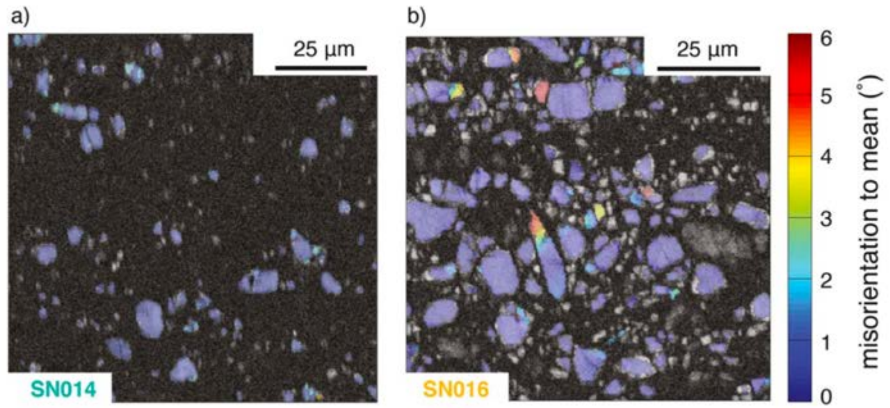


- Work-flow

- Samples develop **weak foliation** indicating that both slip zones as well as the coarser grained material are straining.

EBSD



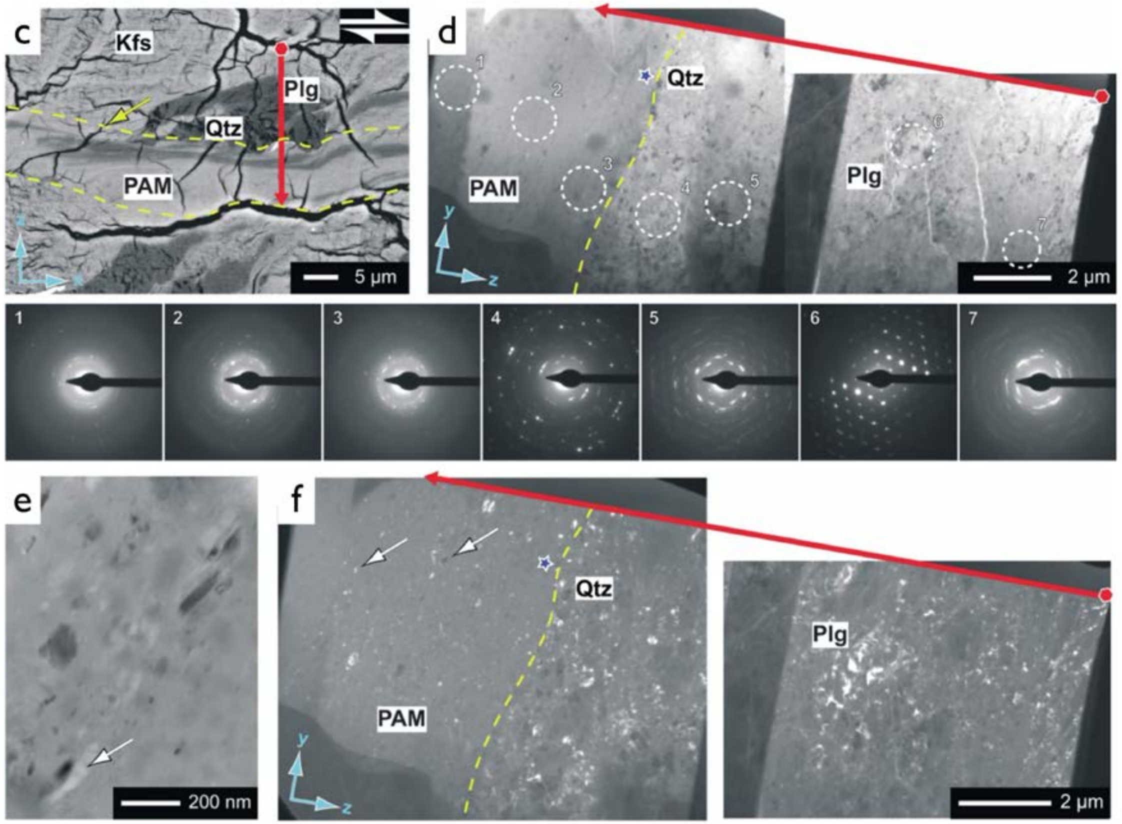


- Abundant **Dauphiné twinning** (no strain accommodated though)
- **{r} maxima** & **{z} minima** align with local σ_1 orientation (Tullis 1970)
- Little intracrystalline deformation suggesting no significant dislocation activity

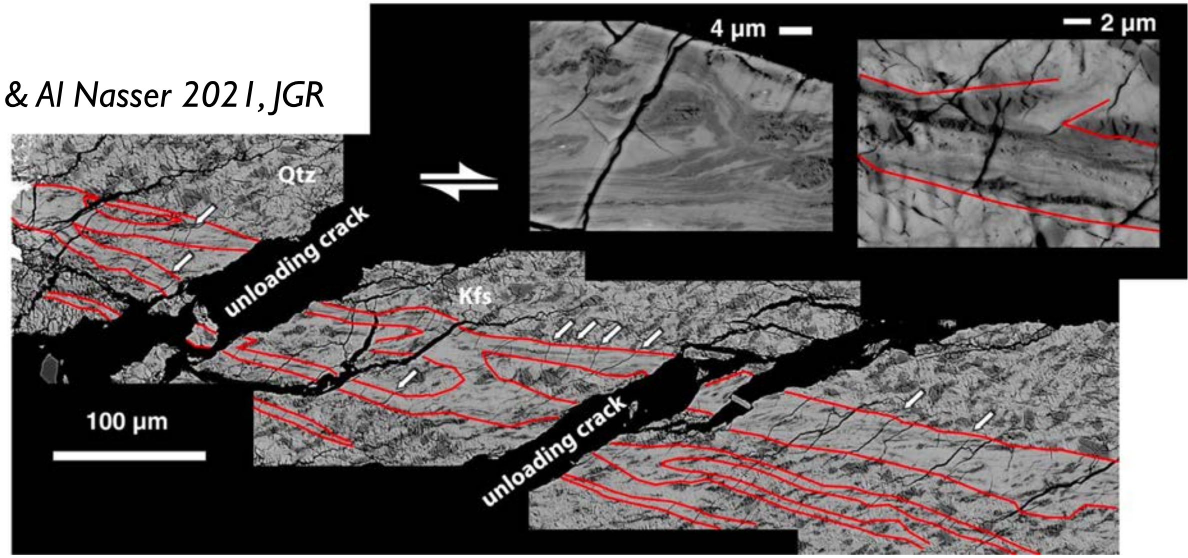
Pec & Al Nasser 2021, JGR

Nano-crystalline to amorphous material in slip zones = viscous element

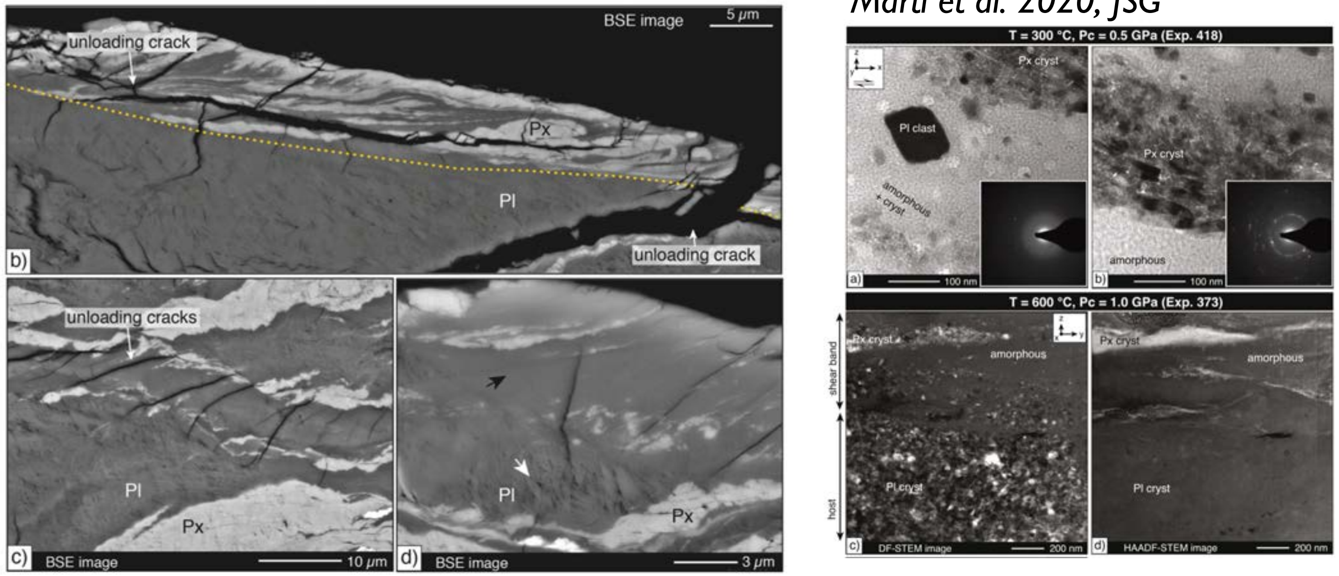
Pec et al. 2016, JGR



Pec & Al Nasser 2021, JGR

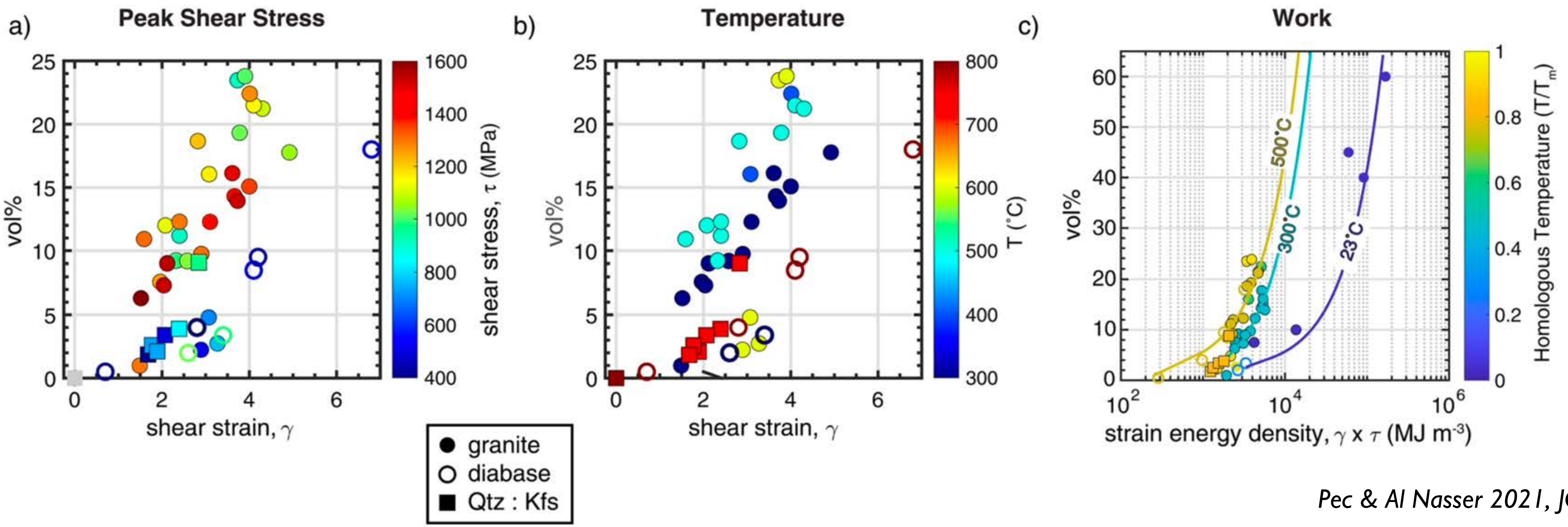


Marti et al. 2020, JSG



- Feldspars are prone to **extreme grain size reduction** to nm-sizes & **amorphization** under a broad range of conditions

Nano-crystalline to amorphous material

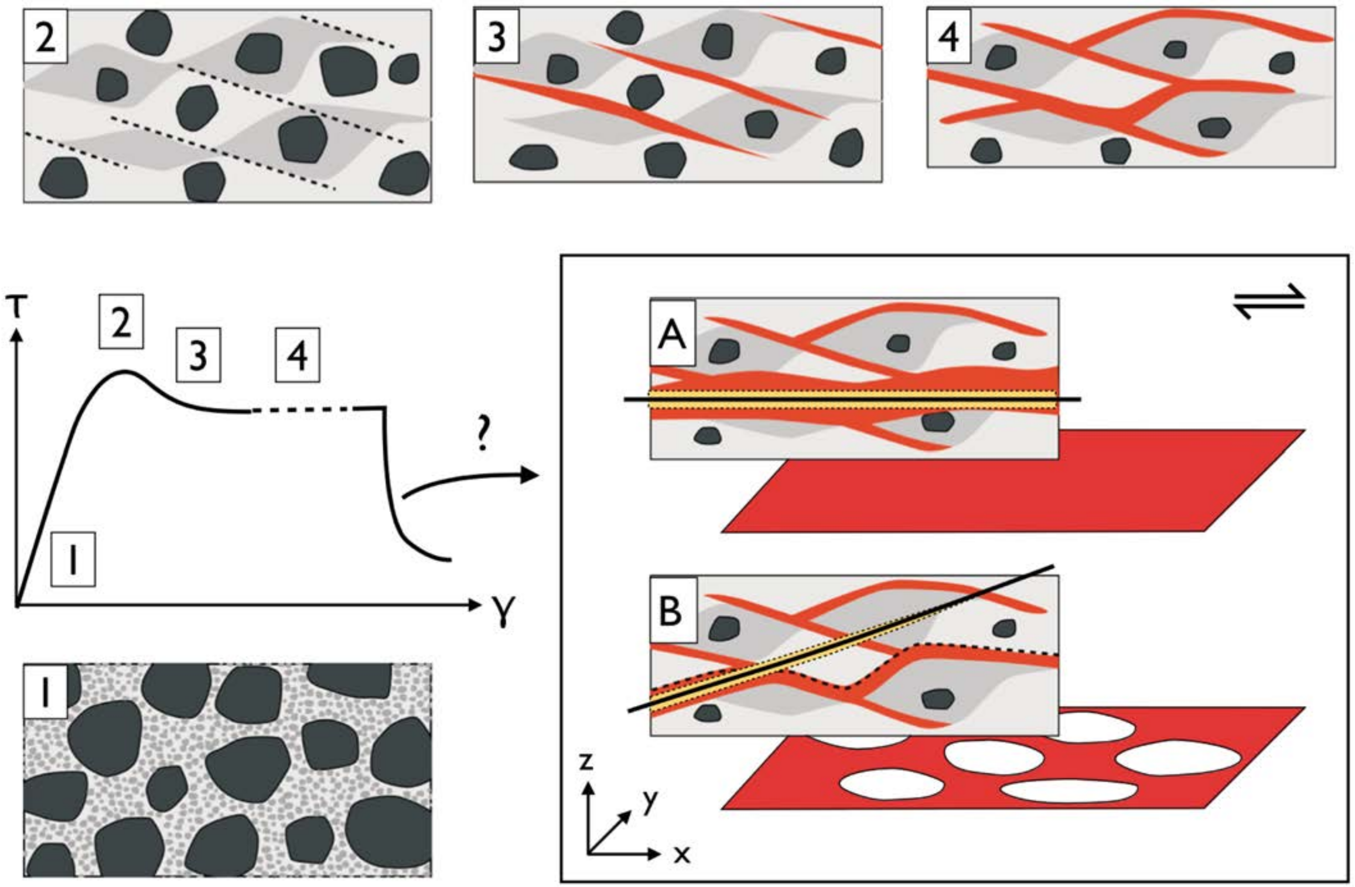


Pec & Al Nasser 2021, JGR

- Amount of nano-crystalline to amorphous material **increases** with **increasing homologous T (T/Tm)** and work input per unit volume.
- Occurs both at **HP-HT** as well as **LP-LT** conditions

Conclusions

- The main deformation mechanisms by volume are **cataclasitic flow** and Dauphine twinning. Most strain, however, is accommodated in **localized slip zones formed of nano-crystalline to amorphous material**
- The PAM forms due to c**omminution and grain size reduction** down to the nanometer scale. **Mechanical-wear-induced amorphization** and/or **pressure-induced amorphization** are the likely physical process leading to the microstructural transformation from crystalline solid to a nanocrystalline to amorphous fluid-like material.
- Nanocrystalline to amorphous materials form in a number of lithologies and under a broad range of conditions in experiments. Their abundance is controlled to the first order by the **input of mechanical work per volume and homologous temperature.**
- The inferred deformation mechanism accommodating strain in the slip zones is a combination of **diffusion creep and viscous flow**. Nanocrystalline to amorphous materials introduce a viscous element into the behavior of fault rocks and **stabilize fault slip** under the studied conditions.
- Weakening occurs once the nanocrystalline material percolates through the sample. **The abundance and geometry of the nanocrystalline to amorphous material controls sample strength.**
- Both **cataclastic faulting** and **viscous flow** in slip zones have to **operate in parallel** to accommodate the imposed strain. This semibrittle flow of polymineralic rocks can be modeled by a frictional-viscous rheology where a frictional slider is coupled in parallel with a (possibly nonlinear) viscous element.



Pec et al. 2016, JGR

References

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Solid Earth

RESEARCH ARTICLE

10.1002/2015JB012513

Semi-brittle flow of granitoid fault rocks in experiments

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Key Points:
- Samples reach a high steady state flow stress which is temperature, normal stress and rate dependent
- Deformation partitions into anastomozing layers containing nanocrystaline and amorphous material
- Nanocrystalline/amorphous slip zones could trigger earthquakes after long periods of slow creep

Abstract Field studies and seismic data show that semi-brittle flow of fault rocks probably is the dominant deformation mechanism at the base of the seismogenic zone at the so-called frictional-viscous transition. To understand the physical and chemical processes accommodating semi-brittle flow, we have performed an experimental study on synthetic granitoid fault rocks exploring a broad parameter space (temperature, $T = 300$, 400, 500, and 600°C, confining pressure, $P_c \approx 300$, 500, 1000, and 1500 MPa, shear strain rate, $\dot{\gamma} \approx 10^{-3}$, 10^{-4},

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RESEARCH ARTICLE

10.1029/2020JB021262

Formation of Nanocrystalline and Amorphous Materials Causes Parallel Brittle-Viscous Flow of Crustal Rocks: Experiments on Quartz-Feldspar Aggregates

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Key Points:
- Strain localizes into viscous slip zones that delimit coarser-grained, cataclastic lenses
- Viscous flow is enabled by a microstructural transformation from microcrystalline to nanocrystalline, partly amorphous material in the slip zones
- Both viscous and brittle processes have to operate in parallel to accommodate deformation

Abstract The brittle-viscous transition in the lithosphere occurs in a region where many large earthquakes nucleate. To study this transition, we sheared bimineralic aggregates with varying ratio of quartz and potassium feldspar. We deformed the samples in a solid-medium deformation apparatus at temperature, $T = 750$°C and pressure, $P_c = 800$ MPa under either constant displacement rate or constant

Review of Scientific Instruments | ARTICLE | scitation.org/journal/rsi

An ultrasound probe array for a high-pressure, high-temperature solid medium deformation apparatus

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ABSTRACT

Inelastic deformation of minerals and rocks is associated with activation of various defects such as fractures, twins, and dislocations. Active and passive ultrasound probes are potential tools to examine the nature of these defects under a broad range of pressure and temperature conditions. Here, we report on the development of an ultrasound probe array that allows us to monitor deforming samples in a high-pressure,