Compaction in the Groningen Gas Field

An overview of our understanding of the compaction behaviour of the Slochteren sandstone

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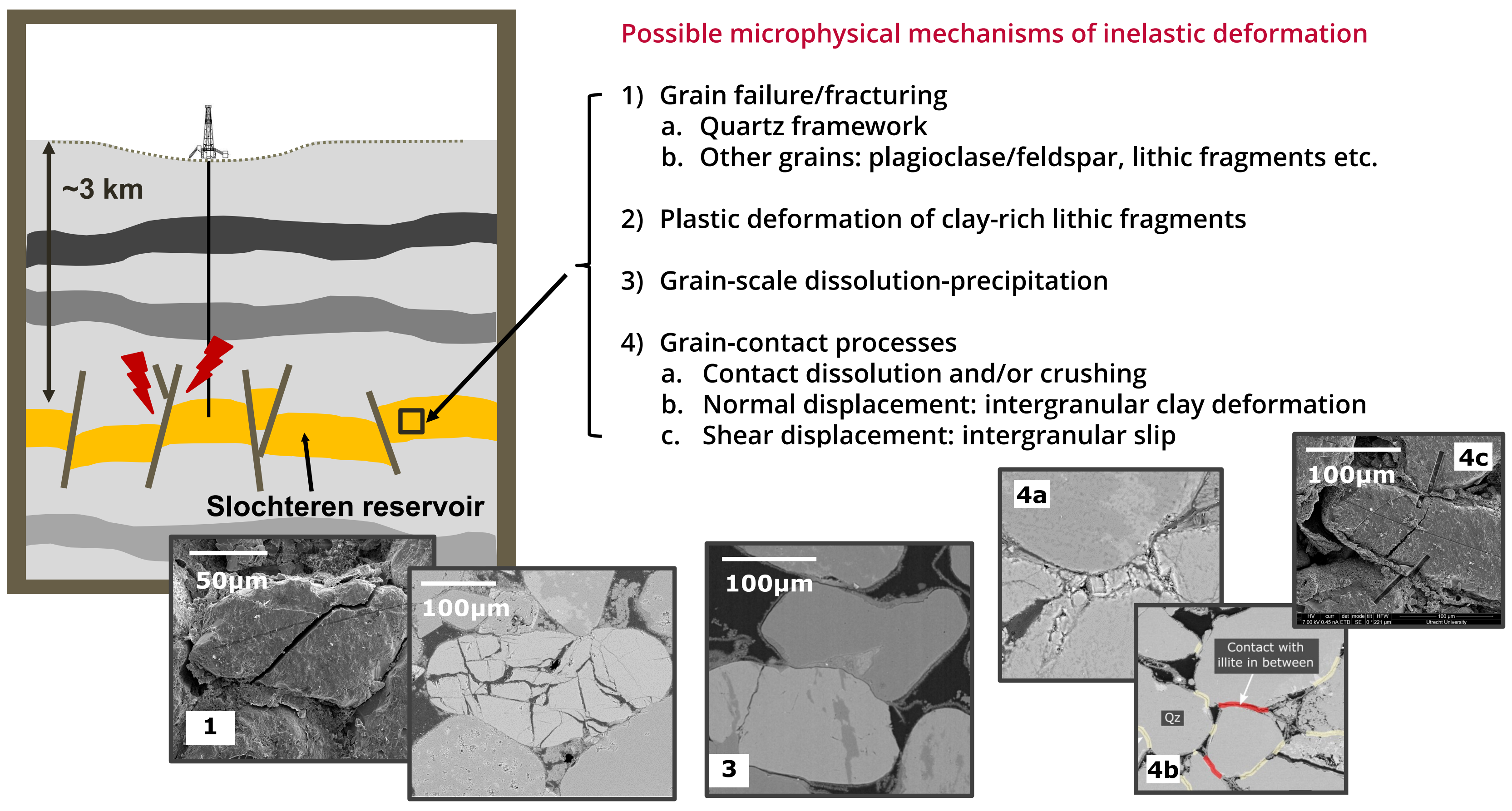
Reservoir compaction: the cause for subsidence and induced seismicity

Prolonged gas production from the Groningen Gas Field has reduced the initial gas pressure from 35 MPa in 1963 to 8 MPa by 2015. The resulting increase in effective overburden stress has led to compaction at the reservoir level. This compaction is expressed at the surface as subsidence, while differential compaction across the many faults in the reservoir has led to induced seismicity. Assuming subsidence at the surface corresponds to compaction at depth, vertical reservoir compaction strains are 0.1-0.3%, resulting from elastic and permanent (inelastic) deformation at the grain-scale. Furthermore, some of the compaction may be rate- or time-dependent, continuing even after production has stopped.

To evaluate the impact of gas extraction and to assess future production-related hazards, identification and quantification of the mechanisms controlling compaction of the reservoir during production and after abandonment is required.



Possible microphysical mechanisms of inelastic deformation

1) Grain failure/fracturing
    a. Quartz framework
    b. Other grains: plagioclase/feldspar, lithic fragments etc.
2) Plastic deformation of clay-rich lithic fragments
3) Grain-scale dissolution-precipitation
4) Grain-contact processes
    a. Contact dissolution and/or crushing
    b. Normal displacement: intergranular clay deformation
    c. Shear displacement: intergranular slip

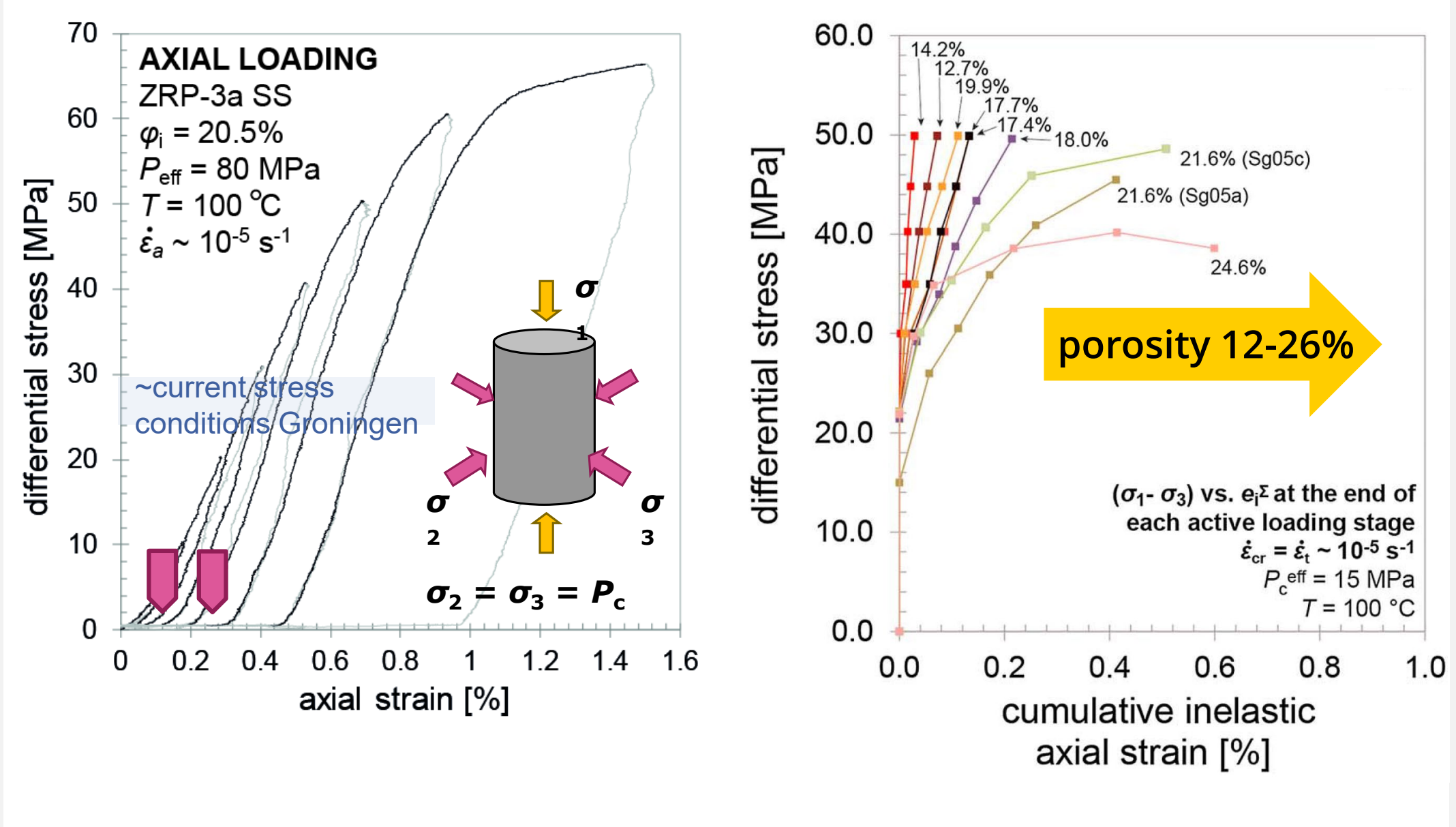
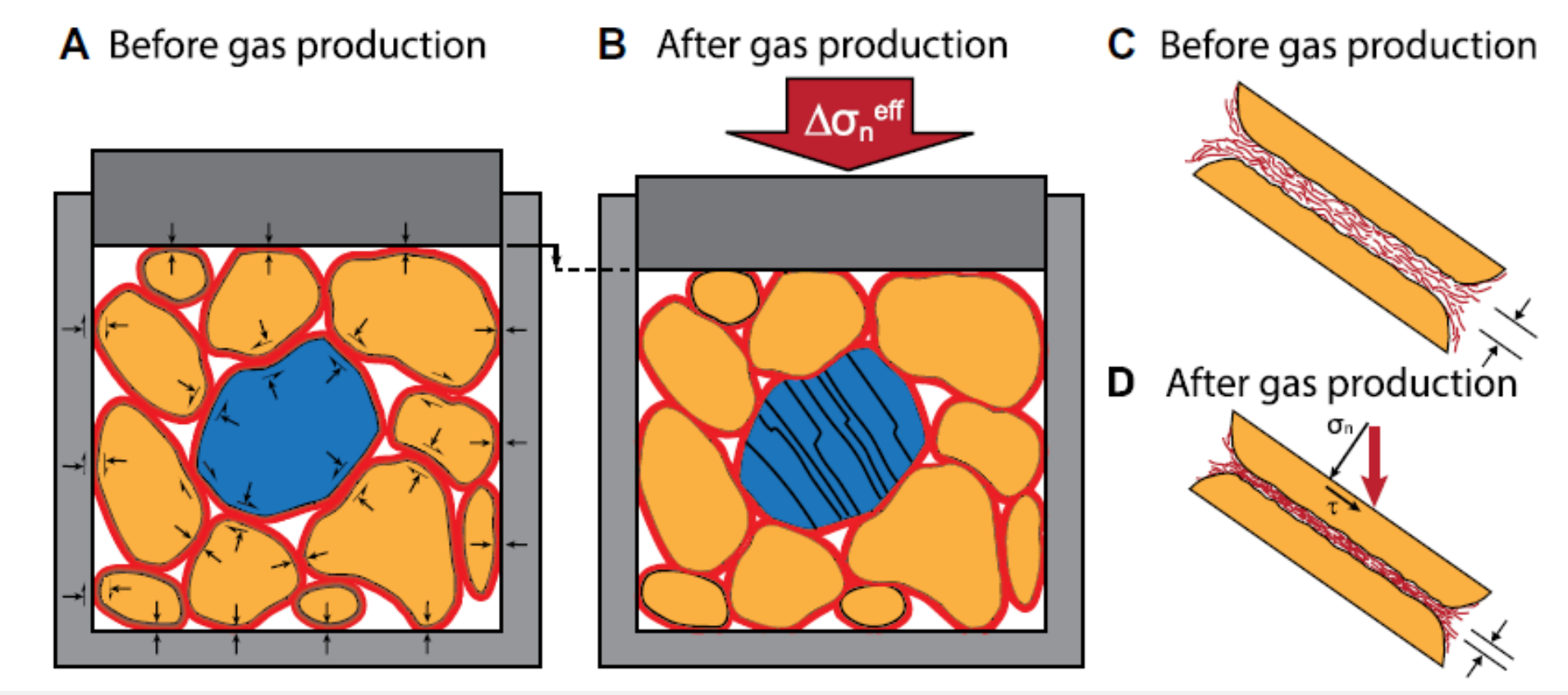


Figure 1 Left: Under Groningen stress conditions, small, permanent deformation is observed (arrows), where behaviour is generally assumed to be purely elastic. Right: The amount of inelastic deformation increases with porosity. Note the rapid increase in inelastic strain in Slochteren sandstone with a porosity of > 20% (Pijnenburg et al., 2018, 2019b).

Main deformation mechanism during production

Based on experimental and microstructural work, **compaction of and slip along thin, intergranular clay layers** controls deformation. As seen in reservoir core, fractured feldspar grains serve as passive markers evidencing this (Pijnenburg et al., 2018, 2019, 2020; Verberne et al., 2020) – collaboration with NAM.



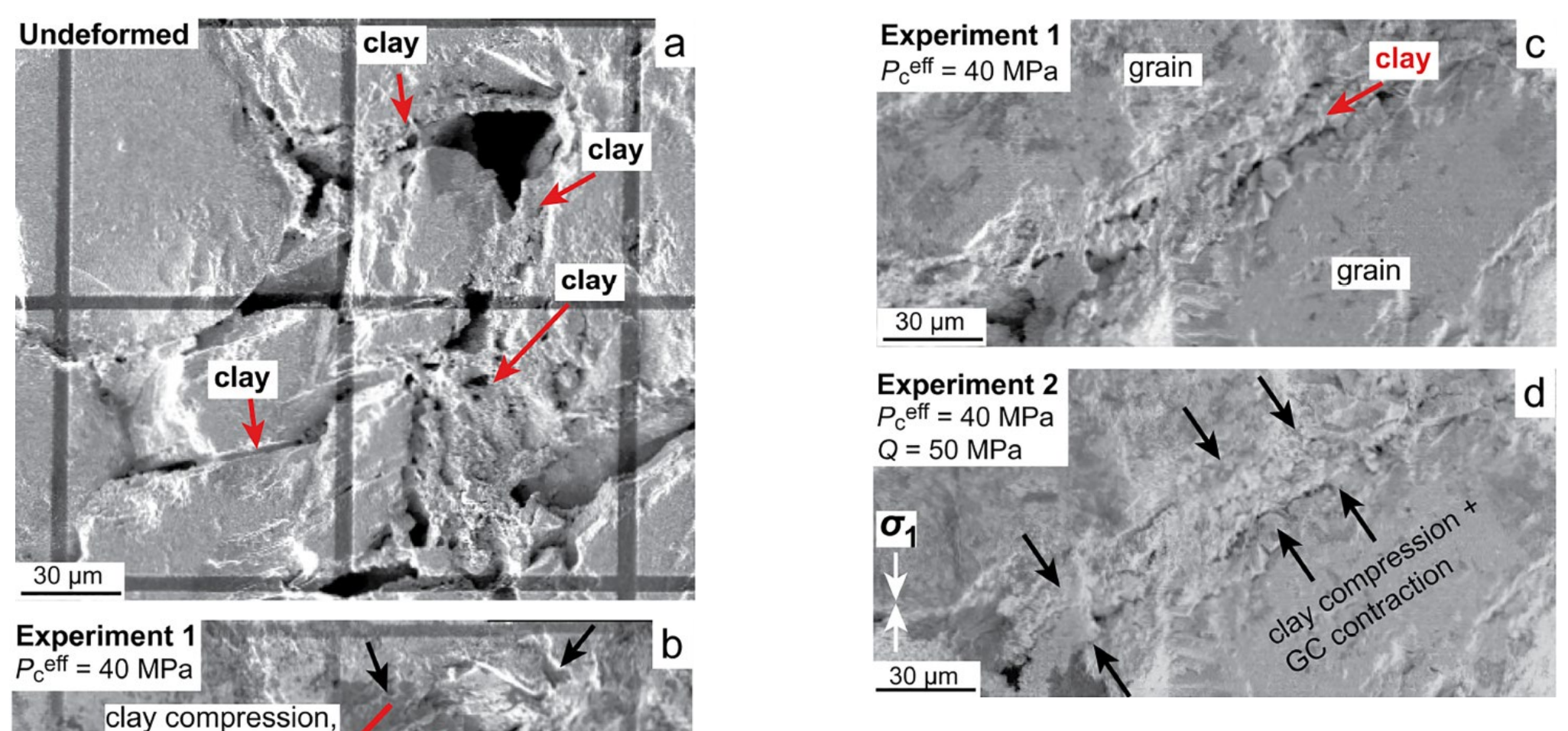


Figure 2 a-to-b: In some locations, shear and compression of clay films leads to grain displacement and closure of pore space. In other locations, clay-coated grain contacts (GC) expand.
c-to-d: Normal compression of intergranular clay leads to GC contraction (Pijnenburg et al., 2019b).

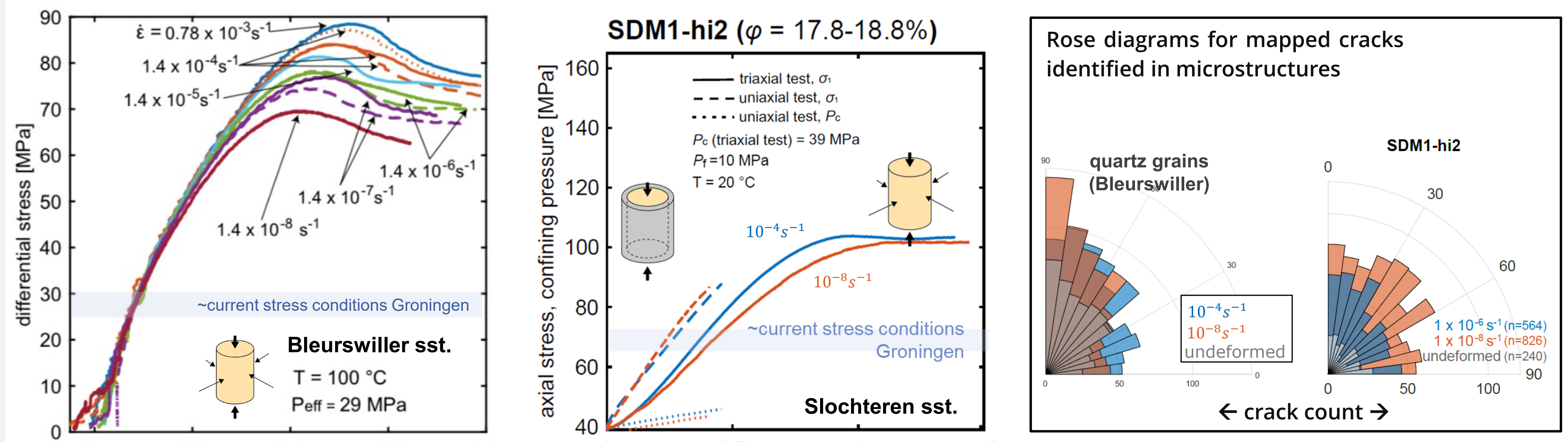


Figure 3 Left: Triaxial experiments at varying strain rates, with slower deformation rates lowering the stress-strain curves (weakening) in Bleurswiller sandstone, an analogue for the Slochteren sandstone. Centre: Similar behaviour is seen in triaxial experiments on Slochteren sandstone. When applying zero-lateral strain boundary conditions, this effect is less pronounced. Right: Microstructural analysis shows that grain fracturing plays an important role in controlling compaction of both sandstones (Shinohara et al., under review; in prep).

Main deformation mechanism after abandonment

On longer time-scales, time-dependent compaction is inferred to be governed by **slow, subcritical crack growth, accompanied by grain rearrangement and slip**. Extrapolating experimental data obtained at the slowest strain rates achievable in the lab (i.e. $10^{-8 \text{ or } -9}$ s^{-1}) to field compaction rates (i.e. 1000 slower), plus data from month-long experiments (Hol et al., 2015), suggests that **additional strains of 10-20%** can be expected by this mechanism (i.e. inelastic strain in excess of what has already been accumulated at rapid/lab deformation rates) (Shinohara et al., under review; in prep) – research performed within the DeepNL Programme.

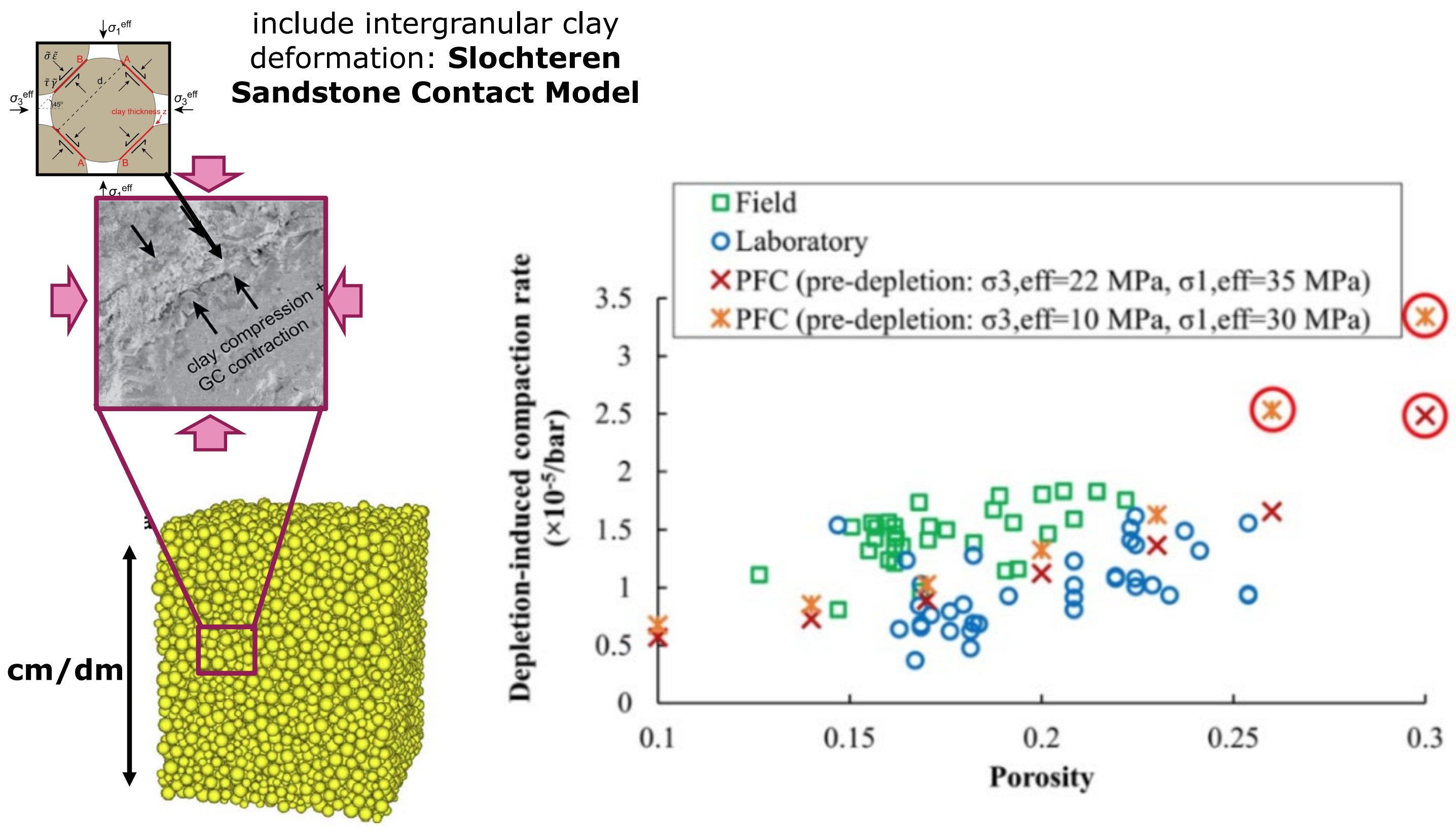
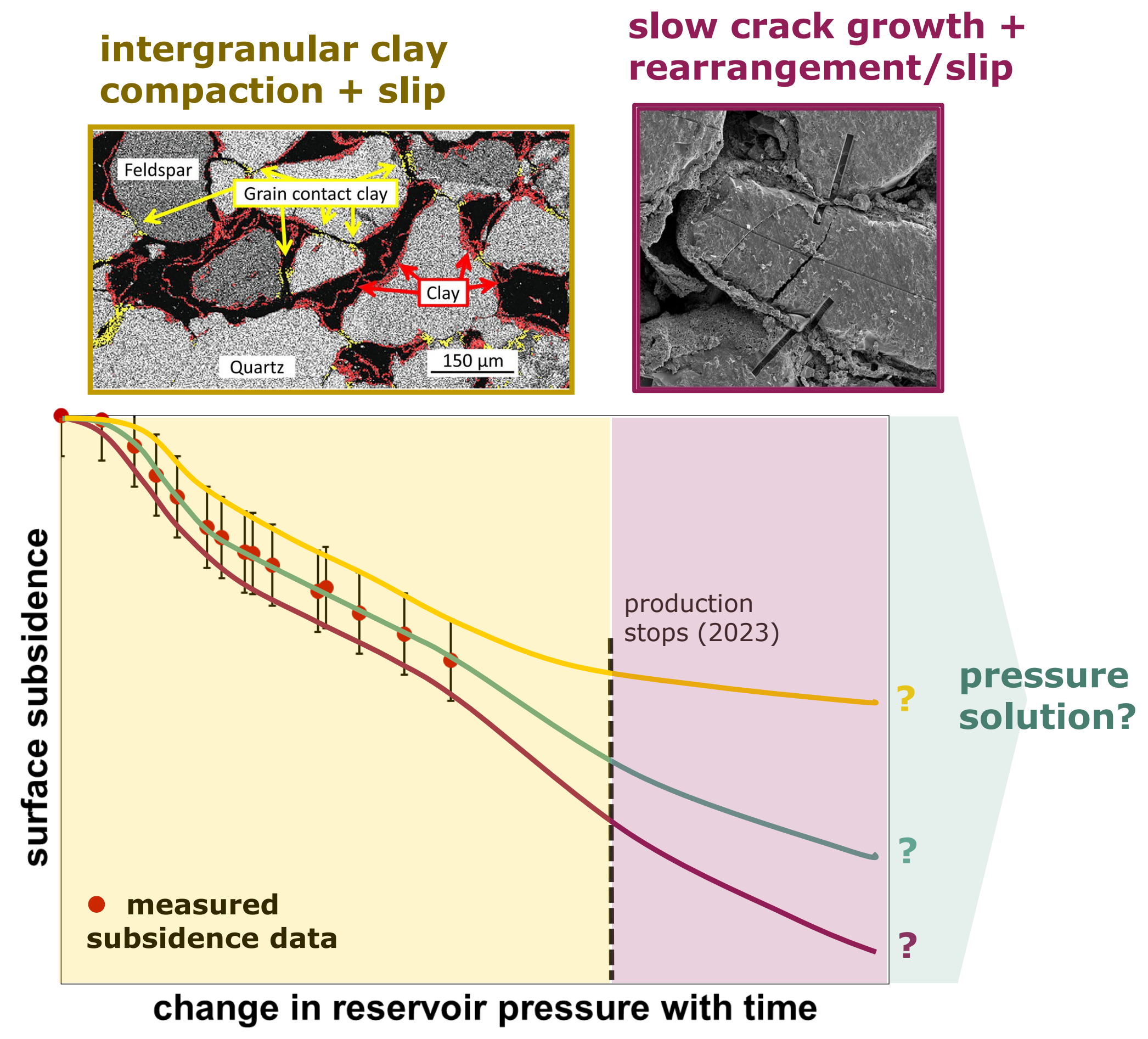


Figure 4 Left: Implementation of rate-insensitive compaction by clay film deformation into a DE model (Mehranpour et al., 2021). Right: DE predictions of compaction rate show good agreement with experimental work by Hol et al. (2018) and field data (Cannon and Kole, 2017).

Implications and conclusions

Rate-insensitive compaction was implemented into cm-scale Discrete Element (DE) models. This allows for the evaluation of compaction in different field locations due to pressure equilibration or repressurisation (Mehranpour et al., 2021; in prep). Rate-sensitive mechanisms will be added at a later stage. To what extent even longer-term compaction behaviour (decades-centuries) will be influenced by even slower creep processes such as pressure solution still requires further investigation and quantification.



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Publications on compaction of the Groningen Gas Field

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‡ various publications by Shinohara, Jefferd and Mehranpour in prep or under review