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Evolution of brittle structures in plagioclase-rich rocks at high-grade metamorphic conditions – Linking laboratory results to field observations

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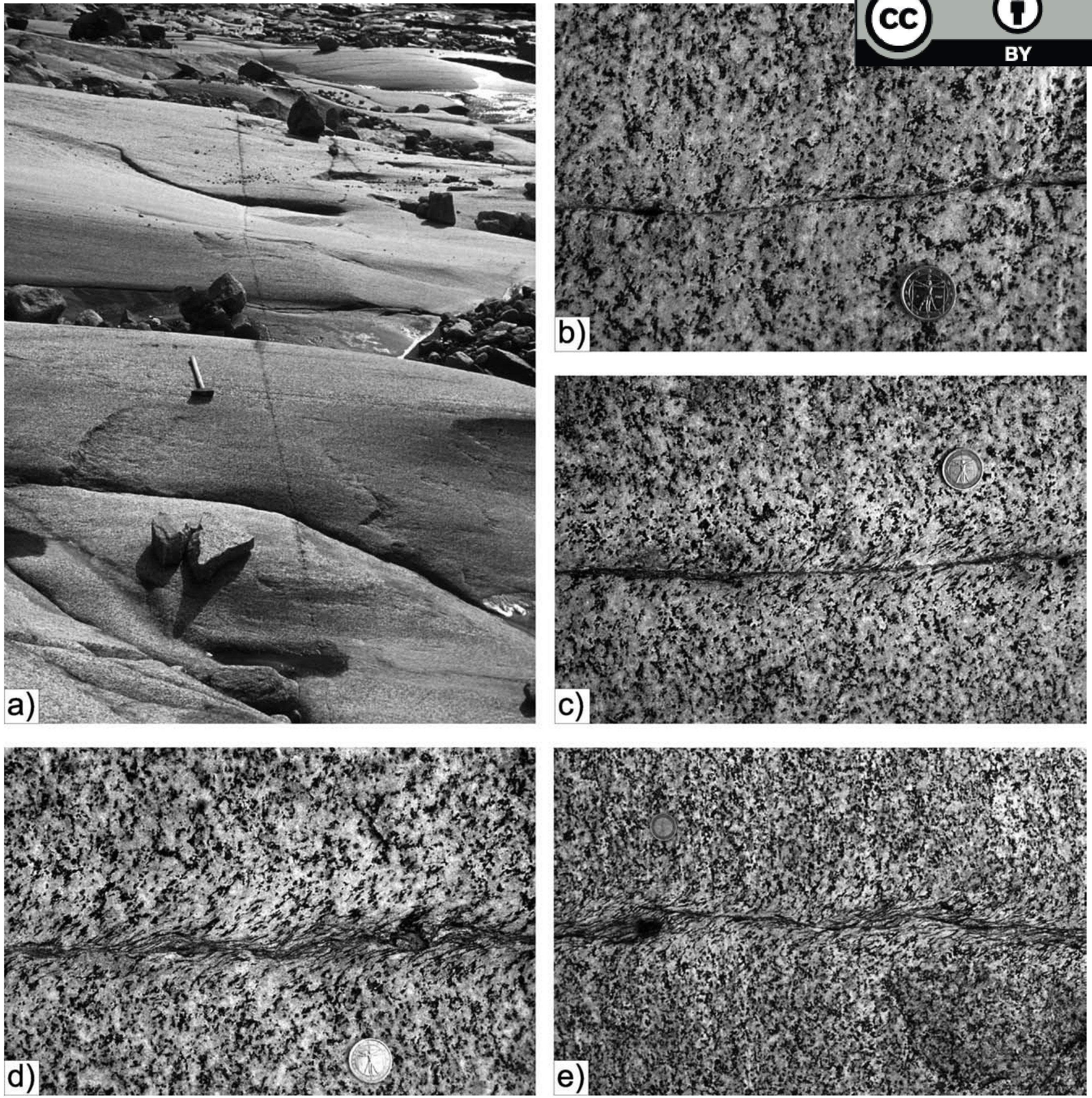
Motivation

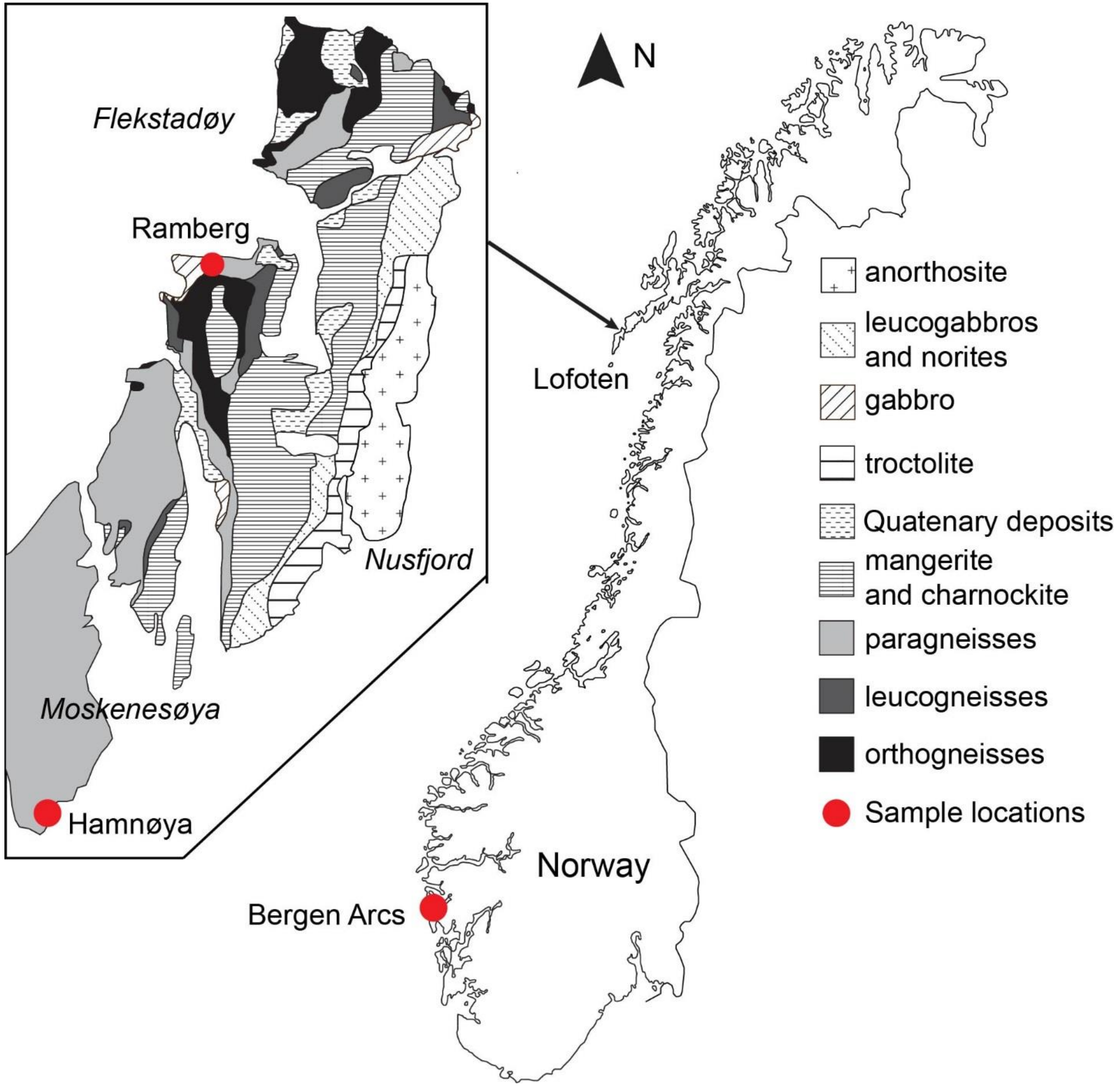
Worldwide we find exhumed rocks from the lower continental crust revealing a close spatial relation between brittle fractures and ductile shear zones that formed under similar high-pressure, high-temperature conditions. Due to this close spatial occurrence of brittle and ductile structures, it has been suggested that ductile shear zones nucleate on brittle precursory structures (Segall & Simpson, 1986; Tullis et al., 1990; Guermani & Pennacchioni, 1998; Mancktelow & Pennacchioni, 2005; Pennacchioni & Mancktelow, 2007; Menegon et al., 2013, and references therein).

The main motivation behind this study was the investigation of the role of water on the structural evolution of faults especially by triggering and sustaining metamorphic reactions.



Mancktelow & Pennacchioni, 2005

Sample locations



Modified after Griffin et al., 1978 and Steltenpohl et al., 2006

- We collected four different samples during field trips to the Lofoten archipelago, N Norway, and the Bergen Arcs, SW Norway.
- The Bergen Arcs sample was used as sample material for the deformation experiments. The Lofoten samples collected close to the villages Hamnøya and Ramberg were used to compare our experimental results with the natural microstructures.

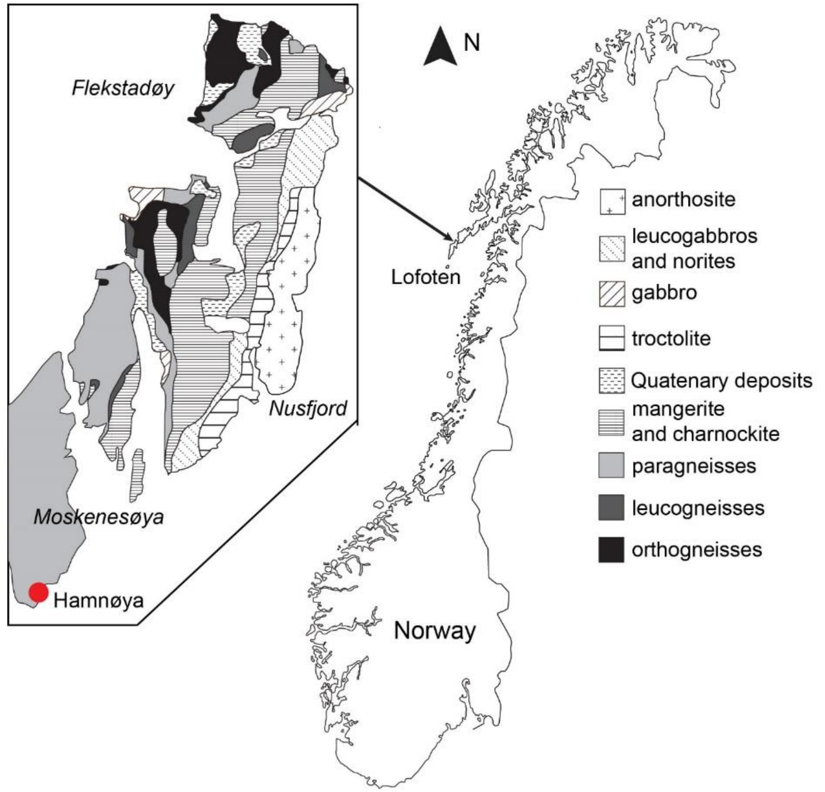
Visit the sample locations:

Ramberg: 68°06'16.3"N 13°15'33.3"E

Hamnøya: 67°56'58.1"N 13°08'14.9"E

Bergen Arcs: 60°31'06.5"N 5°12'31.9"E

Sample location Hamnøya



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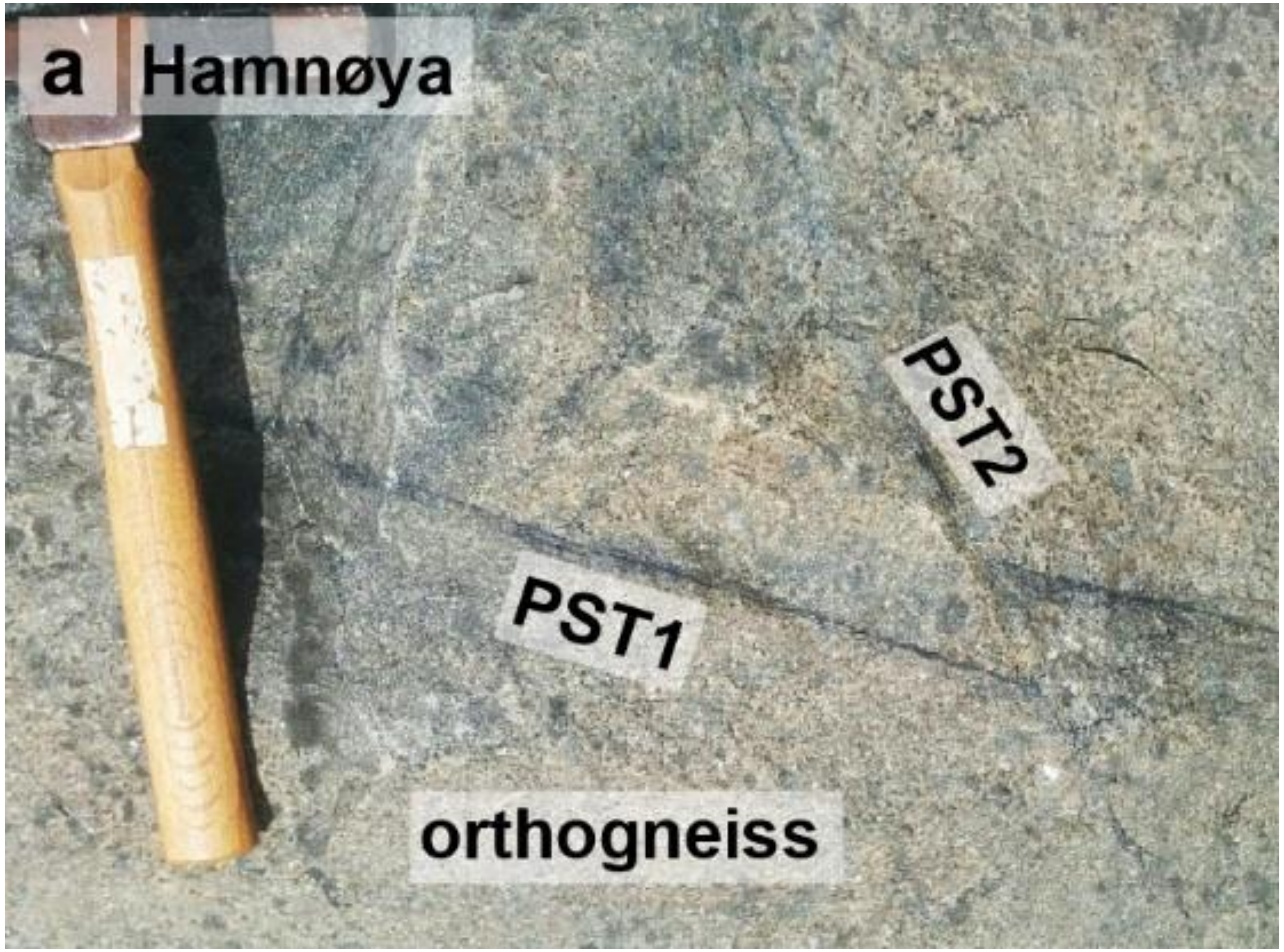
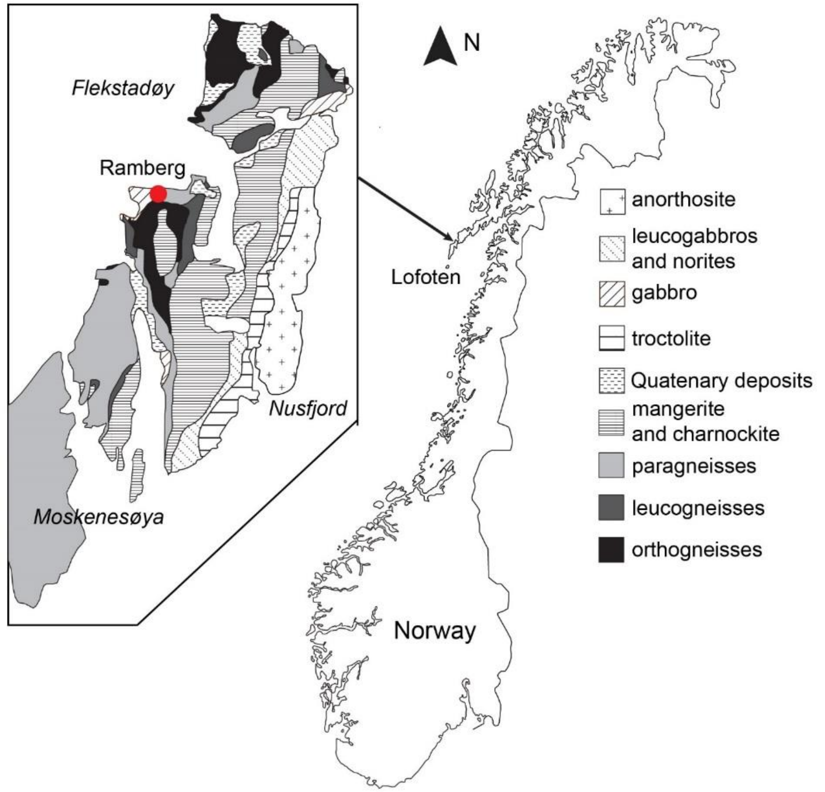


- The Hamnøya location reveals pseudotachylyte networks within an orthogneiss host rock.

Sample location Ramberg



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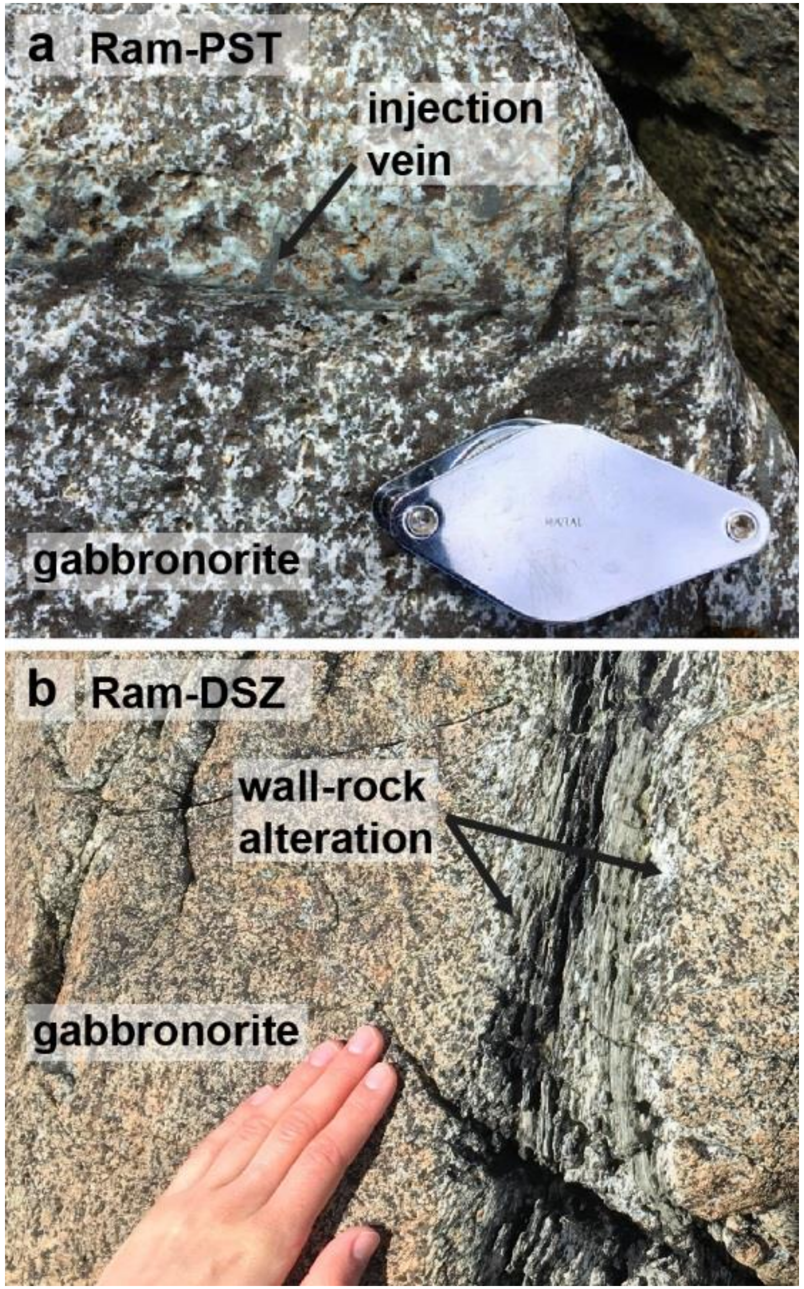
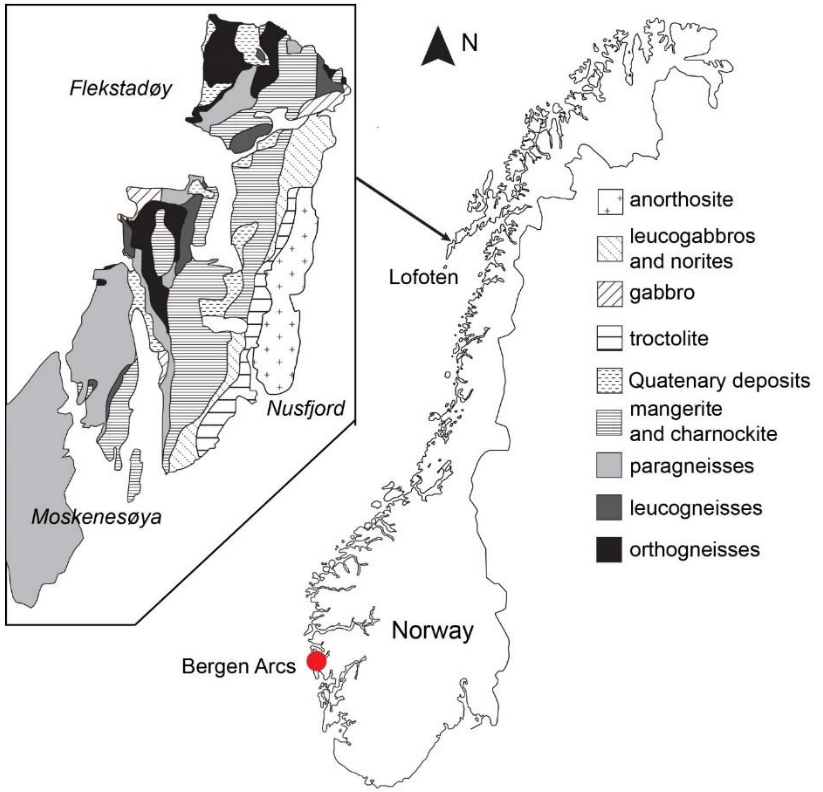


- At the Ramberg location, two samples were drilled out of gabbronorite boulders (a and b).
- The boulder presented in a) demonstrates a thin shear zone with a structure resembling an injection vein within an altered wall rock.
- Another boulder from which we drilled our second sample shows a wider shear zone relative to the shear zone presented in a) and exhibits symmetrical wall-rock alteration.

Sample location Bergen Arcs



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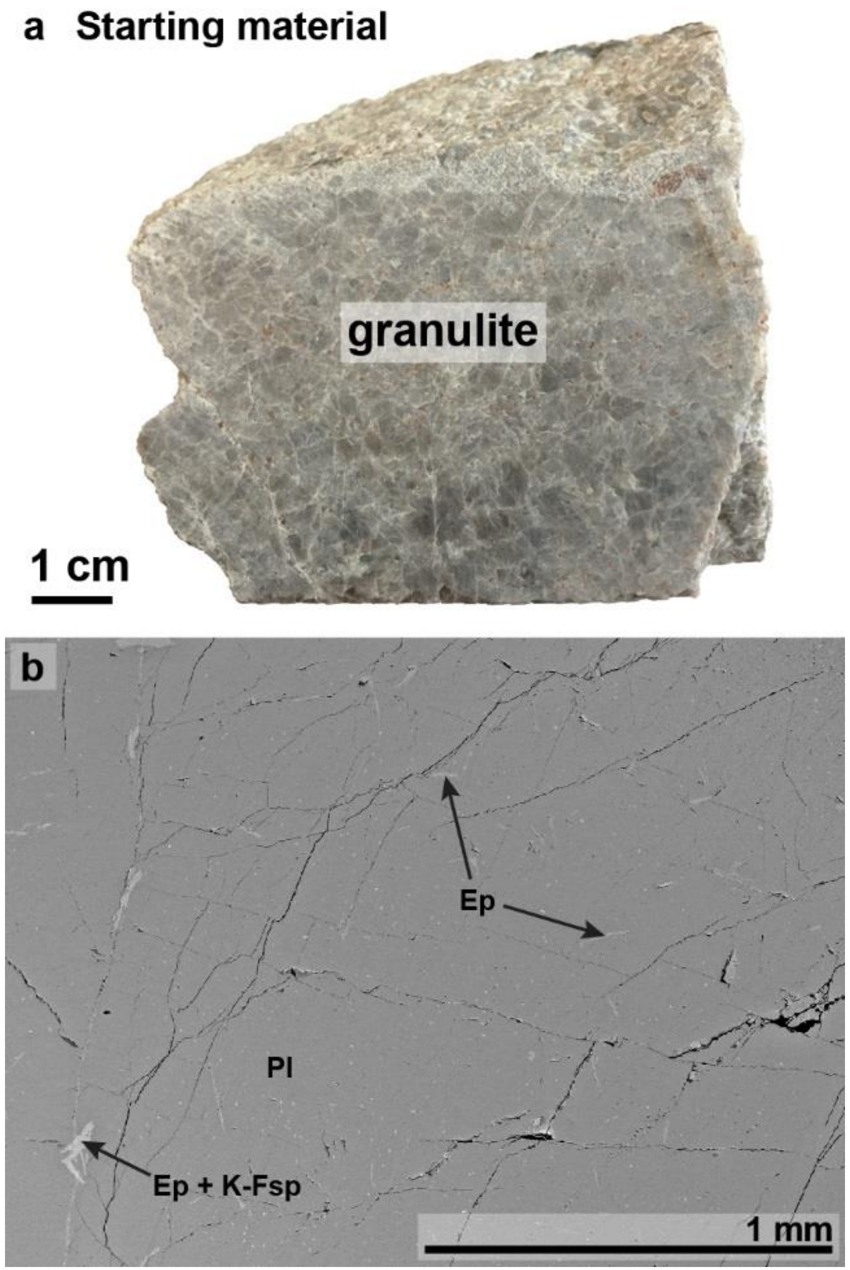


- The sample collected in the Bergen Arcs shows purplish plagioclase grains indicating that the rock experienced only little alteration.
- The backscattered-electron image however demonstrates that there are some epidote needles present.
- The samples were drilled out of the natural rock presented in a). The grain size is with around 0.5 to 3 mm relatively large compared to the drill core size of 3.5×8 mm.

Experimental method & procedure

Griggs-deformation apparatus at Ruhr University Bochum

- In total we performed 8 deformation tests in which we separately investigated the influence of water, total strain, and temperature (see table on the right hands side).
- The confining pressure in every run was 2.5 GPa and the deformation rate was also constant at approx. $5\times10^{-5}\ s^{-1}$.
- Thermodynamic modelling reveals that the ‘as-is’ samples contain <0.76 wt. % H_2O. The water content is a sum of the water present in the rock sample and adhesion water on the sample surface.

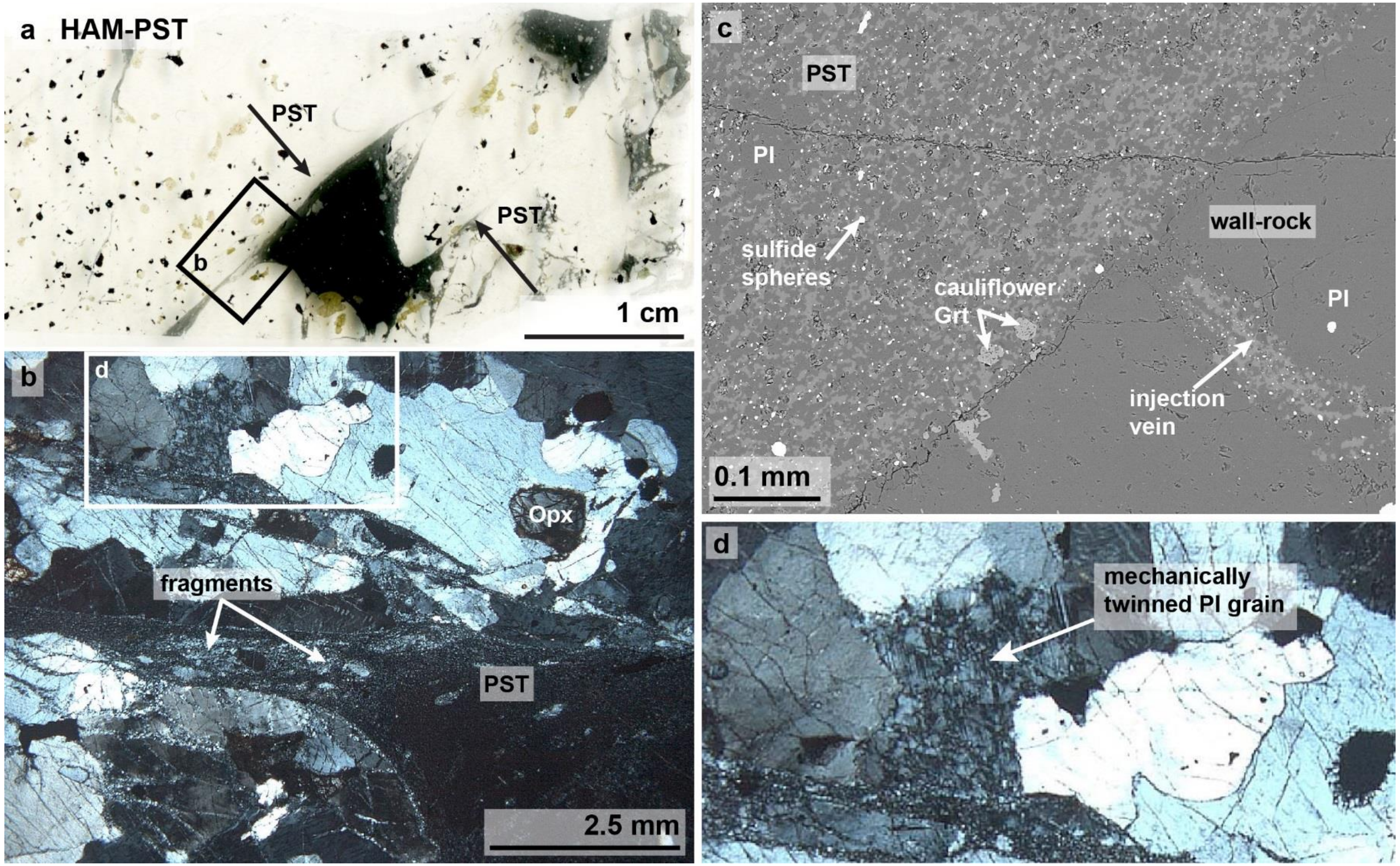
Experimental conditions for the eight deformation experiments

Comment	T [°C]	Total axial strain [%]
’as-is’	700	7
’as-is’	700	36
’as-is’	900	7
’as-is’	900	35
+ 1 wt. H_2O	700	8
+ 1 wt. H_2O	700	33
+ 1 wt. H_2O	900	8
+ 1 wt. H_2O	900	36

Results & Discussion

Natural microstructures

Hamnøya sample:



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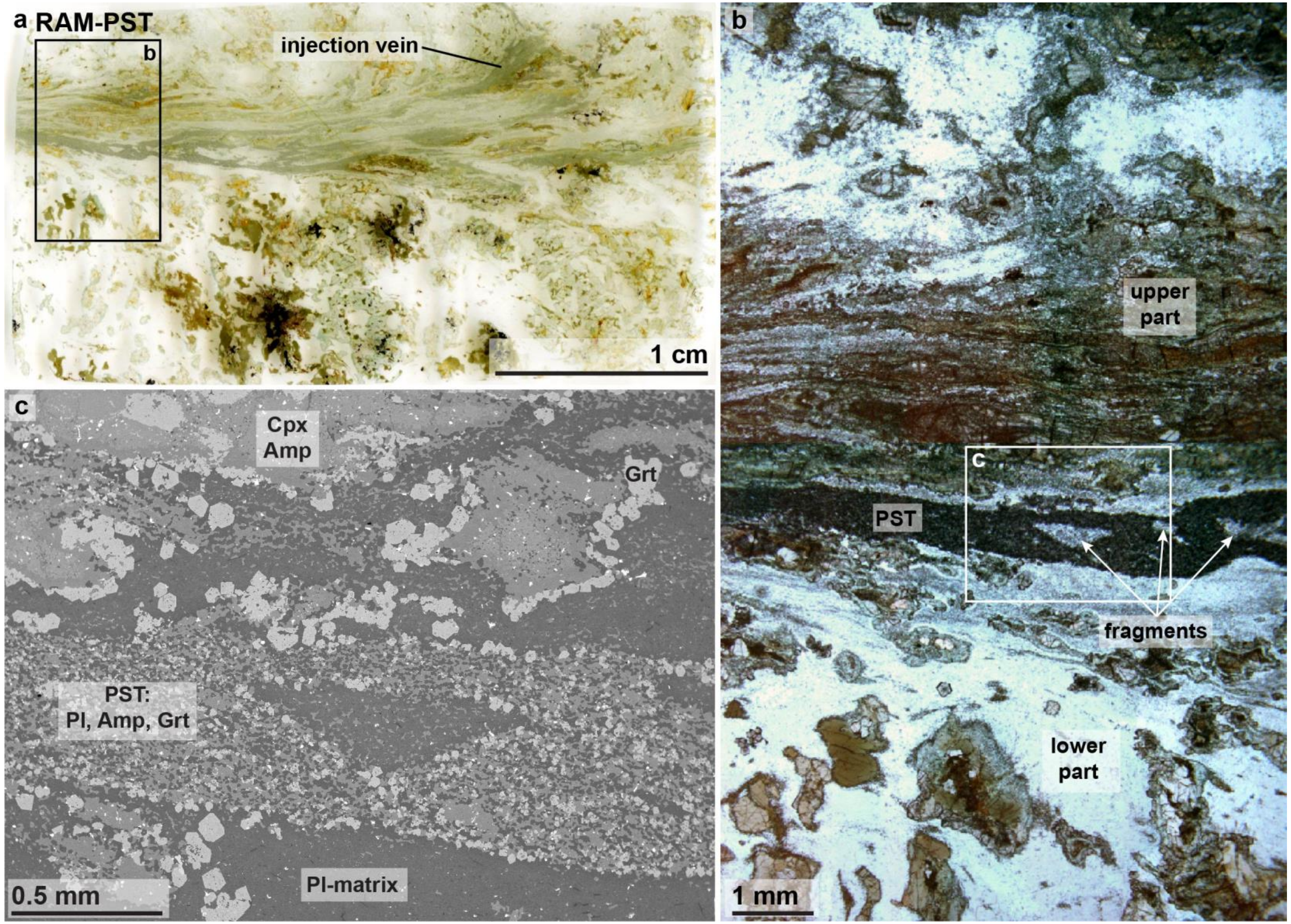
- The sample collected close to Hamnøya, (HAM-PST) shows pseudotachylyte veins containing host-rock fragments, cauliflower garnets and sulphide spheres (a, b, c). We also find injection veins (c). Plagioclase grains in the adjacent wall rock reveal mechanical twins (d).
- The borders between pseudotachylyte vein and host rock are very sharp and both, the vein and the host, show almost no difference in mineralogy consisting of mainly plagioclase and alkali-feldspar together with minor orthopyroxene, apatite, and magnetite.

Ram-PST sample:



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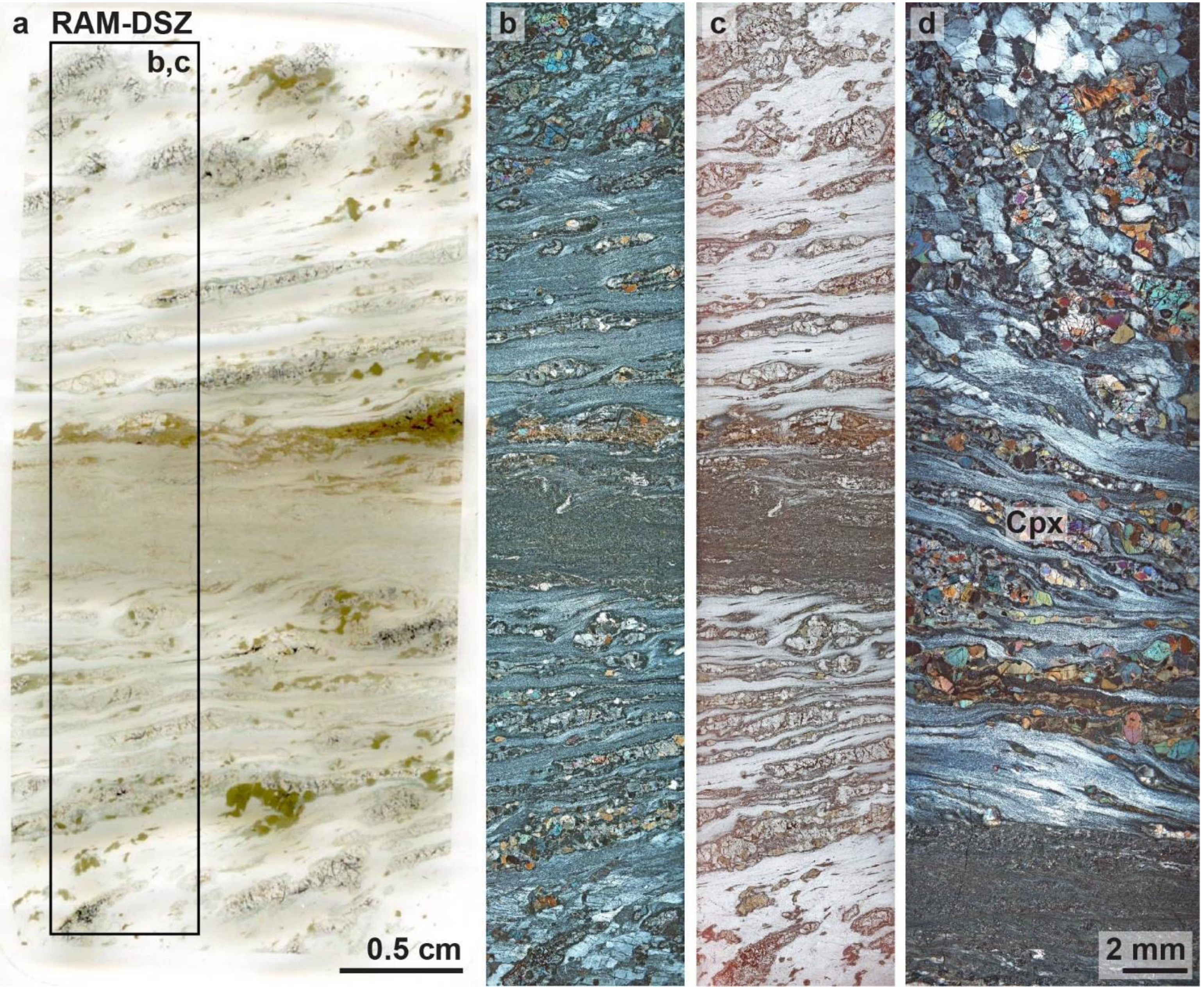
- The sample RAM-PST reveals a central pseudotachylyte vein containing host-rock fragments, cauliflower garnets and sulphide spheres. Major phases found in the pseudotachylyte vein are plagioclase, amphibole and garnet.
- The host rock contains mostly plagioclase together with minor clinopyroxene showing amphibole rims and biotite.
- It appears that the upper part of the vein is much more affected by reaction expressed by the formation of mainly amphibole than the lower part.

Ram-DSZ sample:



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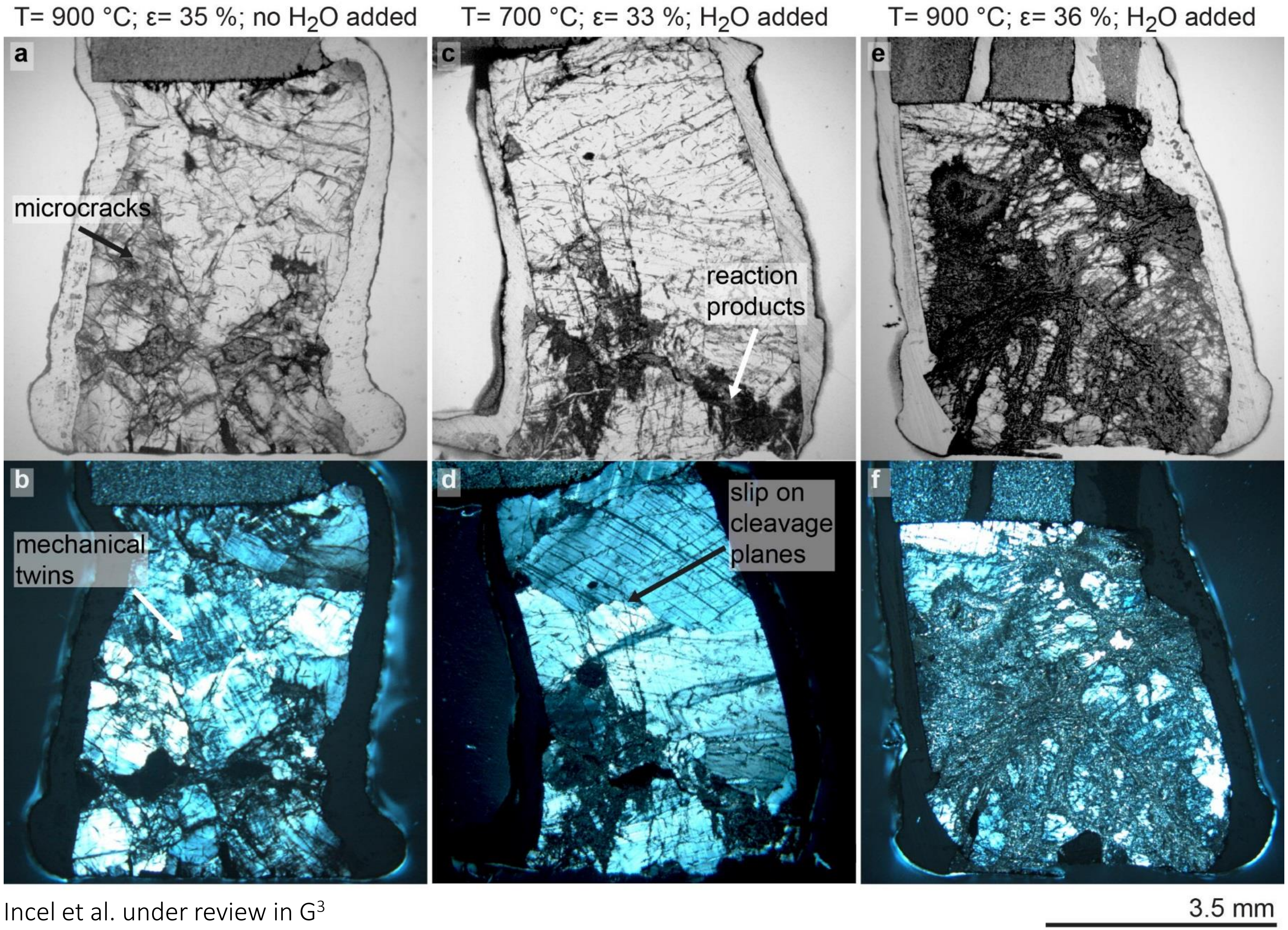
- The second sample collected close to Ramberg (RAM-DSZ) shows a ductile shear zone with amphibole formation within its central part and the adjacent extensively sheared wall rock.

The main difference between the samples collected close to Hamnøya and Ramberg is the formation of amphibole in zones of localized strain in the Ramberg samples indicating hydration.

Experimental microstructures



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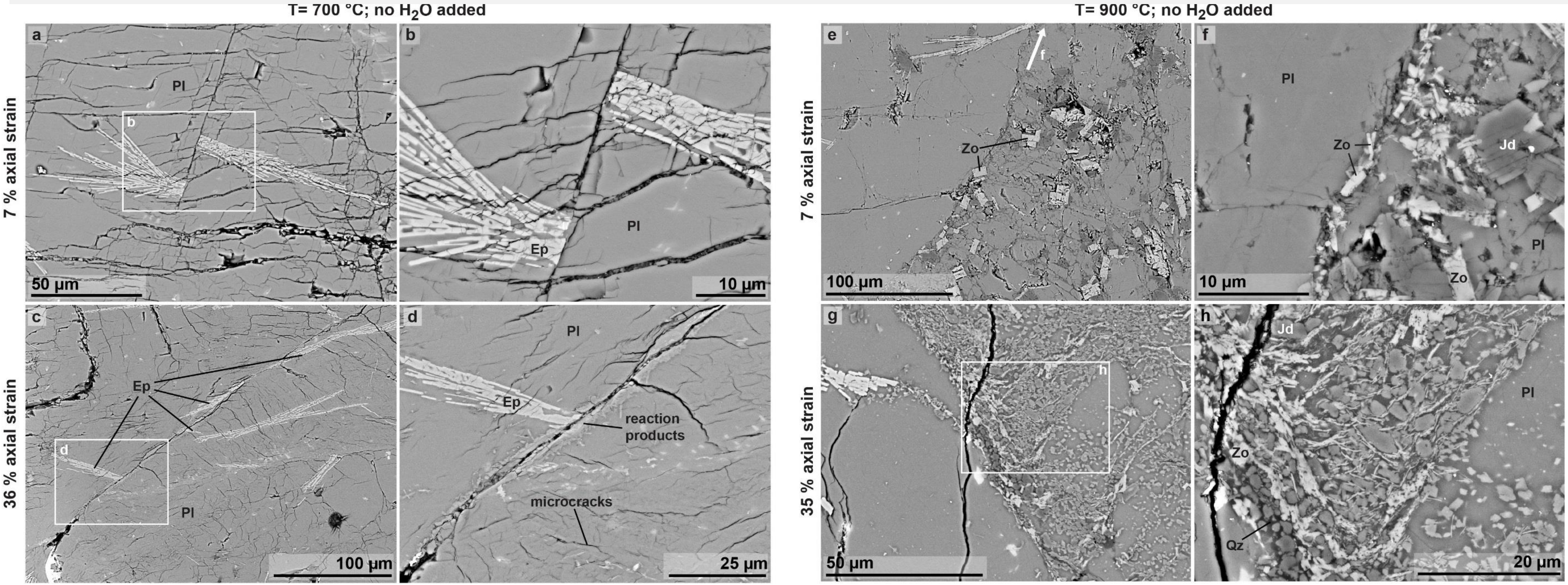
Images taken at the polarized microscope of three representative samples after deformation.

- The microstructure of the high-strain sample deformed at 900 °C ‘as-is’ reveals fractures cutting through several grains as well as microcracks and extensive mechanical twinning of wall-rock plagioclase grains (a, b).
- After deformation at 700 °C to 33 % strain with water added, the sample shows reaction along fractures and within the adjacent host rock (c, d).
- The sample deformed with water added at 900 °C to 36 % strain, is almost completely reacted (e, f).

Backscattered-electron images of the samples deformed ‘as-is’

- Low-strain samples show shear fractures cutting through several grains and microcracks in the adjacent wall-rock.
- At 900 °C the low-strain and the high-strain sample reveal the onset of eclogitization expressed by the growth of zoisite (Zo) and jadeite (Jd) and occasionally quartz (Qz).
- Reaction starts along fractures and along cleavage planes and microcracks in the adjacent wall rock.



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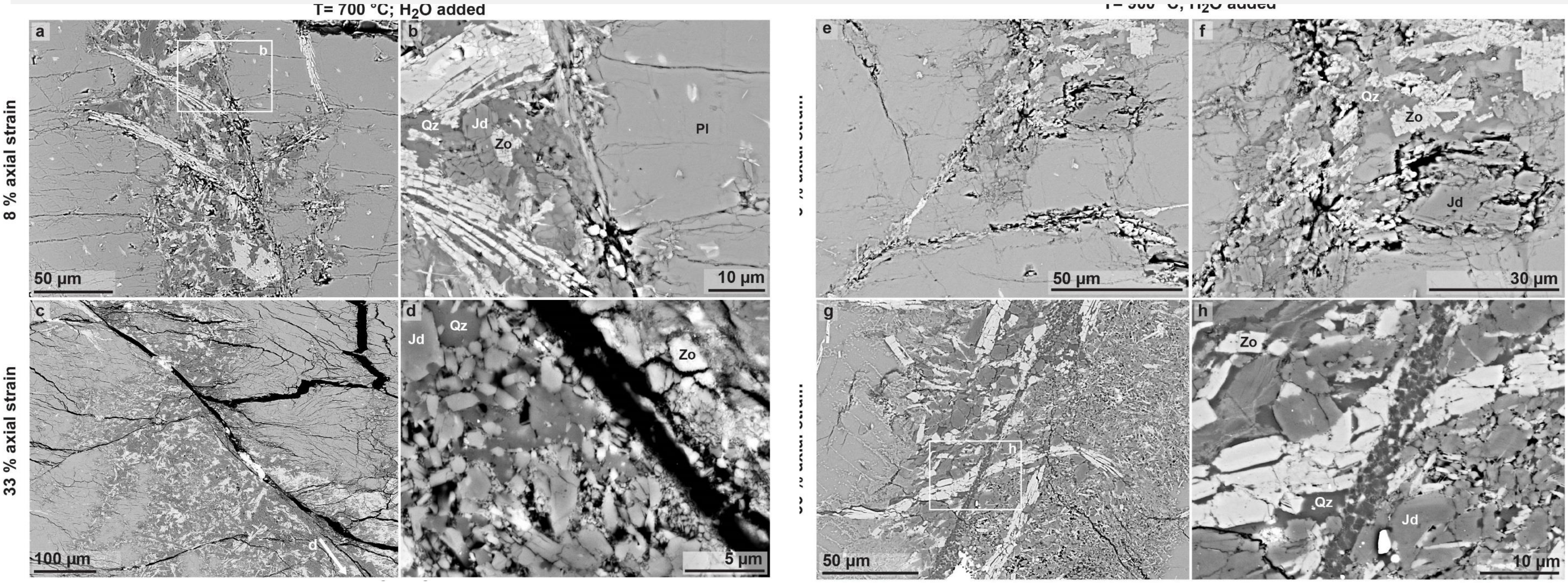
Backscattered-electron images of the samples deformed with water added

- Low-strain samples show fractures and reaction along the fractures and within the wall rock
- Reaction often takes place on only one side of the fracture and is expressed by the growth of zoisite (Zo), jadeite (Jd), quartz (Qz), and occasionally muscovite
  - → The influx of fluids into the wall rock is facilitated by the presence of cleavage planes and therefore occurs predominantly in favourable oriented grains
- The initial fractures are completely overprinted by reaction and subsequent plastic deformation of the reaction products in the high-strain sample deformed at 900 °C



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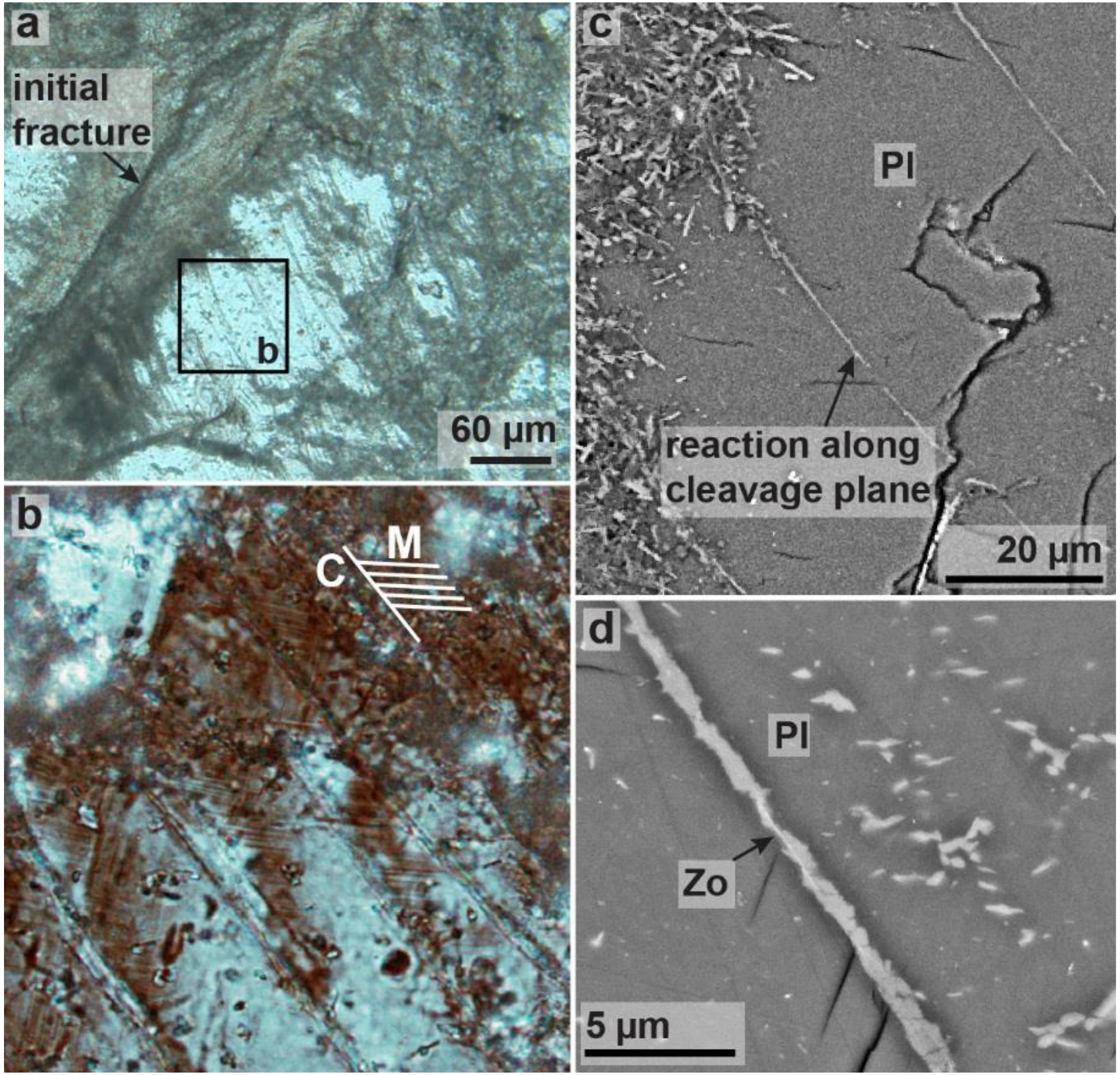

1. Fluids infiltrate the wall rock along cleavage planes, microcraks, and twin planes
2. Reaction commences in these fluid infiltrated zones
3. Strain localizes in the reaction products
4. Hydration and subsequent reaction and localization of strain causes the widening of the zone accommodating deformation

Pl= plagioclase; Zo= zoisite; C= cleavage plane; M= mechanical twin

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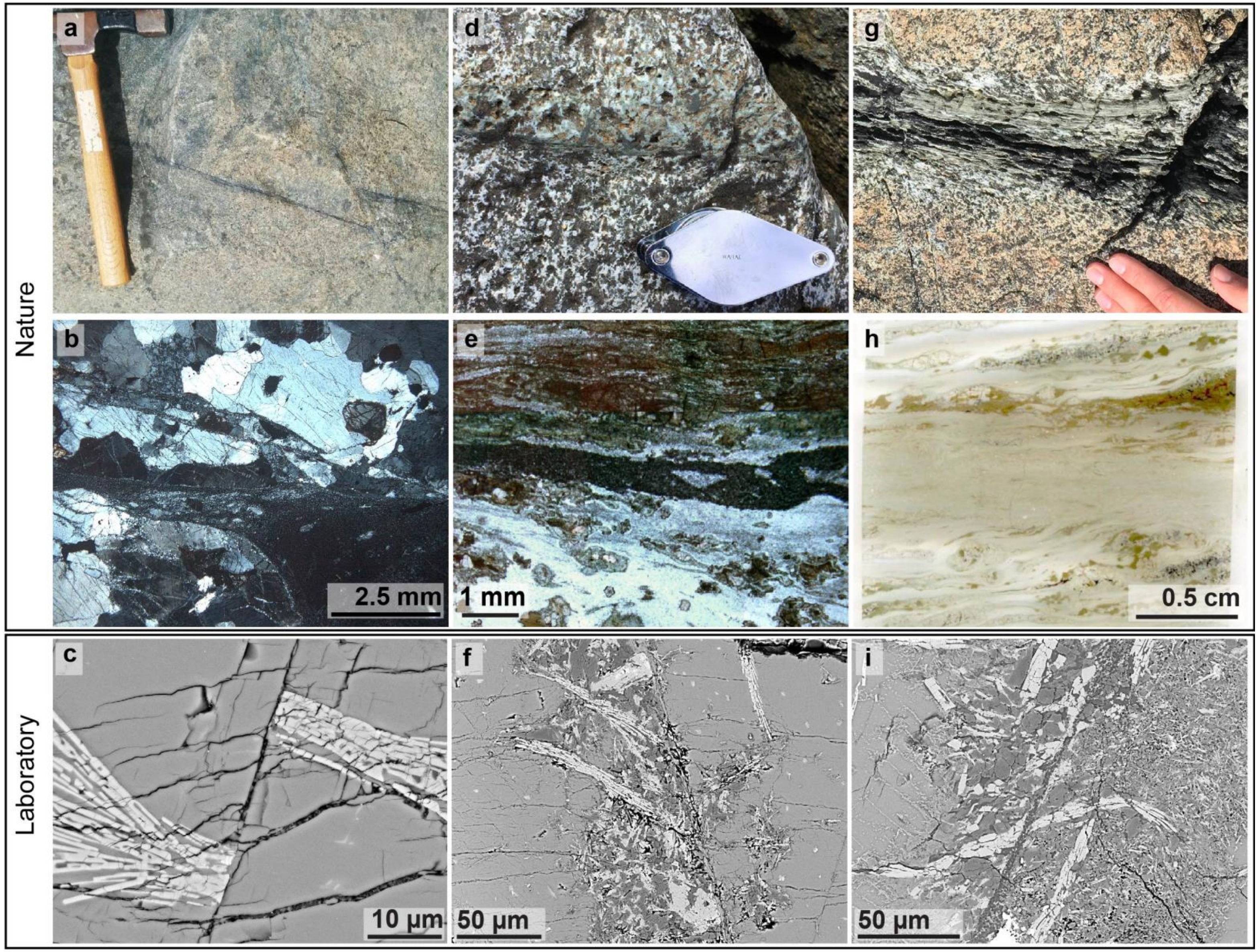
Conclusion



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It is very challenging to directly compare the experimental results with the natural samples, because the natural samples experienced a far more complex deformation history than our experimental samples.

From our experimental samples we observe a deformation sequence of:

1. Fracturing
2. Fluid infiltration
3. Reaction
4. Plastic deformation of the reaction products

The plastic overprint of brittle fractures occurs very rapidly in samples deformed with water added. Therefore, the preservation of brittle features such as pseudotachylytes in nature is much more likely in dry host rocks. We also observe that hydration and reaction within the wall rock adjacent to the fractures causes widening of the zone accommodating deformation.

Acknowledgements

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