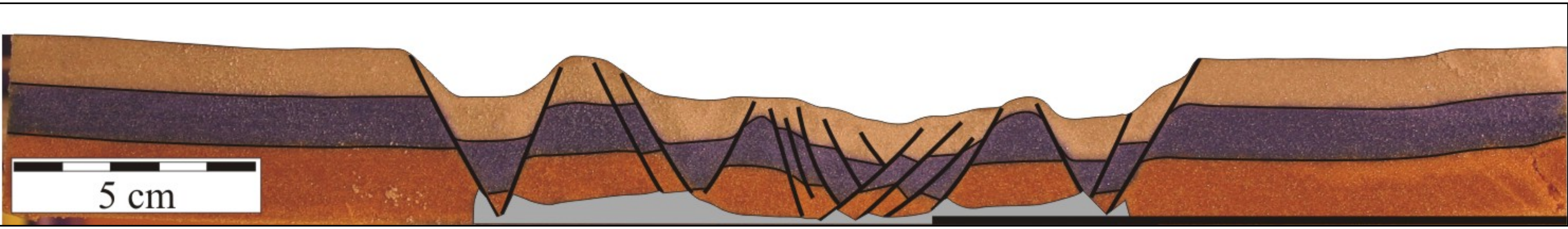
3-D laboratory modelling of lithosphere dynamics: from earthquake surface rupture patterns to crust-mantle interaction



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Geo conferences (WA) Inc.

Outline

- **Introduction to experimental tectonics & scaling**
- **Rheological similarity – brittle & ductile**
- **Particle Imaging Velocimetry (PIV)**
- **Case study I – brittle/granular experiments and earthquake fault rupture patterns**
- **Case study II – isothermal brittle-viscous experiments and drip-tectonics**
- **Case study III – dynamic thermo-mechanical experiments and plate-boundary evolution**

Experimental Tectonics
(aka Analogue Modelling)

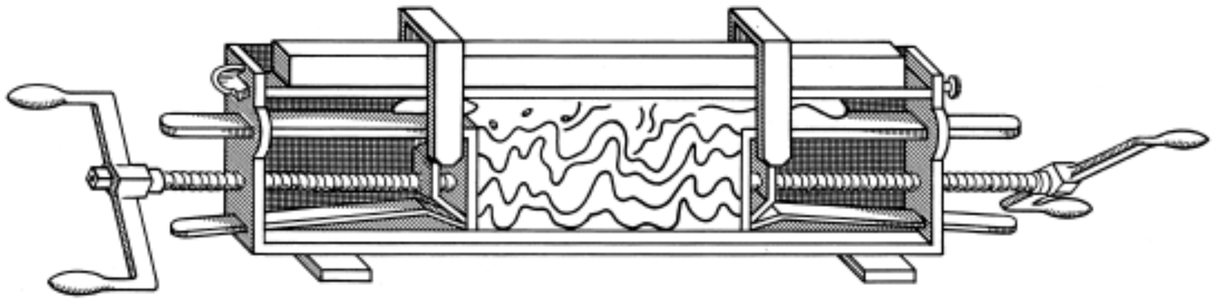
Ranalli (2003)

*The term **experimental tectonics** is nowadays generally used to denote the study of tectonic processes in nature by means of **scale models** in the laboratory. The purpose of scale models is **not simply to reproduce natural observation**, but to **test** by controlled experiments **hypotheses** as to the driving mechanisms of tectonic processes.*

Ramberg (1967)

The significance of scale-model work in tectonic studies lies in the fact that a correctly constructed dynamic scale model passes through an evolution which simulates exactly that of the original (the prototype), though on a more convenient geometric scale (smaller) and with a conveniently changed rate (faster).

Experimental Tectonics
(aka Analogue Modelling)



Hall (1812)

The theoretical basis for analogue modelling comes from the methods of DIMENSIONAL ANALYSIS. **Scaling factors** describe the relationships between a **scale model** (subscript *m*) and the **prototype** (subscript *p*)

The primary scaling factors for length, mass and time

$$\lambda = \frac{l_m}{l_p} \quad \mu = \frac{m_m}{m_p} \quad \tau = \frac{t_m}{t_p}$$

Geometric, kinematic and dynamic similarity must also be satisfied.

Similarity Principles vs Rheology

Geometric Similarity
The model and prototype are geometrically similar if all linear dimensions in the model are λ times the equivalent dimensions in the prototype.

If we scale density with P= ρm/ρp ~ 1, **stress must scale with length**

For brittle behaviour, since rocks have cohesion <50 MPa, the cohesion of the model material must be < 50 Pa. **Hence material properties of granular materials link to geometric similarity.**

Kinematic Similarity
The model and prototype are kinematically similar if the time required for the model to undergo a change in size, shape, or position is τ times the time required for the prototype to undergo a geometrically similar change.

Rocks with viscosities on the order 10^{14} to 10^{20} Pas should be modelled with materials with viscosities 10^{4} to 10^{7} Pas

In practice the time scale, τ is set by the choice of viscous material chosen

Similarity Principles vs Rheology

Dynamic Similarity

Conservation of momentum requires that all body and surface forces acting on a point be zero (Navier-Stokes equation).

If the model and prototype are geometrically and kinematically similar, then they are dynamically similar if the forces in the model are related to the corresponding forces in the prototype by the same scale factor.

Often evaluated by the use of **dimensionless numbers**:

$$\text{Reynolds number,}\quad \mathrm{Re} = \frac{vl\rho}{\eta} = \frac{\text{inertia force}}{\text{viscous force}}$$

$$\text{Ramberg number,}\quad \mathrm{Rm} = \frac{gl^2\rho}{\eta v} = \frac{\text{gravity force}}{\text{viscous force}}$$

$$\text{In tectonics, similar to the Argand number,}\quad \mathrm{Ar} = \frac{F_g}{F_t} = \frac{\text{gravity force}}{\text{tectonic force}}$$

For problems where heat transfer must be scaled:

$$\text{Prantl number,}\quad \mathrm{Pr} = \frac{\eta}{\rho\kappa} = \frac{\text{diffusion of momentum}}{\text{diffusion ofheat}}$$

Hence, rheology is critical to achieve (thermo-) dynamic similarity

Kinematic vs. Dynamic Experiments

Kinematic Boundary Conditions

Most analogue experiments

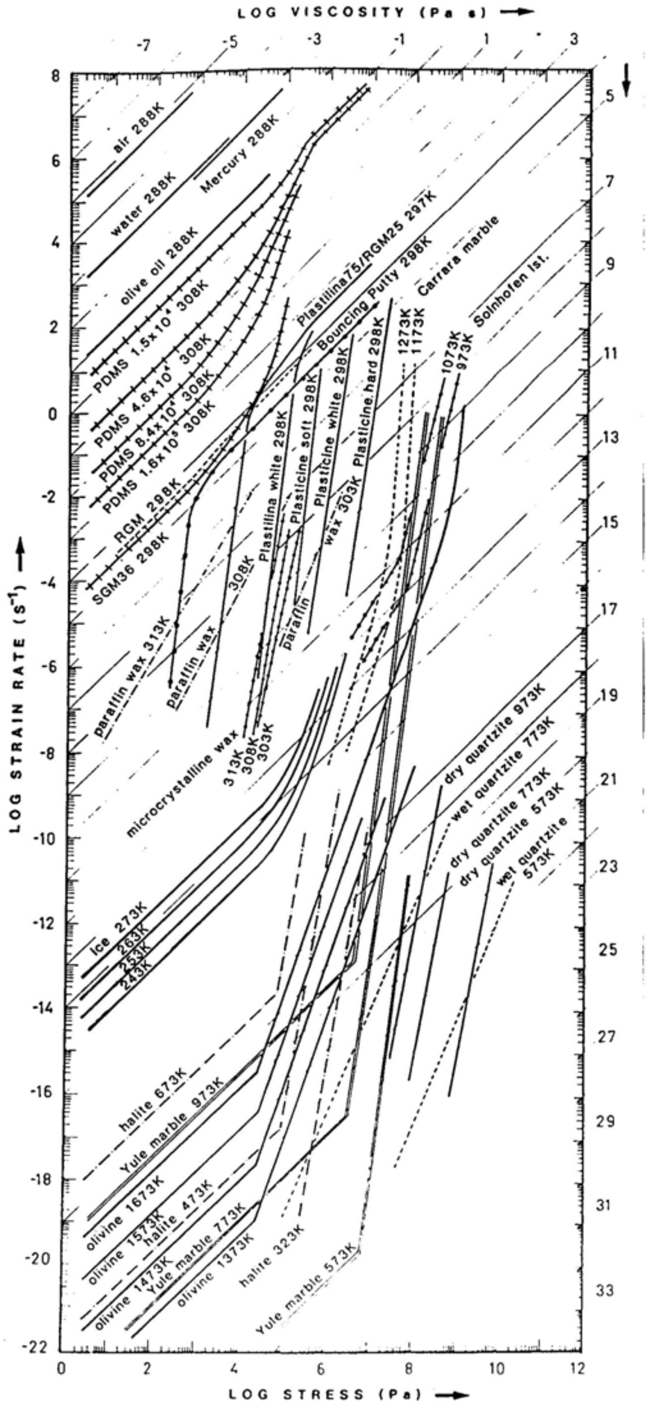
Deformation is driven by a piston at a constant velocity

Dynamic Boundary Conditions

Some experiments, e.g., gravity driven (diapirs, gravity flows, free subduction)

Deformation is driven by internally generated body forces

A major challenge for experimentalists is to design fully dynamic experiments in which stresses and velocities evolve and can be measured with time (and temperature)



Rheological Similarity

(Weijermars & Schmeling 1988)

Another major challenge in analogue modelling is to find or design materials whose rheological properties match as closely as possible those of natural rocks under ductile conditions.

Many available materials are Newtonian or almost Newtonian under experimental conditions.

Ongoing and future work will define new materials that have more desirable properties (e.g., strain rate softening, strain hardening or weakening, temperature dependence, etc.)

Special polymers

Polymer/plastics/clay blends

Filled fluids

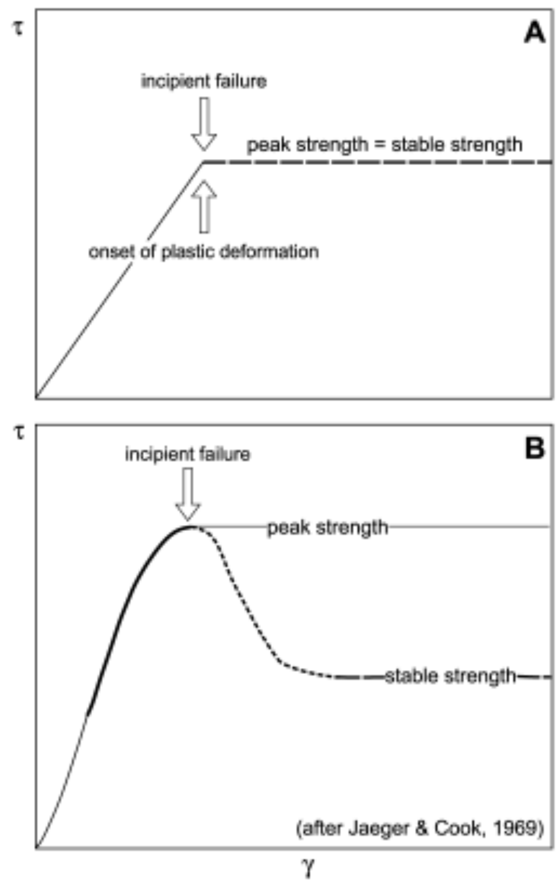
Granular Materials

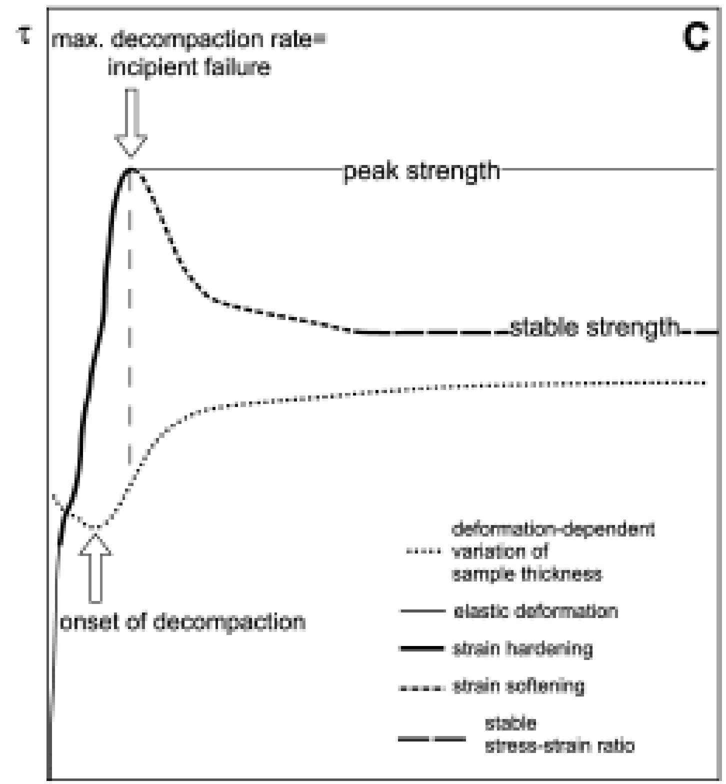
Generally well established for use in analogue modelling for brittle behaviour

Sand, microbeads, microbubbles, sugar, walnut shells, tapioca…………..

Ideal Coulomb

Real rocks





Sand

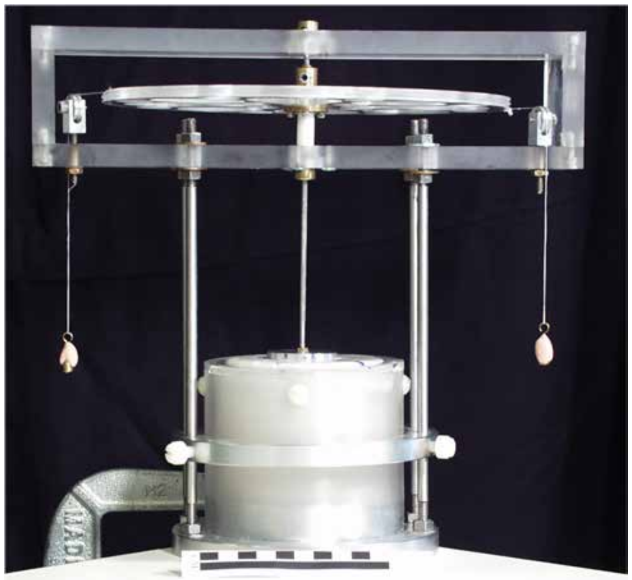
Lohrmann et al. (2003)

Stress-strain curve is very sensitive to material handling (e.g., sieved vs. poured)

Ductile Materials

Material Property Determination

Viscometers

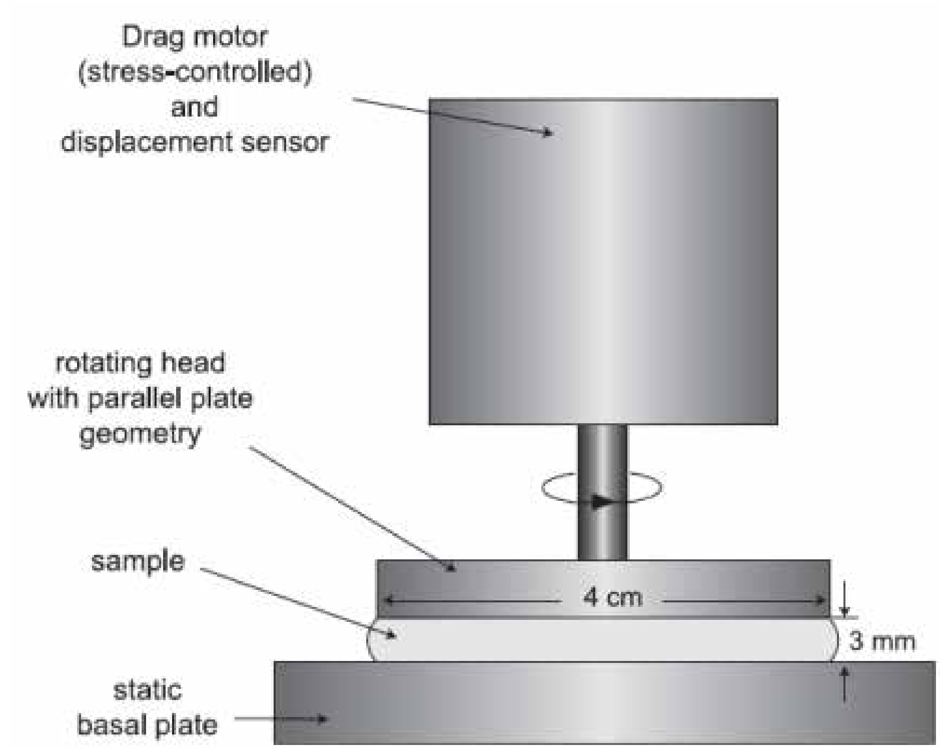


Constant stress

Viscosity

Power law exponent

Rheometers



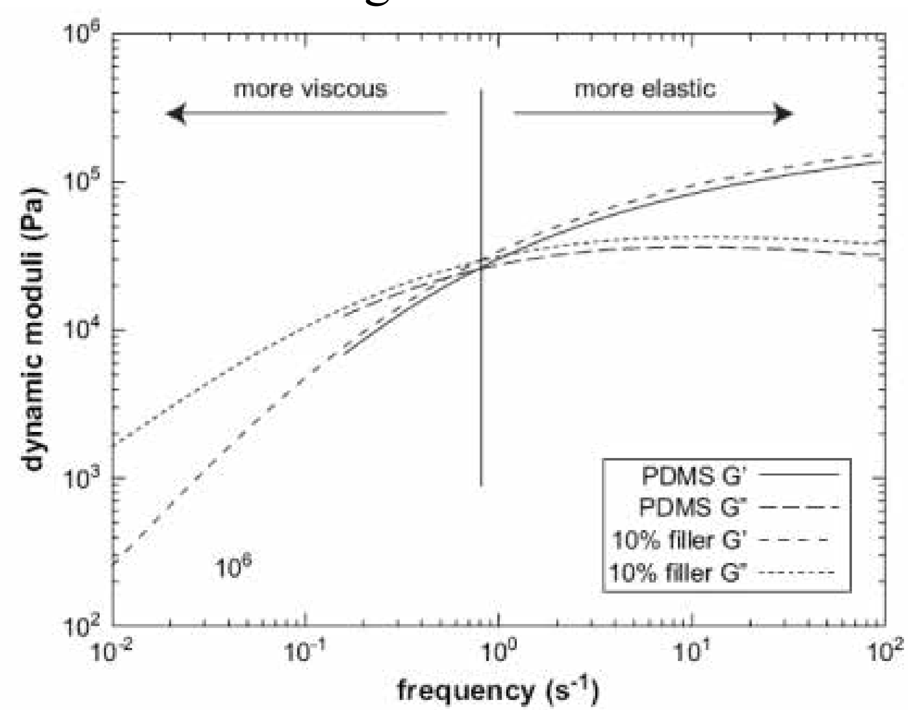
Controlled stress or controlled strain rate

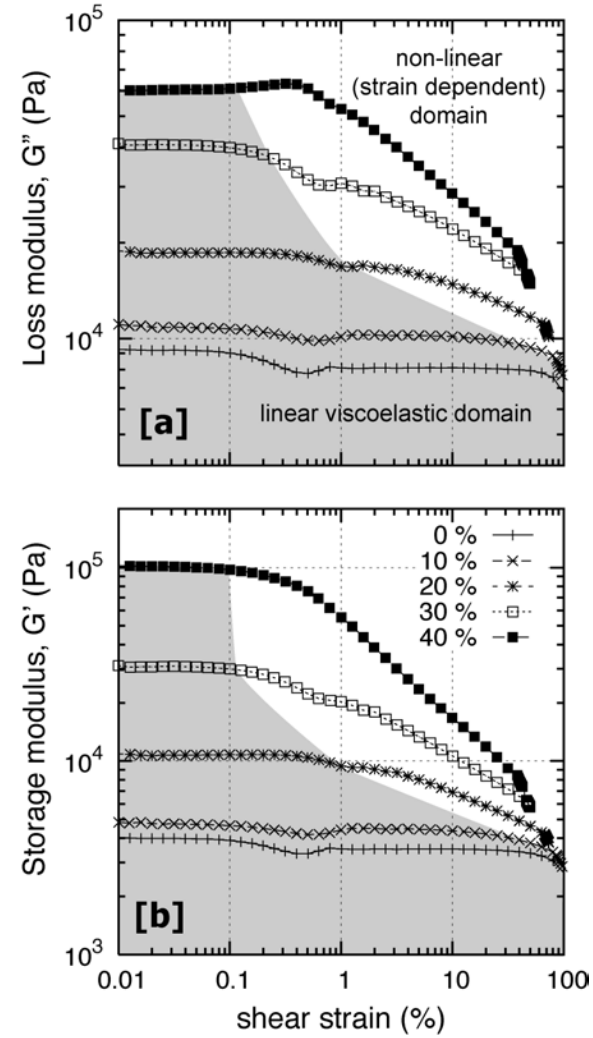
Oscillatory measurements – viscoelastitic properties, complex rheologies…..

S. ten Grotenhius et al. (2002), Boutelier et al. (2008)

Rheometry

Tests: Dynamic (frequency and strain sweeps) – an oscillating shear stress or shear strain is applied to the sample and the shear strain or shear stress is measured – storage and loss moduli





PDMS and PDMS + 10% solid filler – frequency sweep (above)

PDMS + Plasticene mixtures – strain sweep (right)

Deformation Visualization

Time-lapse photography and strain grids

Laser surface scanning (topography)

Digital photogrammetry (topography)

Particle Imaging Velocimetry (PIV)

•Introduced to analogue modelling by Adam et al. (2005)

•2D optical image cross correlation

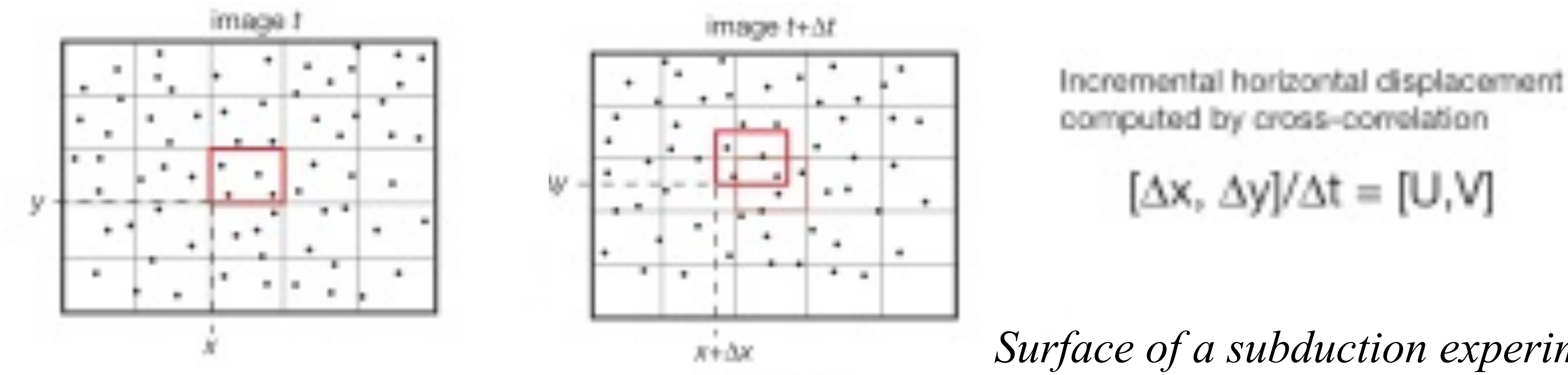
•3D with volume calibration

•Surface flow (deformation) experiments

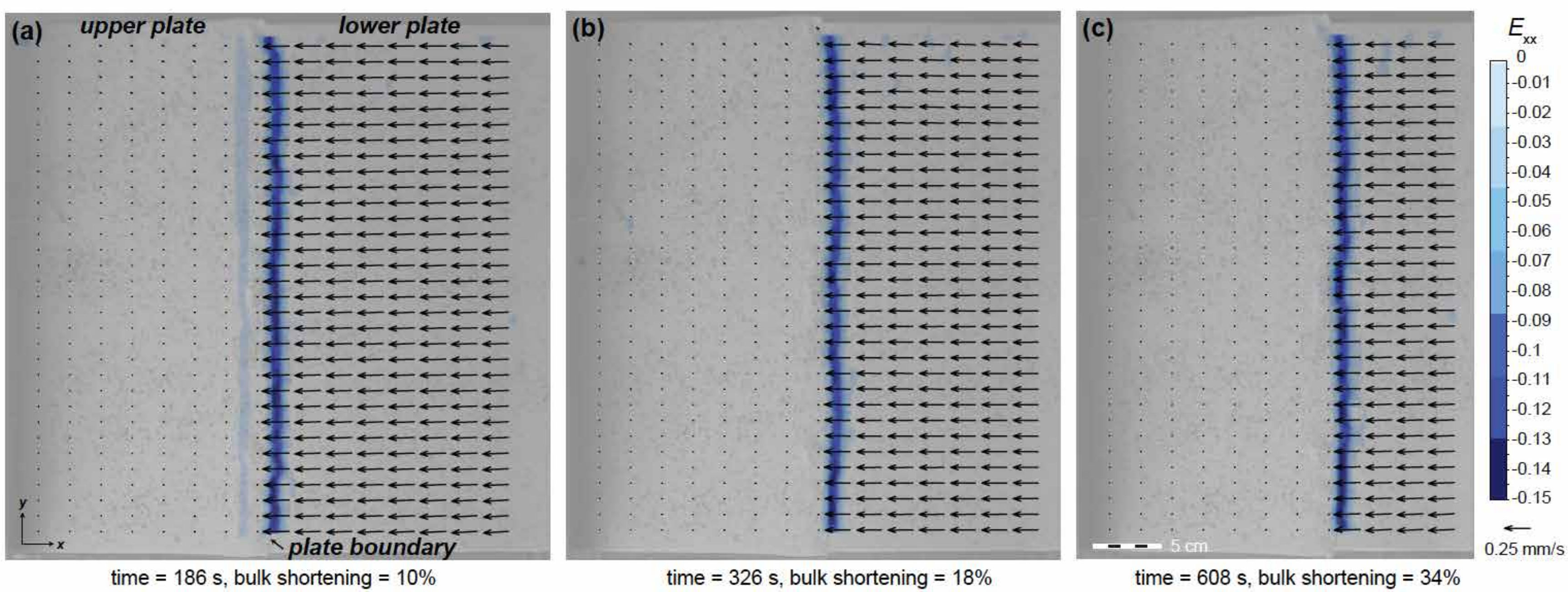
•Fluid flow (tank) experiments

PIV - 2D & 3D optical image cross correlation

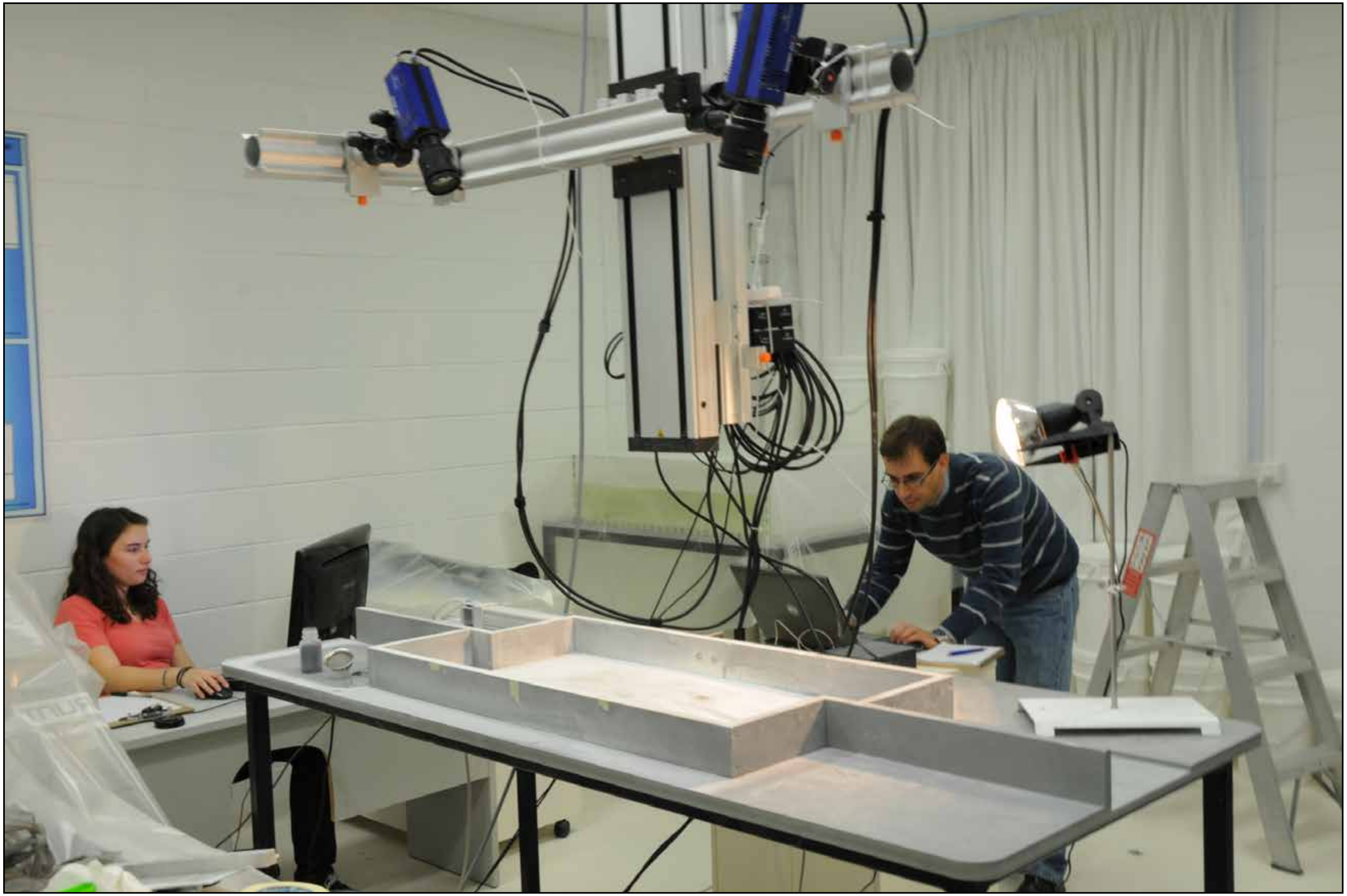
- Velocity field -> Deformation tensor
- Cumulative and incremental normal and shear strains (Eulerian & Lagrangian)
- Cumulative and incremental normal vorticities, etc.



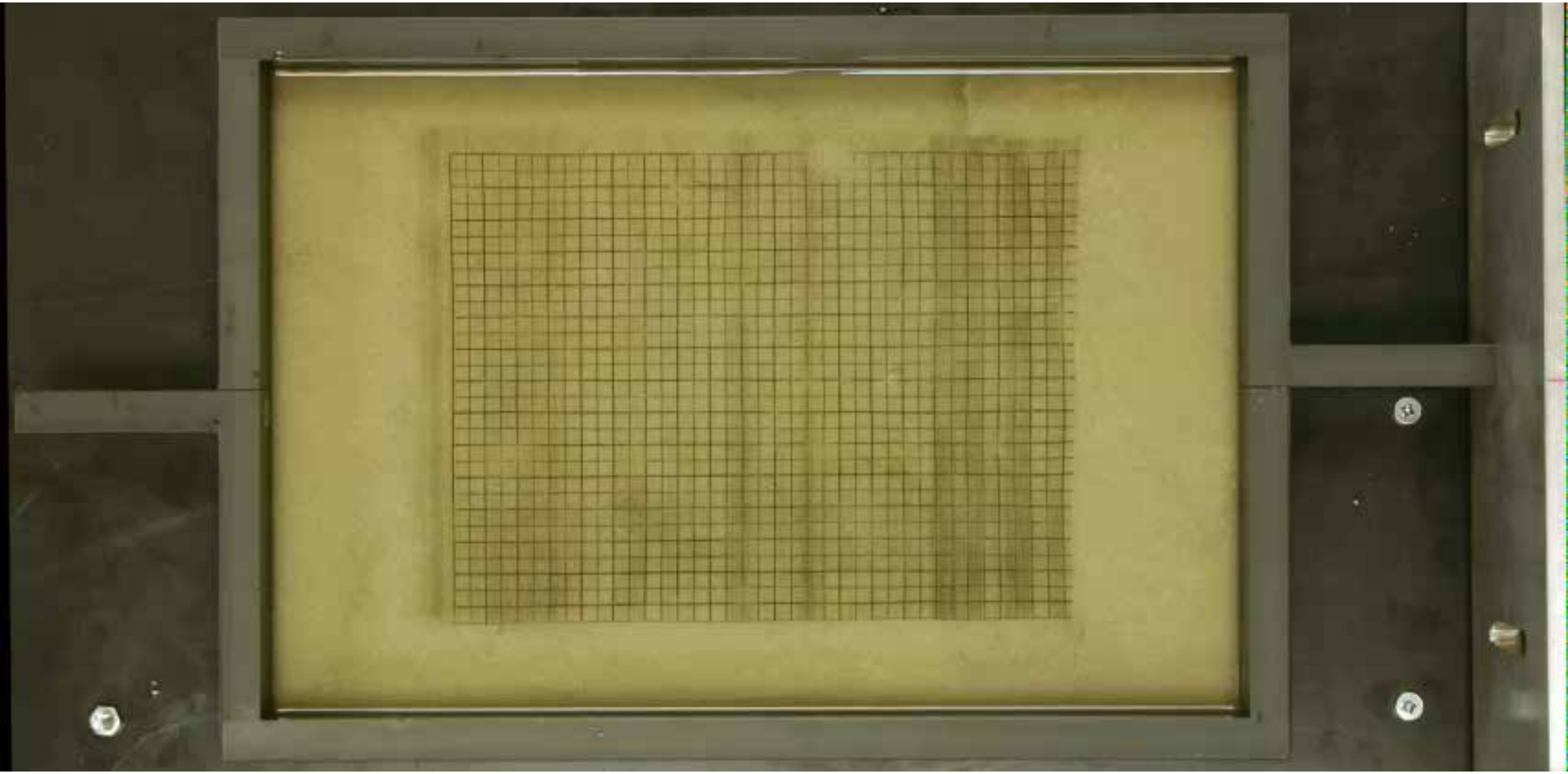
Surface of a subduction experiment



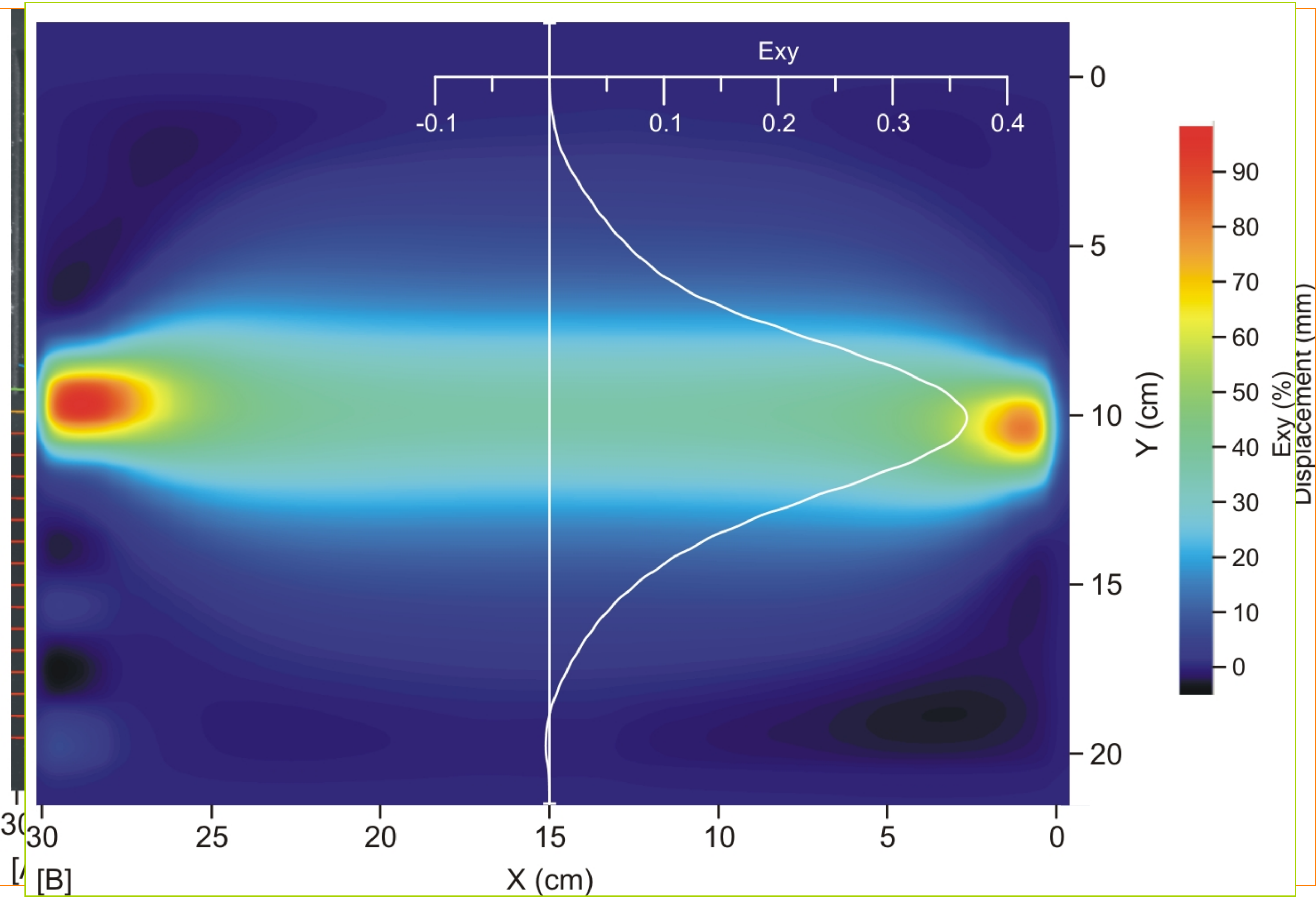
The Analogue Shear Zone



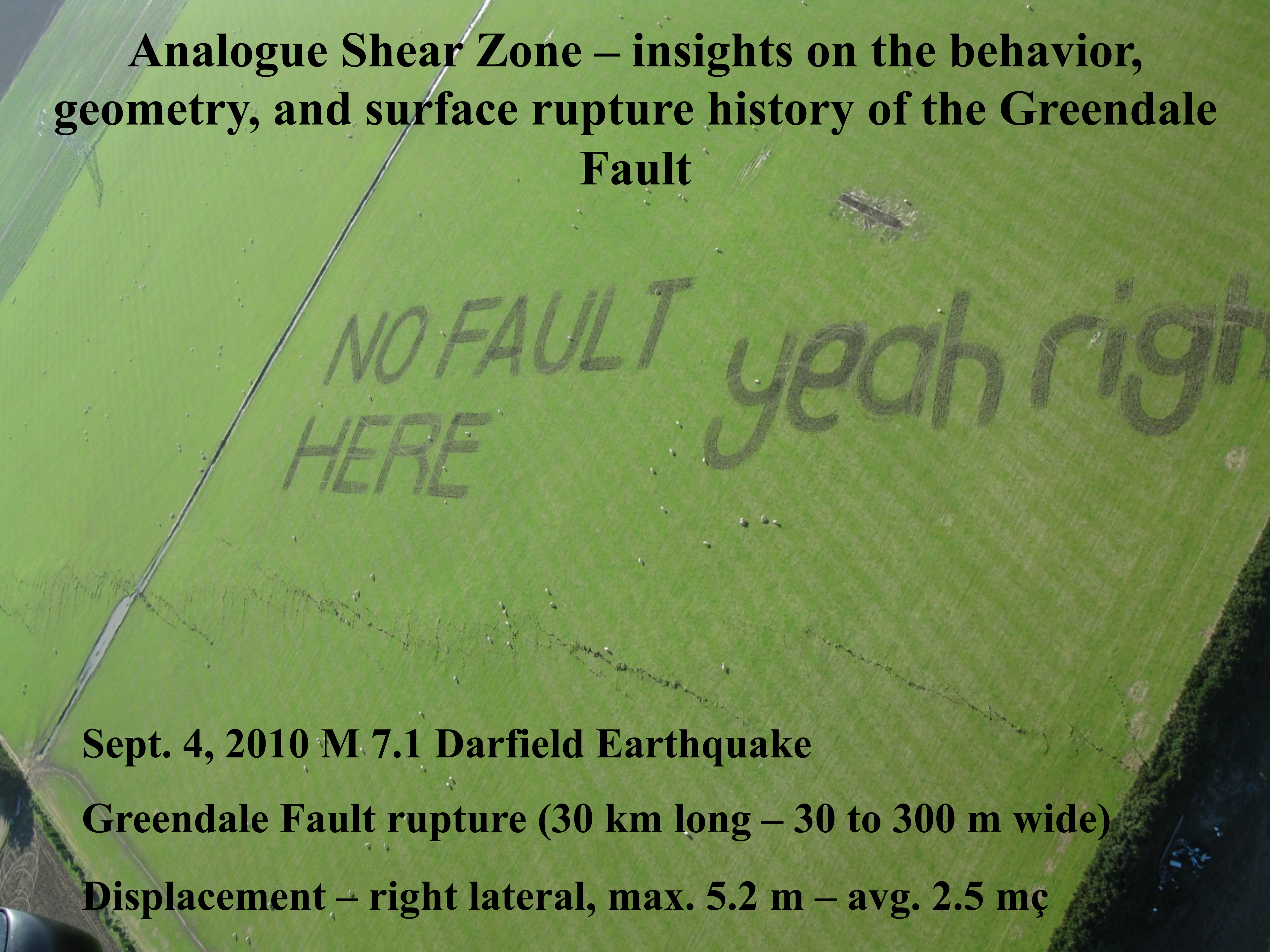
Analogue Shear Zone Strain Evolution



PIV measurements



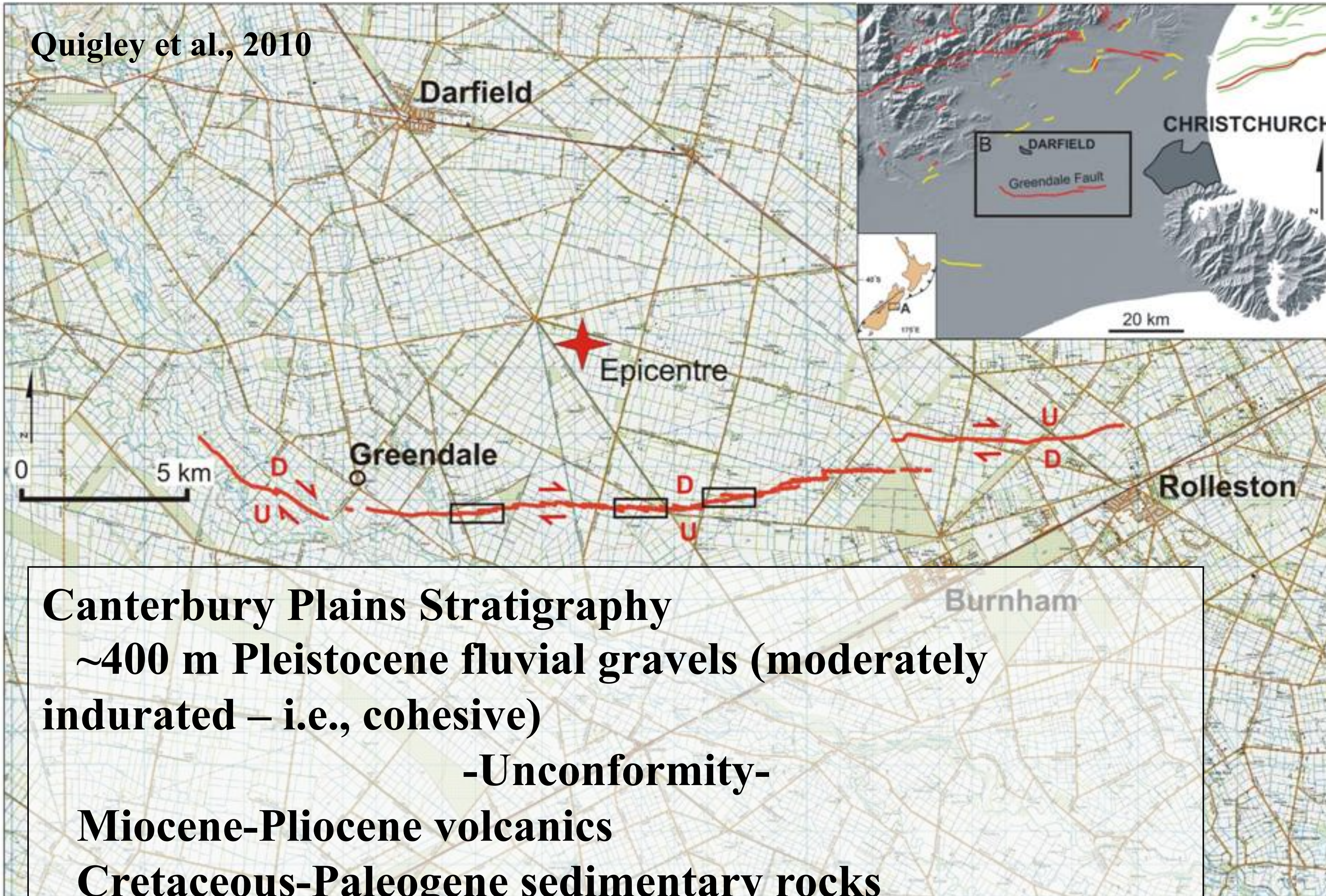
Analogue Shear Zone – insights on the behavior, geometry, and surface rupture history of the Greendale Fault



Sept. 4, 2010 M 7.1 Darfield Earthquake

Greendale Fault rupture (30 km long – 30 to 300 m wide)

Displacement – right lateral, max. 5.2 m – avg. 2.5 mç



Canterbury Plains Stratigraphy

~400 m Pleistocene fluvial gravels (moderately indurated – i.e., cohesive)

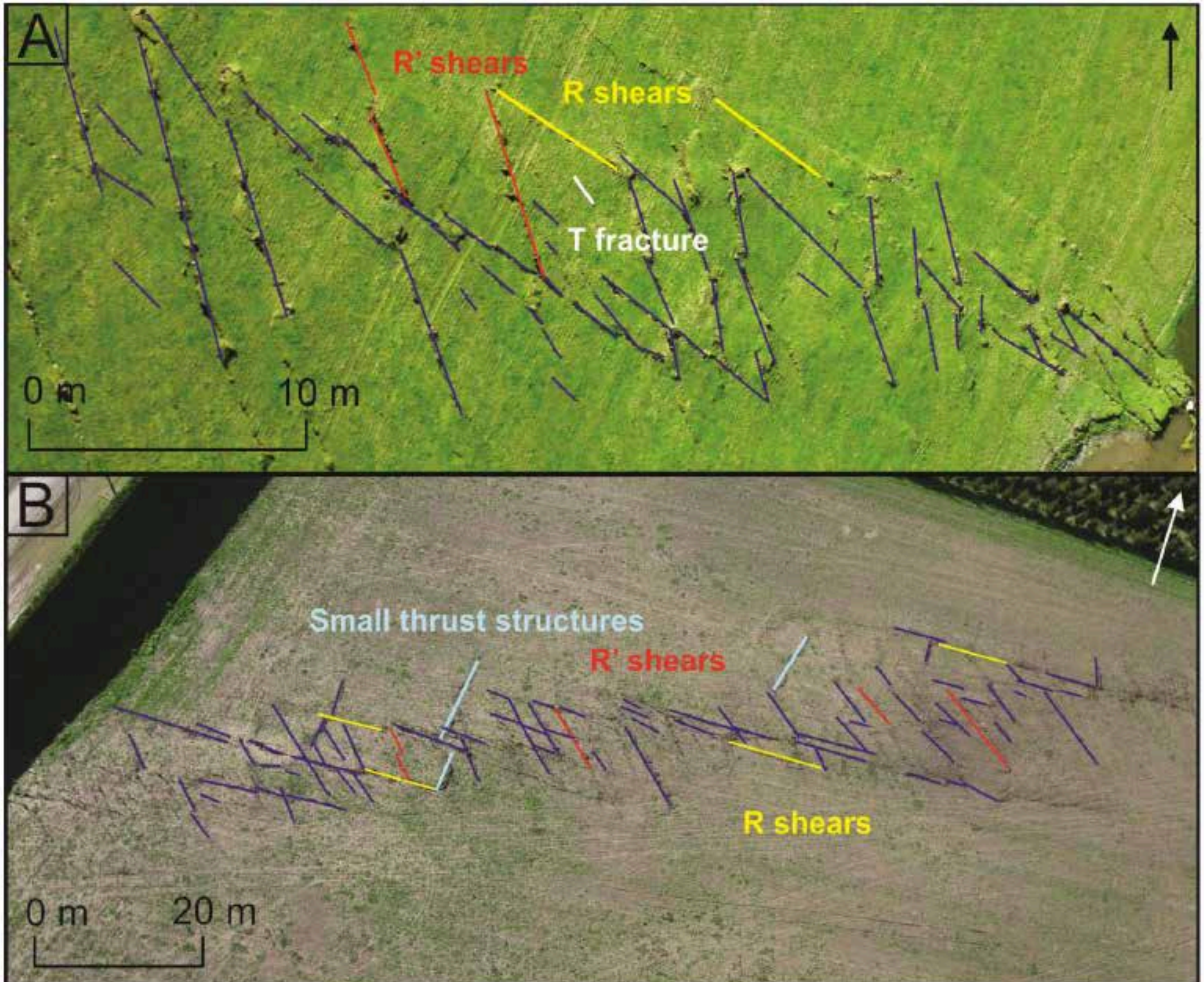
-Unconformity-

Miocene-Pliocene volcanics

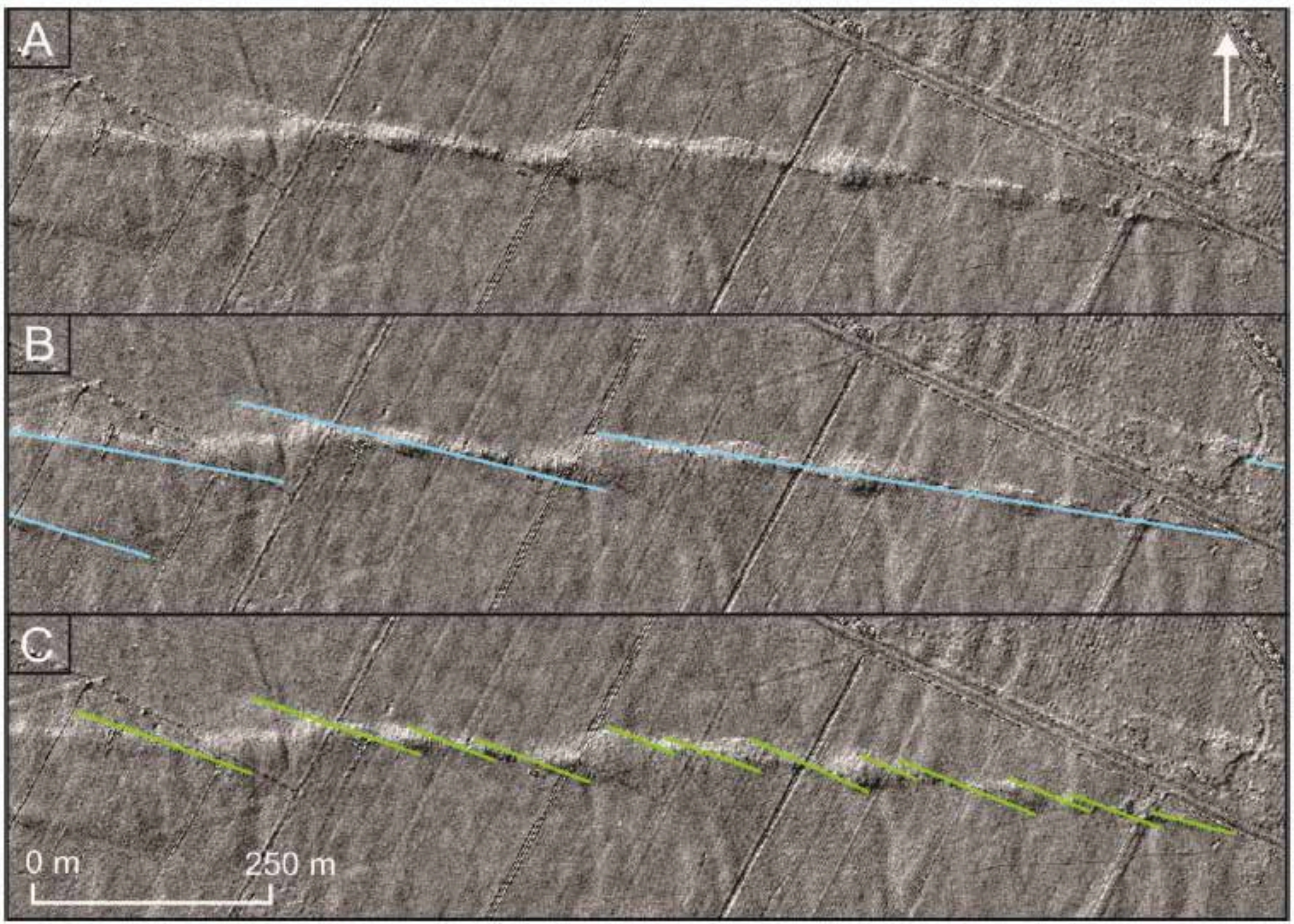
Cretaceous-Paleogene sedimentary rocks

Torlesse basement

Complex rupture patterns – R, R’, T shears, etc.



Fault segmentation, step-overs, pop-ups



Material Selection & Experiment Design

Non-cohesive granular material (sand)

Width of distributed deformation zone scales with thickness. Not capable of forming discrete fractures and observed fracture arrays

Cohesive granular material (talc)

Discrete fractures, fracture arrays, step-overs and pop-ups formed but within a narrow zone of distributed deformation

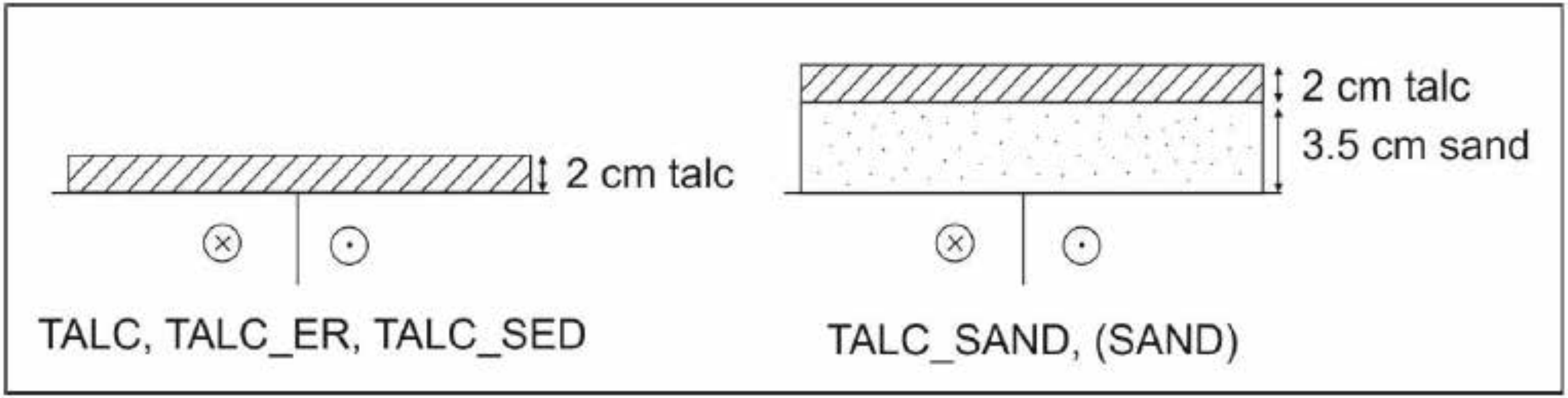
Talc-over-sand experiments

Sand - basal boundary condition of distributed shear

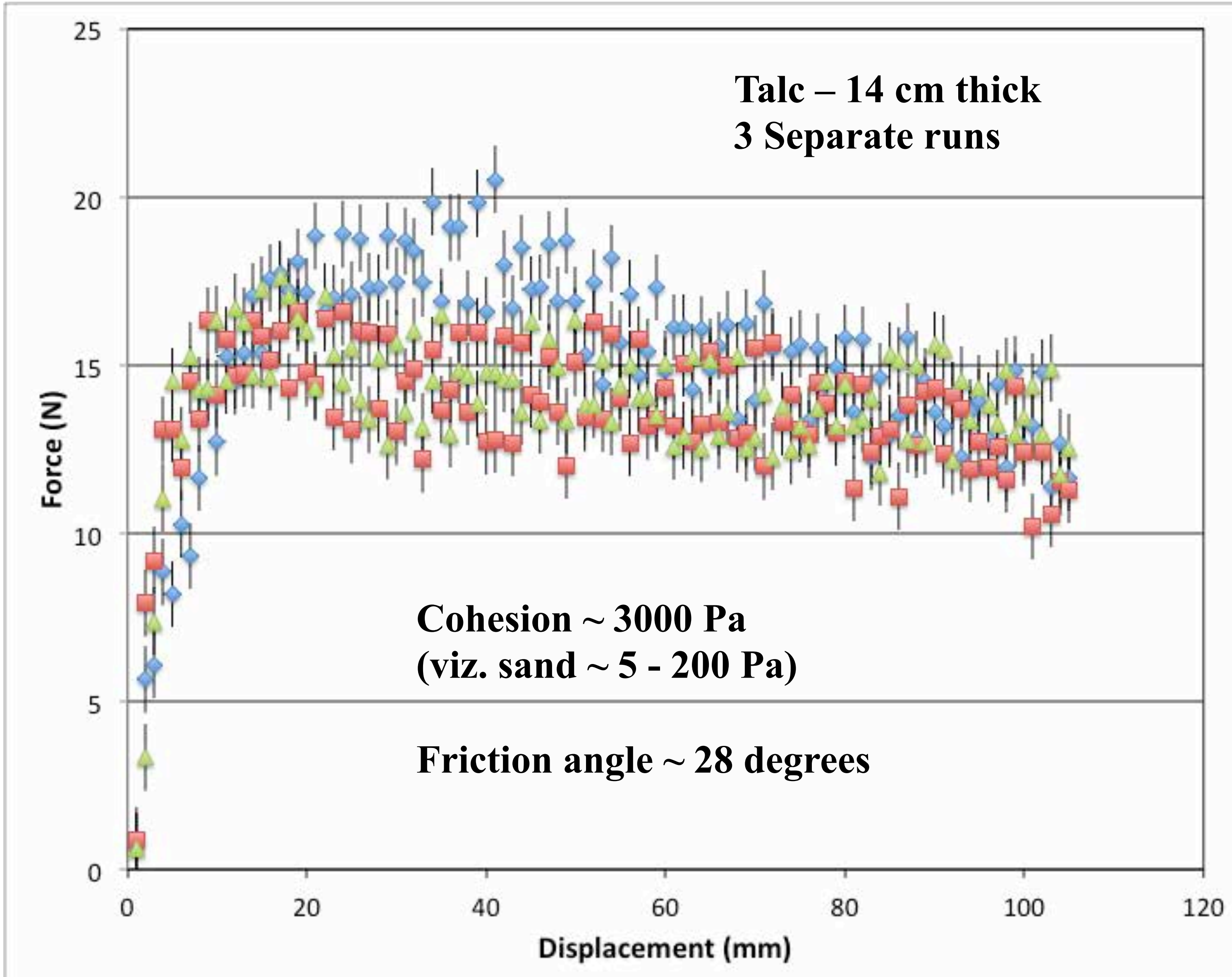
Talc – wide zone of discrete fracturing, including R' shears not observed in single layer experiments

Other variations (not discussed here)

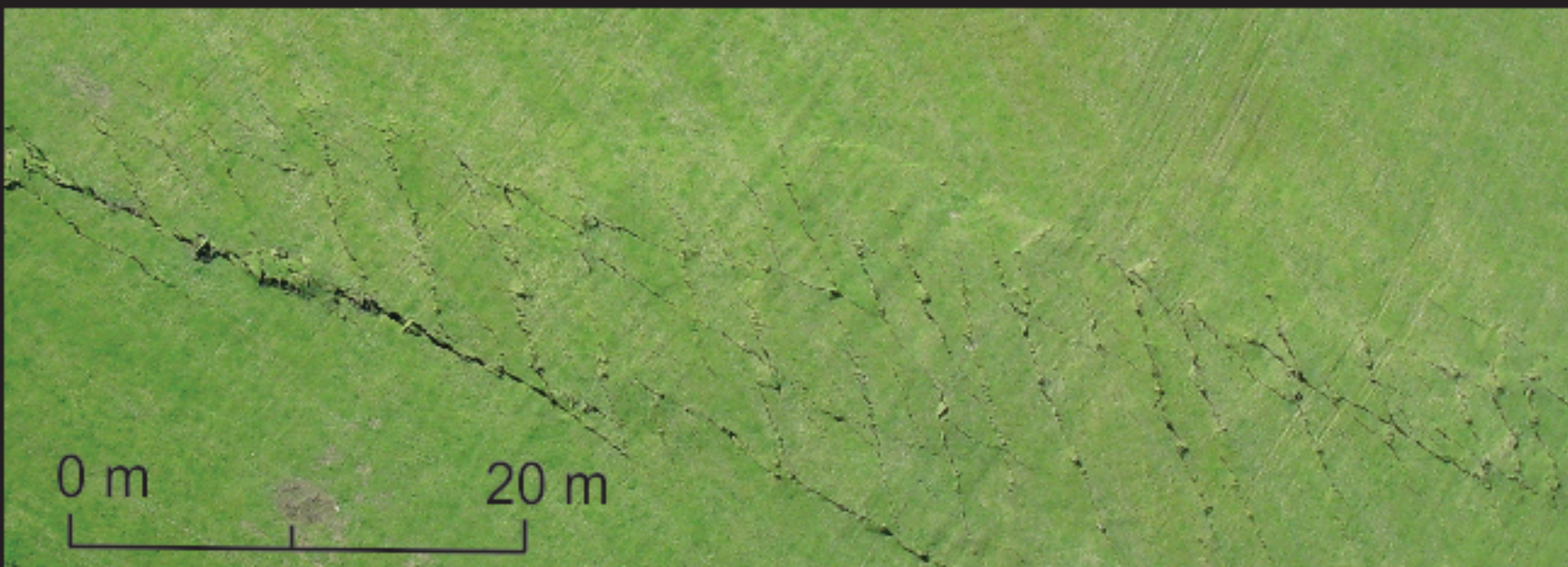
Erosion, sedimentation, fracture reactivation history, large step overs

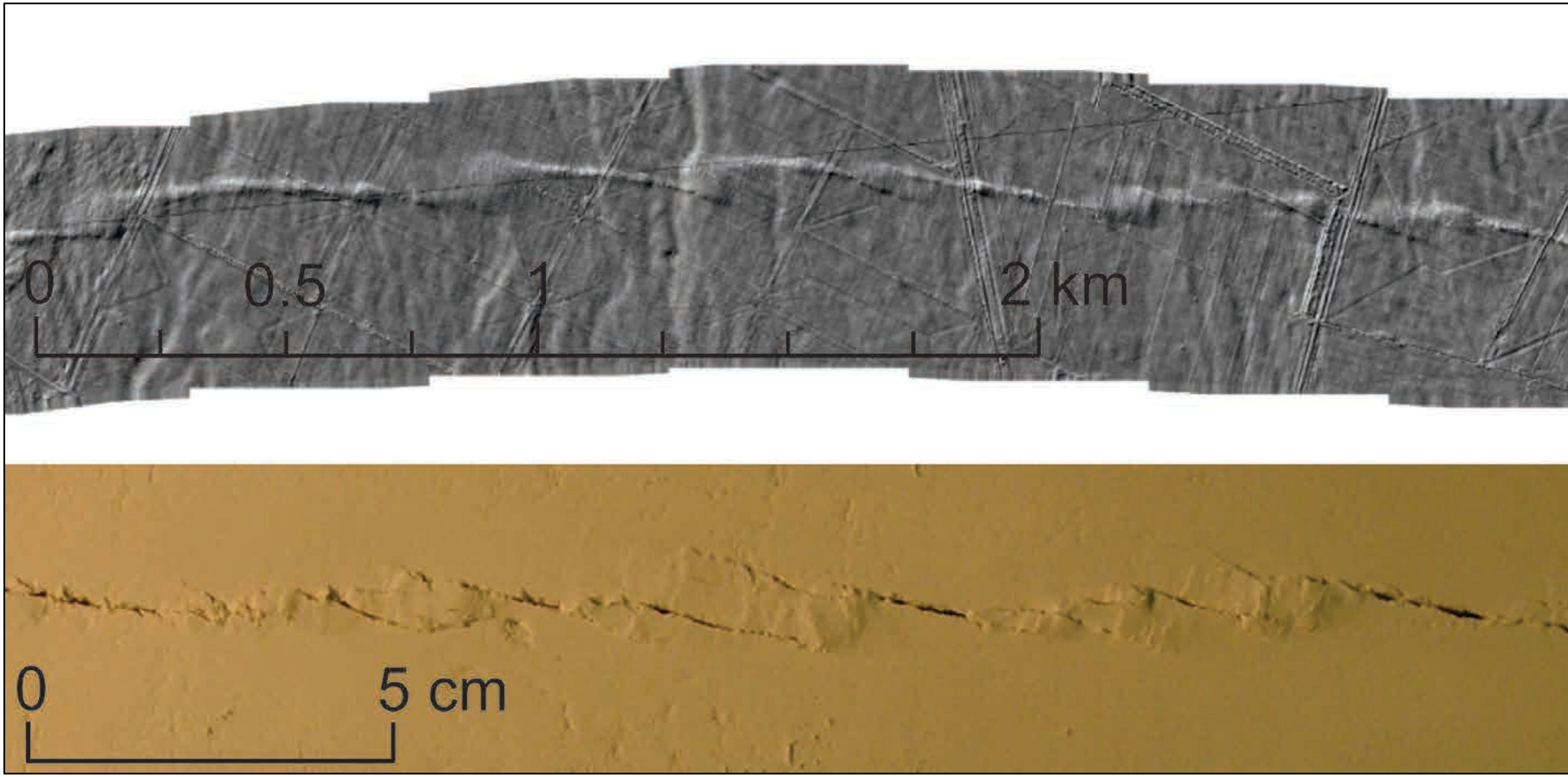


Talc Frictional Properties – Measurement Challenges



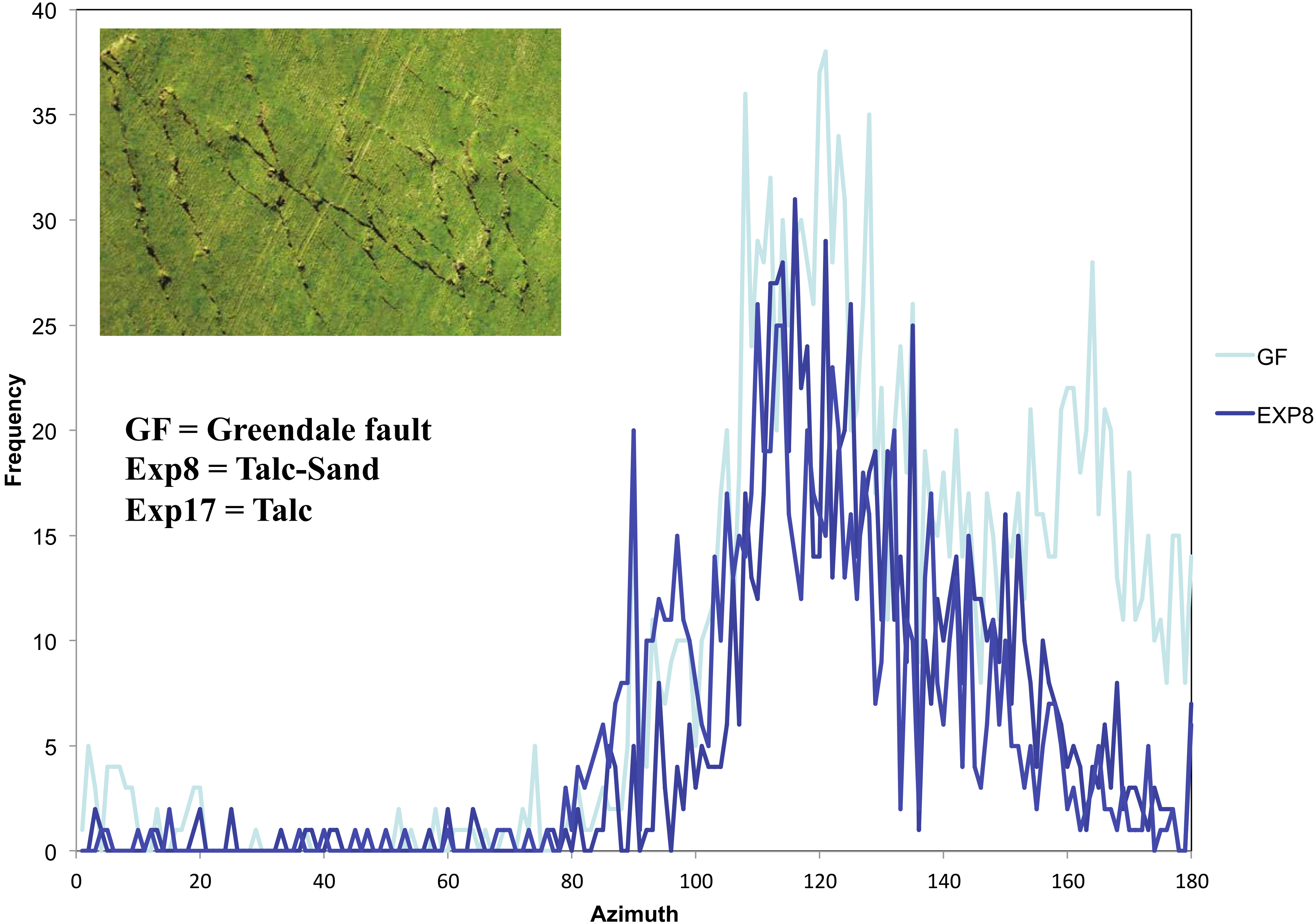
Talc-Sand – Reidel shears (R), R’ shears, linkage, and dilation

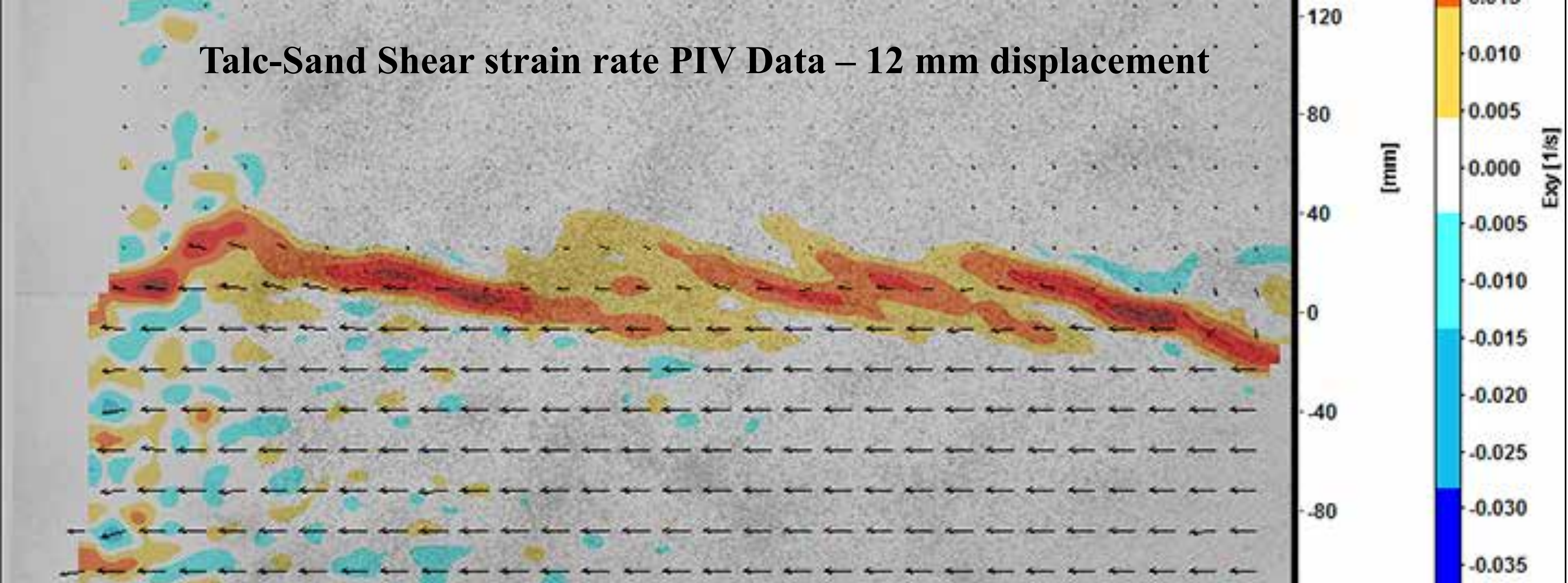


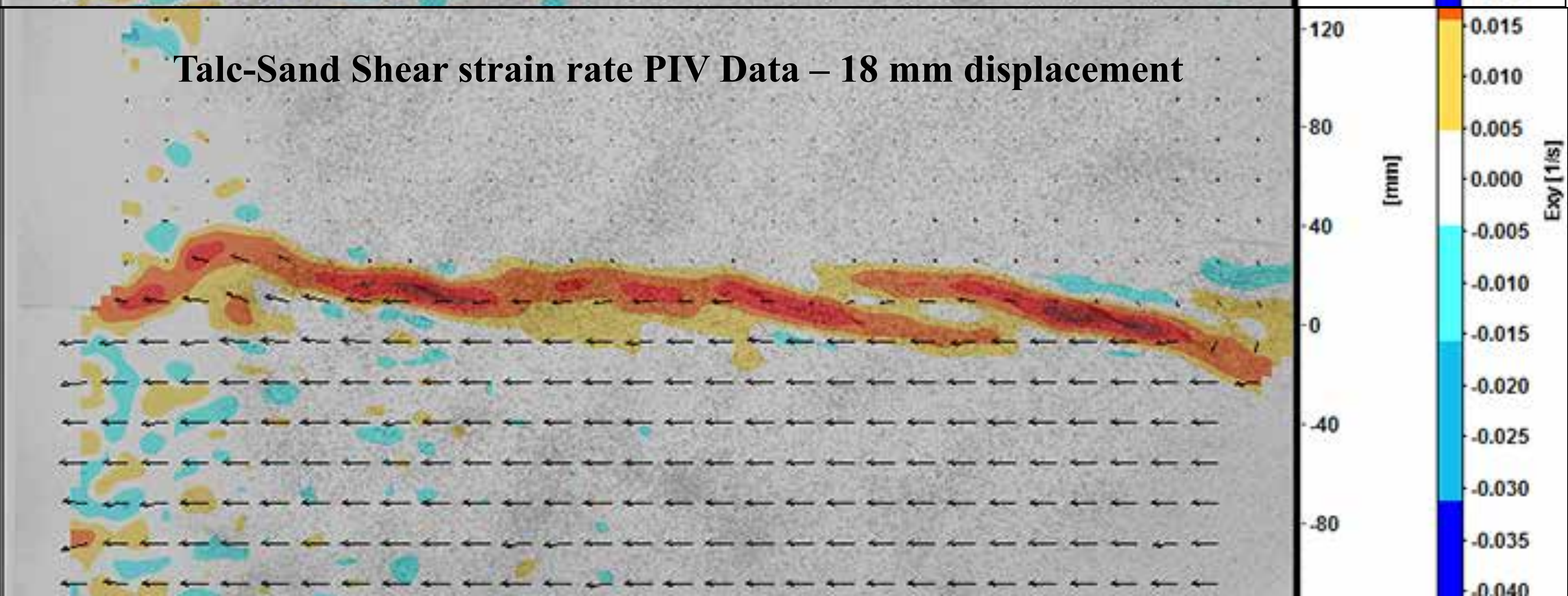


Talc Only – en-echelon Reidel shears, linkage and pop-ups

EXP8, EXP17, and Greendale Fault—Azimuth Frequency




Talc-Sand Shear strain rate PIV Data – 12 mm displacement
120
80
40
0
-40
-80
[mm]
0.010
0.005
0.000
-0.005
-0.010
-0.015
-0.020
-0.025
-0.030
-0.035
Exy [1/s]


Talc-Sand Shear strain rate PIV Data – 18 mm displacement
120
80
40
0
-40
-80
[mm]
0.015
0.010
0.005
0.000
-0.005
-0.010
-0.015
-0.020
-0.025
-0.030
-0.035
Exy [1/s]

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Coupled crust-mantle dynamics and intraplate tectonics: Two-dimensional numerical and three-dimensional analogue modeling

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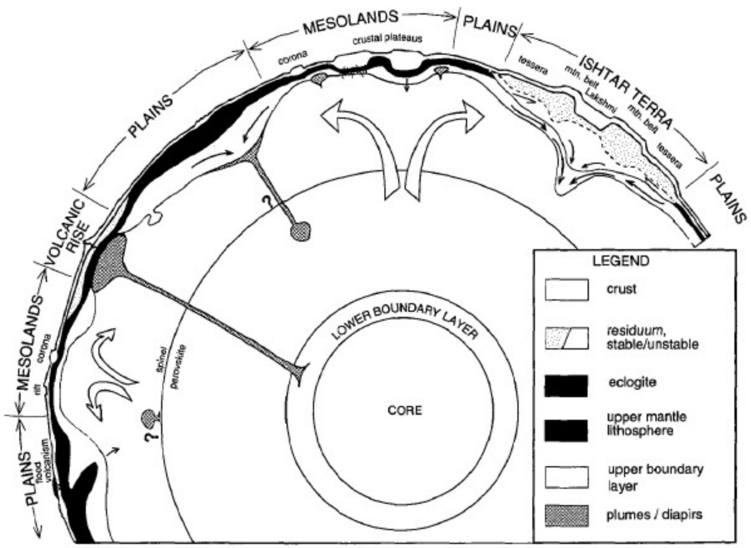
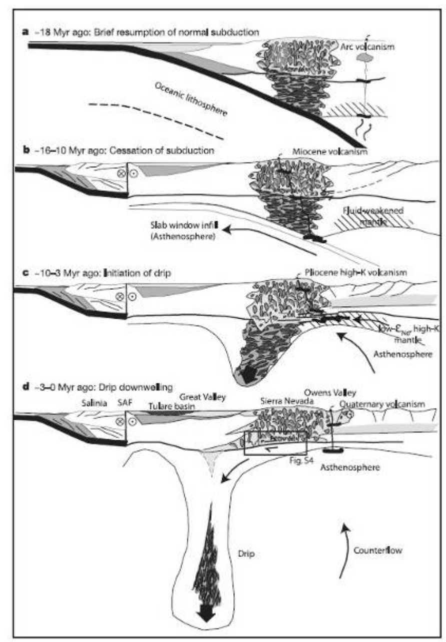
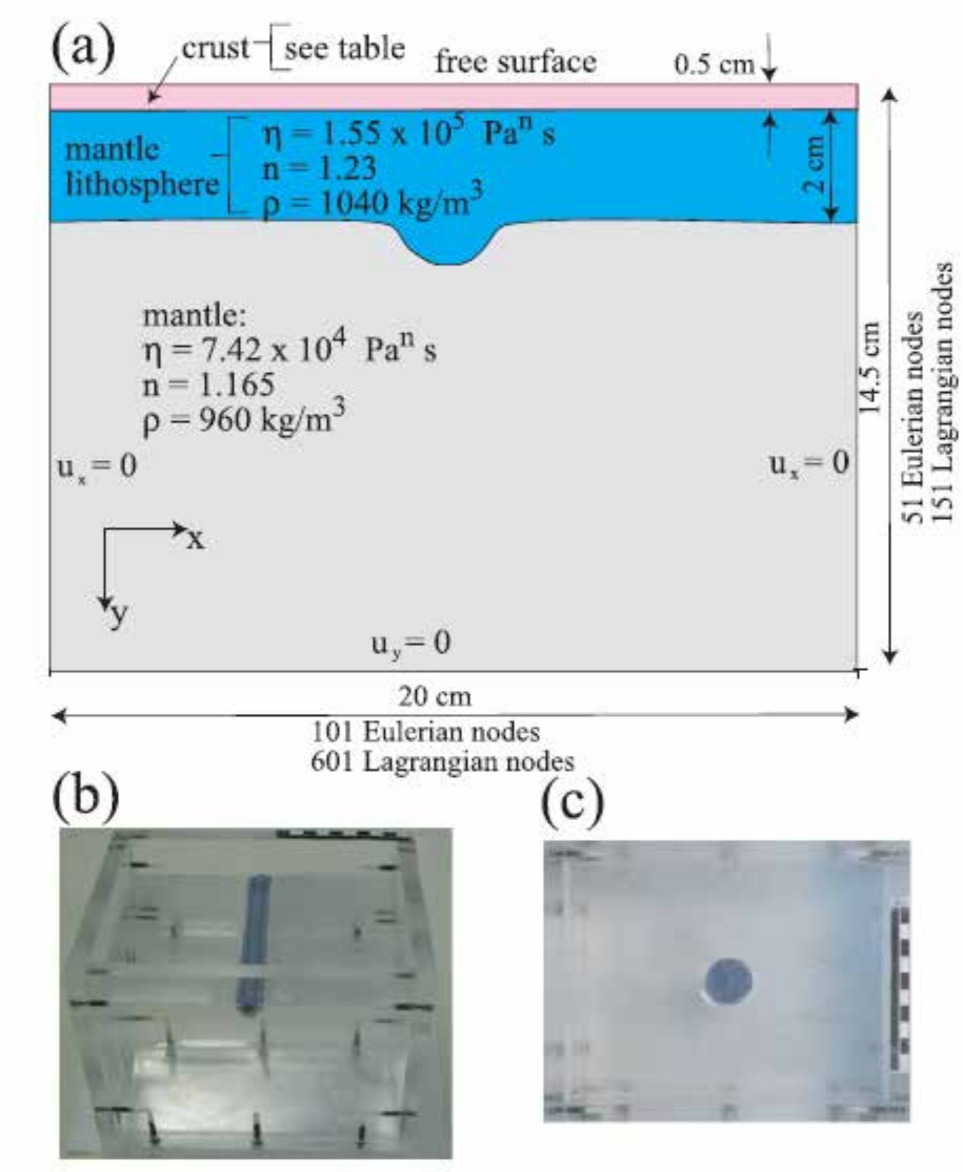


Phillips & Hansen (1994)



Saleeby & Foster (2004)

Model Set UP



Dimensions and properties for both 3D analogue and 2D numerical experiments

Initiator geometries in analogue experiments

Linear vs. point

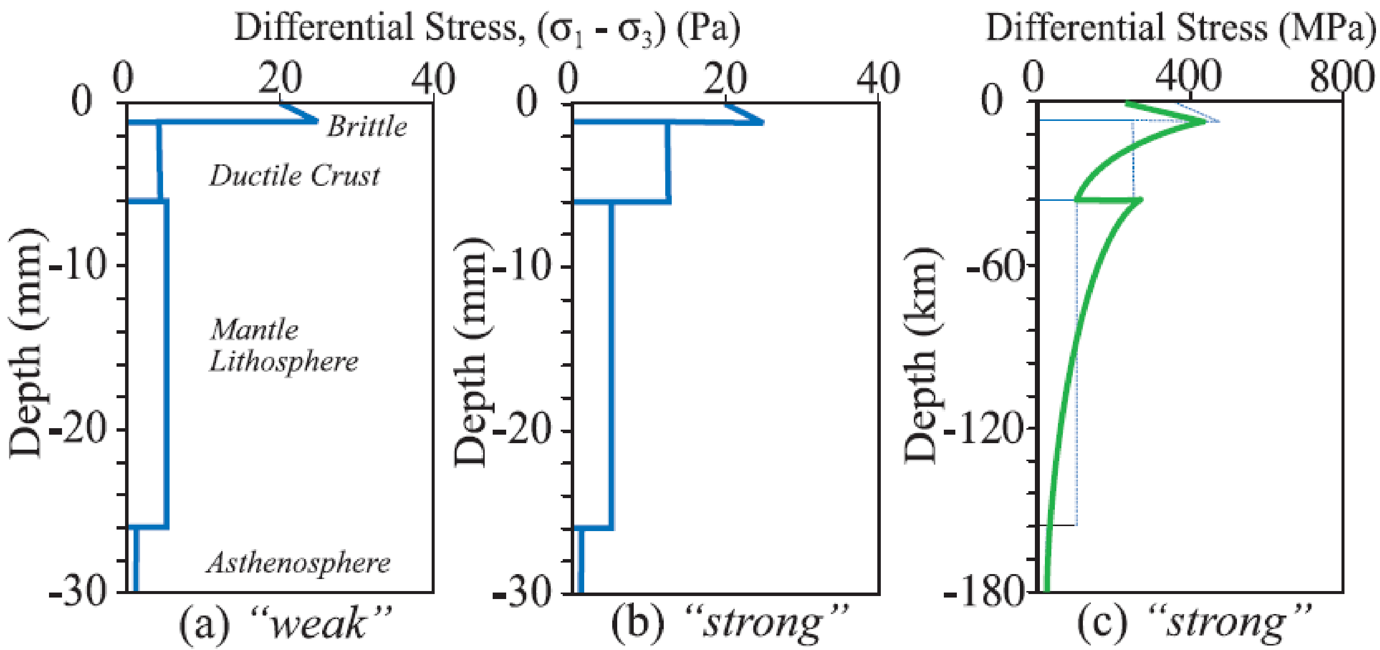
Analogue materials & rheological profiles

Brittle crust: granular (ceramic microspheres & silica sand)

Ductile crust: PDMS + plasticene + glass microbubbles

Mantle lithosphere: PDMS + plasticene

Asthenosphere: PDMS



Numerical Technique

NS Equation and velocity field solved using the arbitrary Langangian – Eulerian finite element method (ALE) (Fullsack (1994)

Code: SOPALE

Model Observation Scheme

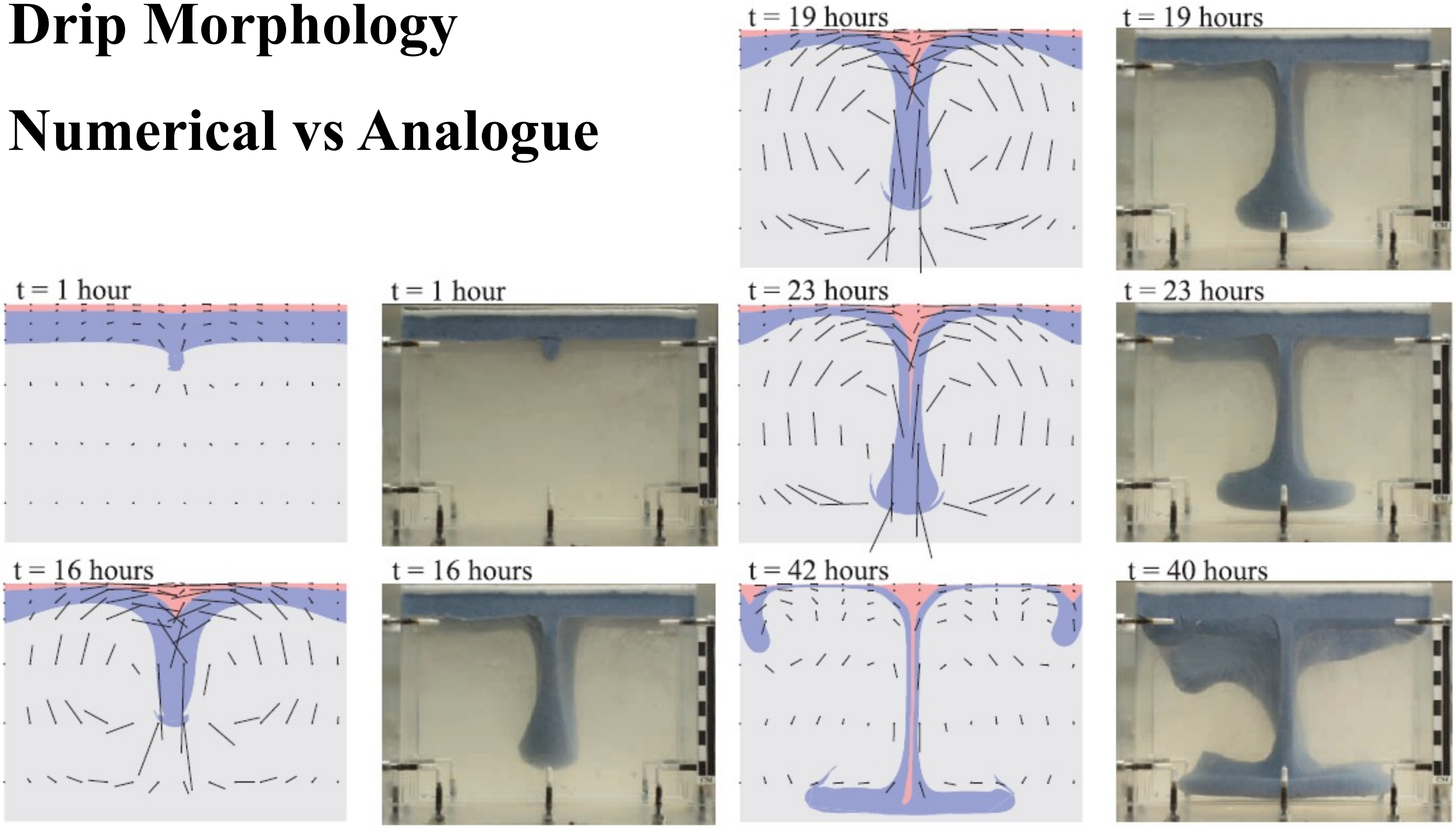
Digital Camera (time lapse)

Laser topography mapping system

Digital Camera (time lapse)

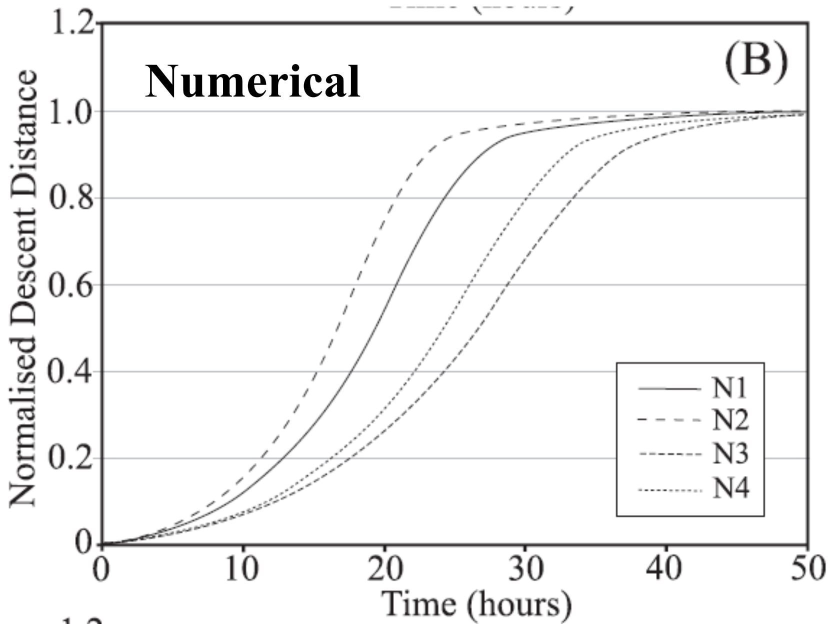
Drip Morphology

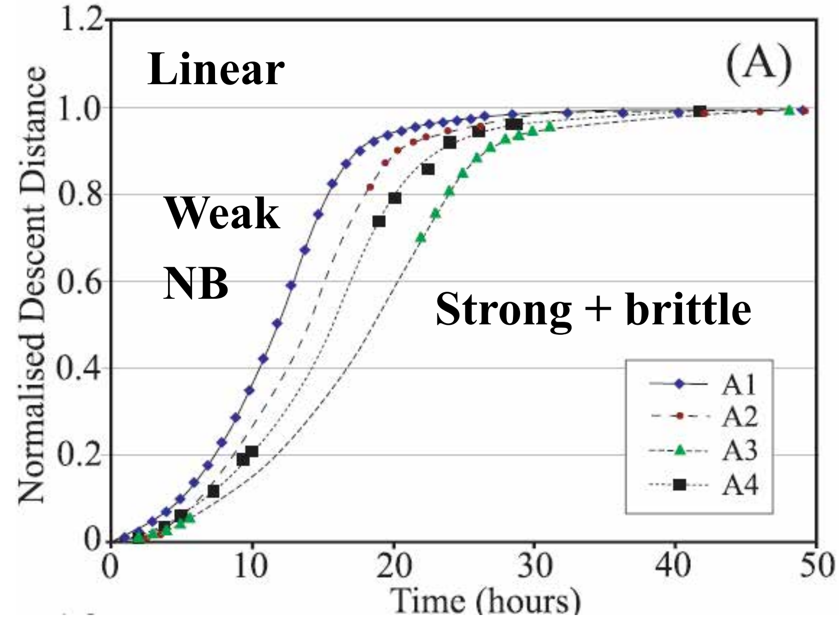
Numerical vs Analogue

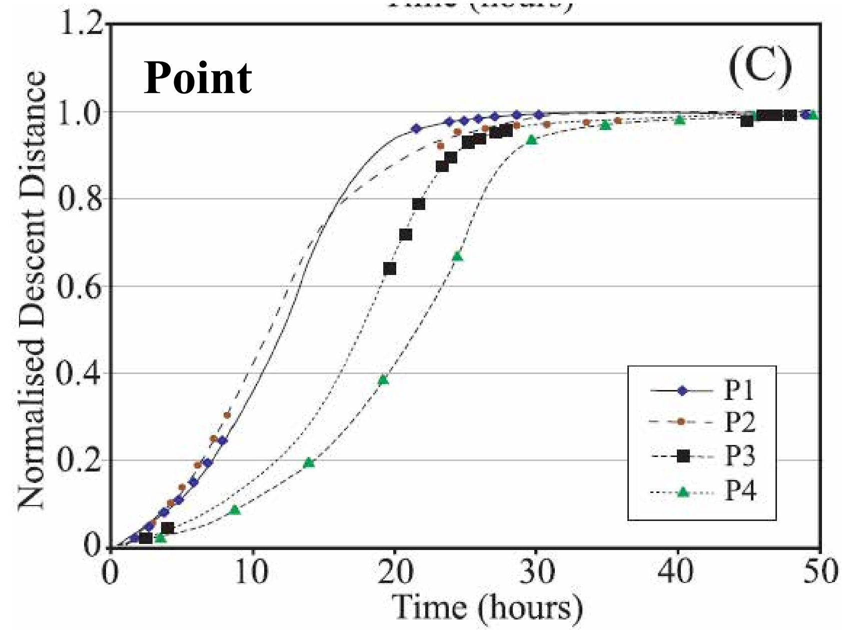


Growth of RT Instability

Numerical vs Analogue



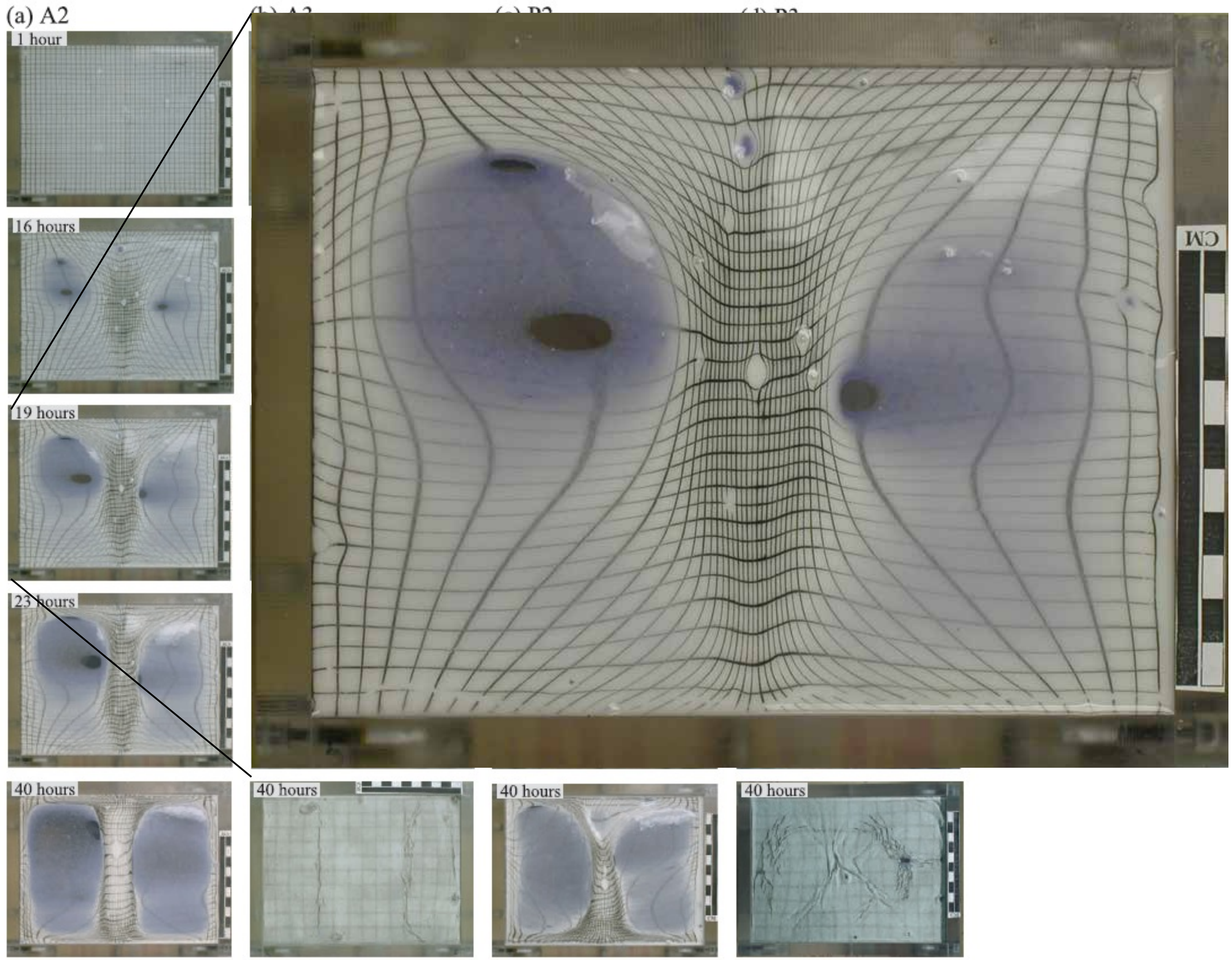




Similar behaviours for numerical, linear and point initiators

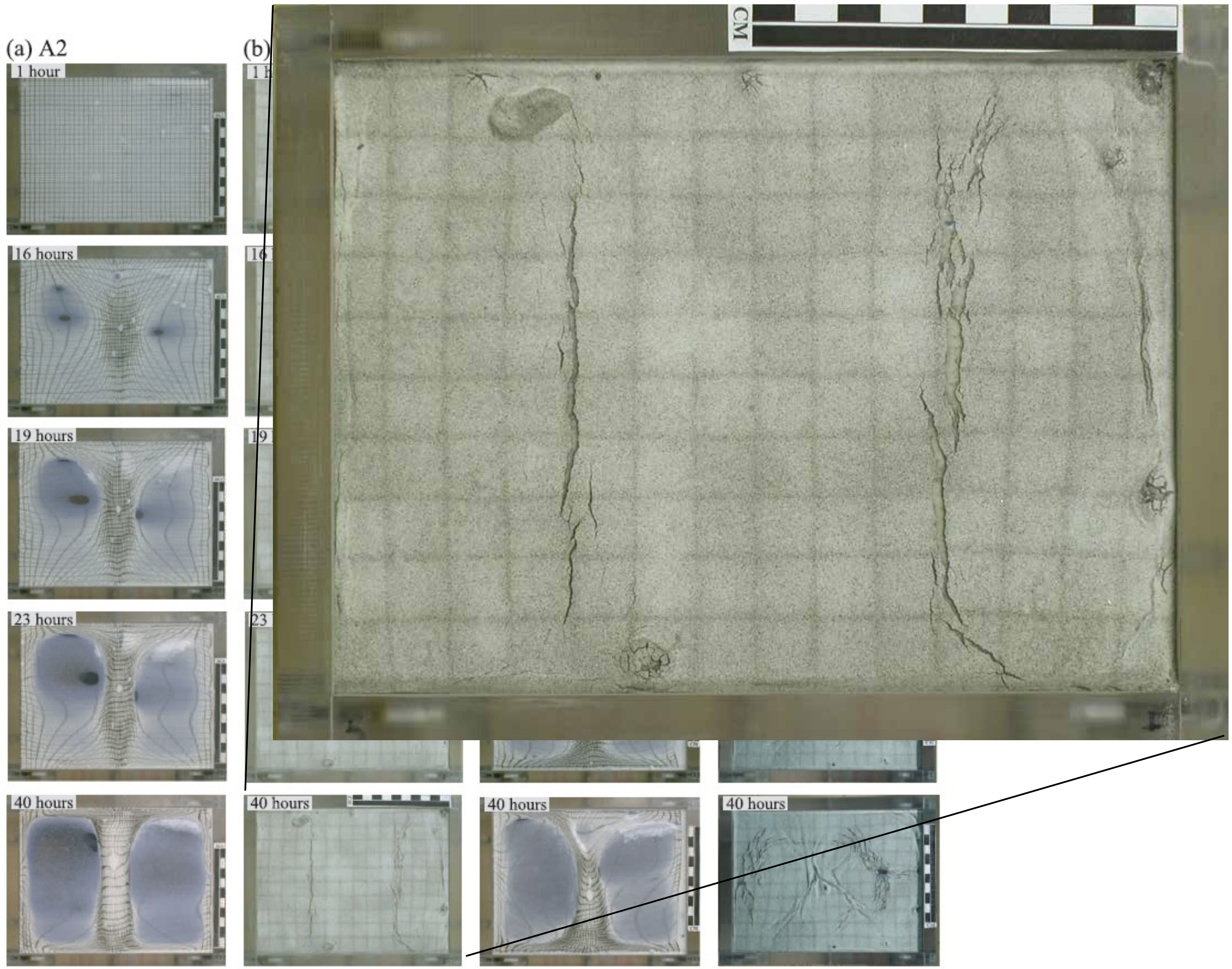
Crustal rheology strongly influences drip descent rate and development

Surface Strain Field



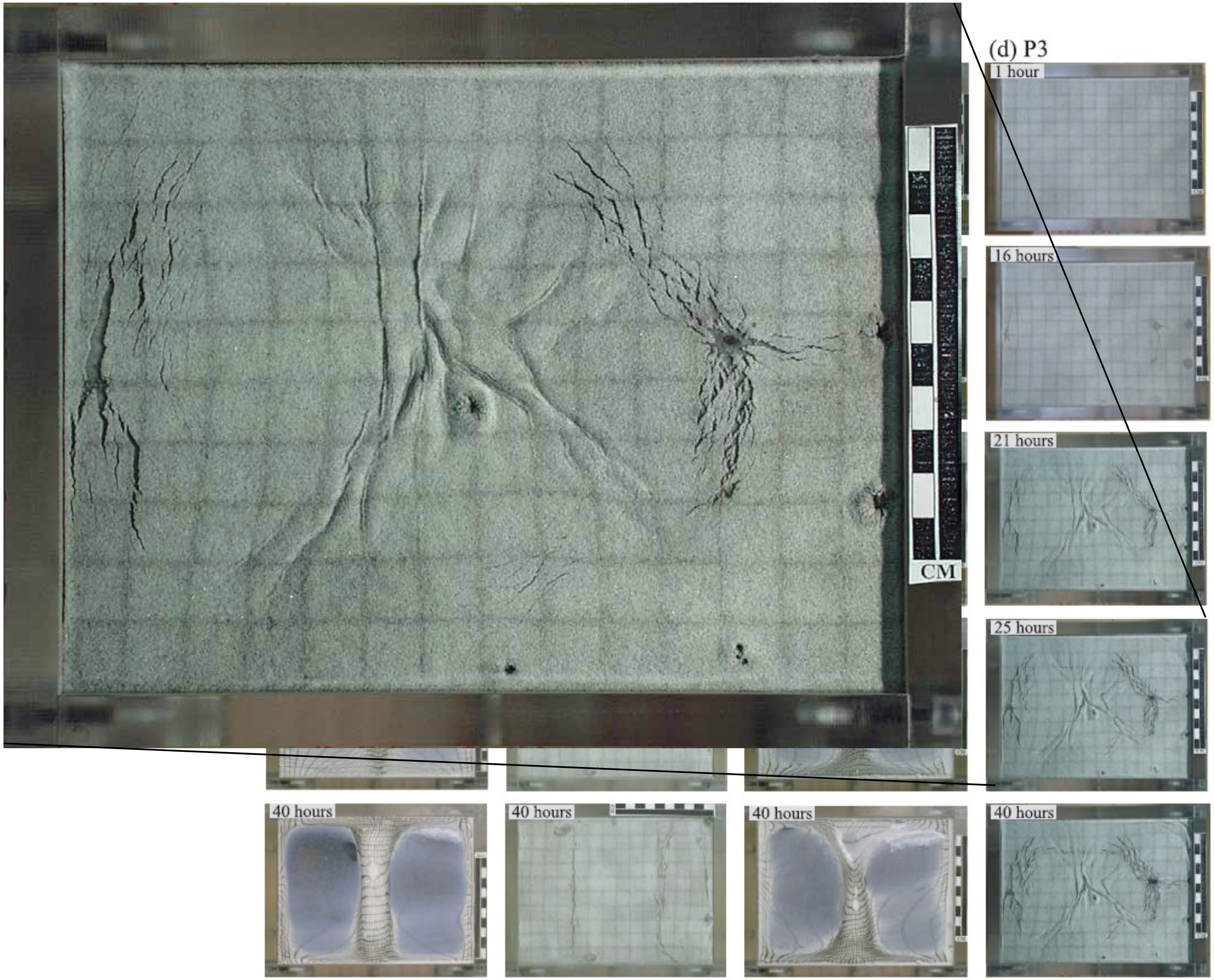
L, W, NB **L, S, +B** **P, W, NB** **P, S, +B**

Surface Strain Field



L, W, NB **L, S, +B** **P, W, NB** **P, S, +B**

Surface Strain Field



L, W, NB **L, S, +B** **P, W, NB** **P, S, +B**

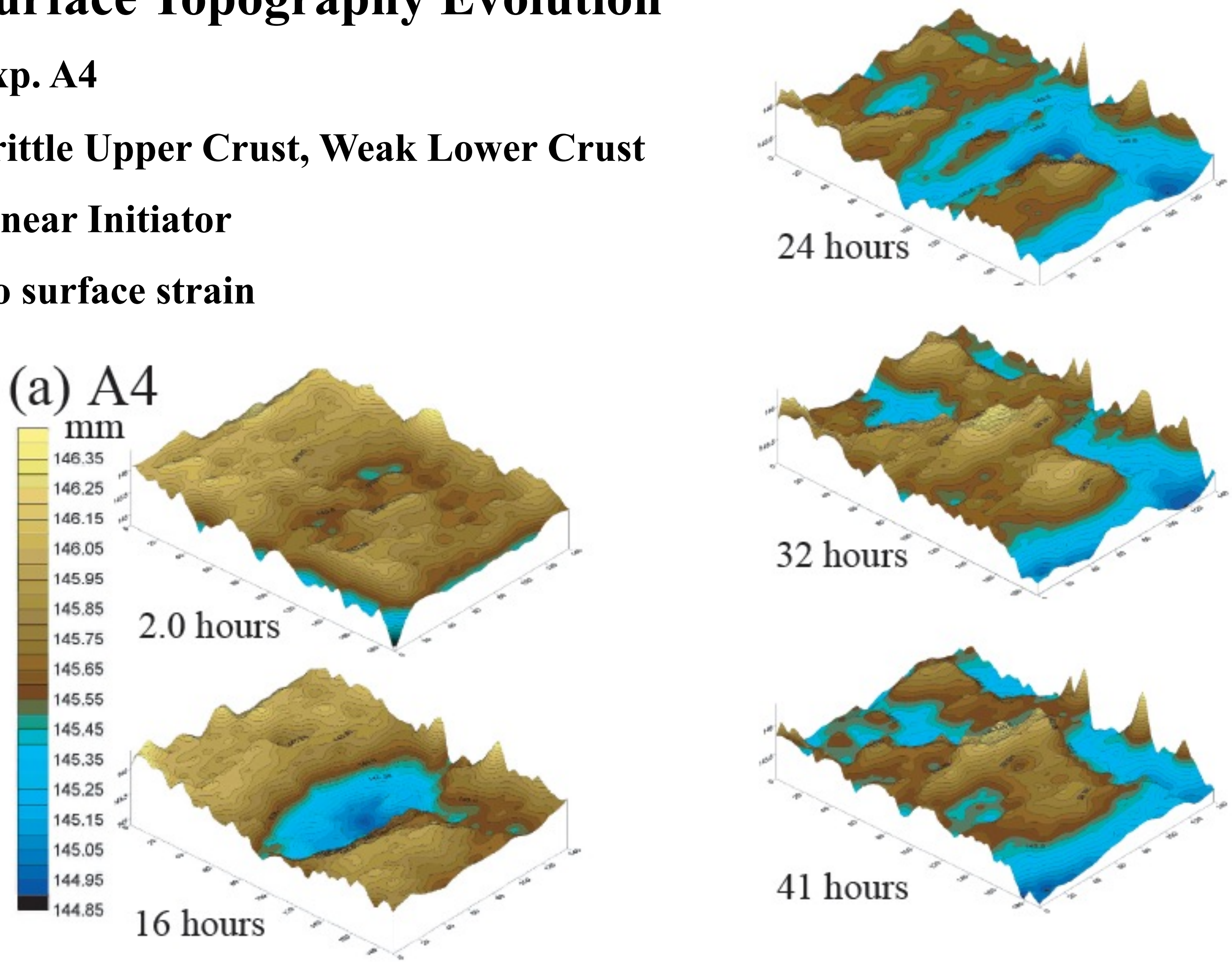
Surface Topography Evolution

Exp. A4

Brittle Upper Crust, Weak Lower Crust

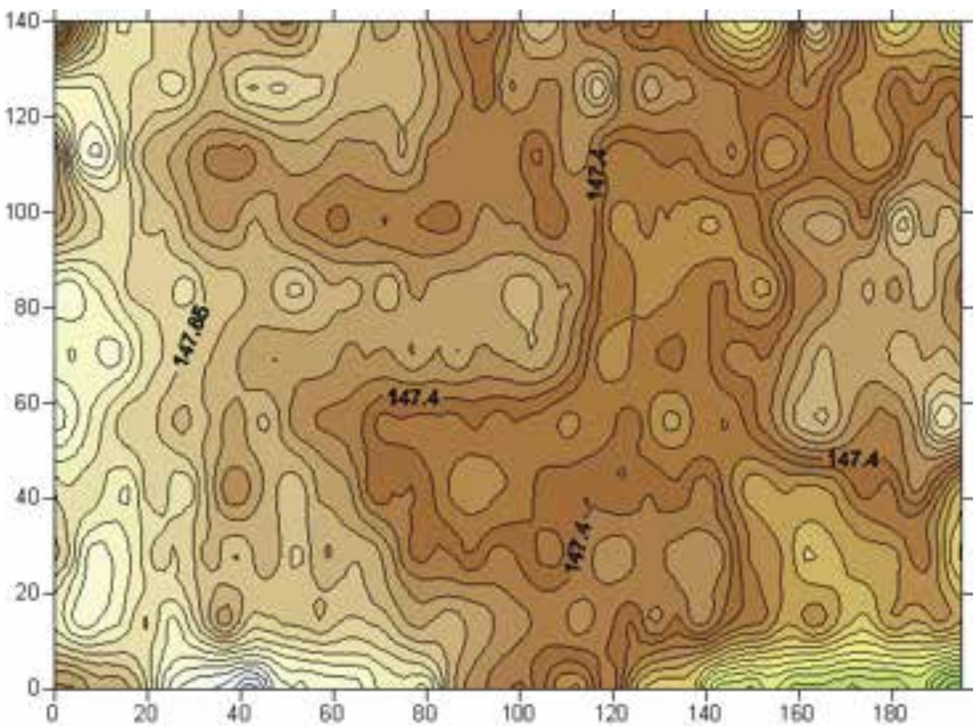
Linear Initiator

No surface strain



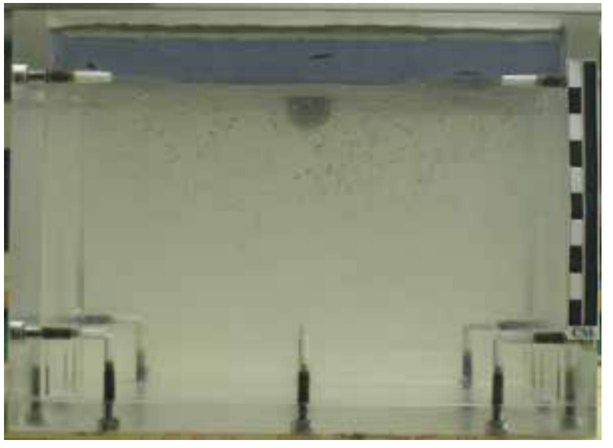
Exp P3 t = 0 hr

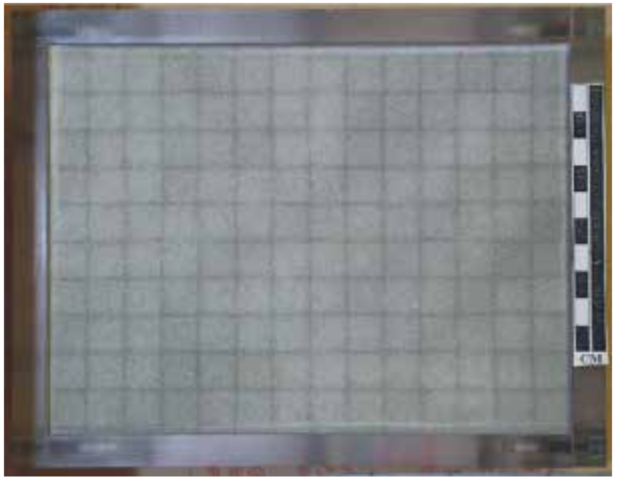
Brittle upper crust, strong lower crust
Point instability



Topography

Side

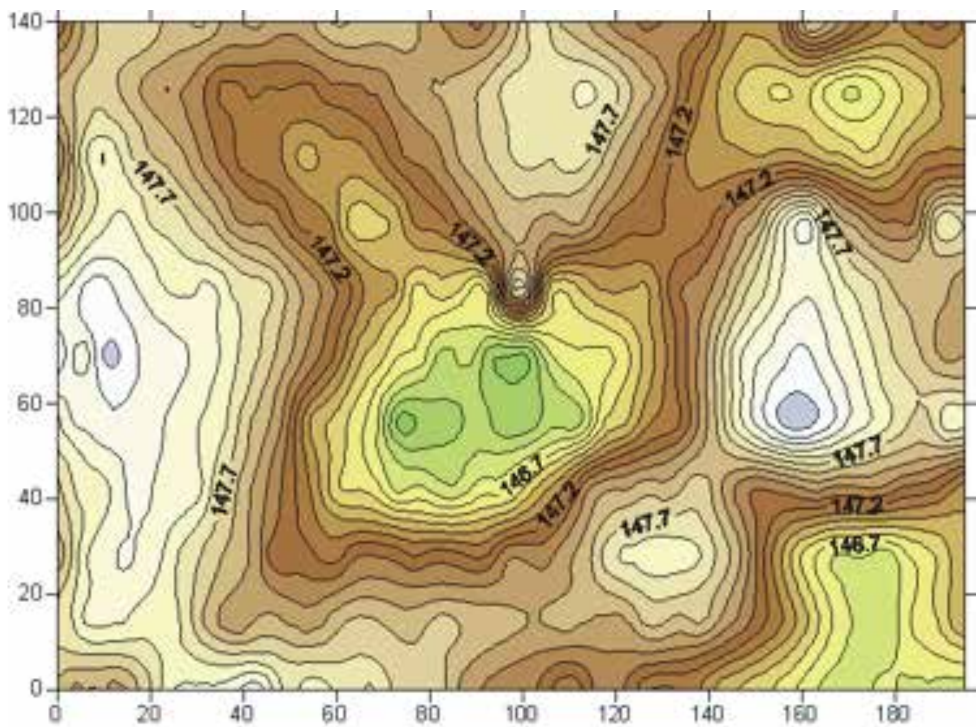




Top

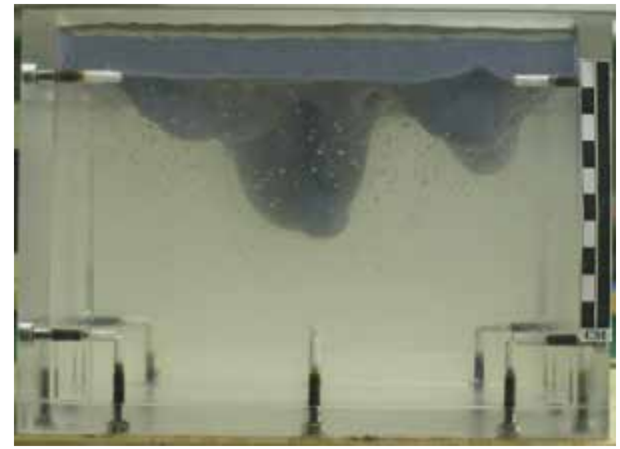
Exp P3 t = 16 hr

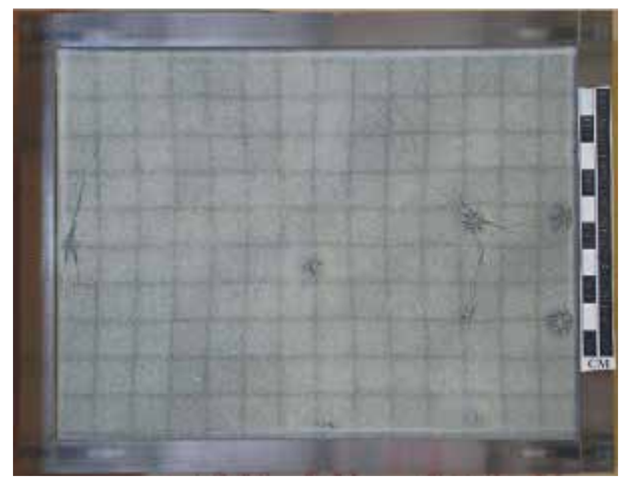
Brittle upper crust, strong lower crust
Point instability



Topography

Side



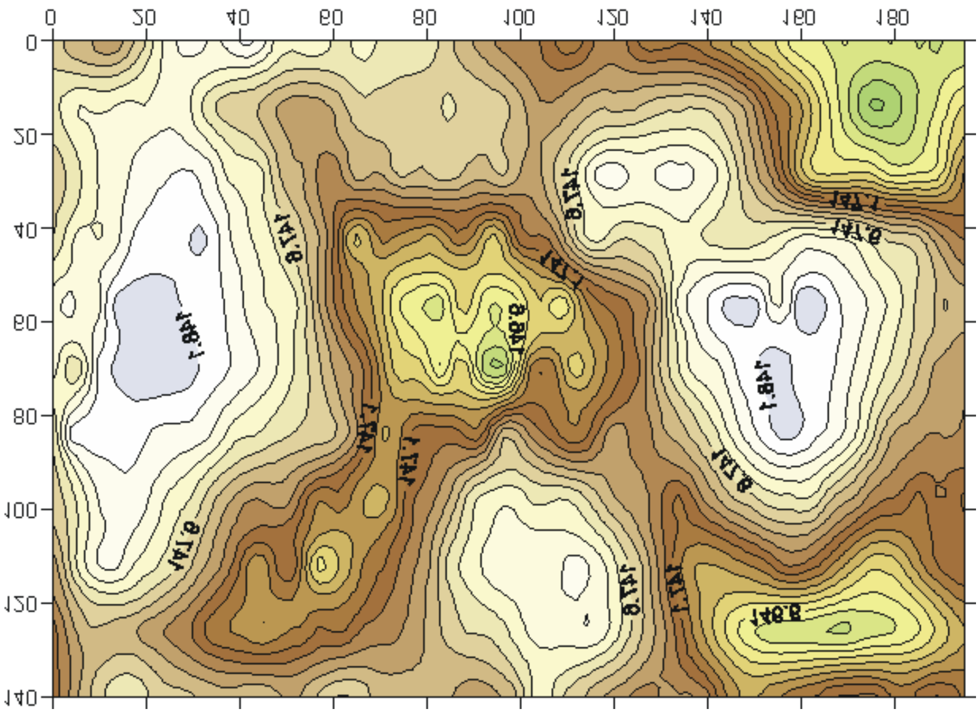


Top

Exp P3 t = 21 hr

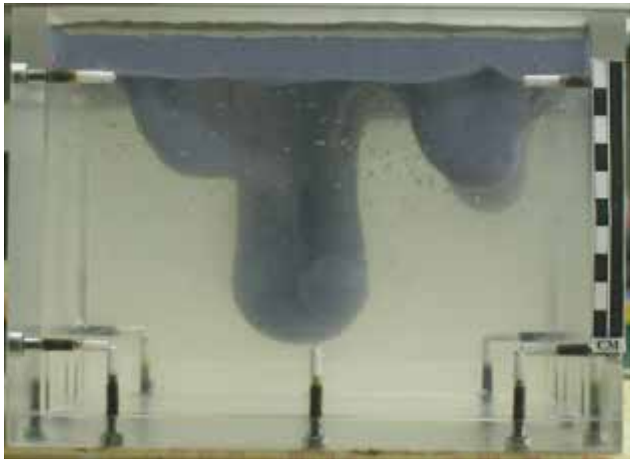
Brittle upper crust, strong lower crust

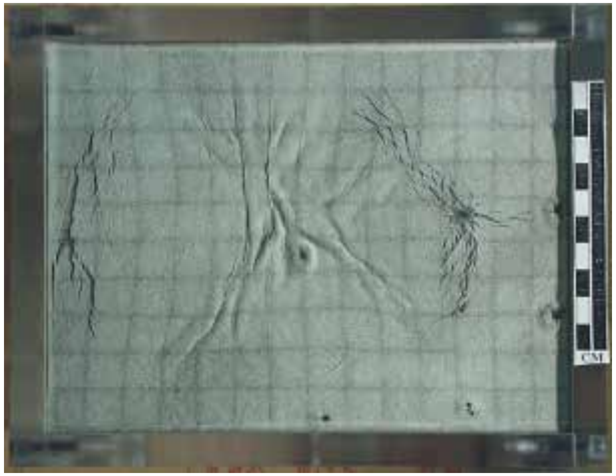
Point instability



Topography

Side

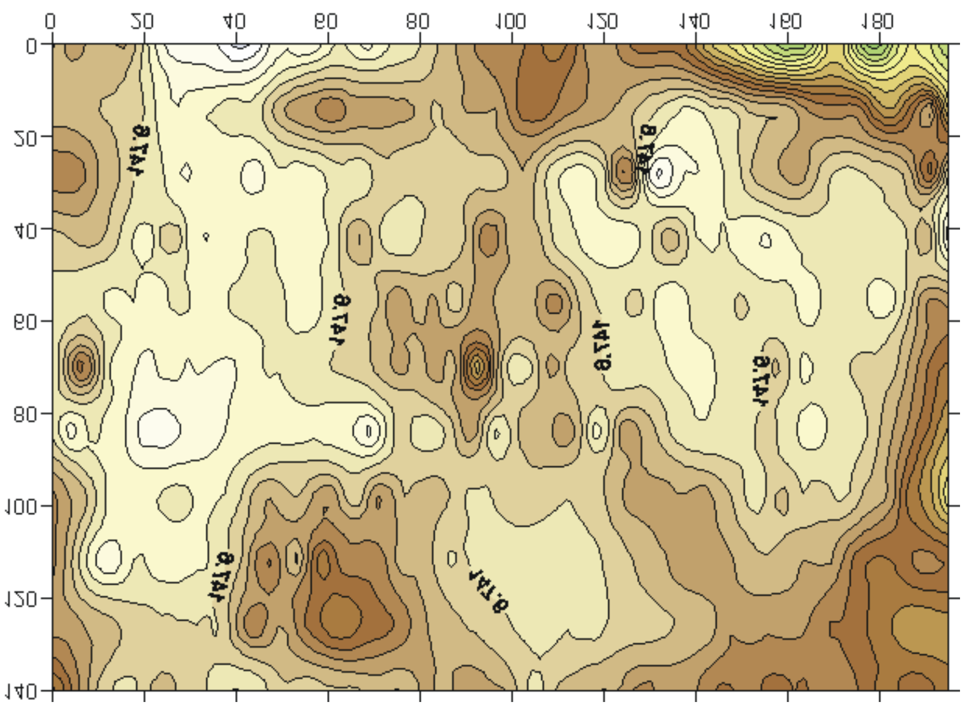




Top

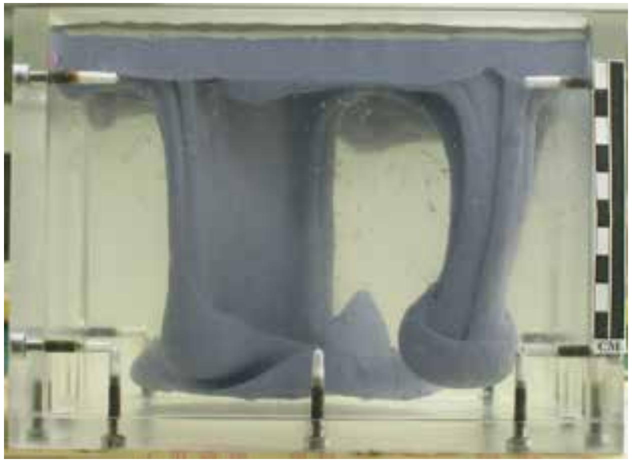
Exp P3 t = 40 hr

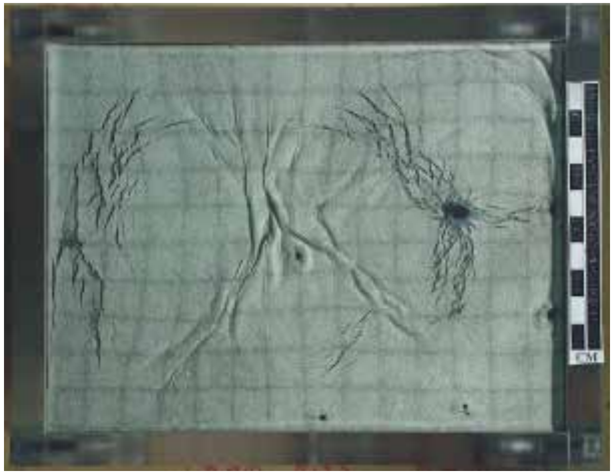
Brittle upper crust, strong lower crust
Point instability



Topography

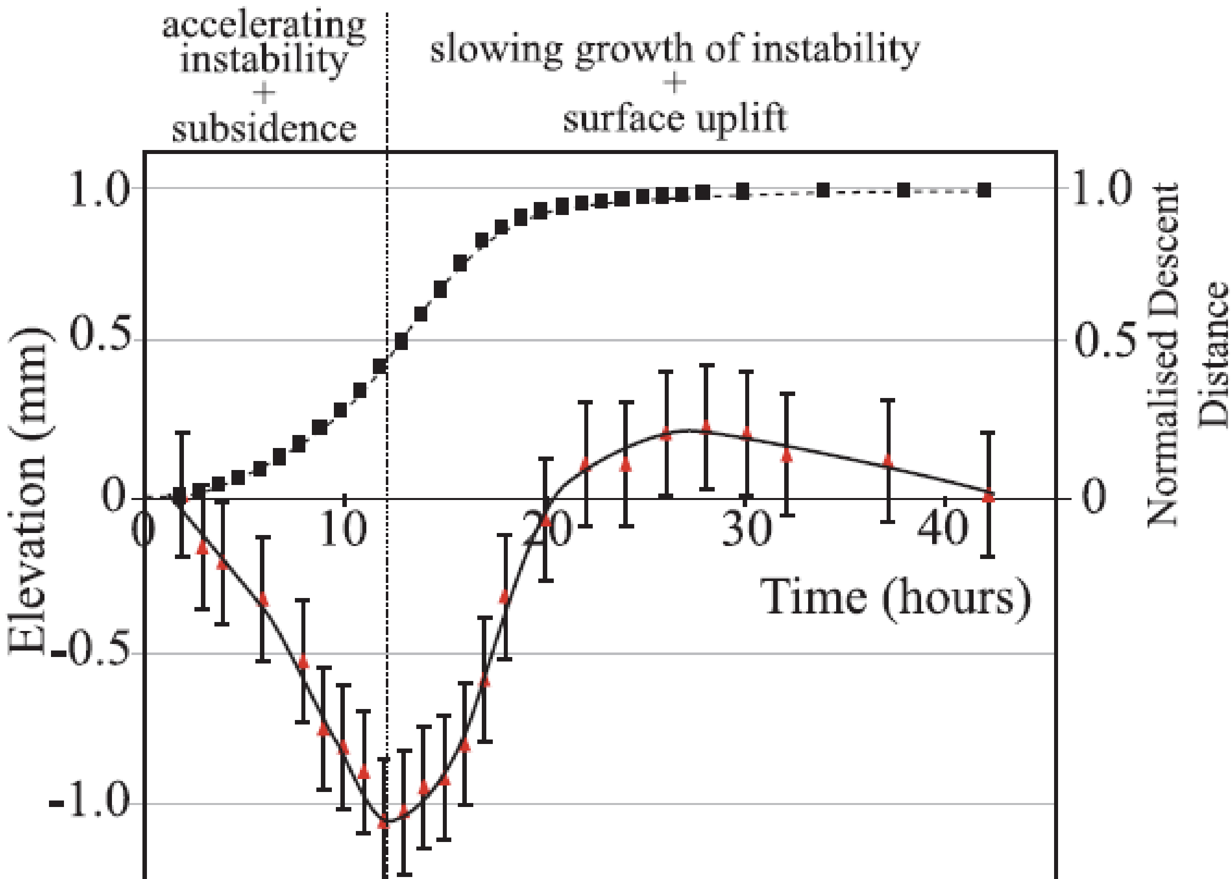
Side





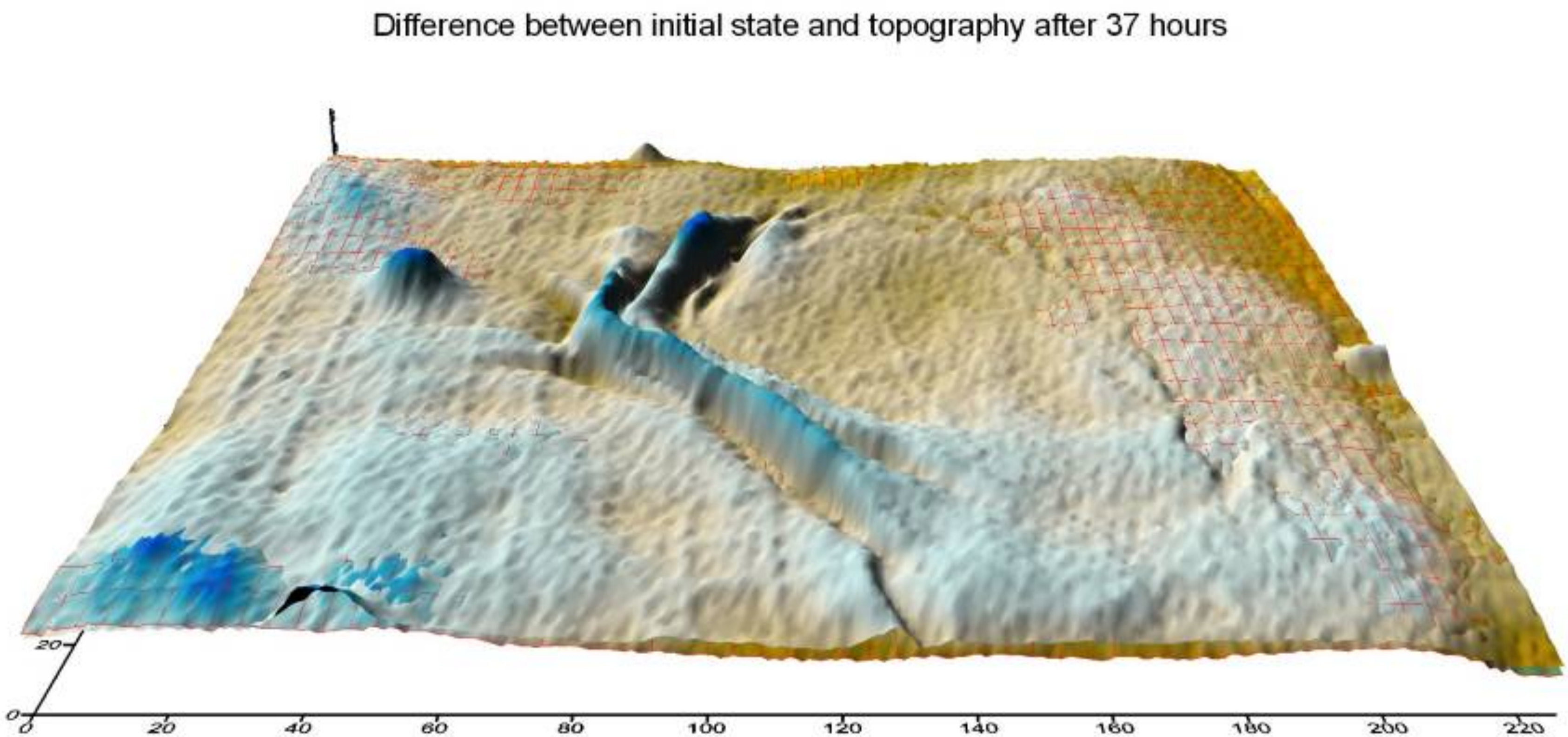
Top

Relationship Between Drip Growth and Surface Topography Evolution



Exp. A1, Linear initiator, strong ductile crust, no brittle crust

3D View: difference between initial and final topography

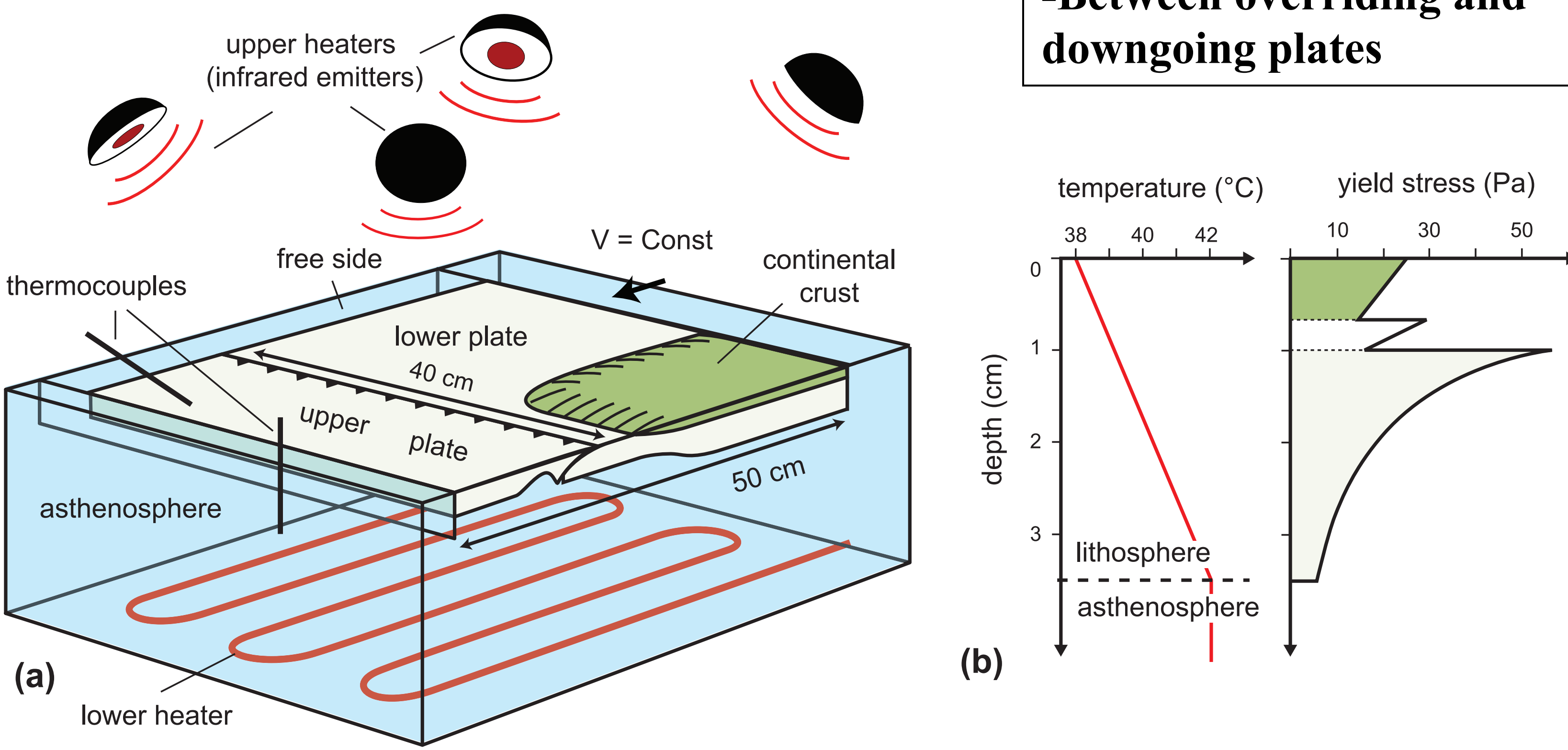


Take home message: drip tectonics is capable of driving complex basin formation and inversion processes and in some cases, curvilinear intraplate orogens.

3D plate boundary evolution from dynamic thermo-mechanical analogue experiments

Setup of 3D experiments

Feedbacks:
-Along strike
-Between overriding and downgoing plates

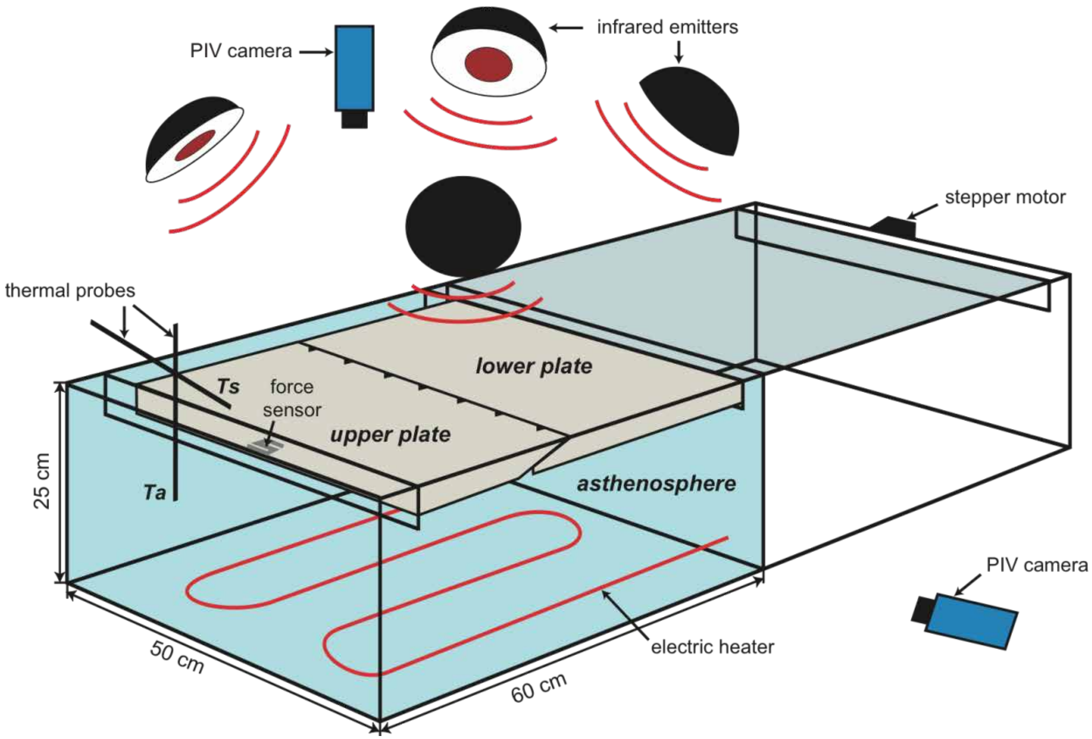


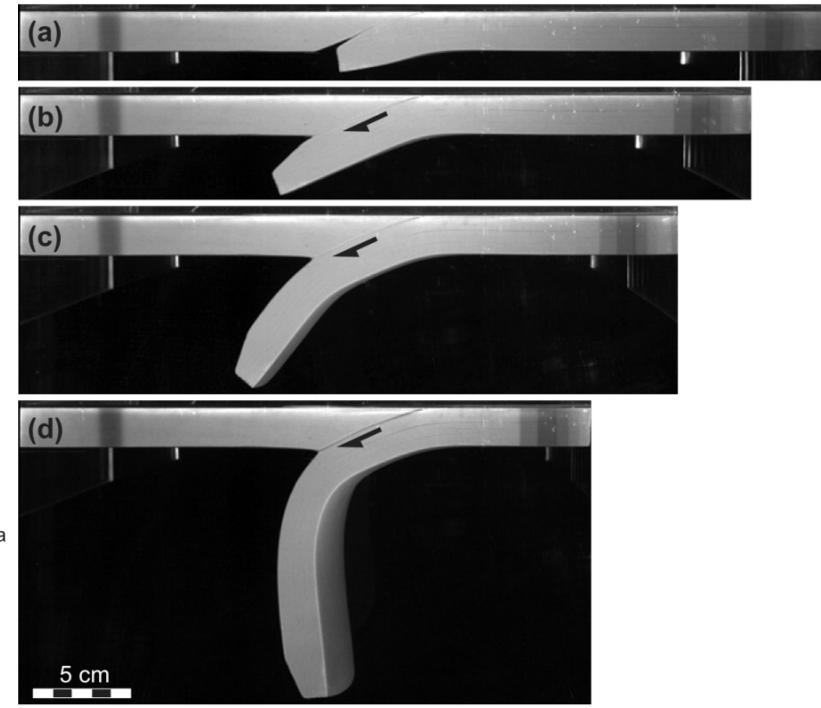
Temperature dependent visco-plastic materials (hydrocarbon based)

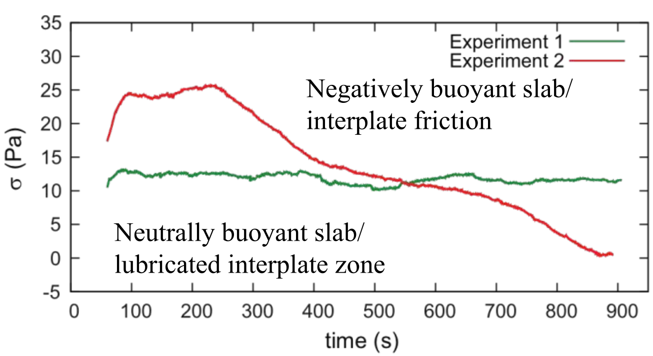
Boutelier & Oncken (2010)

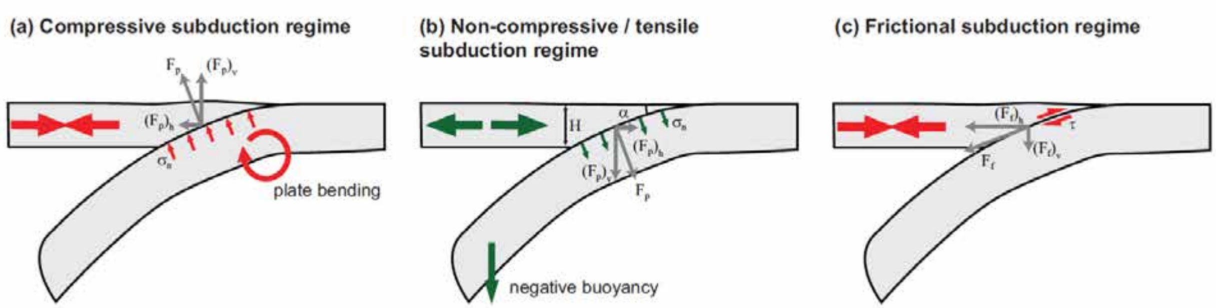
Quantitative monitoring
Including force

Boutelier, Oncken & Cruden (2012, Tectonics)









Slab rollback rate and trench curvature controlled by arc deformation

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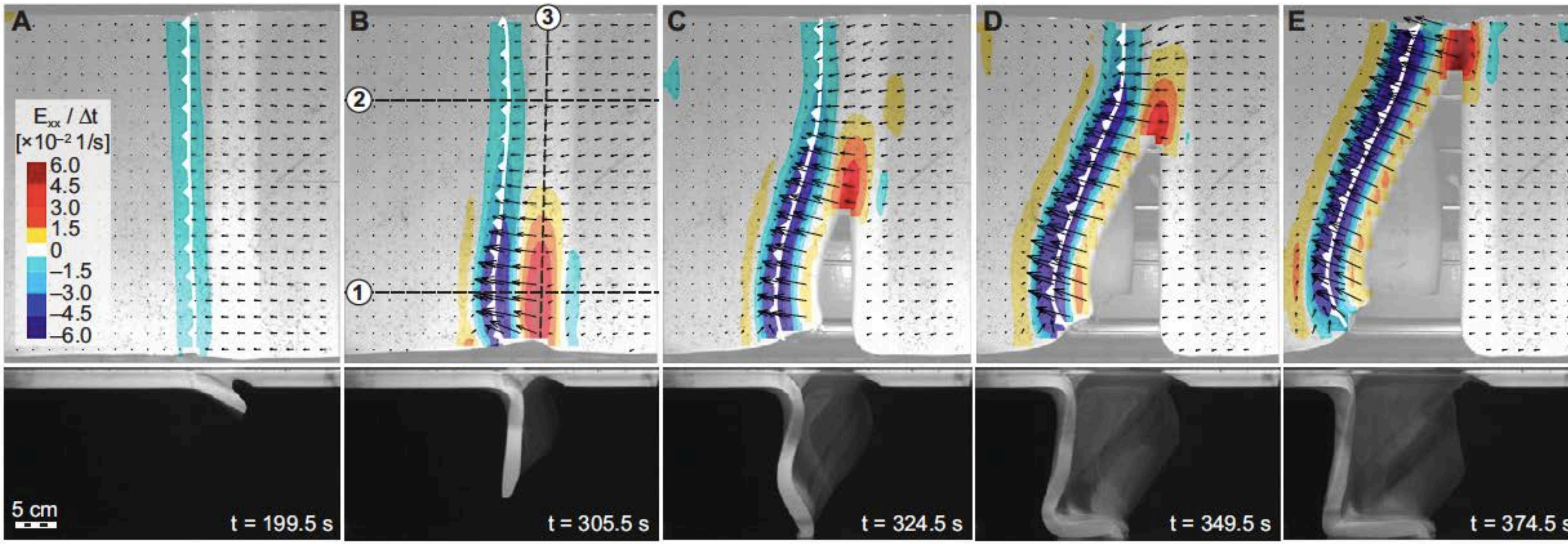
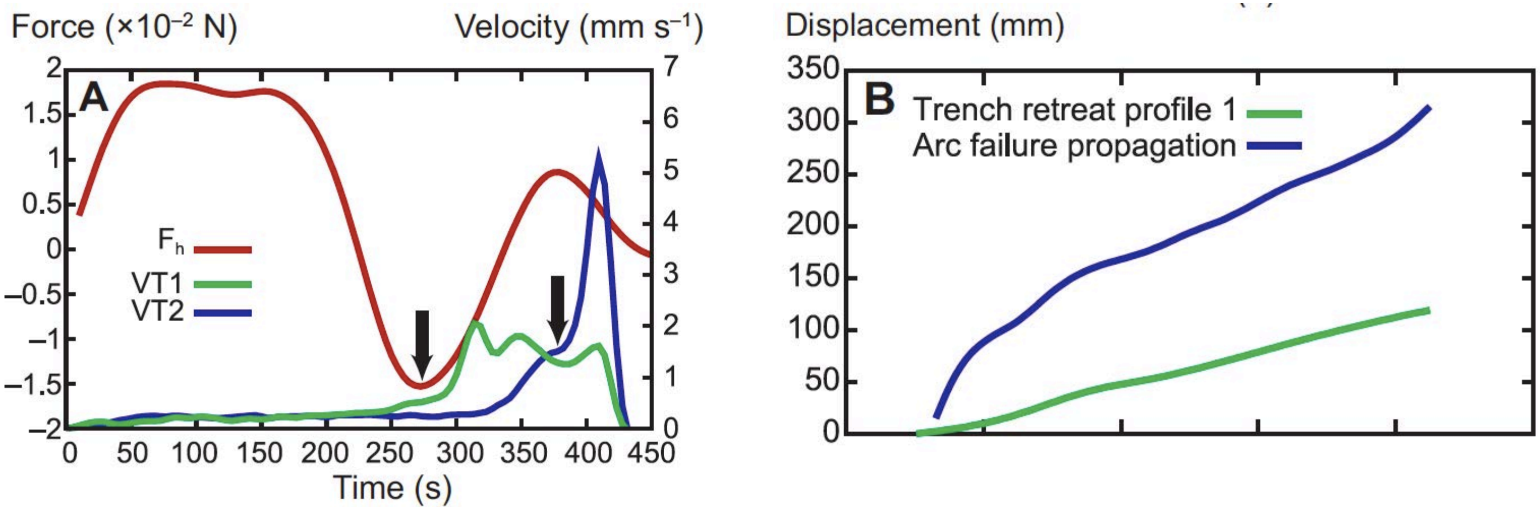
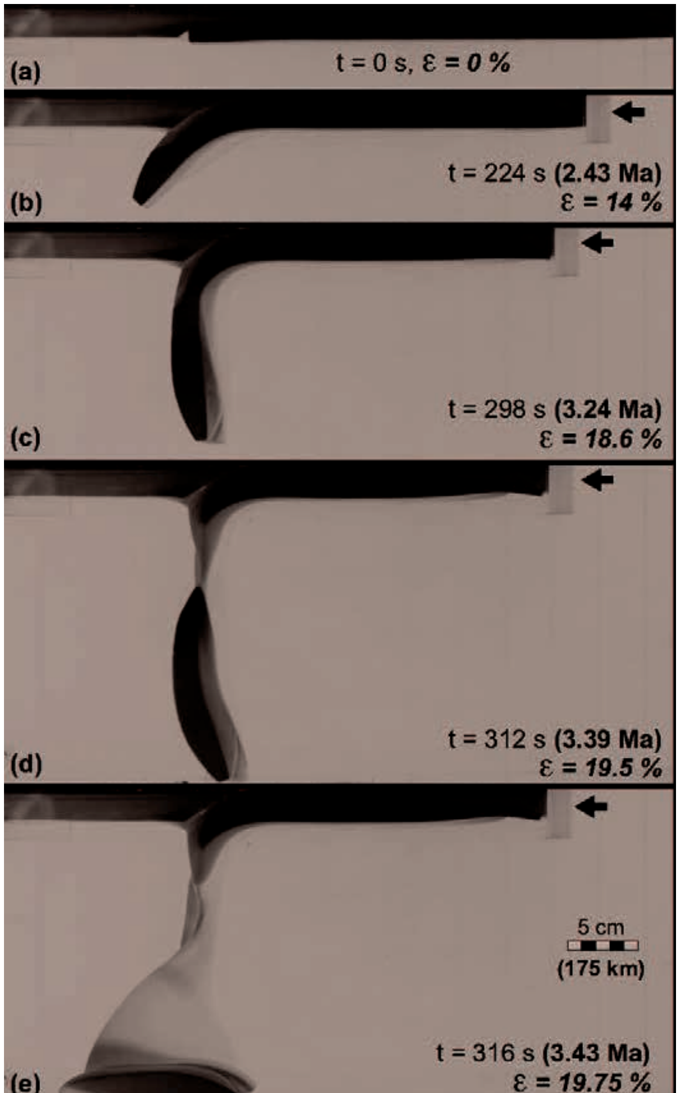
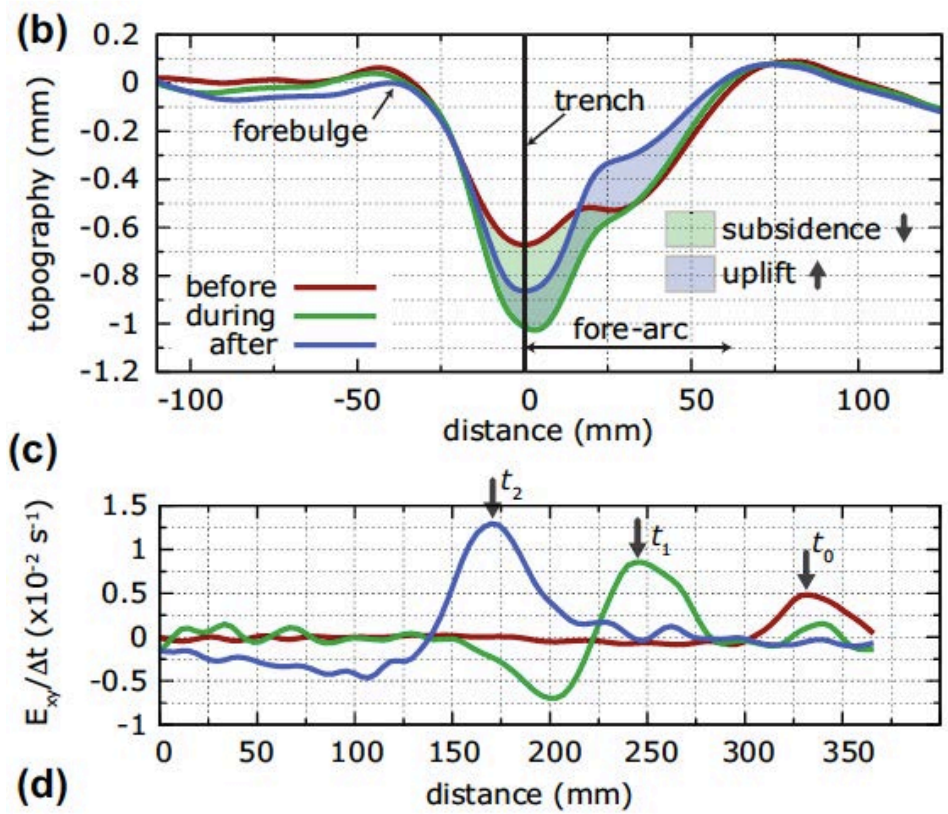




Slab breakoff and dynamic topography in the forearc



Slab breakoff propagates from one side to the other – creating signals in dynamic subsidence and uplift in the forearc and in trench-parallel strain rates



Boutelier & Cruden (in review)

Conclusions

- Analogue modelling is a powerful tool to test many aspects of 3D tectonic deformation at a range of scales. It is complementary to, not a competitor of numerical modelling.
- Considerable potential to discover new materials that can be tuned for modelling geodynamic processes but precise measurement by rheometry is critical.
- Use of quantitative techniques (e.g., PIV) to monitor experiments provides a link between rheology, deformation and natural structures at all scales, including GPS vectors in active tectonics and numerical experiments.
- Fully dynamic, 3D thermo-mechanical analogue experiments are here!