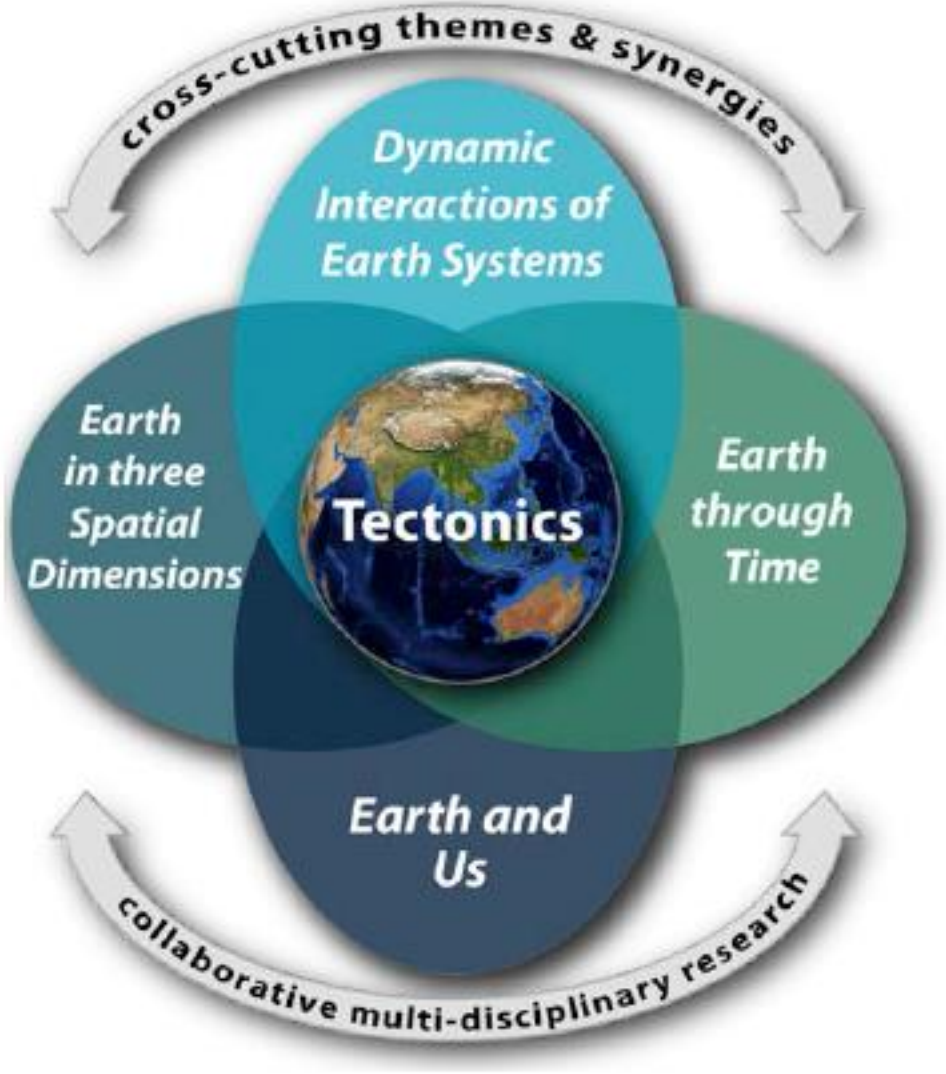
Rheology of the Lower Crust: Concepts, Methods, Observations

1) Lecture 1: Rheology of the Lower Crust: General importance & Recap of Solid state deformation mechanism and flow laws

2) Quantitative Orientation Analysis: How does it work? How can it help me to understand the Lower Crust – rheology

3) Quantitative Orientation Analysis: Examples and Opportunities - Rheology and evolution of the Lower Crust

4) Rheology of the Lower Crust: Other measurements and considerations



Modified after Huntington & Klepeis et al. 2017

Lecture 3: Quantitative Orientation Analysis/Modelling: Examples and Opportunities – Rheology, Character & Evolution of the Lower Crust

1. Case Study – Lower crustal shear zones and reactions
2. Strain localization – Effect of flow law switches - A numerical study
3. EBSD and reactions

1)

The effect of reaction and annealing extent on dominance of deformation mechanisms:

Insights from paired shear zones in the lower crust of Fiordland, New Zealand

S. Piazolo, N.R. Daczko , J. Smith & L. Evans

Macquarie University, ARC Centre of Excellence for Core to Crust Fluid Systems

MACQUARIE UNIVERSITY GEMOC THE UNIVERSITY OF WESTERN AUSTRALIA *Achieving International Excellence* Centre for EXPLORATION TARGETING Curtin University Geological Survey of Western Australia

Background / Aim

- Understanding rheology in the Earths' crust is essential to the quantitative assessment of large-scale plate tectonic processes

- Rheology is directly affected by:
  - what phases are present, their mode and grain size
  - metamorphic reactions may change these

- In this study we investigate
  - the effect of reaction extent and annealing on rheology and strain localization

Smith et al. JMG 2015

Natural Experiment

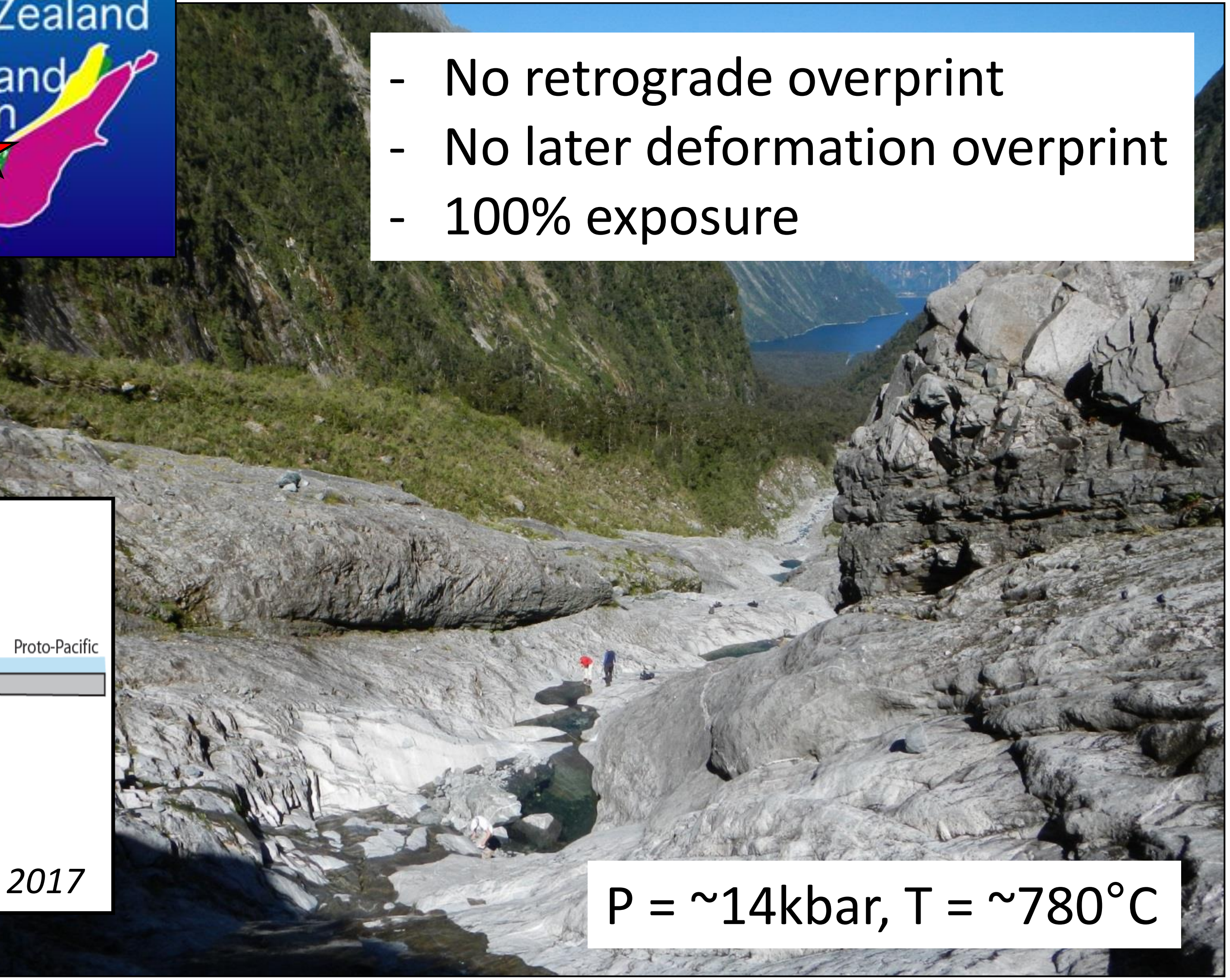
- Vary composition (dyke vs GRZ/host rocks)
- Vary mineralogy (GRZ vs host rocks)
- Vary grain size
- Squeeze it !

Smith et al. JMG 2015

Lower crust

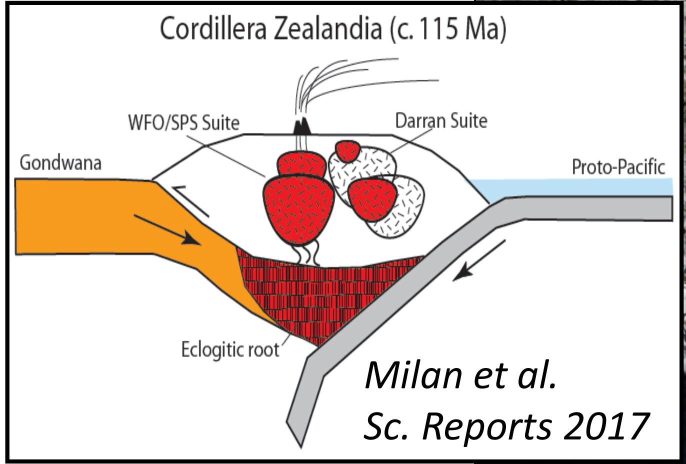
M. Jackson:
Kohistan Arc =
Fiordland

Deep
Continental Arc



- No retrograde overprint
- No later deformation overprint
- 100% exposure

P = ~14kbar, T = ~780°C



Milan et al.
Sc. Reports 2017

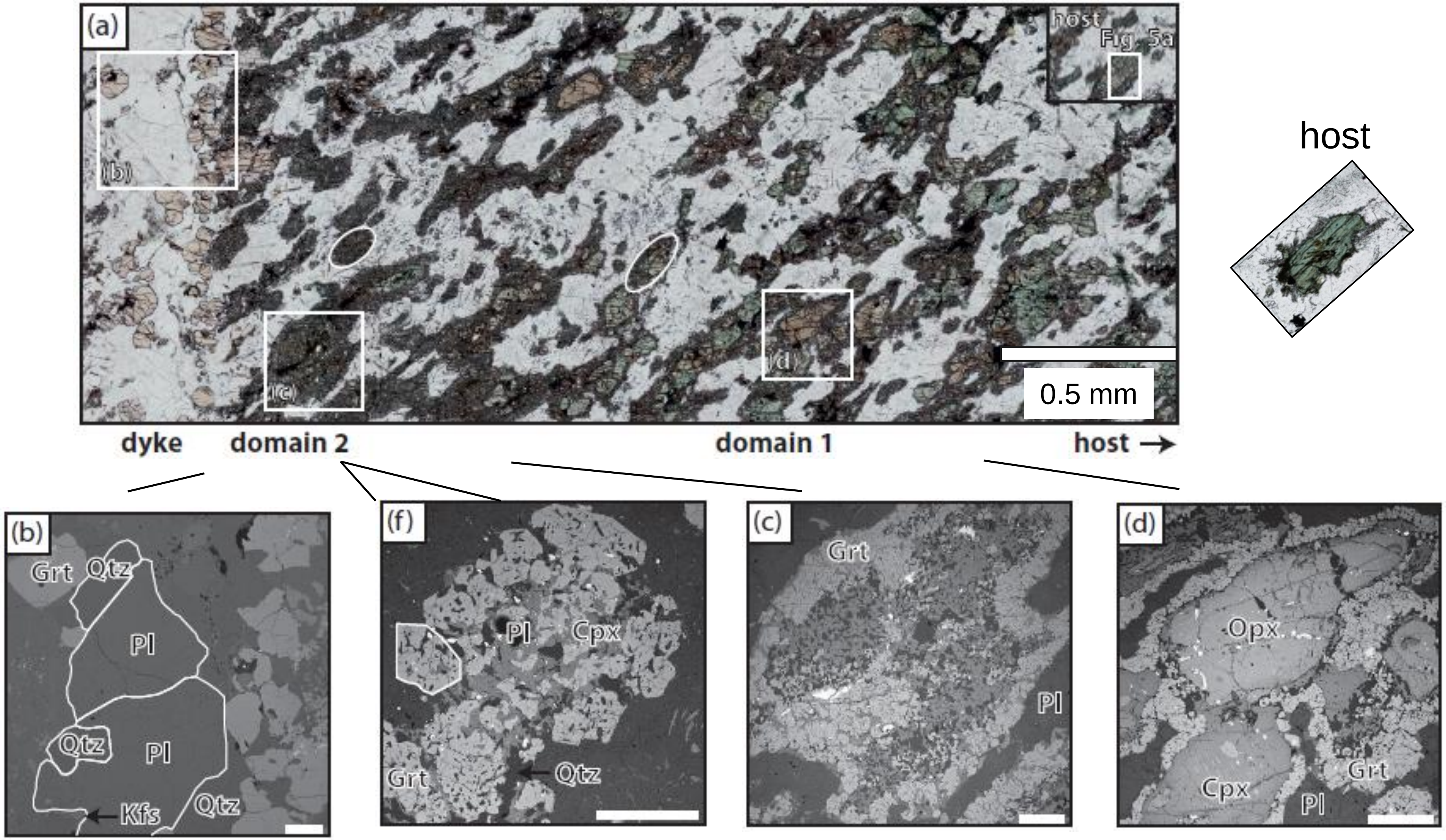
Pembroke Valley, Fiordland, NZ

Smith et al. JMG 2015

Smith et al. JMG 2015

Undeformed Garnet Reaction Zones

- Dehydration (Cpx/Opx ± Hrbl -> Grt + Cpx (new) + melt (H2O))

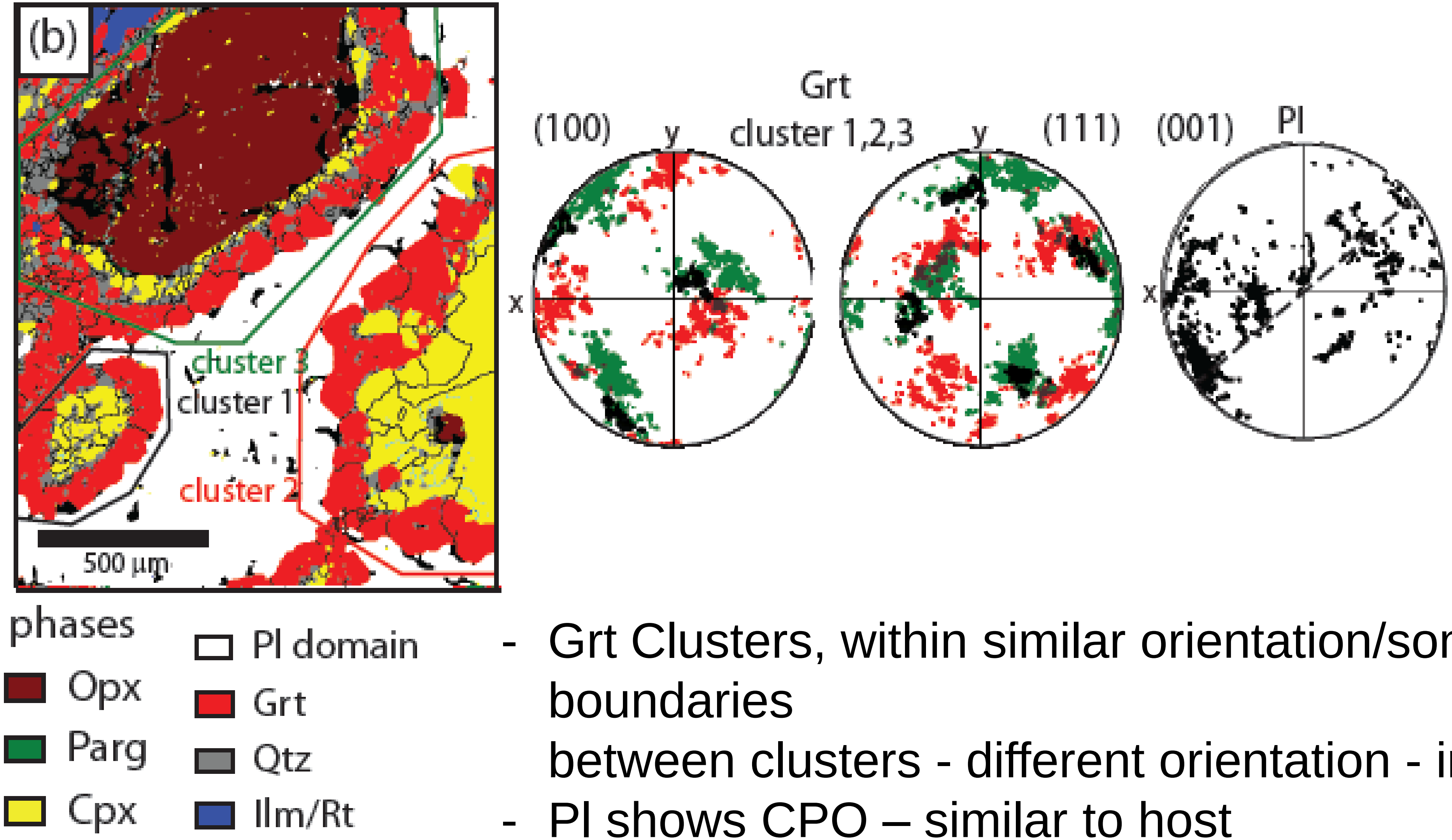


Domain 3:
Complete replacement

Smith, Piazolo et al. JMG, 2015

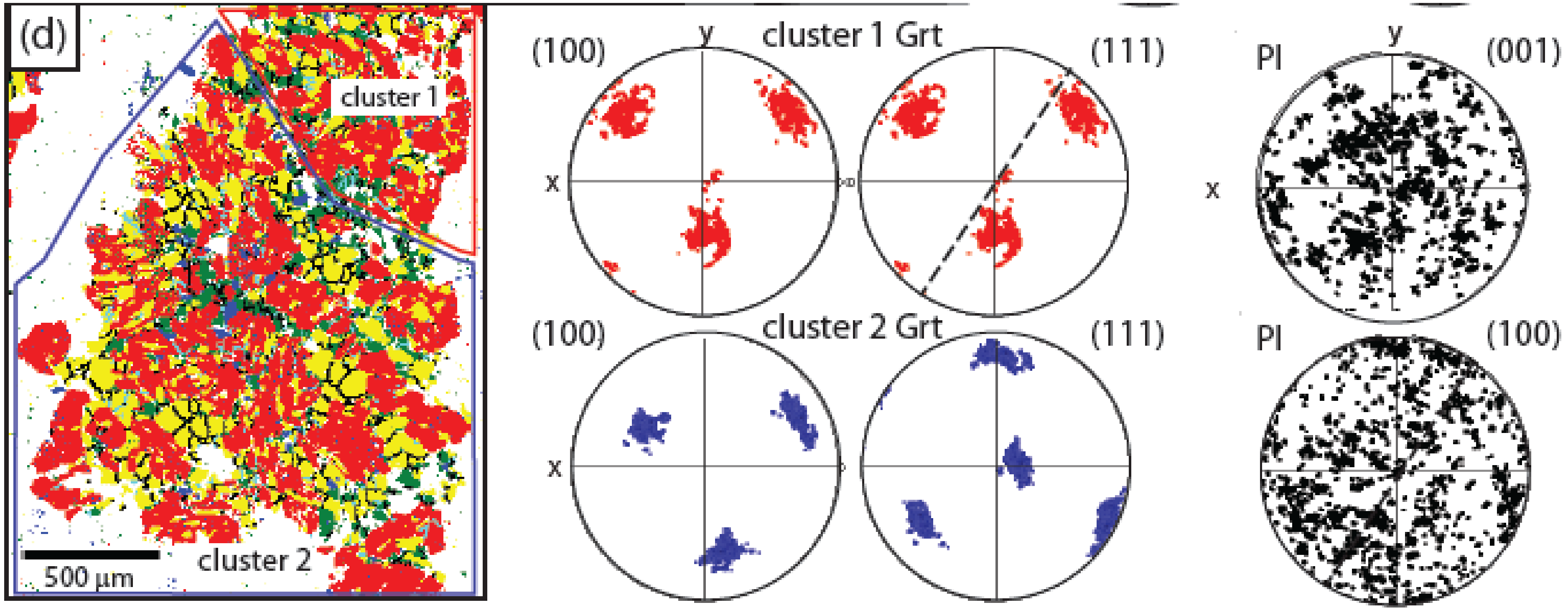
Example: Domain 1 (close to host)

EBSD + EDS analysis



- Grt Clusters, within similar orientation/some subgrain boundaries
  between clusters - different orientation - inheritance
- Pl shows CPO – similar to host

Domain 3 (close to dyke)



- Grt clustering
- New CPX
- Near random CPO for plag

Mancktelow & Pennacchioni 2005

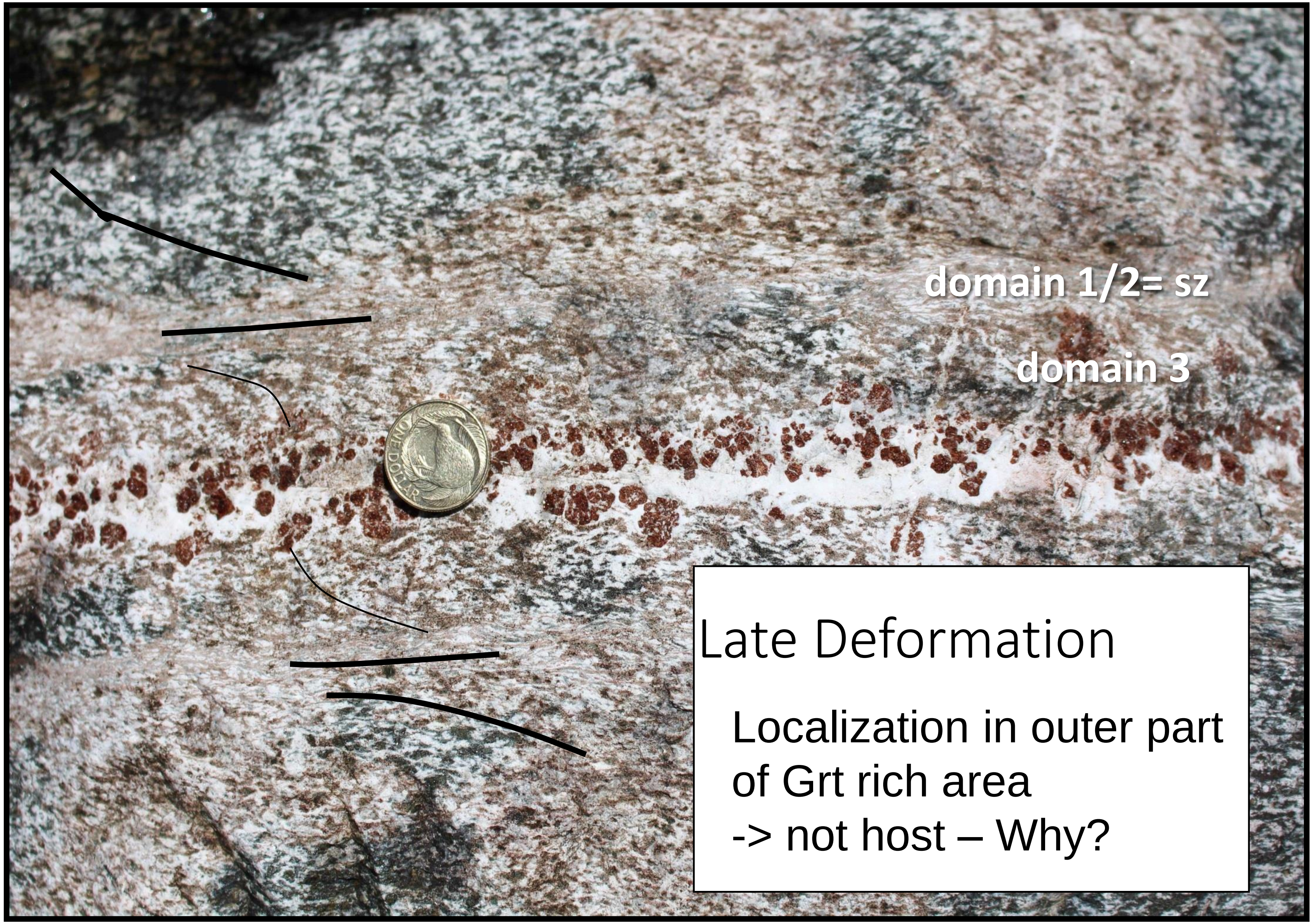
Natural Experiment

Vary composition (dyke vs GRZ/host rocks)

Vary grain size

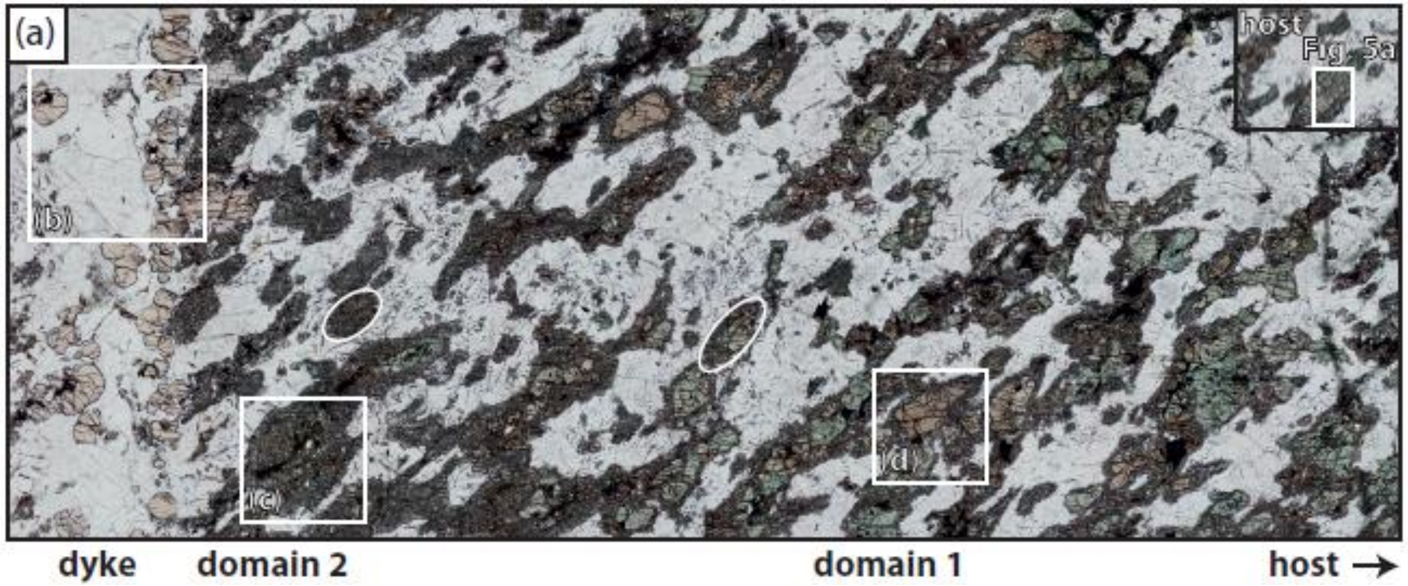
Vary mineralogy (GRZ vs host rocks)

Squeeze it !



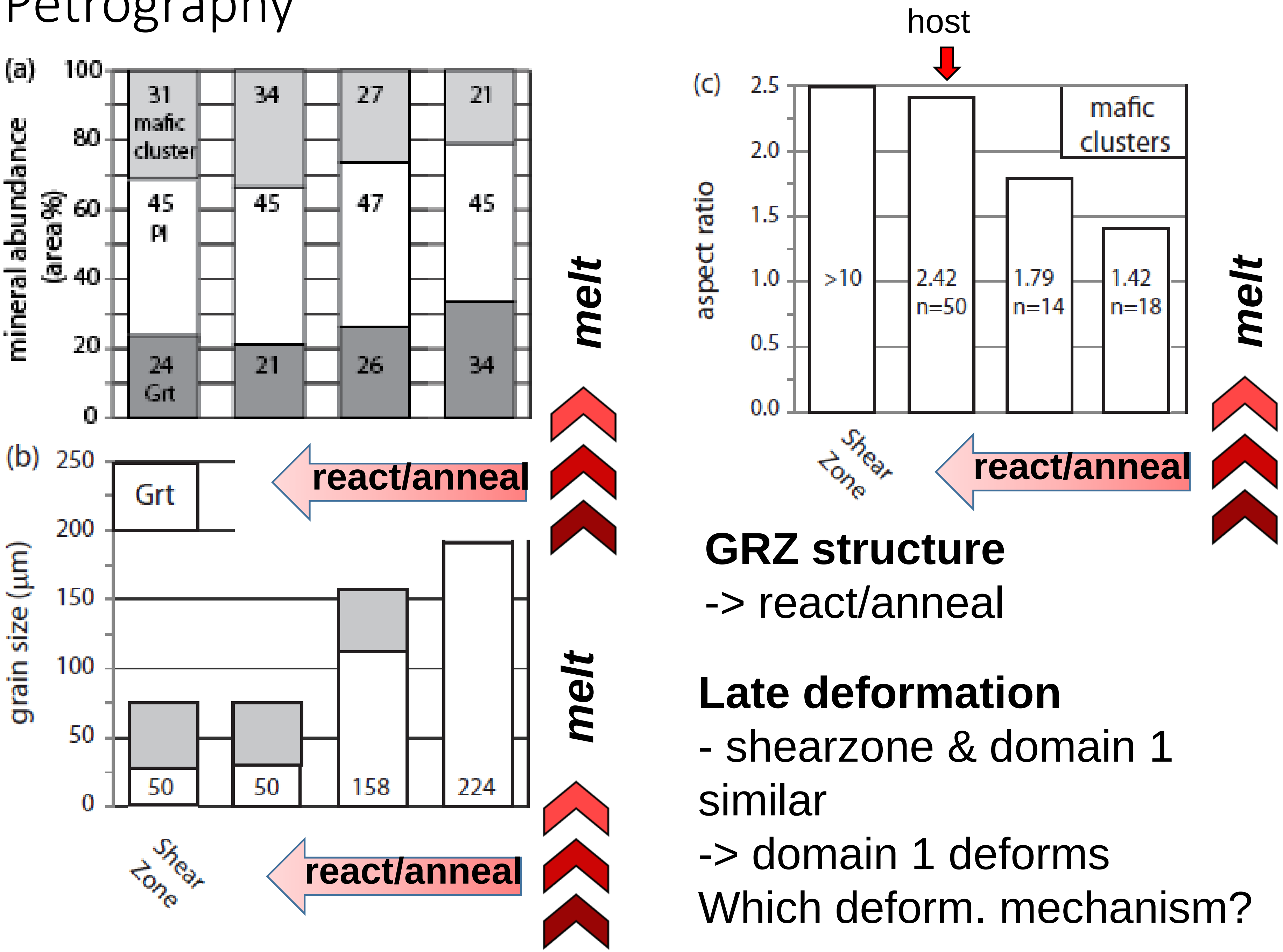
Late Deformation

Localization in outer part of Grt rich area
-> not host – Why?


(a)
(b)
(c)
(d)
host
Fig. 5a
dyke
domain 2
domain 1
host →


Domain 3
Domain 2
Domain 1

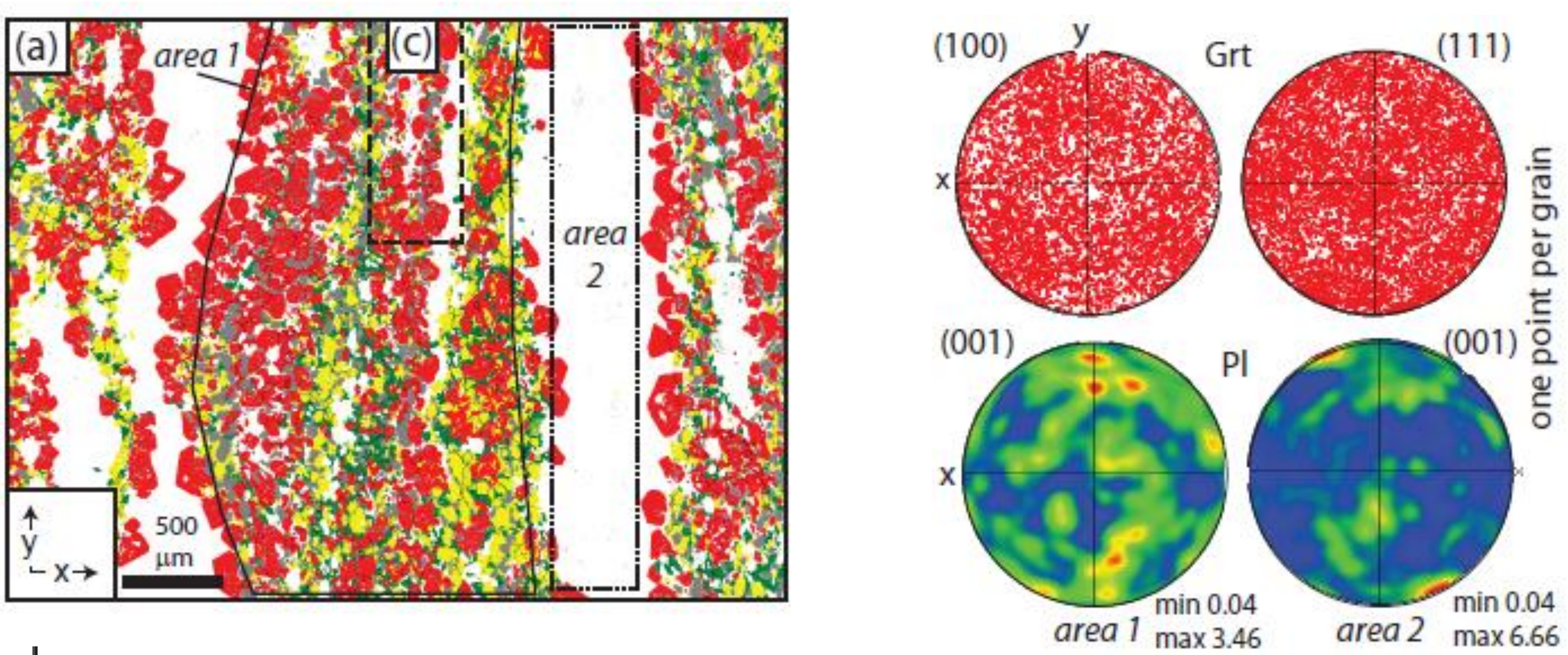
Petrography



GRZ structure
-> react/anneal

Late deformation
- shearzone & domain 1 similar
-> domain 1 deforms
Which deform. mechanism?

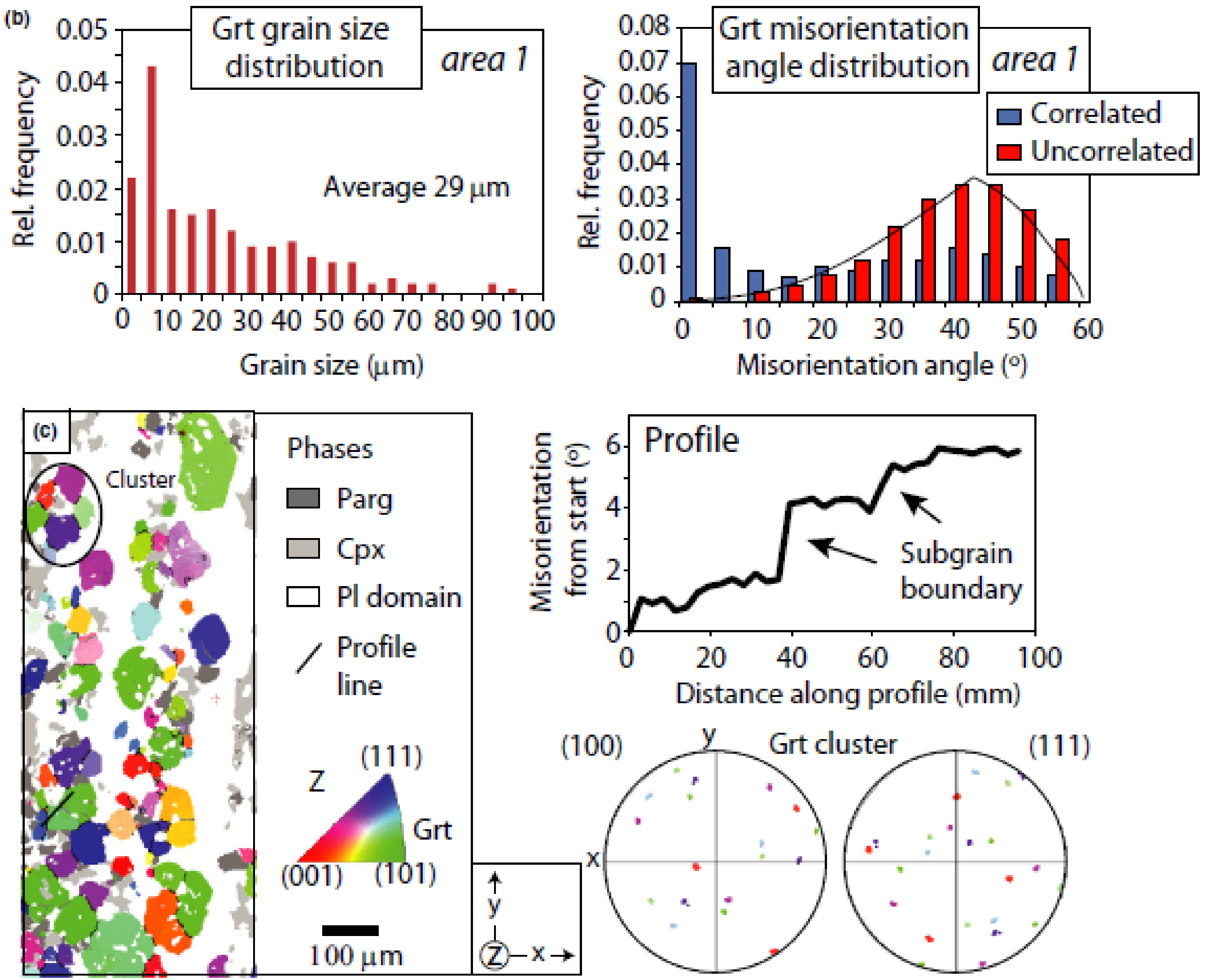
Shear zone: EBSD + EDS analysis



- Bands of grt rich and pl rich areas
- In mixed bands: Grt random orientation – Plag very weak CPO
- Weak CPO for pure plag bands

-> suggests dominance of grain boundary sliding accommodated by diffusion (grt) and dislocation glide (fsp)

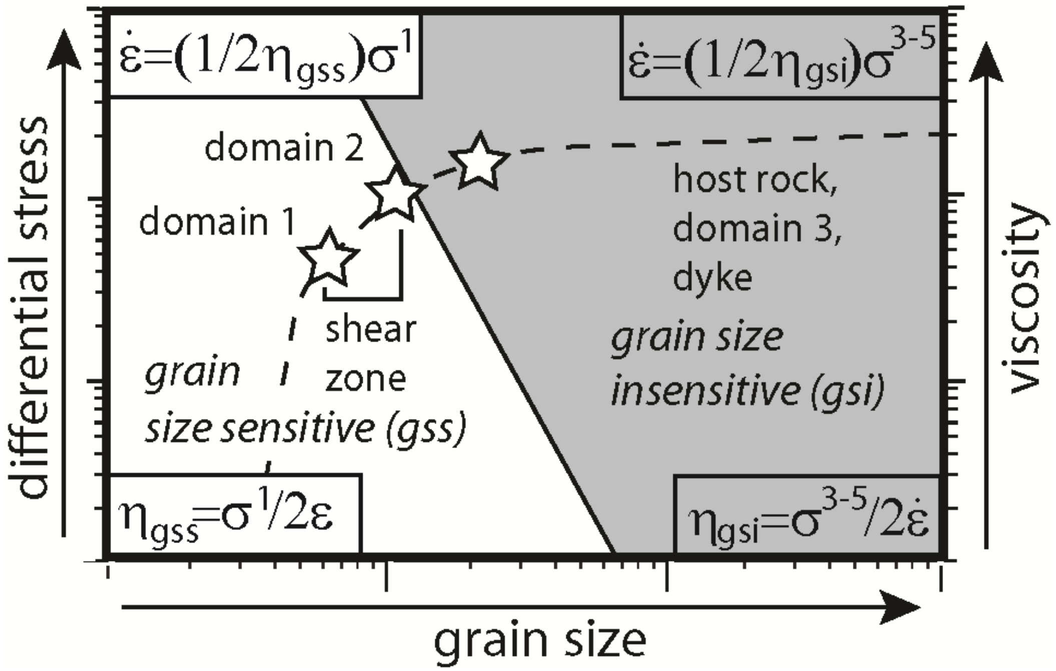
Shear zone: EBSD analysis



Discussion I

Grain size dependent deformation mechanism

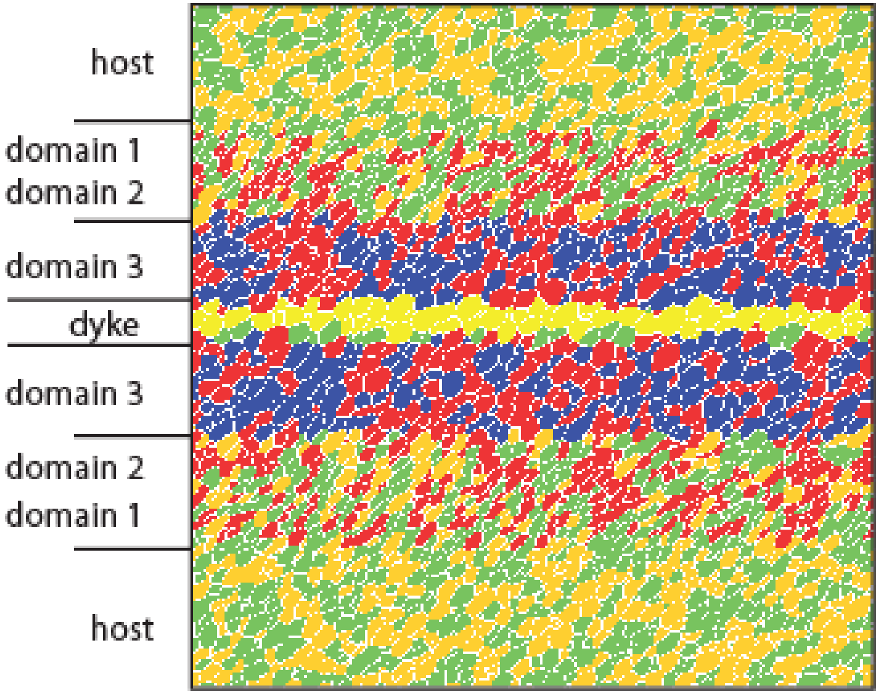
-> change in flow law/effective viscosity



Open Questions

- Is there truly a mechanism change?
- Phase changes versus mechanism change
  -> domain overall viscosity
- What area % of grains need to deform by grain boundary sliding to cause significant strain localization?

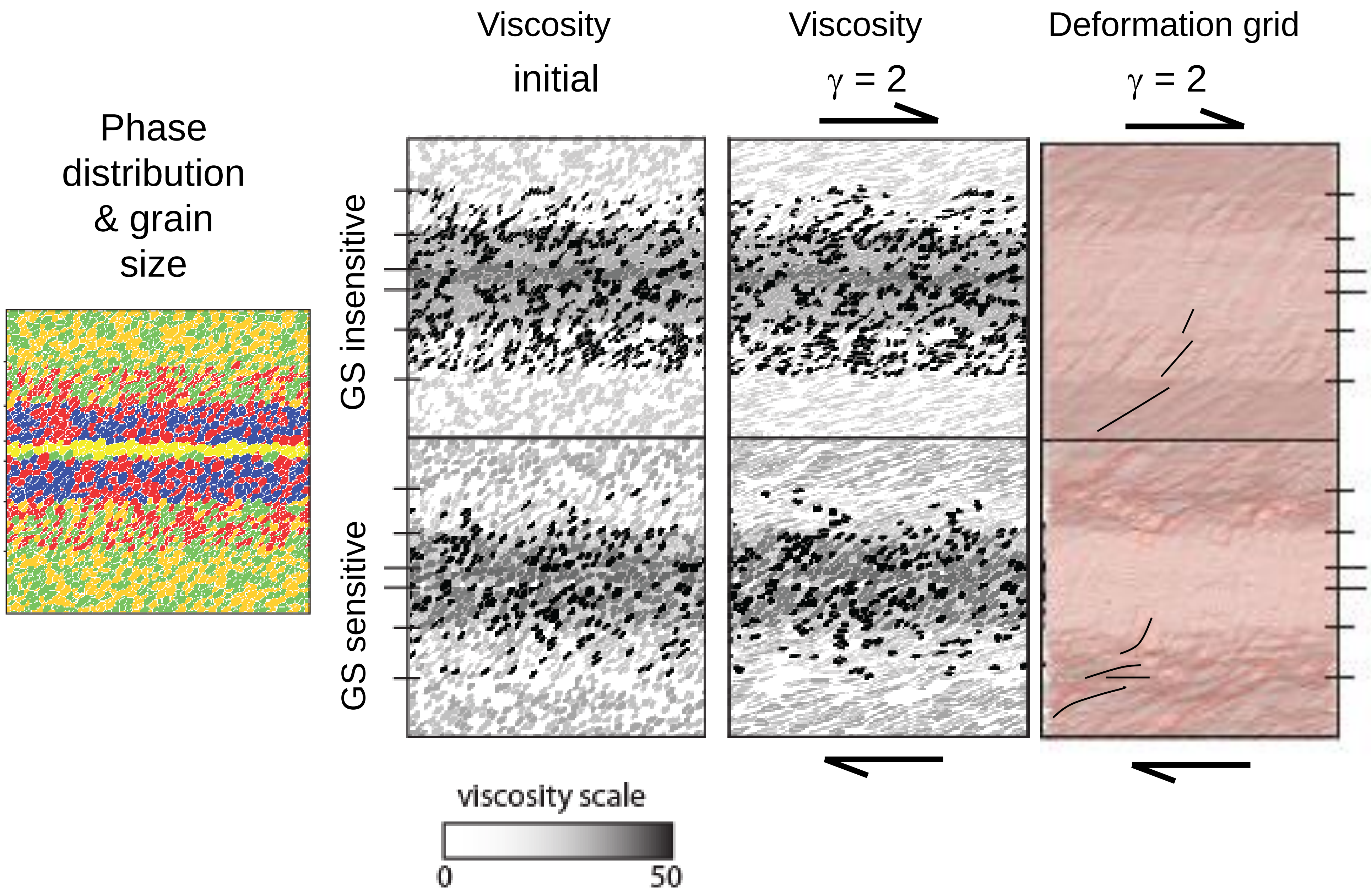
Numerical simulations (Elle/Basil)



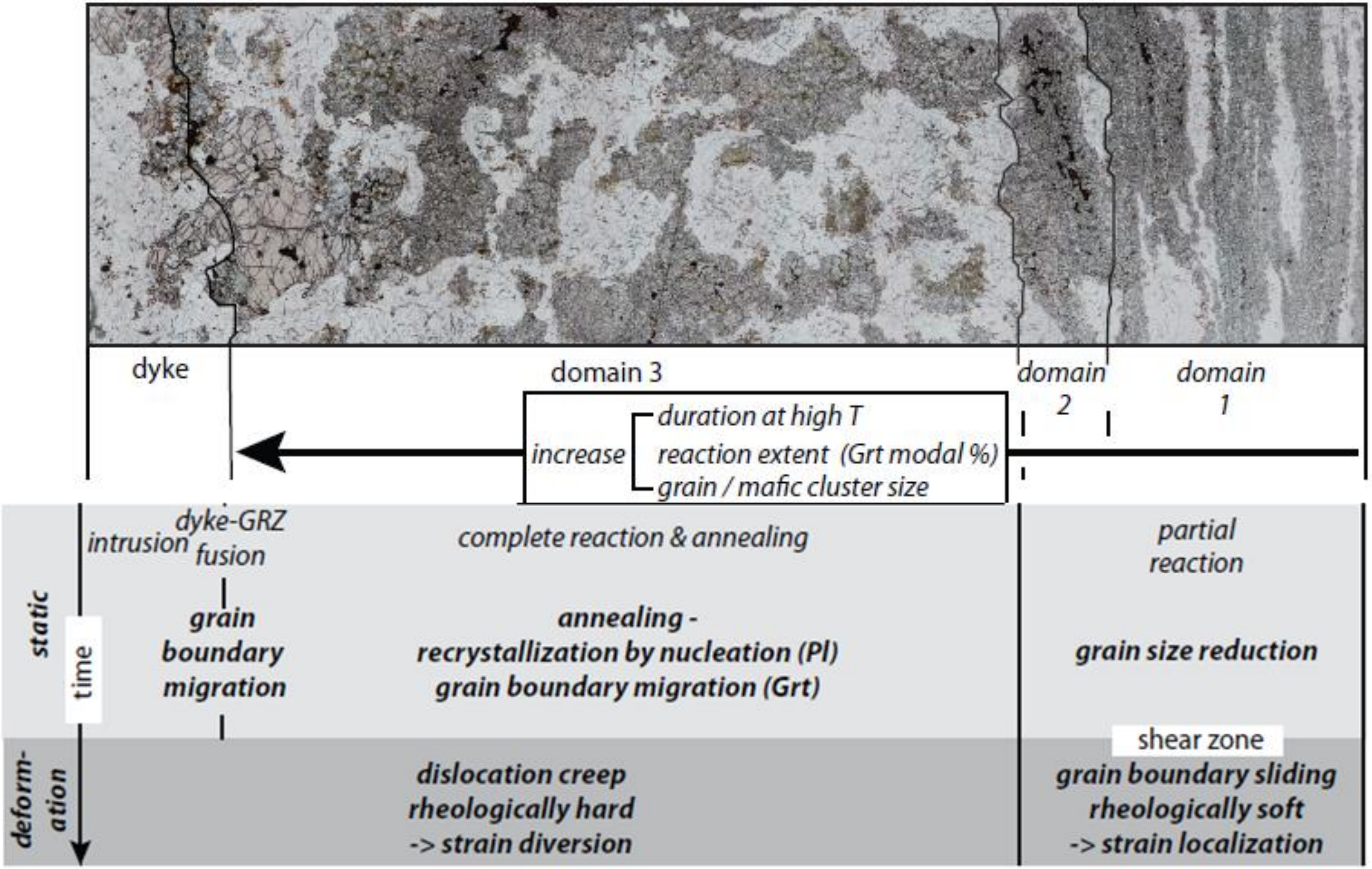
Platform Elle

- Open source
- Specialized for microdynamic modelling
- Viscous deformation

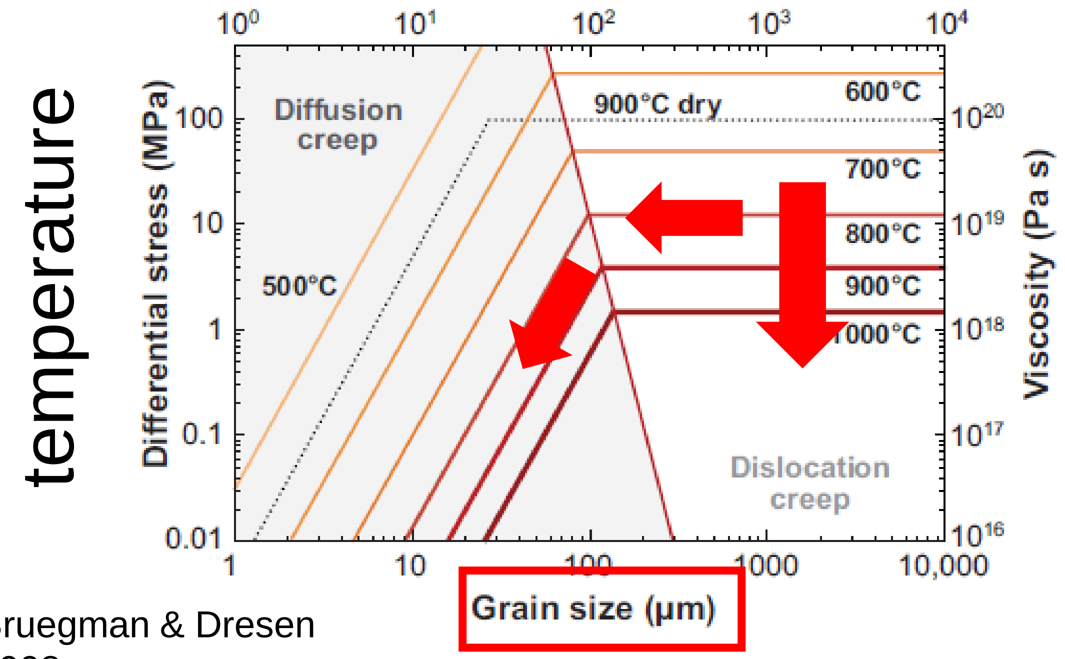
Jessell et al. 2001, Barr & Houseman, 1996, Piazolo et al. 2010, 2019


Phase distribution & grain size
Viscosity initial
Viscosity γ = 2
Deformation grid γ = 2
GS insensitive
GS sensitive
viscosity scale
0
50

Summary


dyke
domain 3
domain 2
domain 1
increase
duration at high T
reaction extent (Grt modal %)
grain / mafic cluster size
static
time
deform-ation
intrusion
dyke-GRZ fusion
grain boundary migration
complete reaction & annealing
annealing - recrystallization by nucleation (Pl) grain boundary migration (Grt)
partial reaction
grain size reduction
shear zone
dislocation creep
rheologically hard
-> strain diversion
grain boundary sliding
rheologically soft
-> strain localization

Weakening of Polyphase rocks



Bruegman & Dresen 2008

Significant Weakening:

-> possible through partial reaction (grain size reduction) rather than/or extreme temperature increase

Smith et al. JMG 2015

Conclusions: Strain localization

- If grain size is sufficiently reduced
  - deformation will occur by grain size sensitive deformation mechanisms (e.g. grain boundary sliding)
  - weakening the zone and localizing deformation in partially reacted areas

- If the mode of rheologically hard phases increases and grain size remains similar to the host rock or also increases, then the reacted rock is strengthened

Smith et al. JMG 2015

2)

Patterns of strain localisation

Gardner, R., Piazolo, S., Evans, L., Daczko, N., EPSL 2017 & in submission (G3)

Strain localisation controls:

- Rheological response to tectonic forces
- Formation of shear zones → control tectonics

Observed patterns of natural shear zones are highly variable:

- Single
- Multiple
- Anastomosing (i.e. interconnected sets of high strain zones)

Heterogeneity in the rocks impacts:

- Strength anisotropy
- Bulk strength
- Evolution of the fabric

➔ **Any change in strength impacts shear zone development**

Aim

Understanding shear zone patterns & lack thereof:

- Influence of the rheology and geometry of pre-existing heterogeneities
- Influence of characteristics of weakening and strengthening processes
- When do we not see shear localization?

Method: Elle/Basil modelling platform

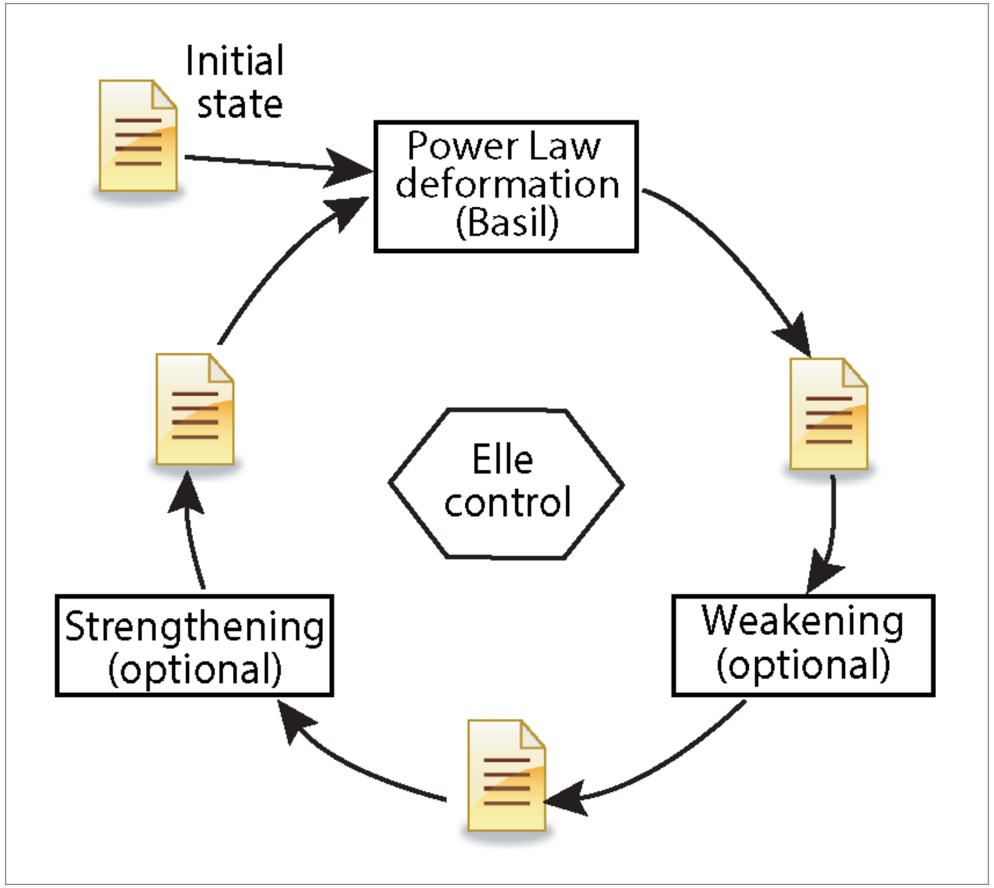
Gardner, R., Piazolo, S., Evans, L., Daczko, N., EPSL 2017 & in submission (G3)

Weakening process: →

- Stress threshold above which an area is weakened
- Simulates stress induced grain size reduction (recrystalisation)
- e.g. dislocation creep to diffusion creep

Strengthening process: →

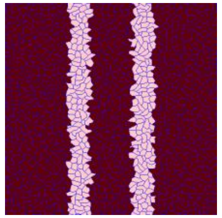
- Time threshold above which an area is strengthened
- Simulates age related grain size increase or strain hardening
- e.g. diffusion creep to dislocation creep

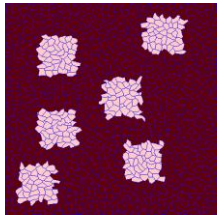


SET 1: 20% weak phase in a load bearing framework

- Variety of geometries tested
- Weak material (20%, light) is Newtonian (n=1)
- Strong material (80% dark) is non-Newtonian (n=3)

5x stronger than the weak material

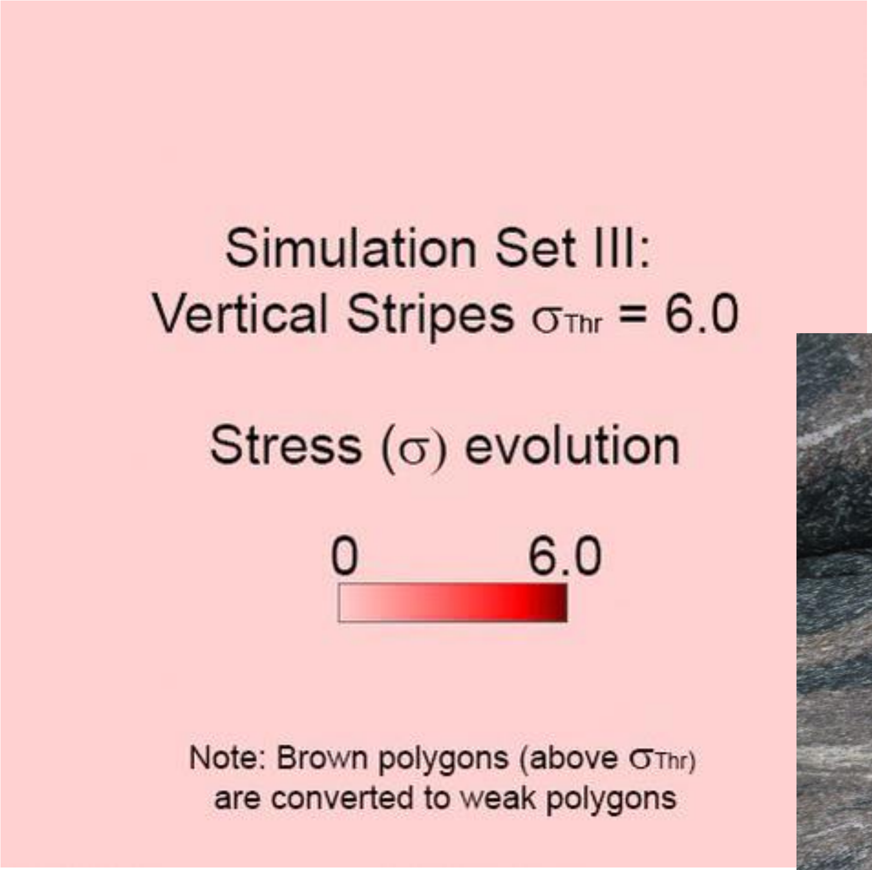


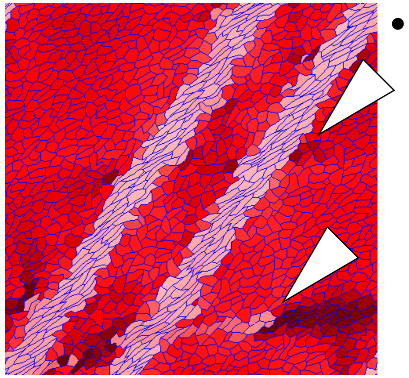


Demonstration of weakening

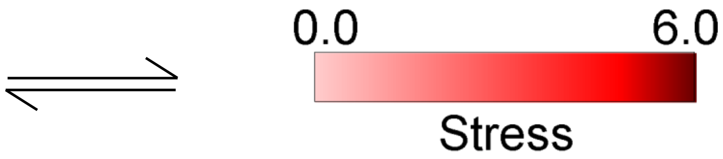
IWL = interconnected weak layer

Set stress threshold → weakening (e.g. lower T)



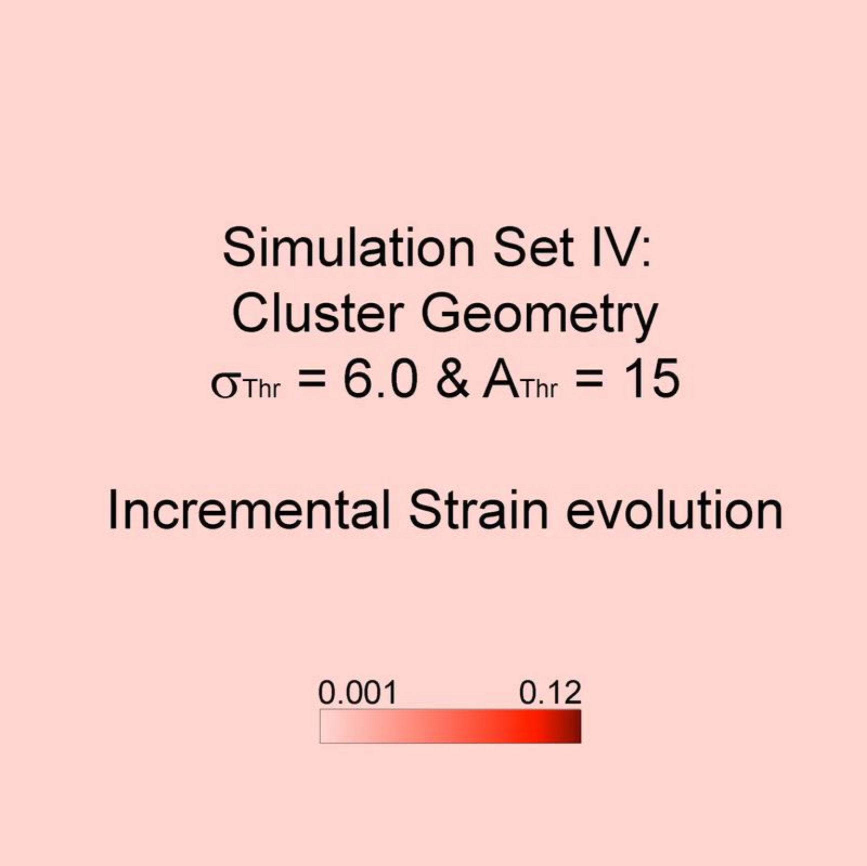


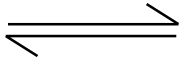
- Stress varies along weak material edge until IWL is initiated

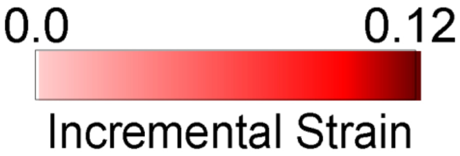


SZ pattern related to weakening

High stress threshold, less weakening (e.g. lower T)

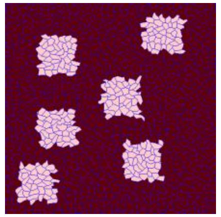


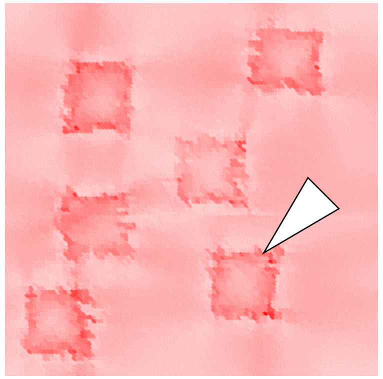




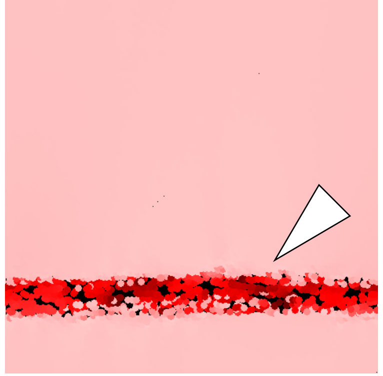
High age threshold

→ Limited strengthening to focus on weakening effect





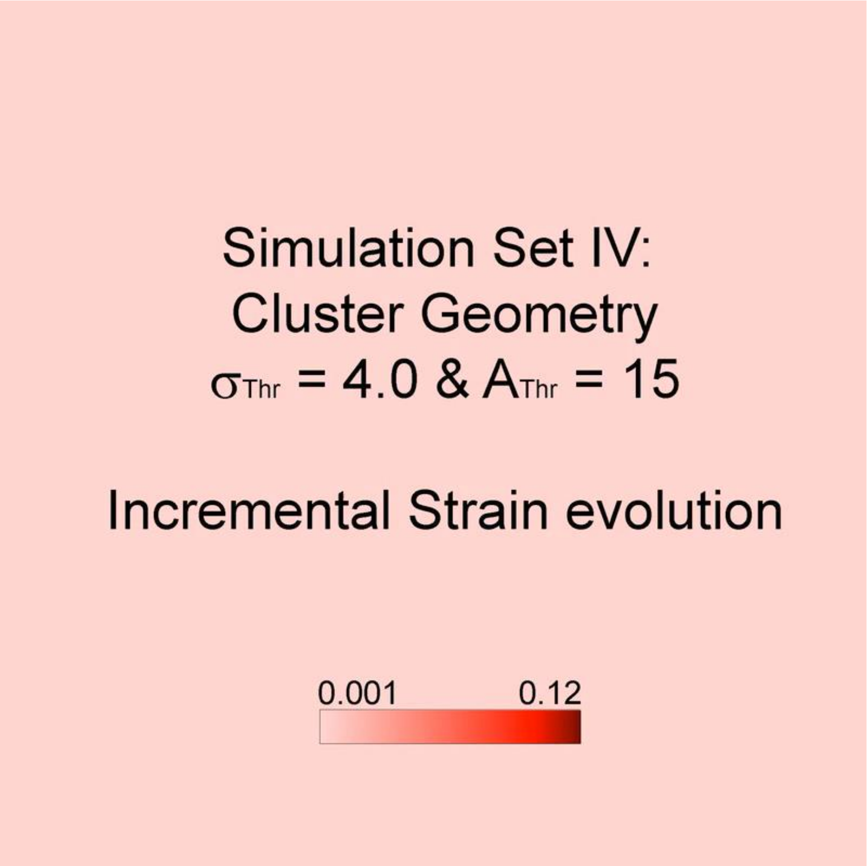
- Strain initially focused into the weak geometry

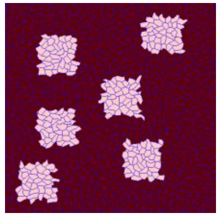


- One IWL formed with strain focused into the single IWL

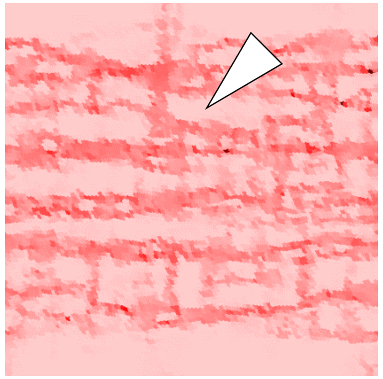
SZ pattern related to weakening

Low stress threshold more weakening (e.g. higher T)

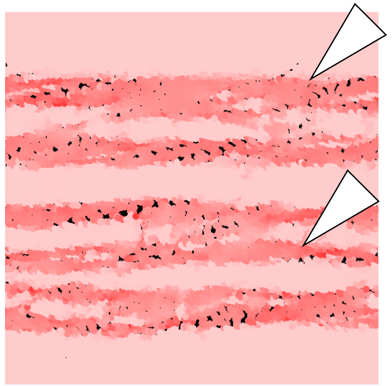




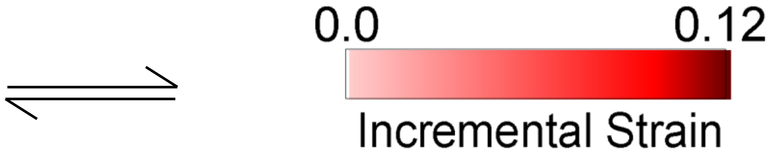
High age threshold
→ Limited strengthening to focus on weakening effect



- Anastomosing IWLs



- Many IWLs formed with all IWLs concentrating strain



SZ pattern relates to weakening

Gardner, R., Piazolo, S., Evans, L., Daczko, N., EPSL 2017 & in submission (G3)

Take home message:

• Models validate field examples & our geological intuition in that strain localizes into:

- Single SZs (in stronger rocks)
- Multiple anastamosing SZs (in weaker rocks)

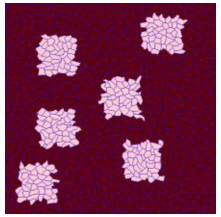
Field examples:

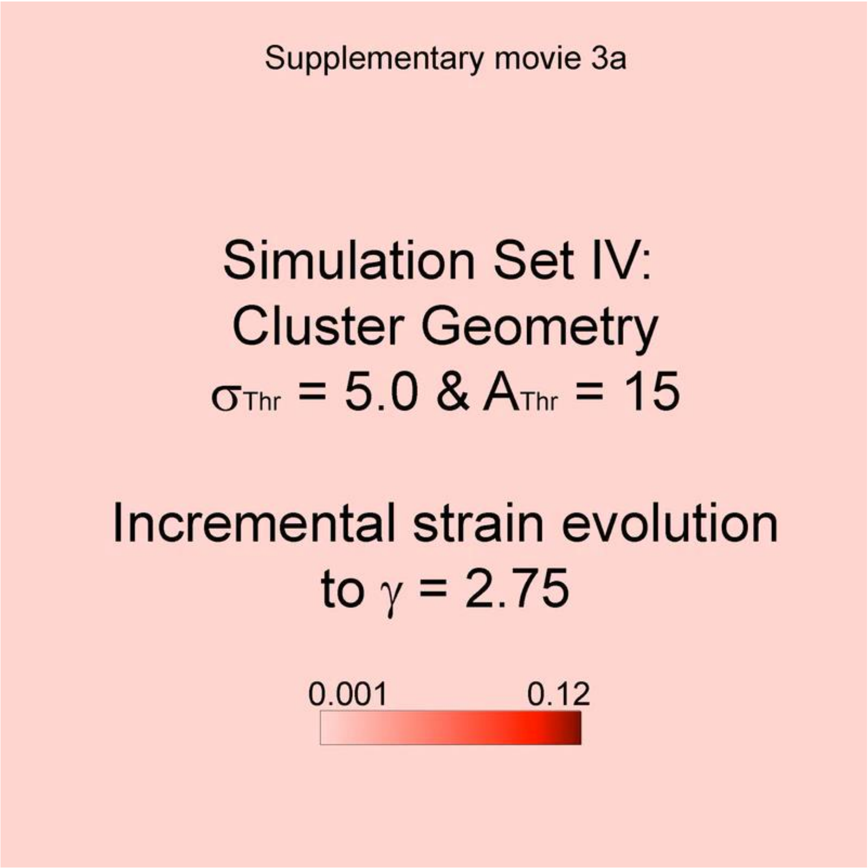
- Kohistan arc NW Pakistan (Arbaret et al., 2000)
- Rainy Lake Zone, Canada (Carreras et al., 2010)

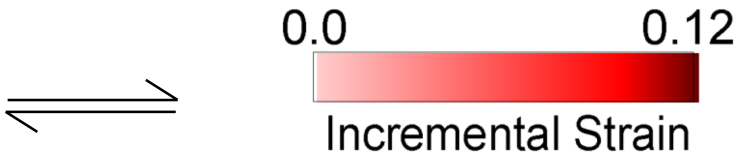
➔ Concentration of strain into fewer shear zones at lower temperatures

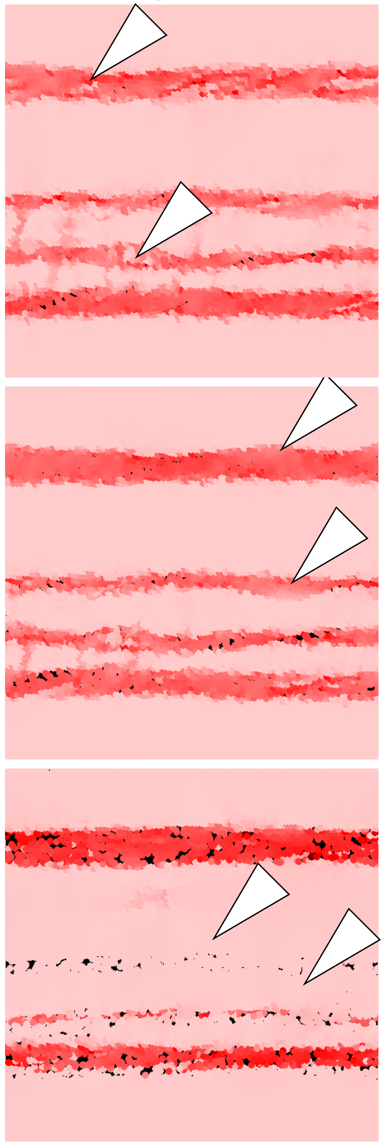
SZ activity related to strengthening

High age threshold → less strengthening (e.g. slow strain hardening)





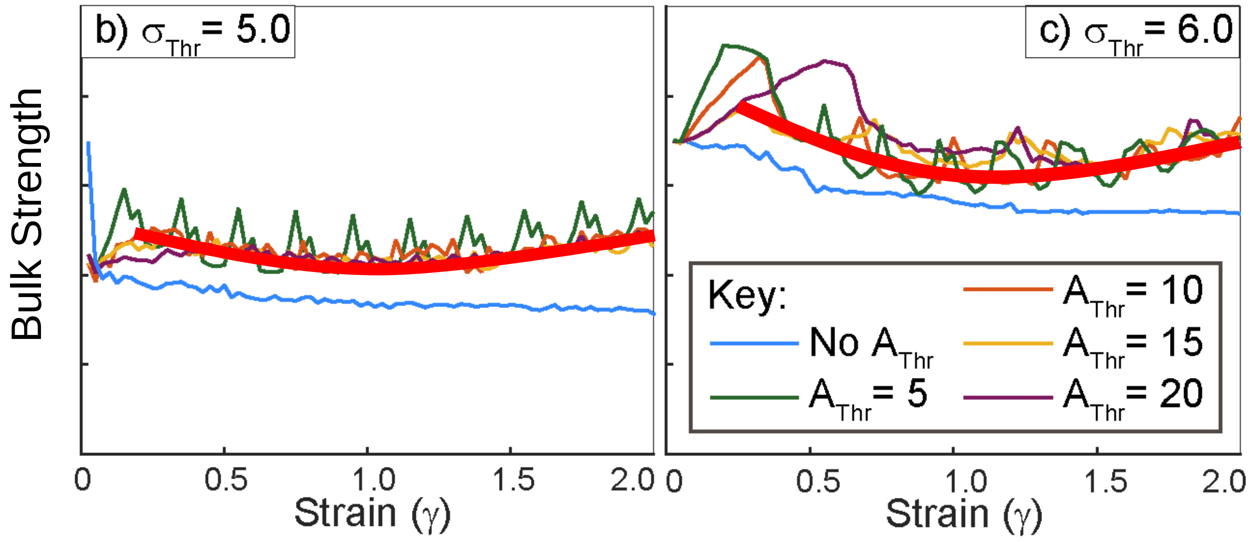




- Location of incremental strain moves within IWL
- Multiple separate IWLs form
- IWL turned off (no strain concentrated) later in simulation

SZ activity related to strengthening

Gardner, R., Piazolo, S., Evans, L., Daczko, N., EPSL 2017 & in submission (G3)



Strengthening process influence

- Bulk strength is cyclic based on the age threshold (model effect)
- Weakening process dominates initially (to γ of ~1)
- Then strengthening process gradually dominates
- IWLs turned off later (no strain concentrated) in the simulation

SZ activity relates to strengthening

Gardner, R., Piazolo, S., Evans, L., Daczko, N., EPSL 2017 & in submission (G3)

Take home message:

- Strain localization is not stable within a single deformation event

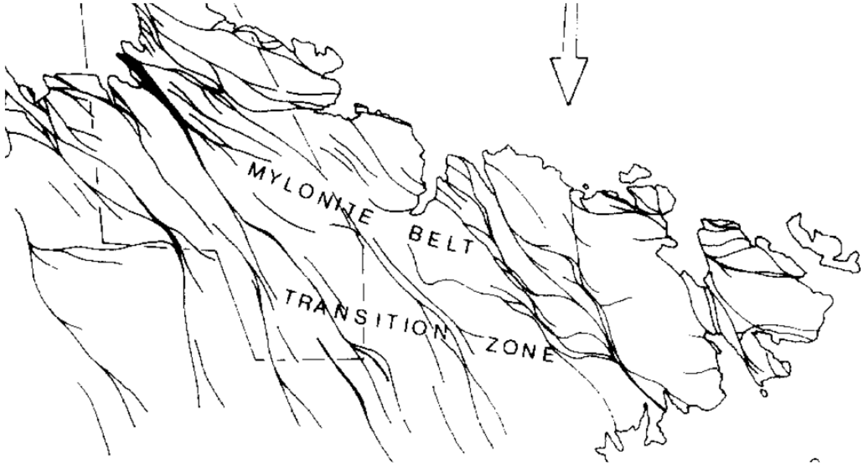
& Within each IWL

& Between IWLs

- Model predicts within a deformation event, where multiple SZs initiate, the narrower ones will cease activity before the wider ones.

→Fewer IWLs (shear zones) will dominate as narrower IWLs are turned off

→Shear zones now observed in a rock were not necessarily all active at the same time



Carreras & Casas 1987

Patterns of strain localisation

Gardner, R., Piazolo, S., Evans, L., Daczko, N., *EPSL 2017* ***& in submission***

- **Strain localization/non localization controls:**
- Rheological response to tectonic forces
- Formation of shear zones or not → control tectonics

- **Observed patterns of natural shear zones are highly variable:**
- Single
- Multiple
- Anastomosing (i.e. interconnected sets of high strain zones)

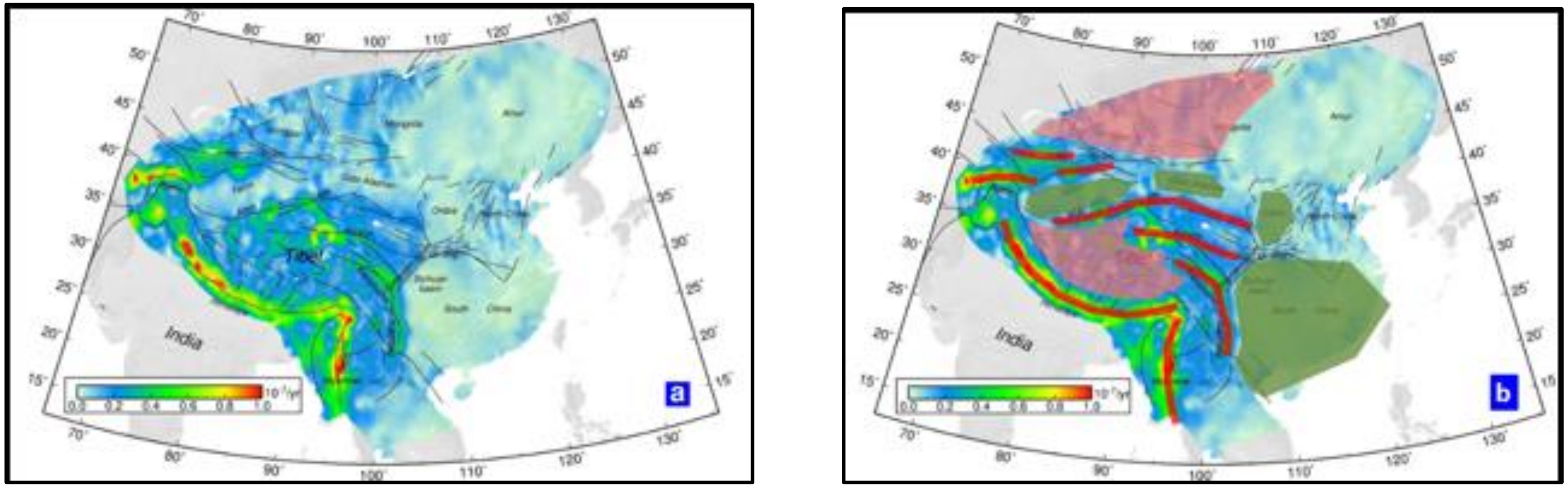
- **Heterogeneity in the rocks impacts:**
- Strength anisotropy
- Bulk strength
- Evolution of the fabric

Aim

Understanding shear zone patterns & lack thereof:

- Influence of the rheology and geometry of pre-existing heterogeneities
- Influence of characteristics of weakening and strengthening processes
- When do we not see shear localization?

Continuous – discontinuous deformation?



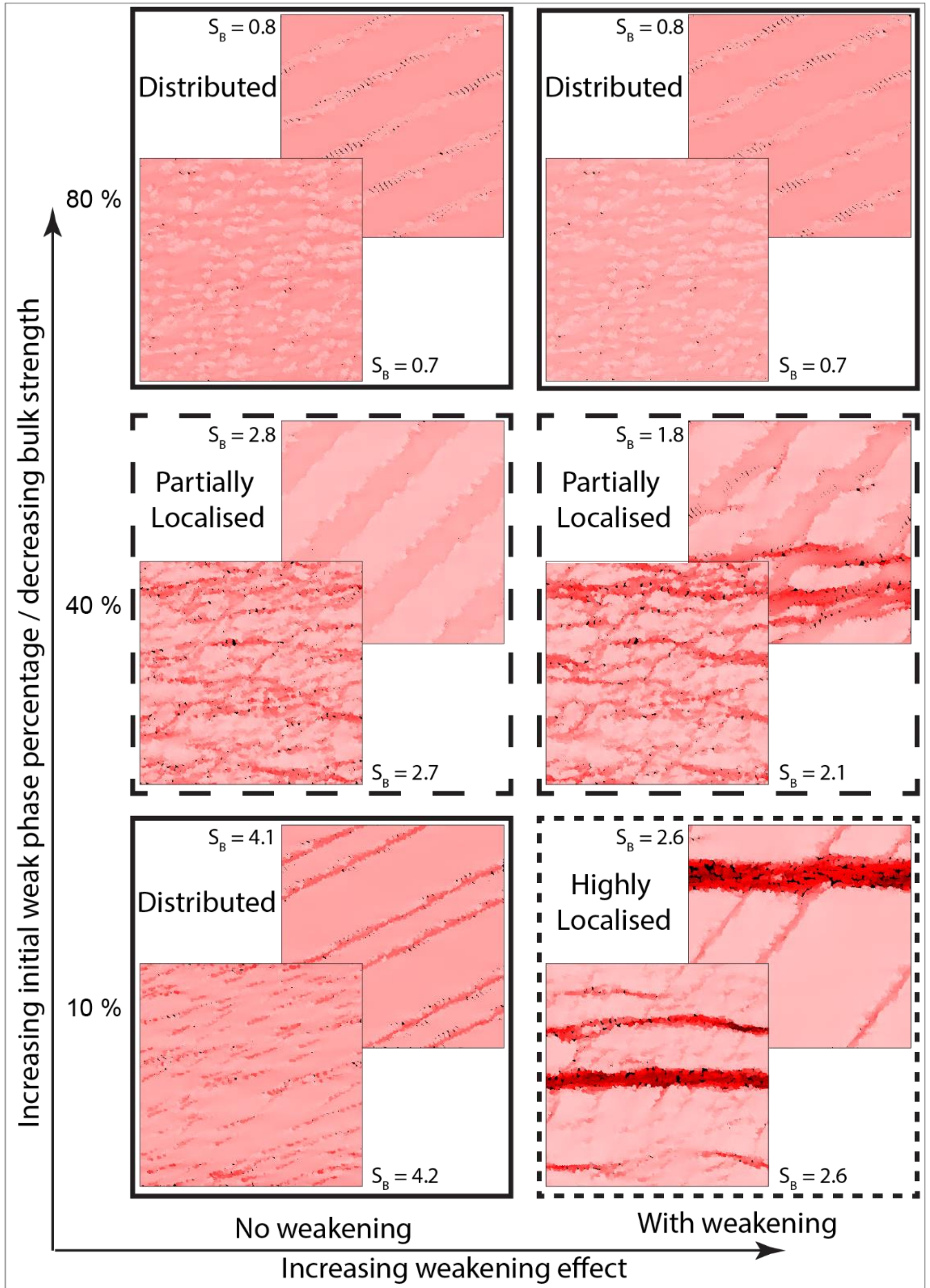
Zheng et al., 2017

Some clear high strain zones

Some distributed strain

Some no strain

Crustal flow – in some parts -> What does that mean?



Distributed strain:

-> Geometry plays minor role

Gardner, R., Piazolo, S., Evans, L., Daczko, N., in submission (G3)

To be strong:

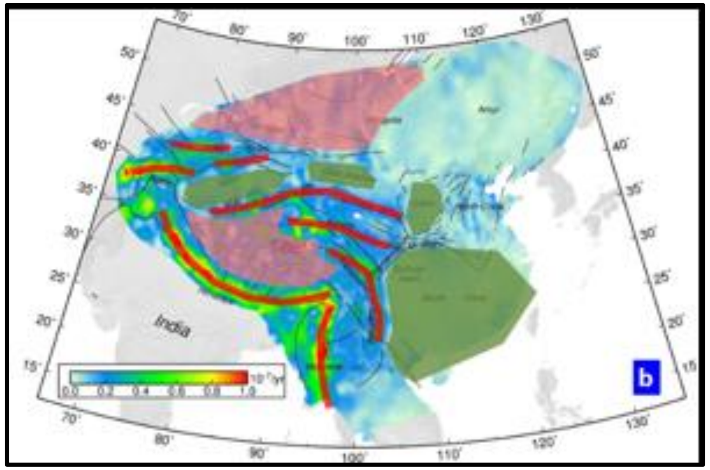
- No weakening mechanism
- Little soft phase% (10/20%)

To be soft:

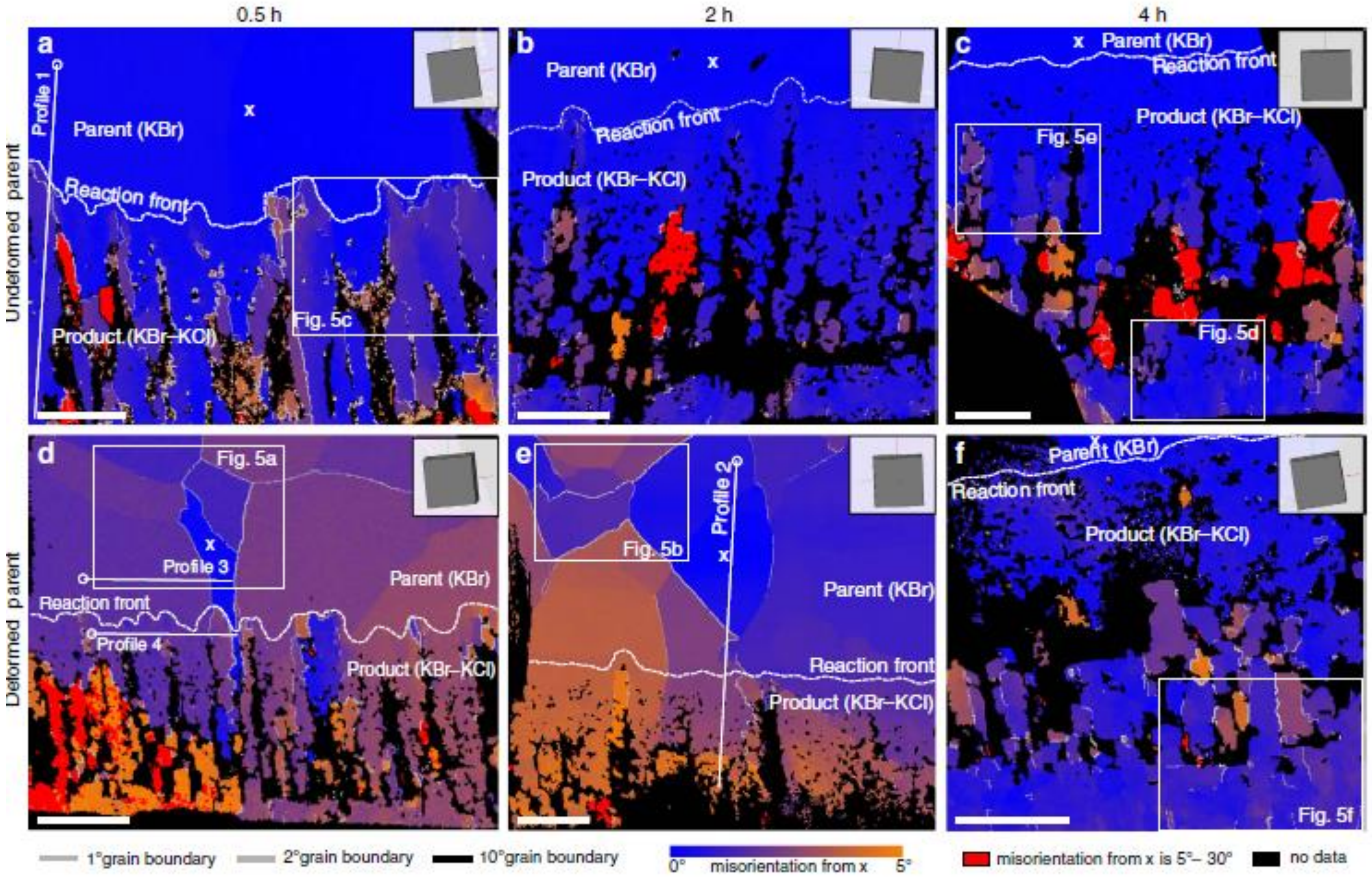
- With or without weakening
- weakening process not needed if high % soft
- High soft phase %

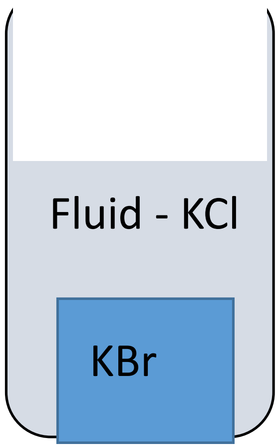
-> high amount of micas/ high amount of melt – distributed melt phase.

Yesterday:
Mafic complex
very little/no strain localization
Melt on boundaries – soft!!



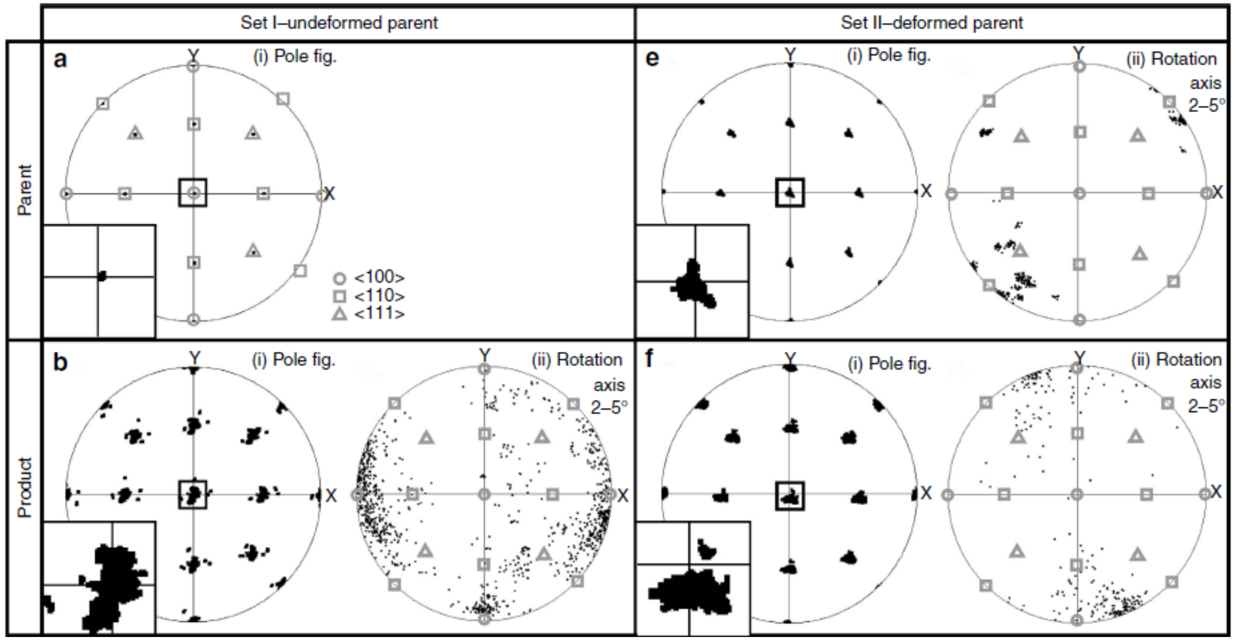
3) *Pseudodeformation as a signature for fluid mediated replacement reactions*

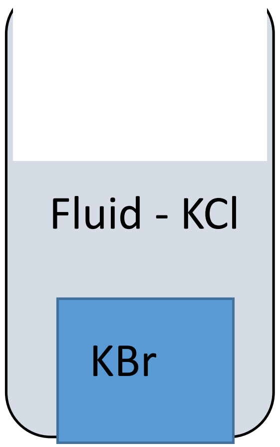




Spruzeniece, Piazolo, Maynard-Casely, Nat. Comms. 2017

Pseudodeformation as a signature for fluid mediated replacement reactions



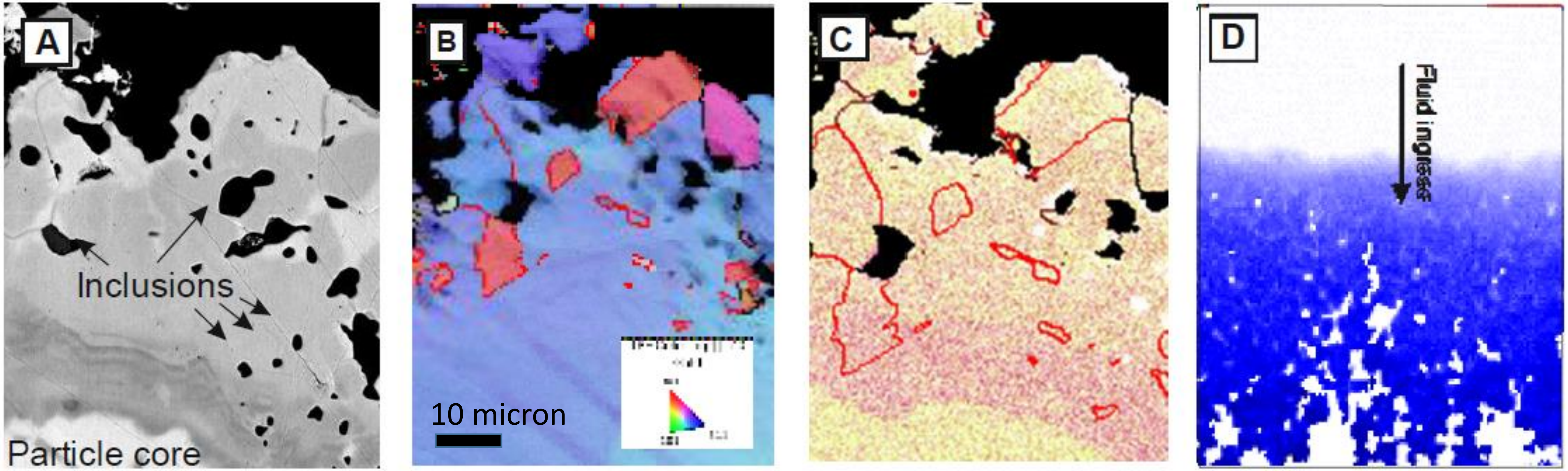


Fluid-rock reaction
- fluid mediated dissolution and precipitation / growth
- pseudo-deformation features
- Needs in depth analysis

Spuzience et al. Nat. Comms. 2017

Pseudodeformation as a signature for fluid mediated replacement reactions

Same in Gold



BSE EBSD Ag counts KBr->KCl

Watch out – in many other minerals – e.g. Fsp, Zircon, titanite !!! Dating effects!! (e.g. Giuntoli et al. JMG 2018)

Chapman et al. in prep.

Thank you & Questions