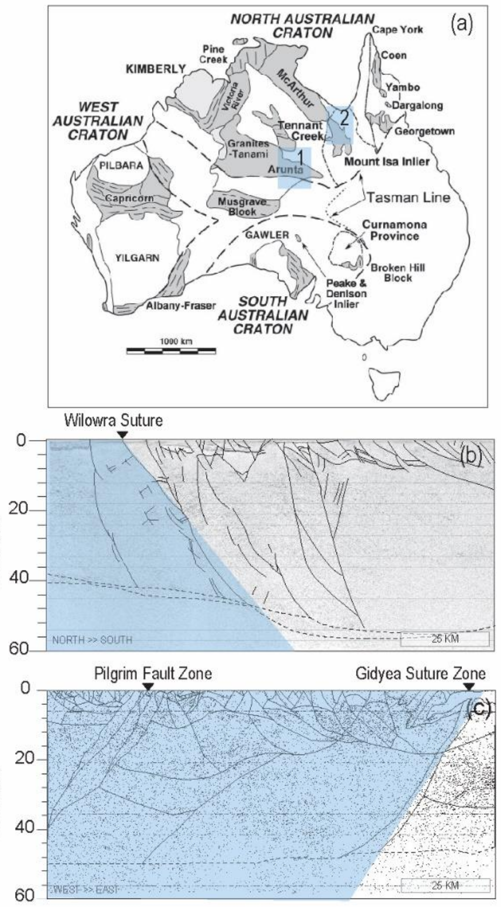
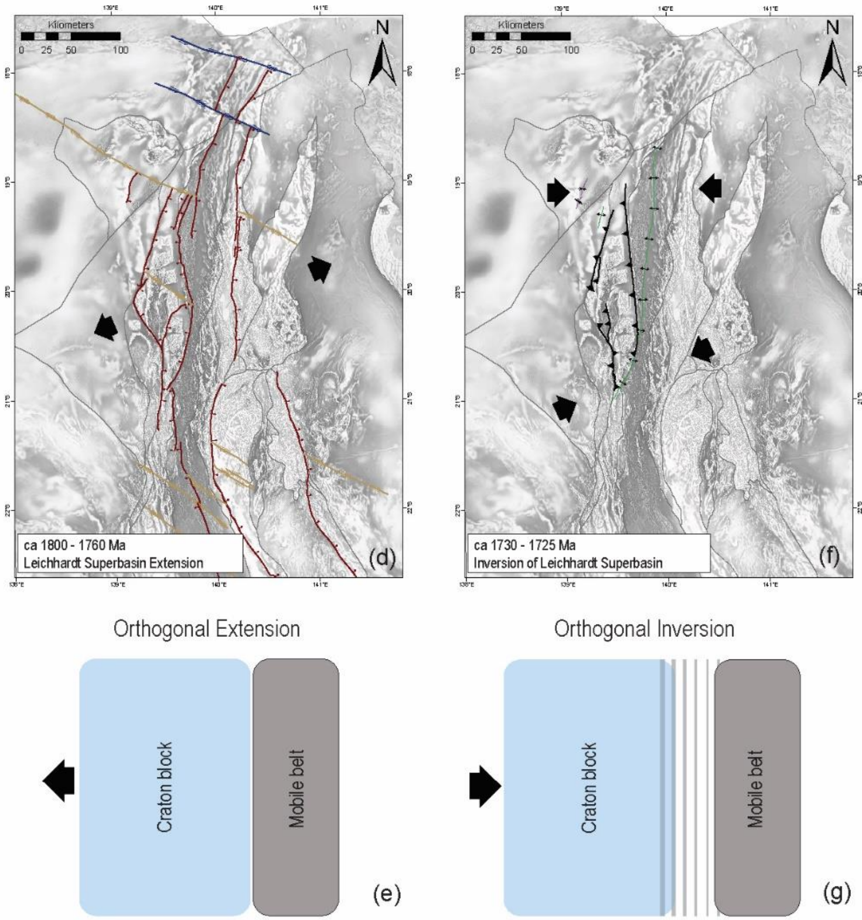
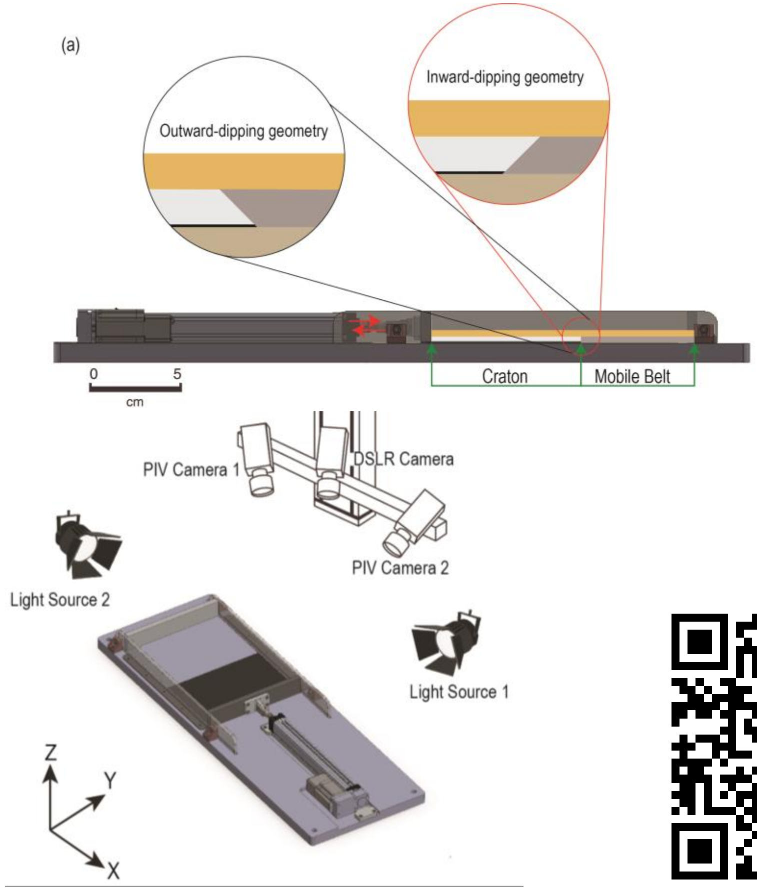
The effects of inward and outward dipping craton margin geometry on upper crustal deformation: Insights from analogue modelling

Fatemeh Amirpoorsaeed, Anindita Samsu, Peter Betts, Alexander Cruden, Robin Armit





Hypothesis: The geometry of the craton margin play a significant role in controlling the deformation style and strain partitioning at the edges of craton.



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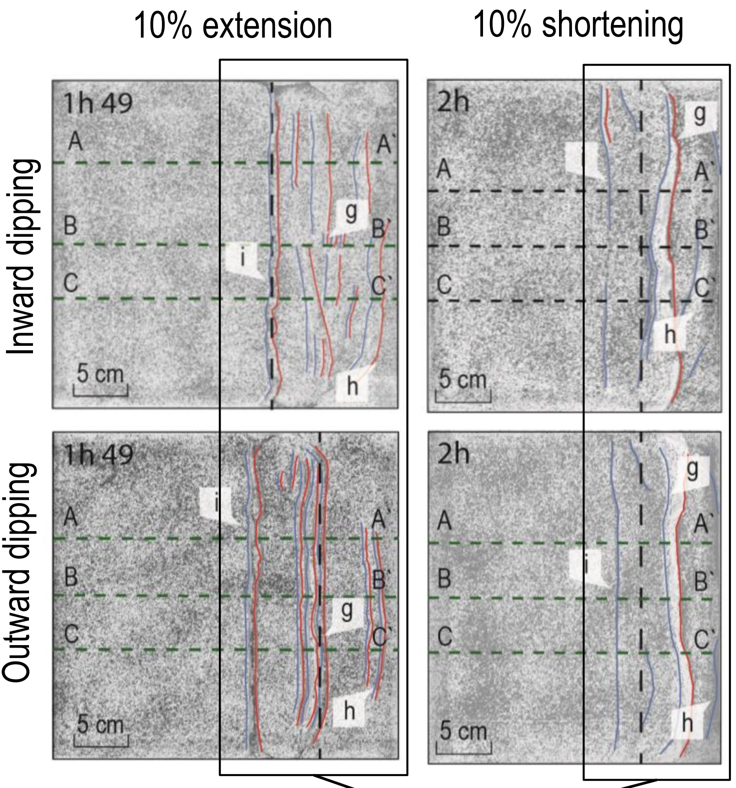
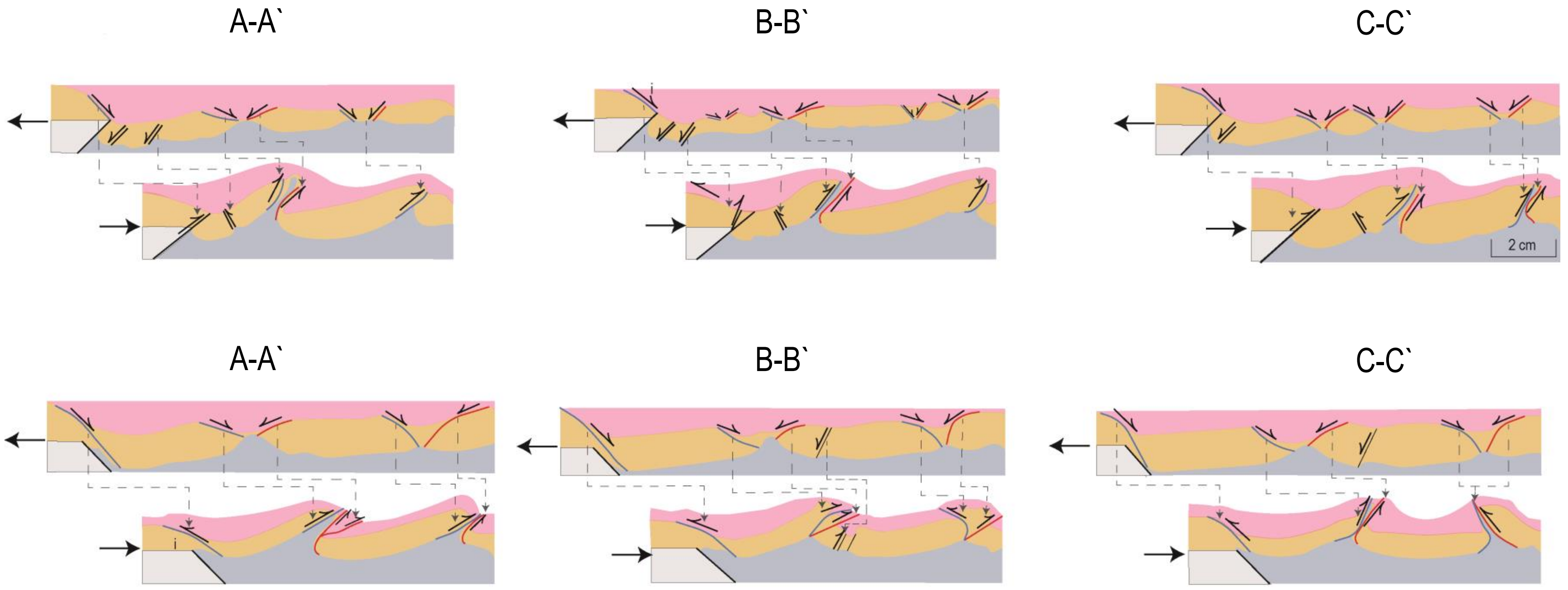
TS8.2: Analogue and numerical modelling of tectonic processes

PICO3b.10 / EGU23-13434



Part of the cross sections shown in the images on the right →



- Rifts mainly formed by boudinage and necking in the lower crust for both inward and outward dipping models. However, the inward dipping model led to numerous smaller faults, while the outward dipping model produced a single major normal fault along the craton margin.
- Upon shortening, the inward dipping model showed modest basin inversion above the craton margin, with most strain accommodated away from the margin. The outward dipping model experienced more intense inversion at the margin, but with lower strain and smaller reactivation of normal faults away from the margin.
- **We concluded that the geometry of a craton margin exerts a first-order control on the deformation of the crust during rifting and subsequent inversion.**

The effects of inward and outward dipping craton margin geometry on upper crustal deformation: Insights from analogue modelling

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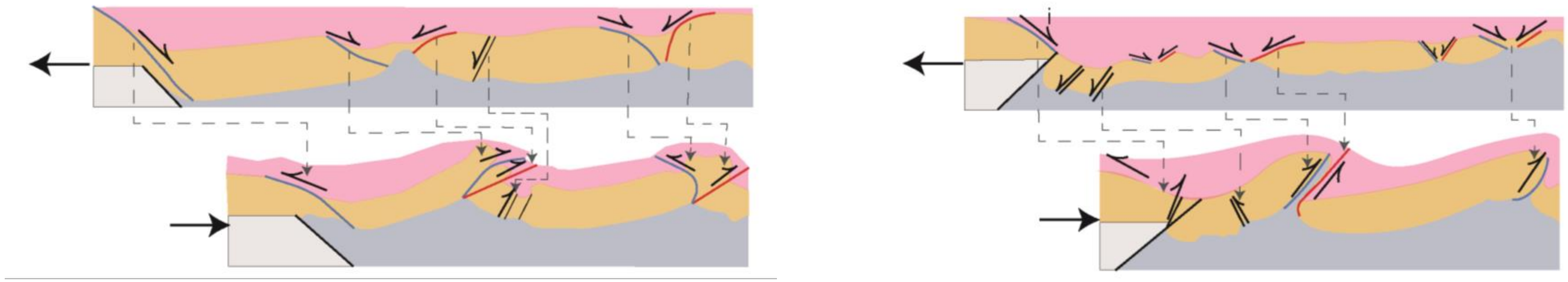
Background → Setup → Results → Key Findings → Conclusion



Abstract:

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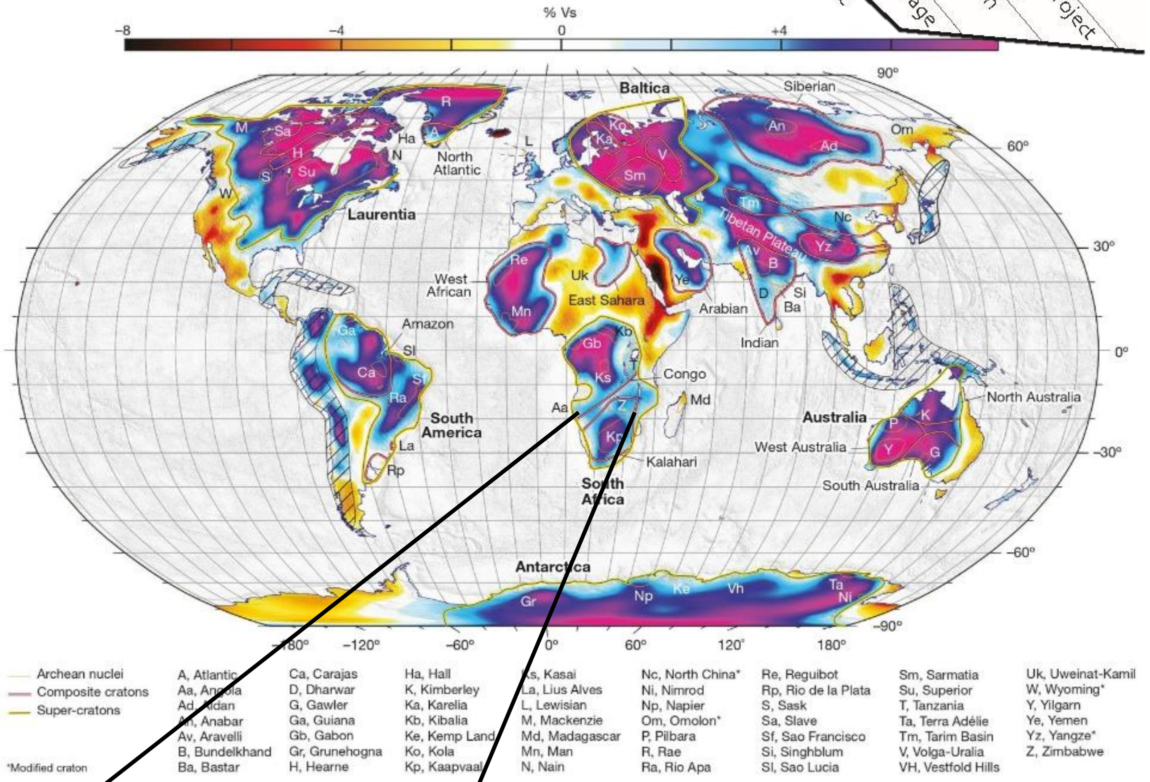
Background - Definitions

- **Let's start with some simplified definition!**

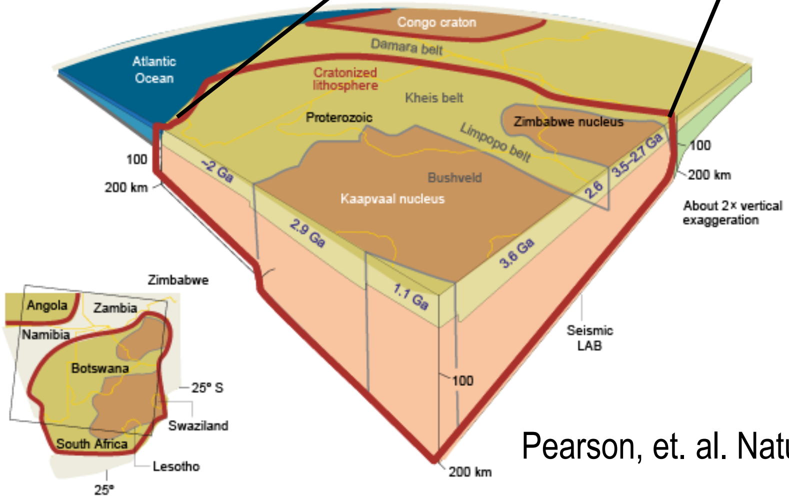
- **Cratons are:**
  - Coherent and thick blocks of lithosphere
  - Typically, stable for over a billion year
  - Amalgamation of Archean and Proterozoic blocks
  - Surrounded with mobile belts

- **Craton margins are:**
  - Thin and unstable
  - Wedge-shaped geometries
  - Regions of increased metamorphic grade
  - Prone to reactivation and experienced multiple stages of extension and shortening
  - Subject to reworking and intense deformation

- **Craton margins are also known as the location of high mineralization!**



Pearson, et. al. Nature, (2021)



Pearson, et. al. Nature, (2021)

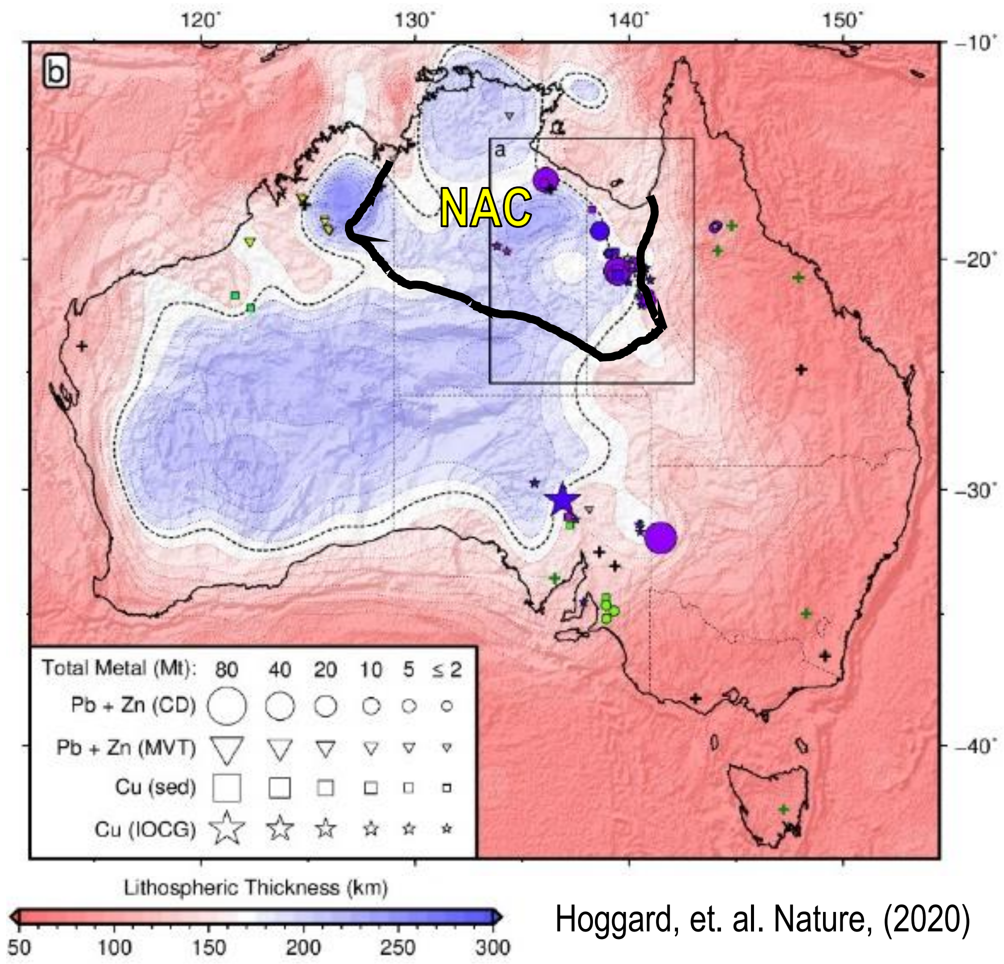
Background - Gap

- **Scientists** have been interested in craton margins due to their characteristics and correlation with mineralization:
  - **Hoggard et al., 2020**
    - 85% sediment-hosted base metal deposits are located withing 200 km from the craton margins
  - **Groves et al., 2020**
    - Most deposit types are sited within 100 km of the margins of Archean cratons.

BUT

- Why some segments of craton margins are highly mineralized, and some are barren?!
  - For example, the eastern margin vs southern margin of North Australian Craton (NAC) →
  - What elements of these margins are different from one another?

- **Let's have a deep look at NAC margins**

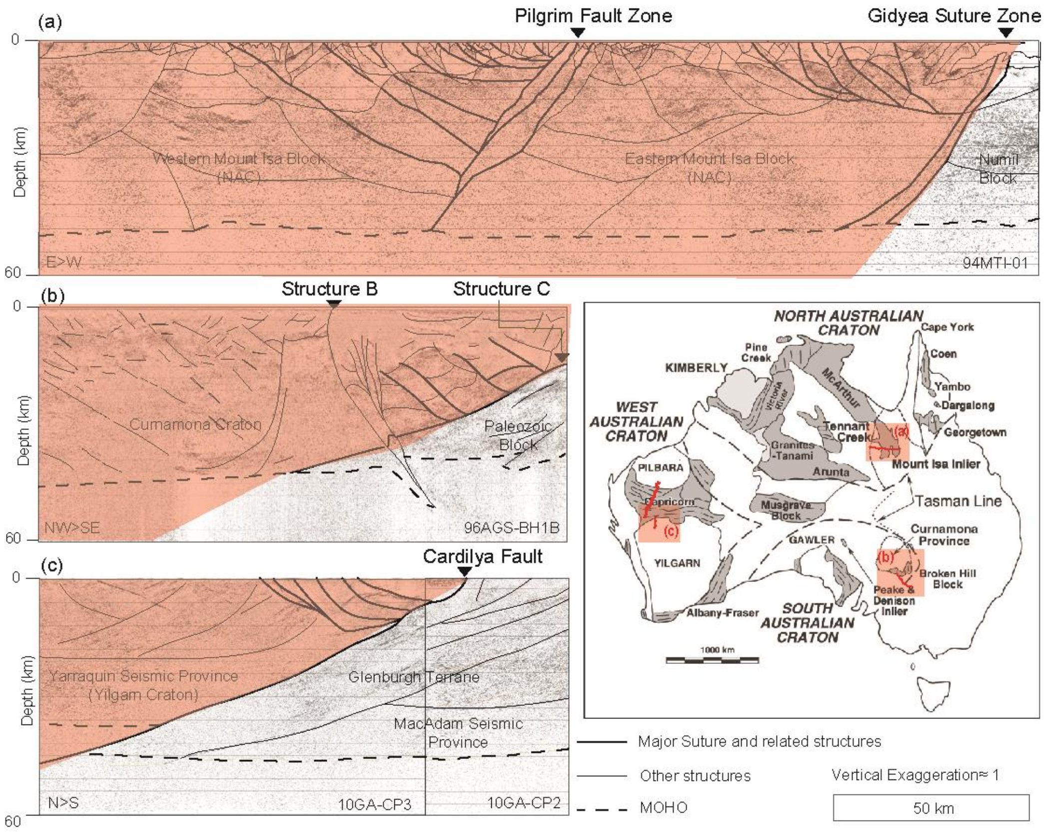


Hoggard, et. al. Nature, (2020)

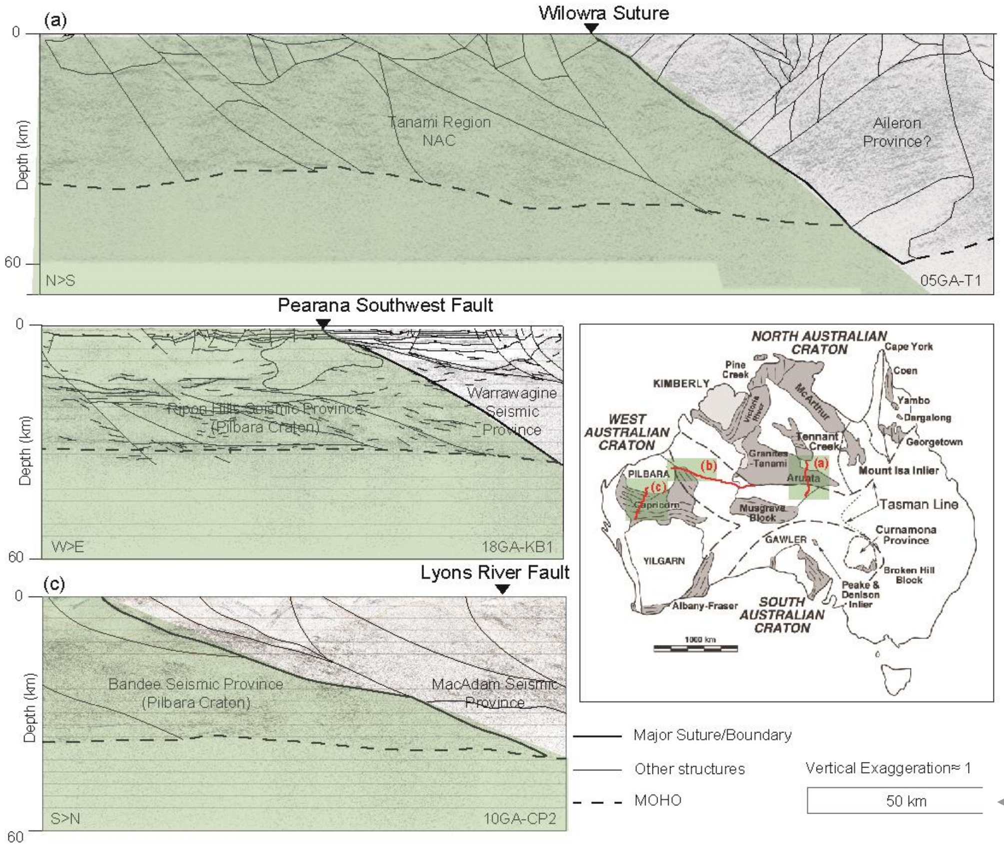
Background – Australian Cratons

- **Deep seismic profiles** across the margins of Australian Cratons show two main geometries: **Inward and Outward dipping**
- Different geometry of craton margins have different deformation pattern → **does the geometry of craton margin have any impact on deformation?**

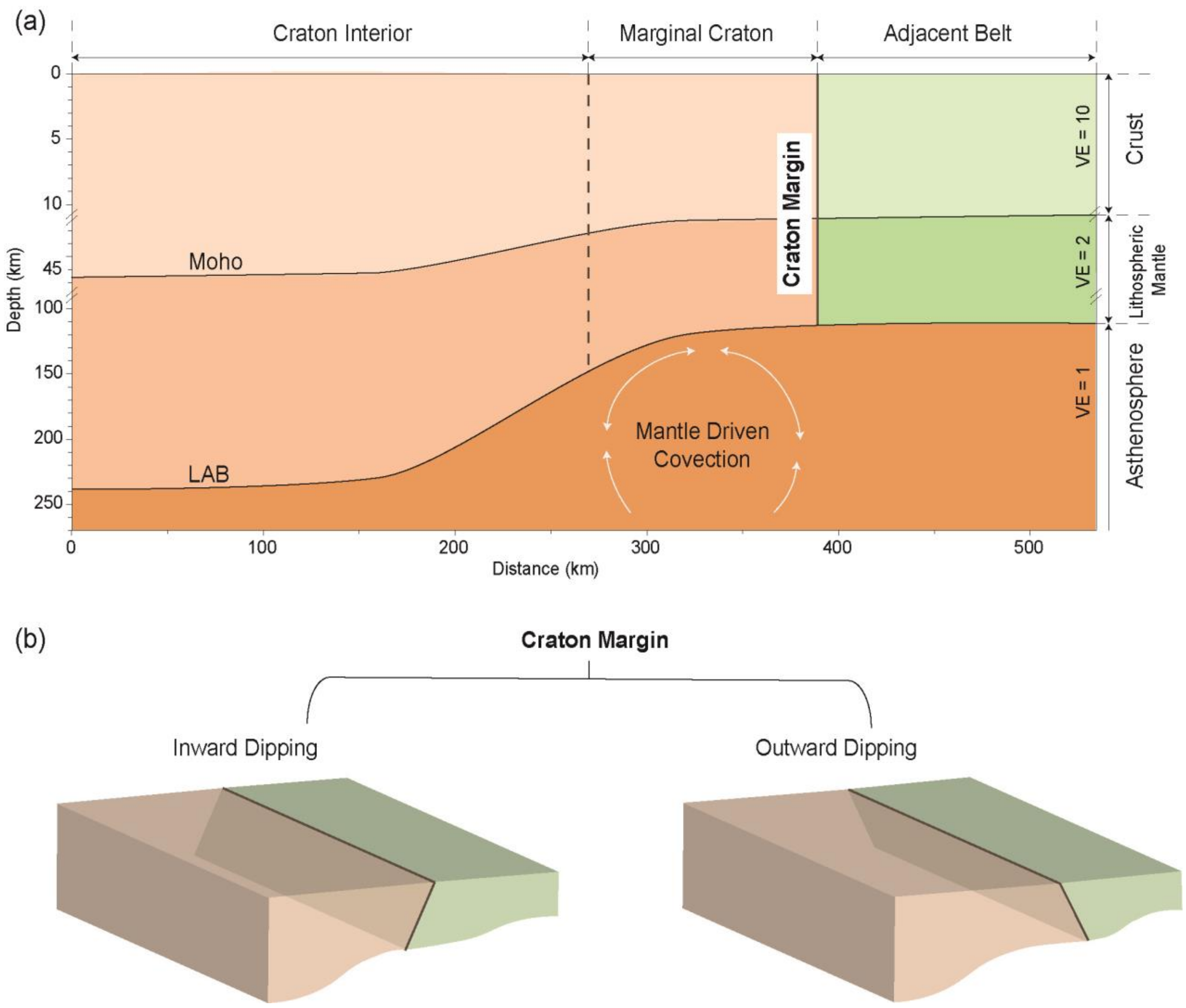
Dipping towards the craton interior – Inward dipping



Dipping away from the craton interior – Outward dipping



Background – Hypothesis



- Based on deep geophysical data we know that the craton margin is a wedge-shape geometries that can be:
  - **Inward or Outward dipping**
- The impact of the varying geometry on the deformation and subsequently mineral system has not been studies!!

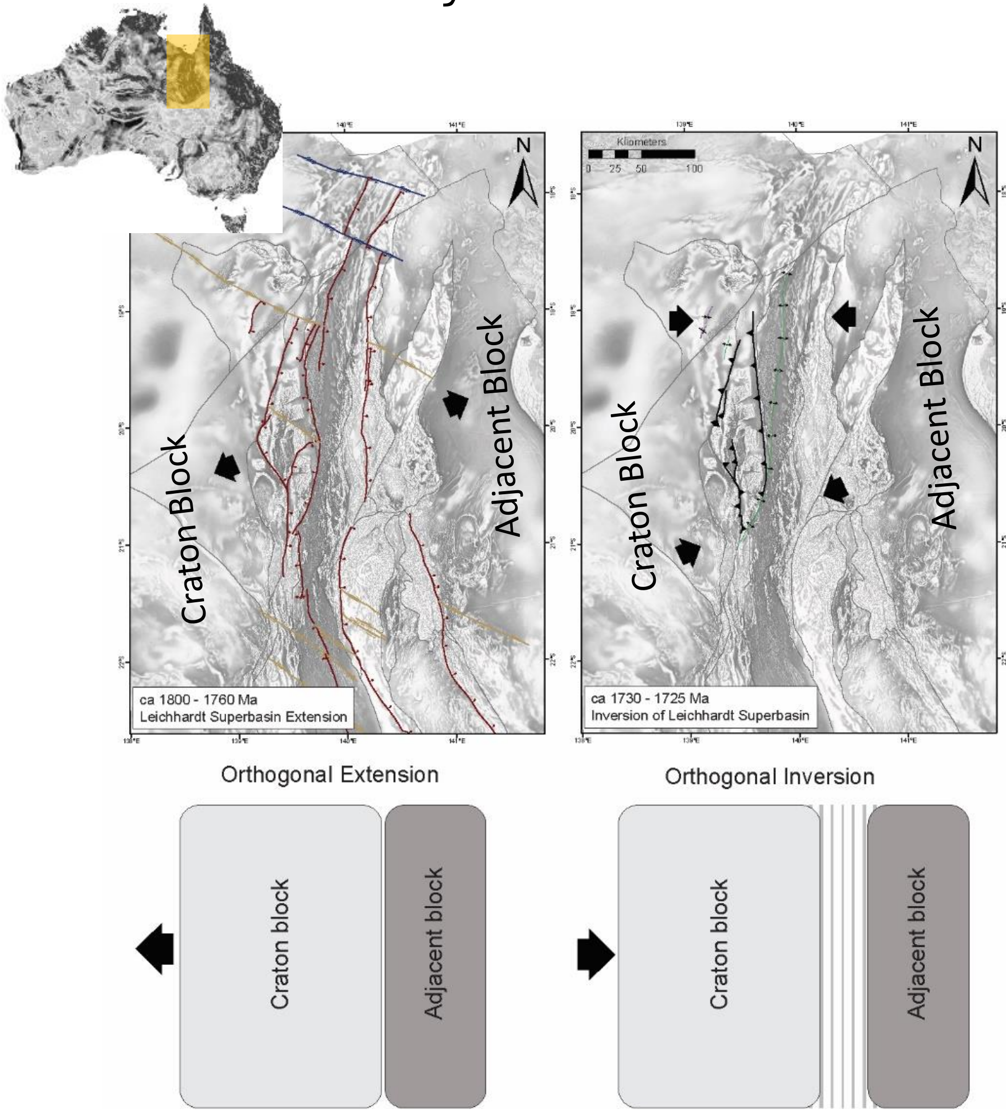
Hypothesis:

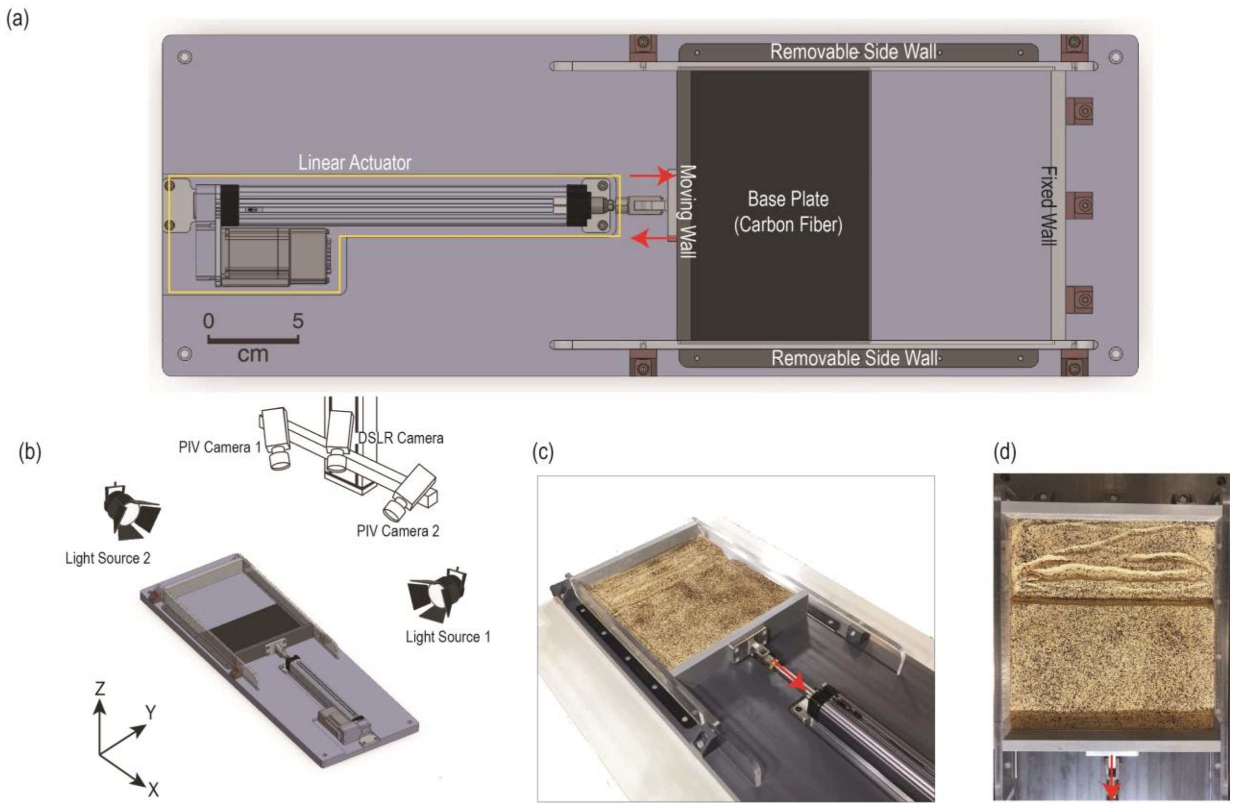
The geometry of the craton margin play a significant role in controlling the deformation style and strain partitioning at the edges of craton.

- **Let's test this! We need an apparatus!**

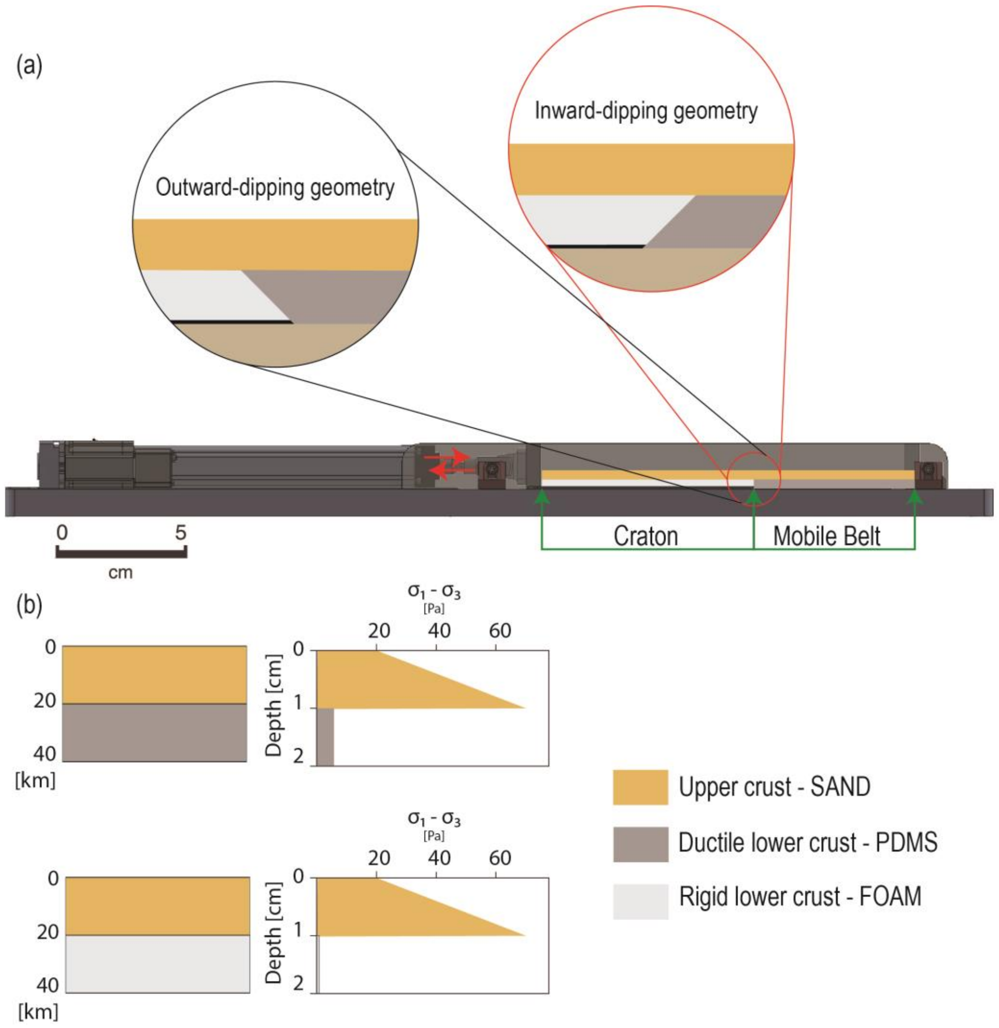
Setup – Design

- Setup design was inspired by rifting and basin inversion at Mount Isa Inlier, eastern margin of North Australian Craton (1800-1740 Ma - Formation of the Leichhardt Superbasin).
    - A crust scale model that simulate orthogonal extension followed by inversion
- Experiment setup with moving base plate, moving wall, and linear actuator.
- Model represents upper and lower crust with rigid foam and ductile material.





Setup – Material Scaling



- Analogue experiments use scaled-down lengths, time, and forces to simulate natural conditions.
  - A length scale ratio of 5×10^{-7} was used, with a model crustal thickness of 20 mm corresponding to a natural crustal thickness of 40 km.
  - Time scaling factor of 1.41×10^{-10} means 1 hour in the experiment corresponds to 0.82 million years in nature.
- Ductile lower crust was modeled using a polydimethylsiloxane (PDMS) and iron filling (IF) mixture with a density of 1200 kg/m^3.
- Brittle upper crust modeled using granular materials, with a mixture of quartz sand and hollow ceramic Envirospheres.

Table 3-1. Scaling and Experimental Parameters for the Analogue Models

			Thickness		Density		Viscosity	
		Material	*Model (mm)*	*Nature (km)*	*Model (km/m³)*	*Nature (km/m³)*	*Model (Pa.s)*	*Nature (Pa.s)*
Upper crust	*Brittle*	*Sand*	*10*	*20*	*10*	*20*	*N/A*	*N/A*
Lower crust	*Ductile*	*PDMS-IF*	*10*	*20*	*10*	*20*	*3.1×10^{4}*	*1×10^{21}*
Lower crust	*Rigid*	*XPS Foam*	*10*	*20*	*10*	*20*	*N/A*	*N/A*

Scaling factors: Model/prototype	*$L^* = 5 \times 10^{-7}$*	*$\rho^* = 0.444$*	*$\eta^* = 3.1 \times 10^{-17}$*
Time scaling factor:	*$t^* = \eta^* / (\rho^*. g^*. L^*)$*	*$t^* = 1.4 \times 10^{10}$*	
Velocity scaling factor:	*$v^* = L^* / t^*$*	*$v^* = 3.58 \times 10^{3}$*	*1 hr in model ~ 0.82 Myr in nature*
Gravity scaling factor:	*$g^* = g_m / g_p = 1$*		*6 mm/hr in model ~ 20 mm/yr in nature*

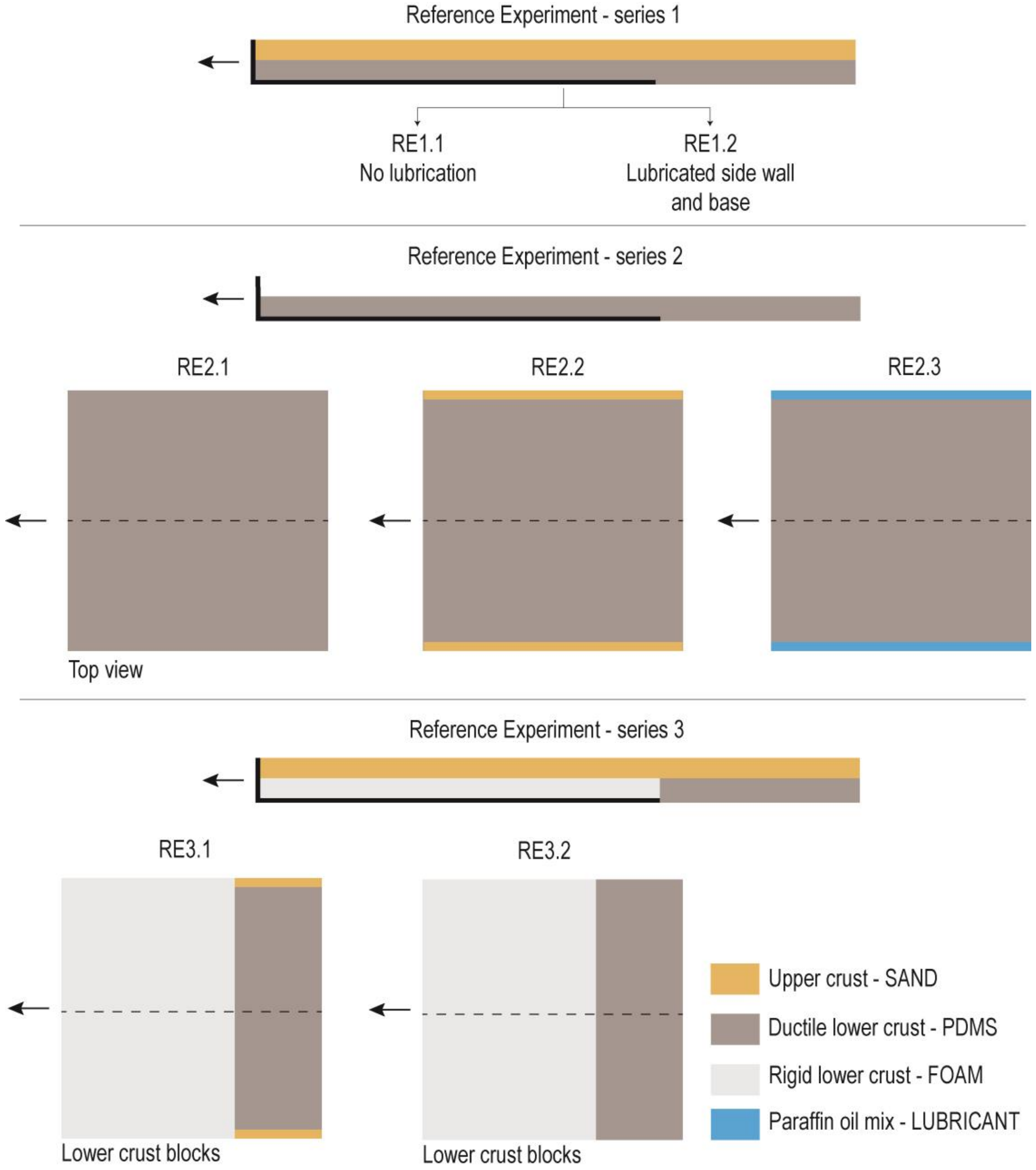
Setup – Experimental Design

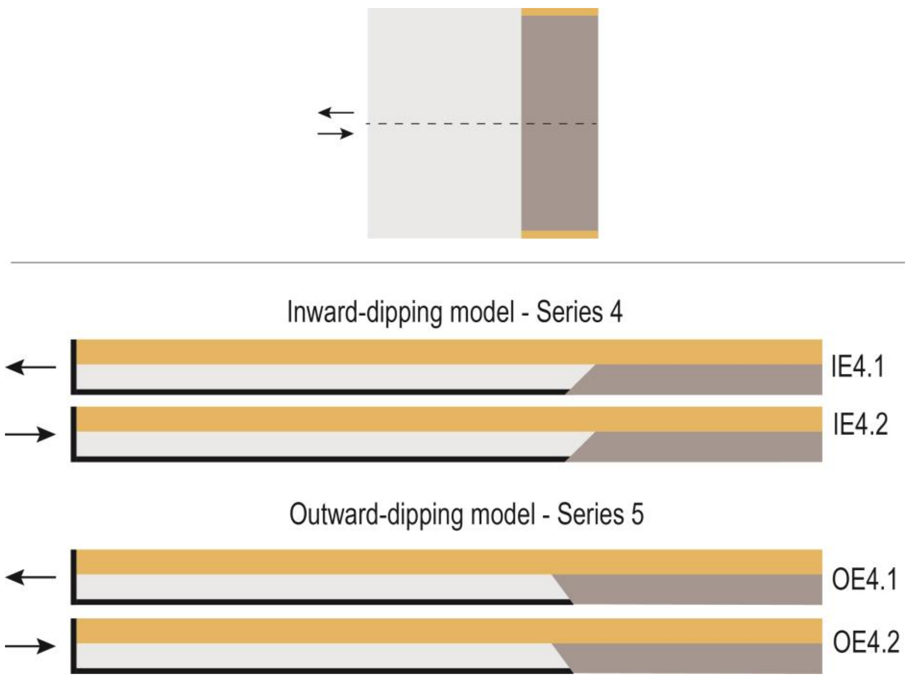
- Since the setup was specifically designed for this study, we needed to define the boundary effects and minimize them.

Experiment	*Kinematic*	*Lower crust*	*Upper crust*	*Foam edge dipping*	*Side wall boundary conditions*	
Series 1						Reference Experiment Series 1 (define the boundary effects)
RE1.1	*Extension*	*PDMS*	*Sand*	*N/A**	*Not-lubricated*	
RE2.1	*Extension*	*PDMS*	*Sand*	*N/A*	*Lubricated*	
Series 2						Reference Experiment Series 2 (reduce the boundary effects)
RE2.1	*Extension*	*Foam + PDMS*	*N/A*	*Vertical*	*Lubricated*	
RE2.2	*Extension*	*Foam + PDMS*	*N/A*	*Vertical*	*Sand strips*	
RE2.3	*Extension*	*Foam + PDMS*	*N/A*	*Vertical*	*Oil strips*	
Series 3						Reference Experiment Series 3 (minimize the boundary effects)
RE3.1	*Extension*	*Foam + PDMS*	*Sand*	*Vertical*	*Sand strips*	
RE3.2	*Extension*	*Foam + PDMS*	*Sand*	*Vertical*	*Lubricated*	
Series 4						Inward dipping Experiments Series 4
IE4.1	*Extension*	*Foam + PDMS*	*Sand*	*Inward – 45°*	*Sand strips*	
IE4.2	*Inversion*	*Foam + PDMS*	*Sand*	*Inward – 45°*	*Sand strips*	
Series 5						Outward dipping Experiments Series 5
OE5.1	*Extension*	*Foam + PDMS*	*Sand*	*Outward – 45°*	*Sand strips*	
OE5.2	*Inversion*	*Foam + PDMS*	*Sand*	*Outward – 45°*	*Sand strips*	

* *N/A – Not Applicable*

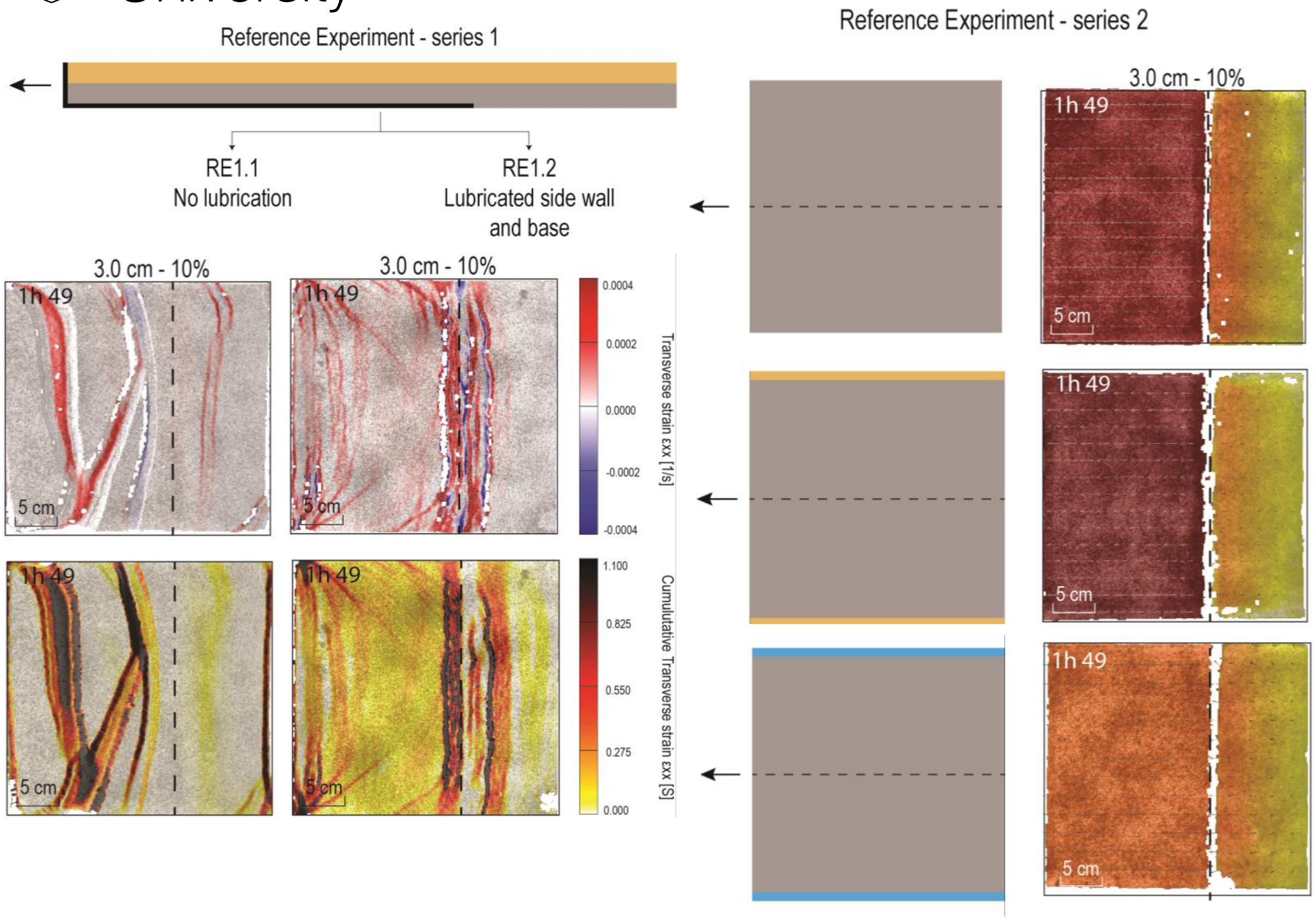
Setup – Experimental Design





The models were extended by 10%, followed by the introduction of infill sediments to simulate basin conditions. Subsequently, the models were shortened by 10%.

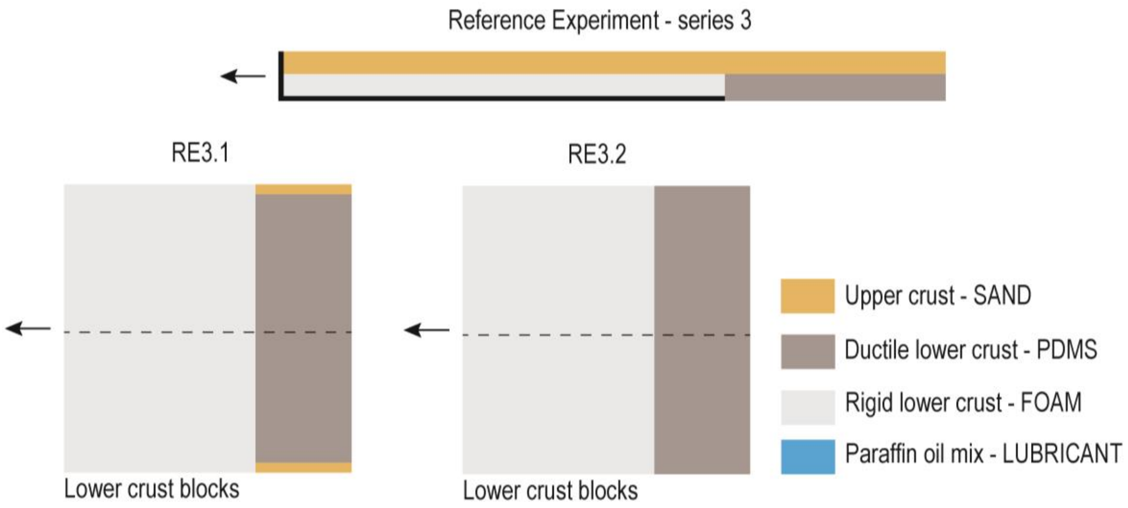
Results – Reference Experiments

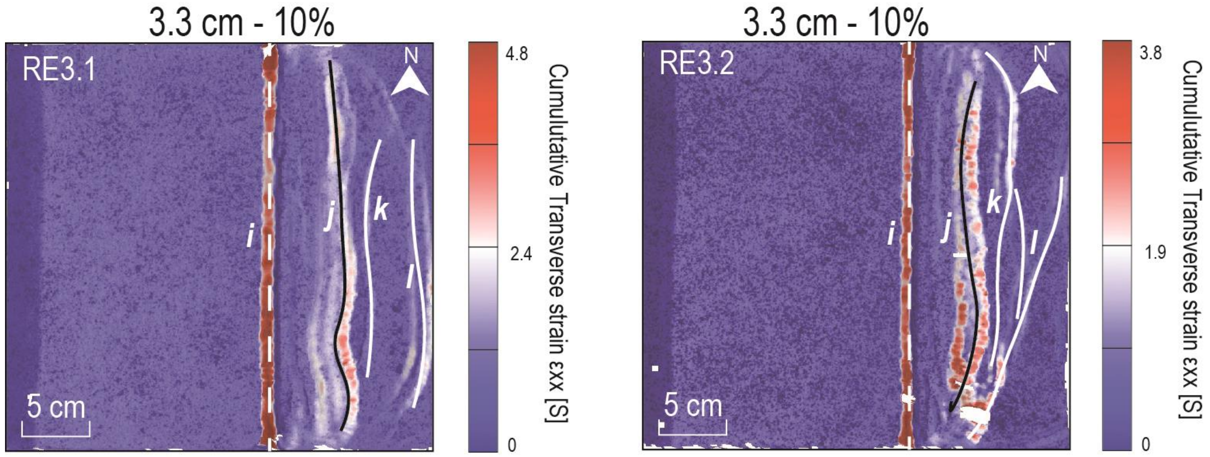


- **Model RE1.1:** Lower crust adheres to sidewalls, causing extension rifts to curve.
- **Model RE1.2:** Lubrication reduces basal boundary effect, but lateral side boundary effect remains.
- **Model RE2.1:** Homogeneous velocity distribution, but tilt observed at the top and bottom of the model.
- **Model RE2.2:** No movement on top of sand strips, sense of movement straight in line with actuator.
- **Model RE2.3:** High velocity and movement above oil strips, allowing ductile material to flow easily.

- **Model RE2.2 is the best solution for reducing boundary effects.**
- **Although, there is still a grip next to the moving wall, let's use a rigid foam as the cratonic lower crust, it may minimize the boundary effect!**

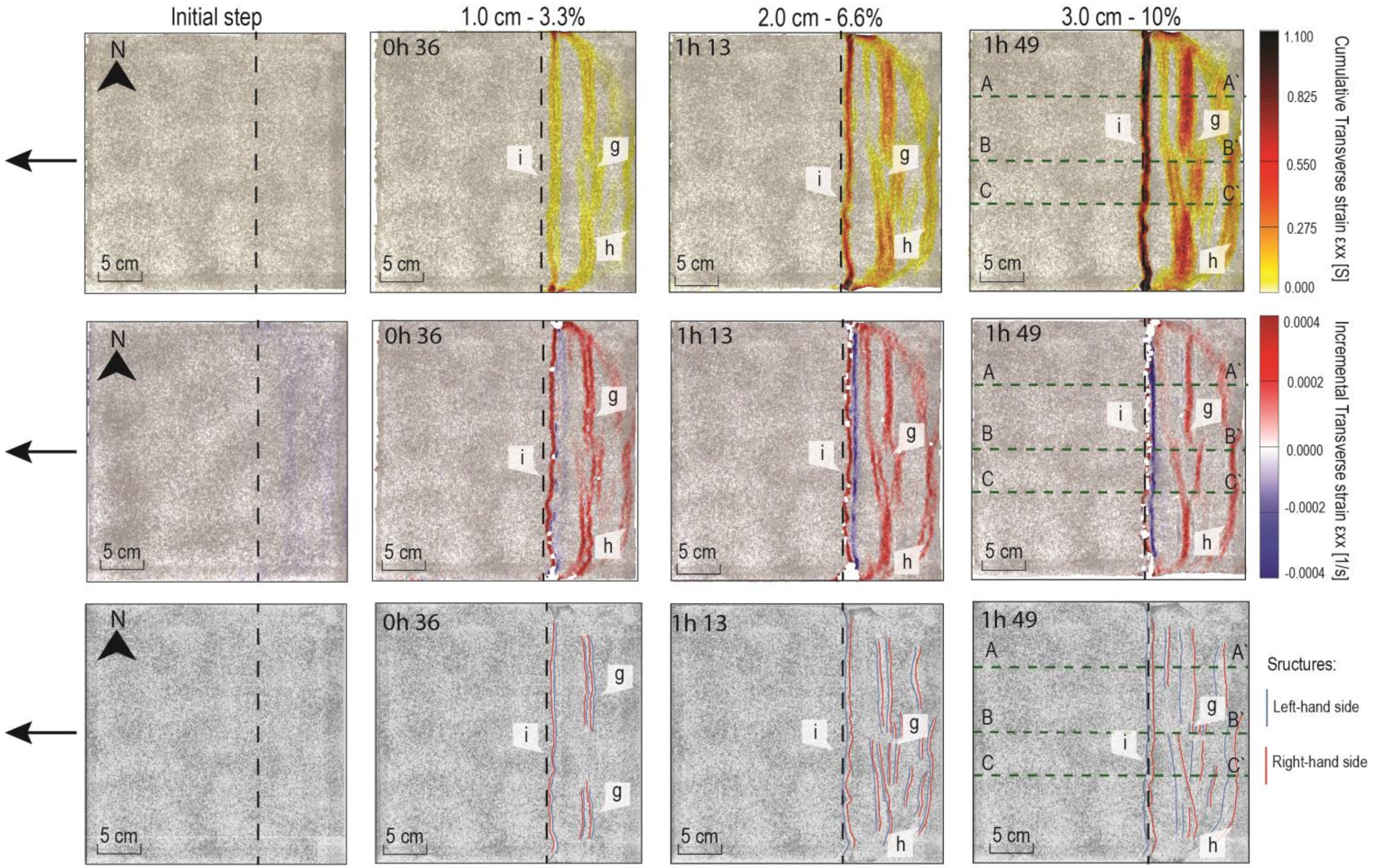
Results – Reference Experiments





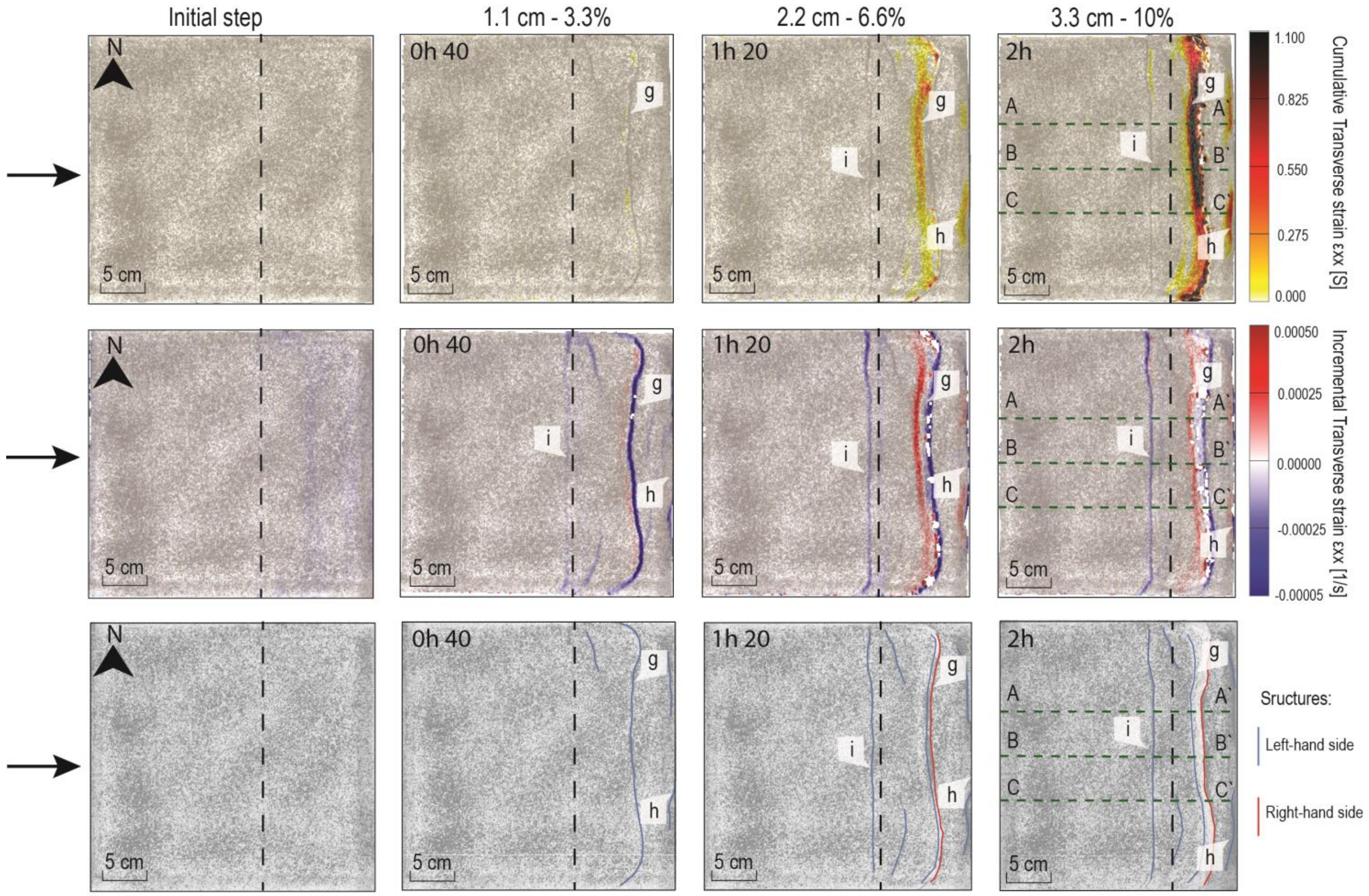
- Now, we have the rigid foam as cratonic lower crust sitting on moving base plate, we can use ductile material to simulate the mobile/adjacent belt.
- **Model RE3.1:** Boundary effects caused by sidewall and ductile material significantly reduced.
- **Model RE3.2:** Sidewall grip on ductile lower crust persists with lubrication.
- **Conclusion:** To create a crust model that simulates the craton and model belt with a **focus** on deformation at the craton margin the best approach is:
  - Use a rigid foam as the craton block
  - Lubricate the base
  - Apply 10% extension/shortening over 1 hour
  - Pace sand strips next to the sidewalls.
- Now let's test the inward vs outward dipping geometry, for this we can create a 45-degree dipping at the foam edge that is either inward or outward!

Results – Inward Dipping Extension



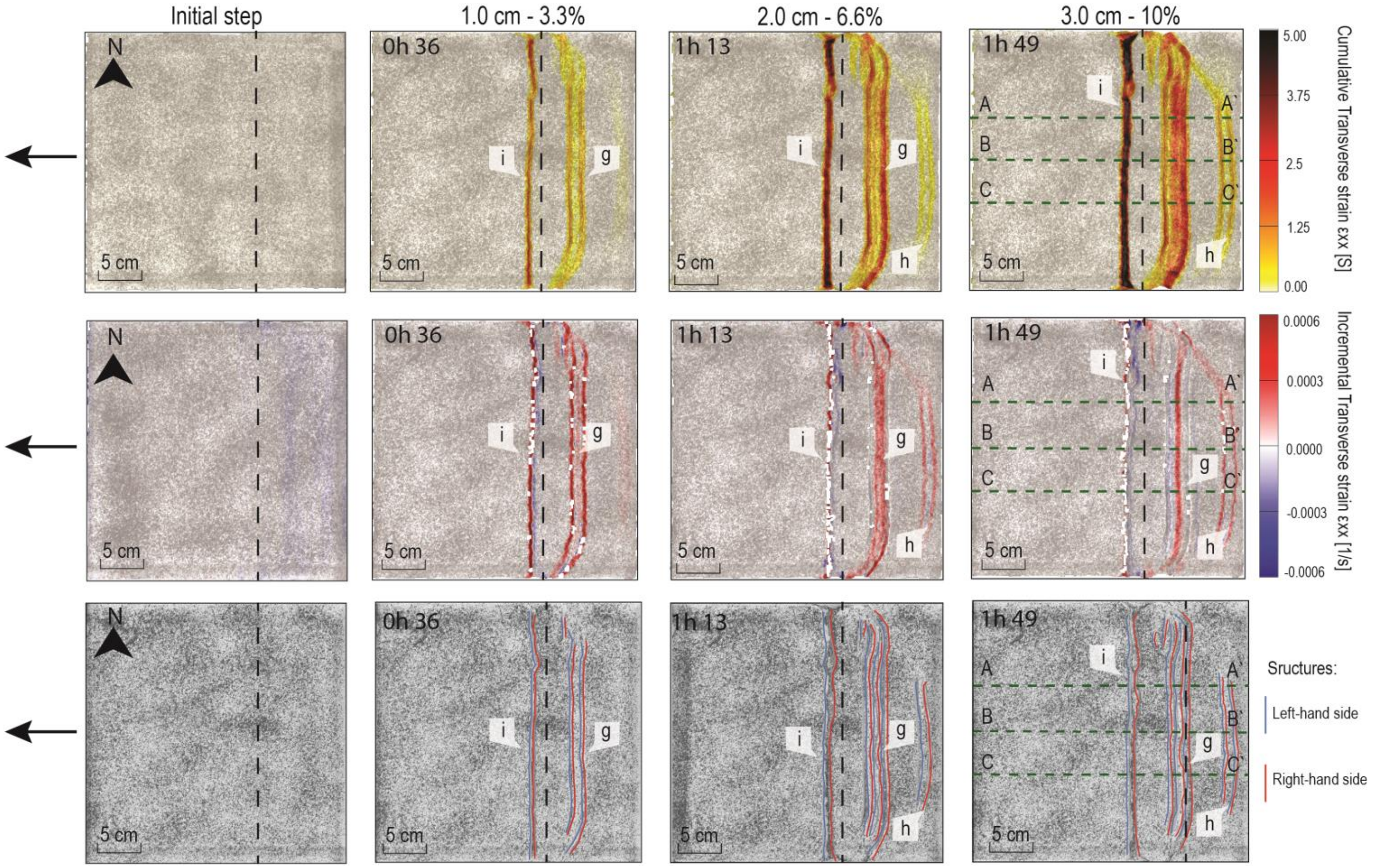
- **Three main rifts formed during extension:**
- **Rift (i):**
  - starts forming at 1 cm extension at the foam edge above the rheological discontinuity
  - As extension continues, rift (i) creates a half-graben feature that gets deeper and accommodates a major portion of strain.
- **Rift (g):**
  - develops on the outboard of the foam
  - It doesn't deepen as much as rift (i)
  - as extension progresses, rift (g) branches out into a V-shape near the center, forming a segmented rift model
- **Rift (h):**
  - forms adjacent to the fixed wall
  - without deepening as much as the main rift (i)

Results – Inward Dipping Shortening



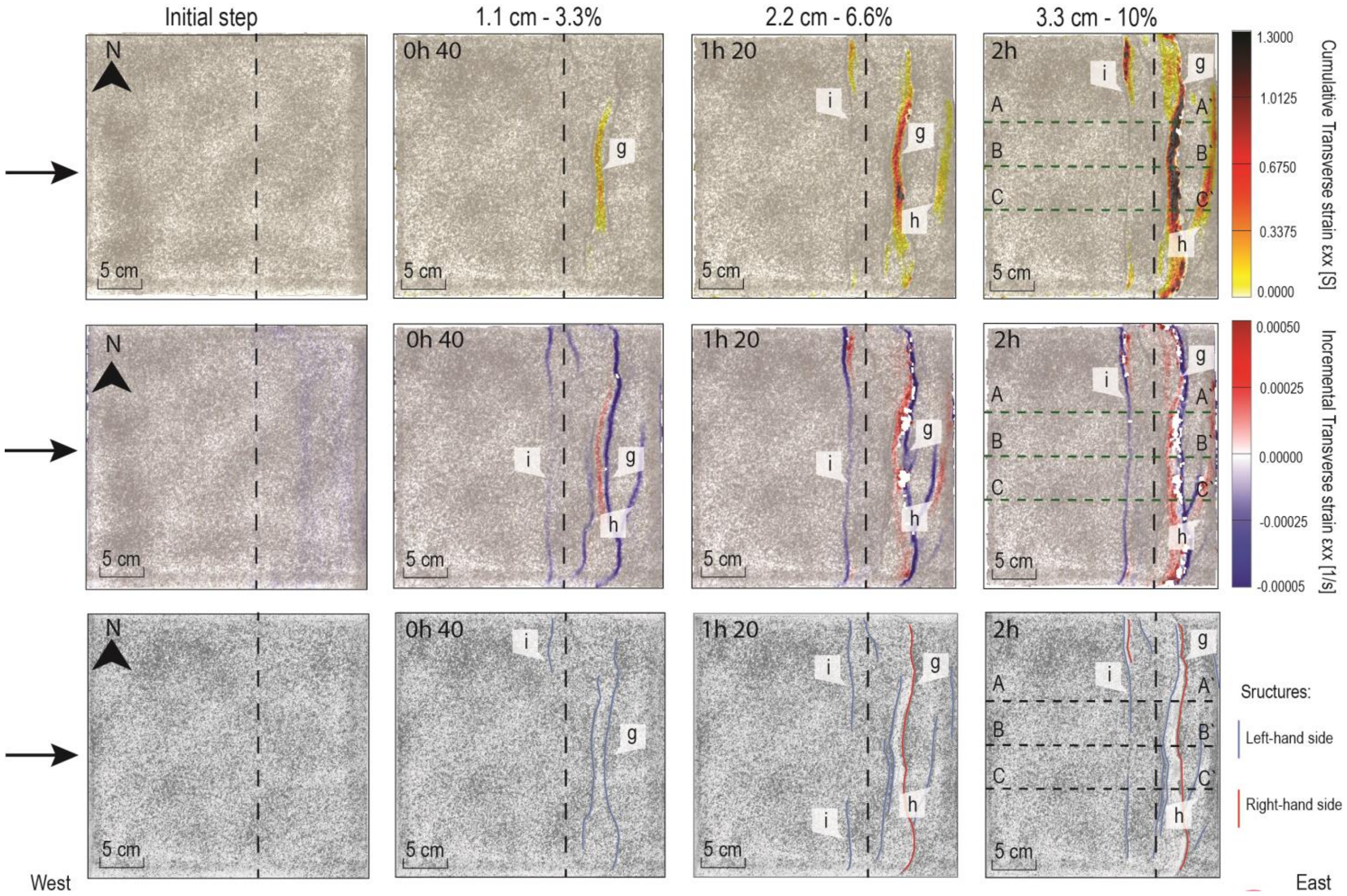
- **Structures reactivated during shortening.**
- Reactivation begins along the rift-related structures on the east side of the foam edge
- Up to 2.2 cm shortening, the reactivation at the foam edge remains indistinct, coinciding with the inversion of infill sediments of rift (i).
- The first structure evident in the incremental strain map and top-view image at 1 cm extension is structure (g), which forms as a result of rift (g) being reversed. A high amount of strain is accommodated along this structure as shortening progresses.
- Sediments in the graben are inverted due to the reverse reactivation of normal faults.
- Rift (h) is reactivated, with some degree of uplift observed, but less intense compared to the other structures.
- The shortened model exhibits resistance at the edge of the foam (i), while reactivation is more facile at locations away from the foam.
- **The experiments show that the inversion process has different effects on the rift structures, with some being more easily reactivated and others experiencing resistance, depending on their location relative to the foam edge.**

Results – Outward Dipping Extension



- **Three main rifts formed during extension:**
- **Rift (i):**
  - emerges above the foam edge and deepens without increasing in width as the extension progresses. It is a continuous structure that doesn't deform further and is considered as a half-graben geometry.
- **Rift (g):**
  - appears further eastward in the middle of the ductile lower crust, widening as extension progresses. This rift accommodates more than 3S strain by the end of the extension and exhibits significant necking.
- **Right (h):**
  - develops closer to the fixed wall at a later stage of the extension process, remaining smaller due to its proximity to the fixed wall and distance from the moving wall. Around 1 S strain is accommodated near the end of extension along this rift.

Results – Outward Dipping Shortening



- **The reactivation of inherited extensional structures during inversion leads to the formation of reversed geometries.**
- As shortening advances, strain is accommodated along structure (g) on the model's east side. Notable reactivation occurs in the middle of the ductile lower crust, where rift (g) initially formed.
- A smaller degree of strain is accommodated along structure (i) directly above the edge.
- A smaller extent of strain is accommodated along the reactivated rift (h) near the fixed wall.

- **In conclusion, the structures exhibit reduced resistance to reactivation, and the structures characteristic of 10% shortening are discernible in this analysis.**

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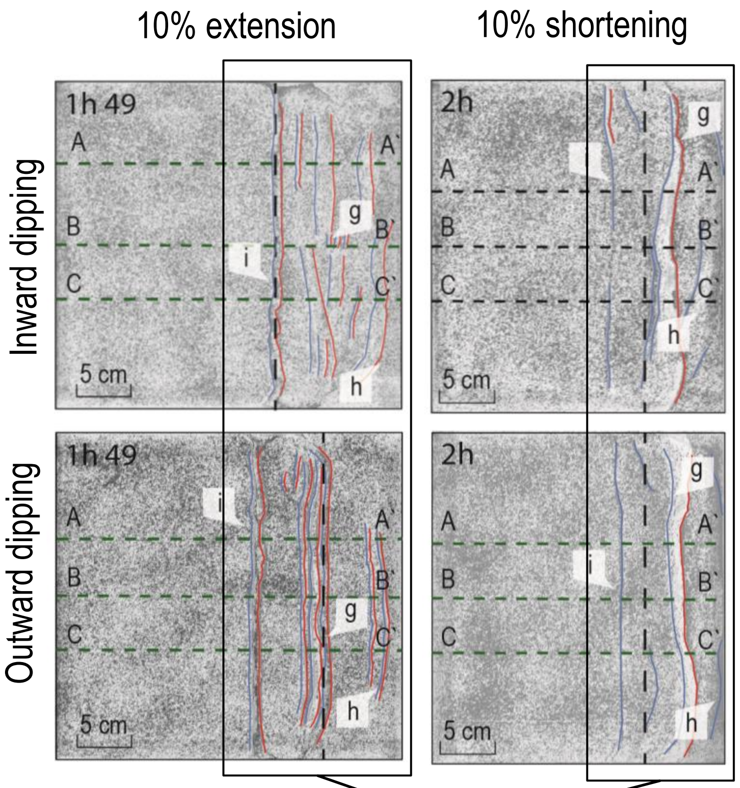
Results – Inward vs Outward



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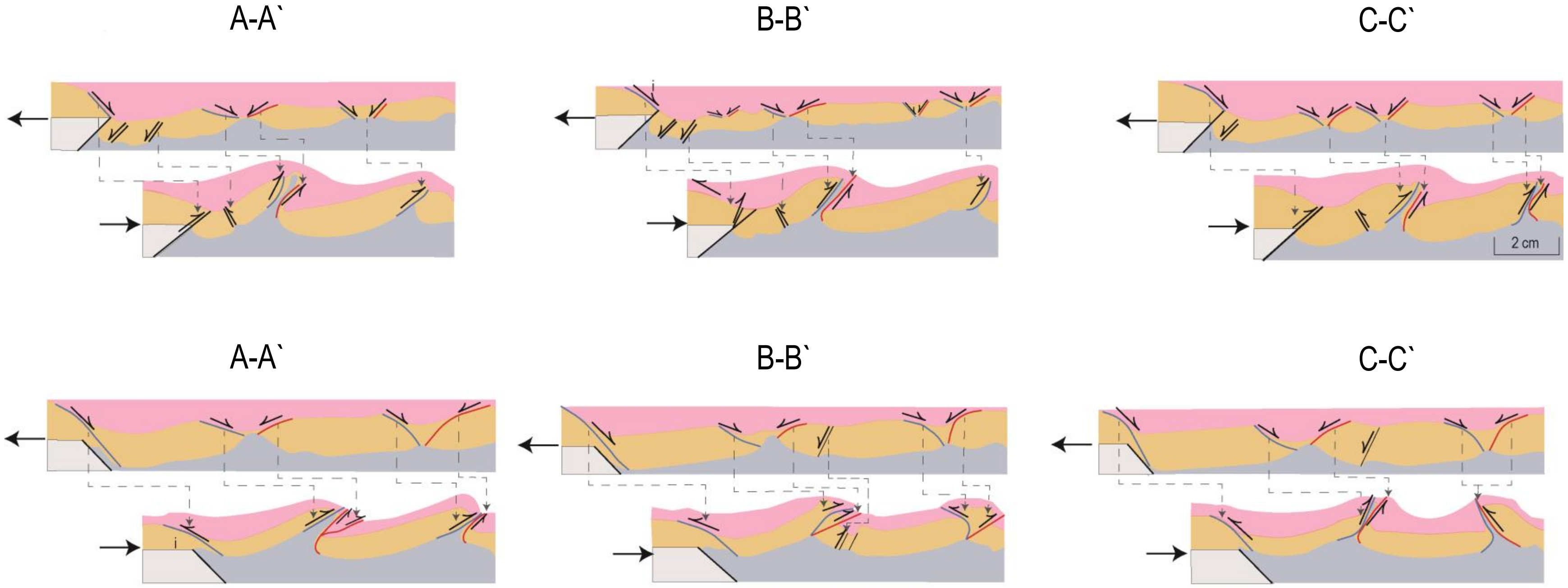
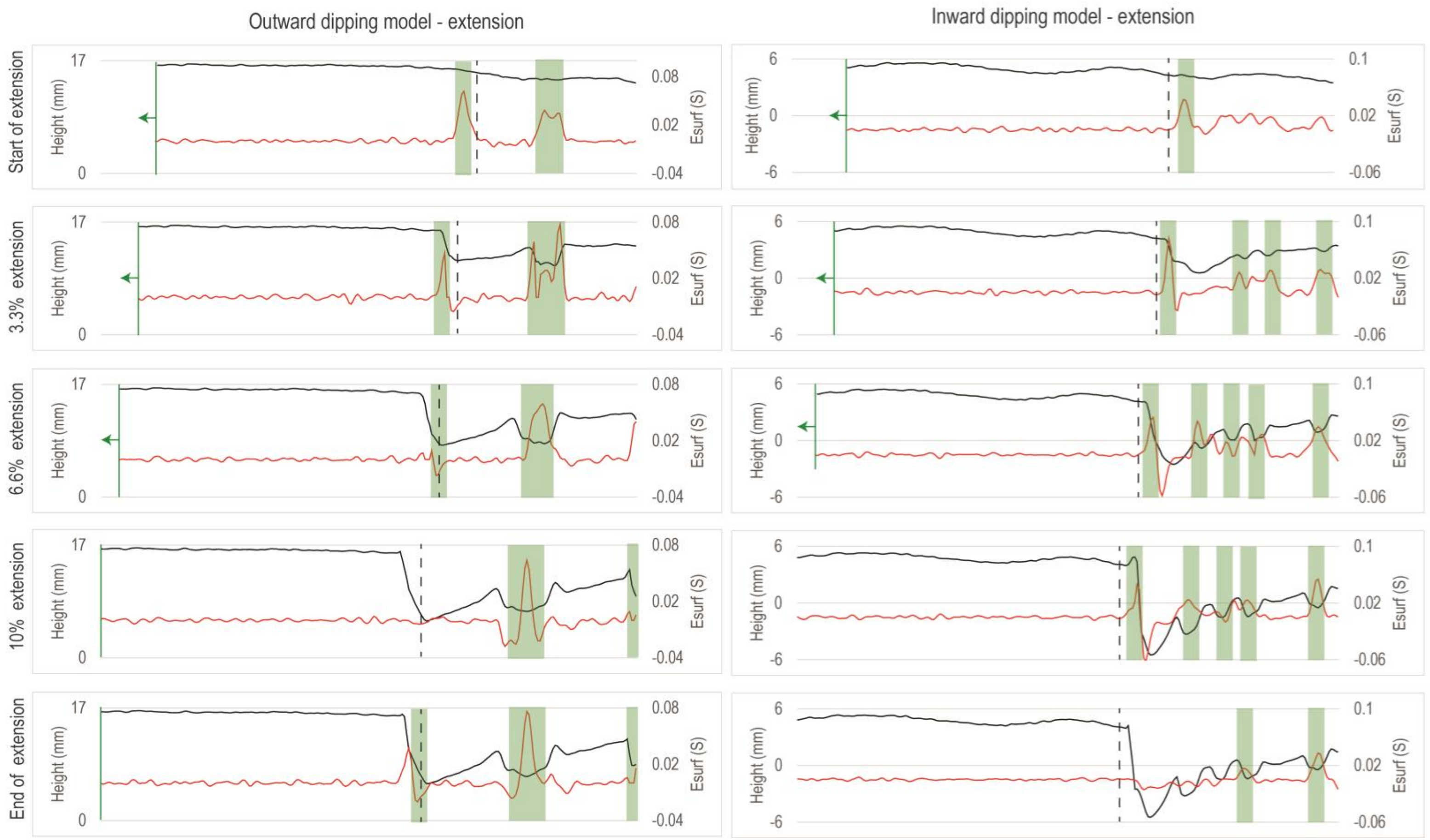


- In both inward and outward dipping models, the extension phase is characterized by necking-boudinage in the lower crust and the development of asymmetric half-grabens and rifts with varying depths and strain accommodation.
- During the compression phase in the inward-dipping model, the rift above the craton margin remains inactive, while the structure along the craton margin becomes active. In contrast, in the outward-dipping model, the rift, which is parallel to the geometry, serves as the primary structure that gets reactivated.

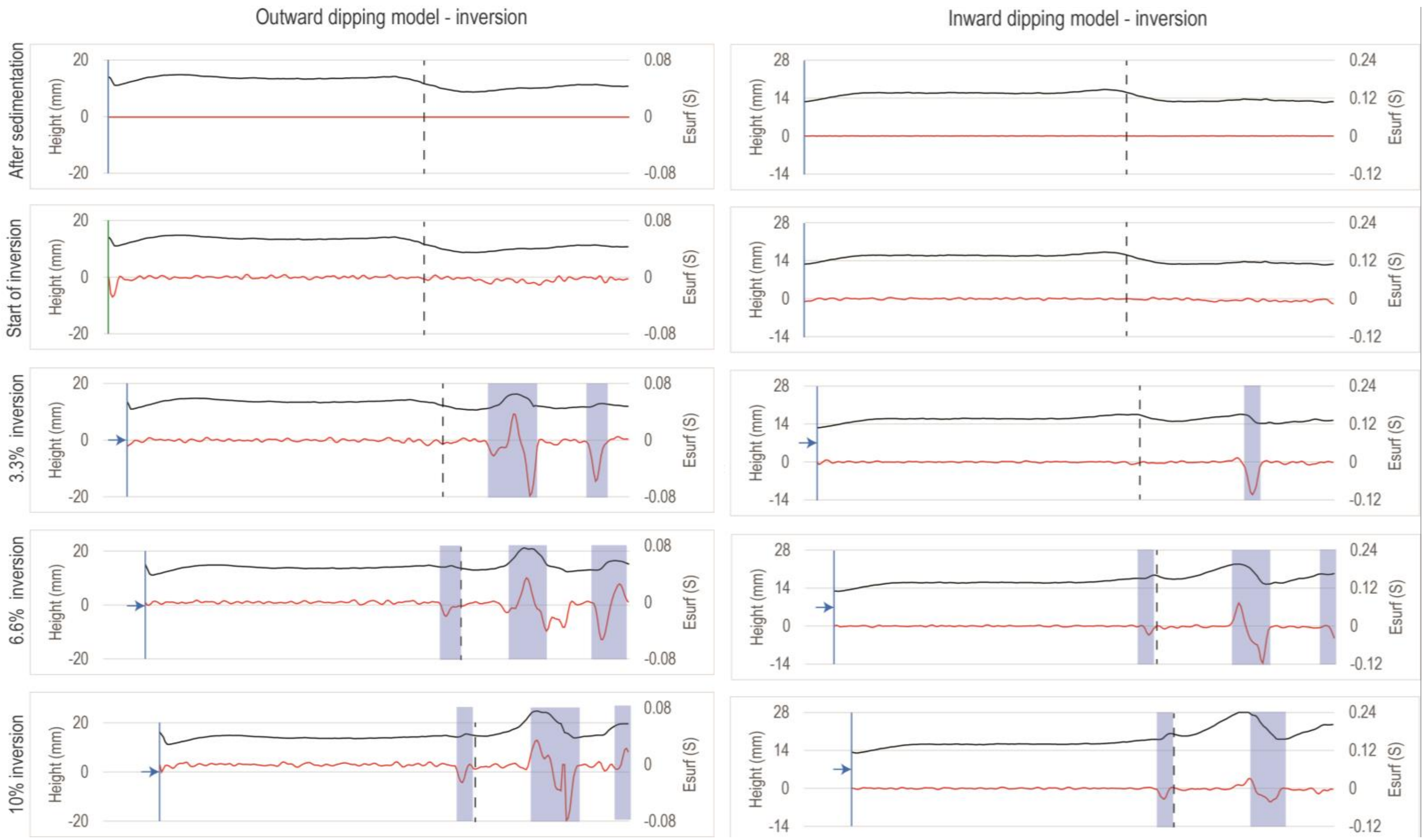
Key Findings – Inward vs Outward Extension



- Outward dipping model shows extensive thinning, significant subsidence at the foam edge, and a major rift where strain is accommodated.
- Inward dipping model displays even strain distribution throughout the material, with significant strain in the lower crust.

- Black line – topography
- Red line – surface strain
- Green polygon – low or high peak in strain

Key Findings – Inward vs Outward Shortening



- In the inversion phase, the inward dipping model exhibits resistance at the foam edge while the outward dipping model experiences notable inversion away from the edge in the middle of the ductile lower crust.
- Both models display a smaller degree of strain accommodated directly above the edge along structure.

- Black line – topography
- Red line – surface strain
- Blue polygon – low or high peak in strain

Conclusion

- The study investigated whether the geometry of craton margins influences deformation in the upper crust during rifting and subsequent inversion.
- Analogue experiments were conducted based on the geometries of the eastern and southern margins of the North Australian Craton, which has experienced multiple stages of extension and shortening.
    - Extension:
        - During the extensional phase of both inward and outward dipping experiments, rifts were mainly formed by boudinage and necking in the lower crust.
        - The inward dipping model resulted in a number of smaller faults, while the outward dipping model showed the propagation of a single major normal fault along the craton margin.
    - Shortening:
        - Subsequent shortening of the inward dipping model resulted in modest basin inversion above the craton margin, indicating that most of the strain was accommodated by reactivation of normal faults away from the margin.
        - Inversion of the outward dipping craton margin model showed more intense inversion at the margin compared to the inward dipping model, with lower strain and smaller reactivation of normal faults away from the margin.
- **The study concludes that the geometry of a craton margin exerts a first-order control on the deformation of the upper crust during rifting and subsequent inversion.**
    - This has significant implications for understanding the tectonic evolution of craton margins and the associated mineral systems.
    - It also suggests that the geometry of craton margins should be taken into account when modeling deformation during rifting and subsequent inversion.

THANK YOU

Feel free to contact me if you have further questions:

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