Simulating Melting of Fault Gouge at the Local Scale

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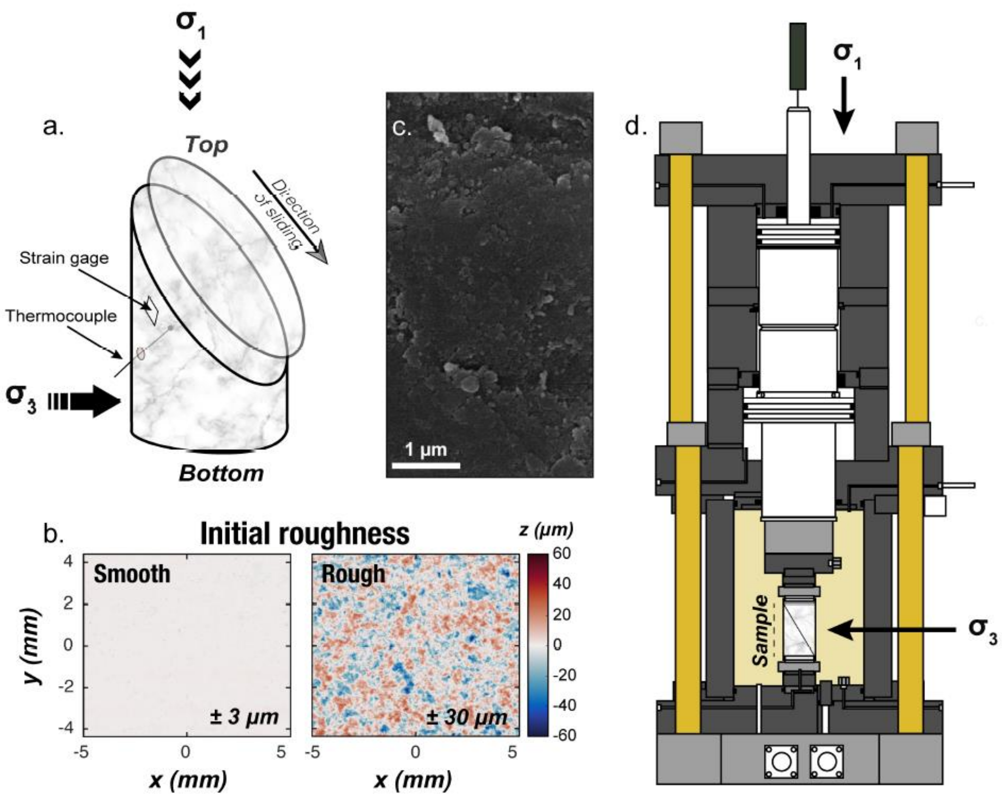
I – Introduction

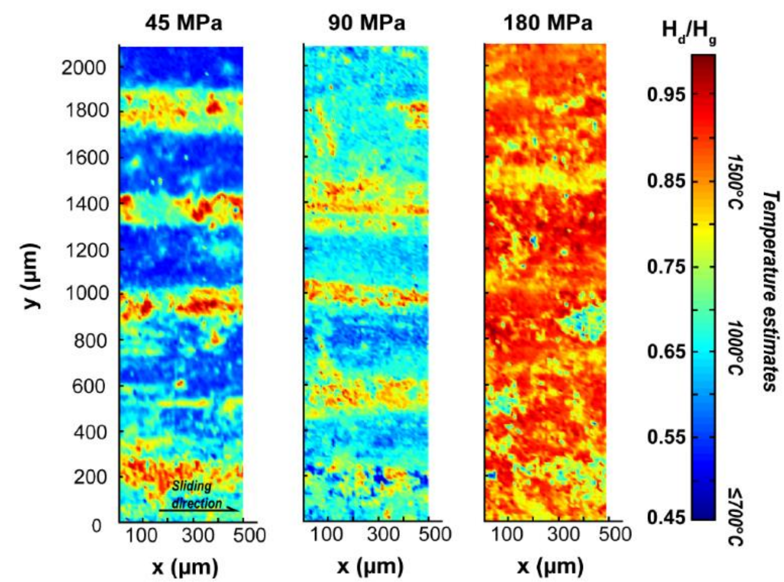
Motivation of the study:

- Saw-cut triaxial experiments on Westerley granite under σ_3=45-180MPa (Aubry 2020)
- Temperature trackers (amorphous carbon layer) showed clear evidences of flash heating



Saw-cut triaxial experiment

Local temperature increase mapped by carbon deposition technique



Aubry et al. (2019), GRL, 45(22)

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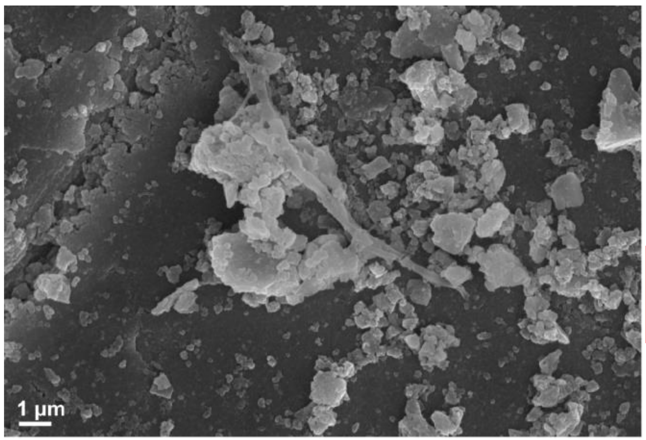
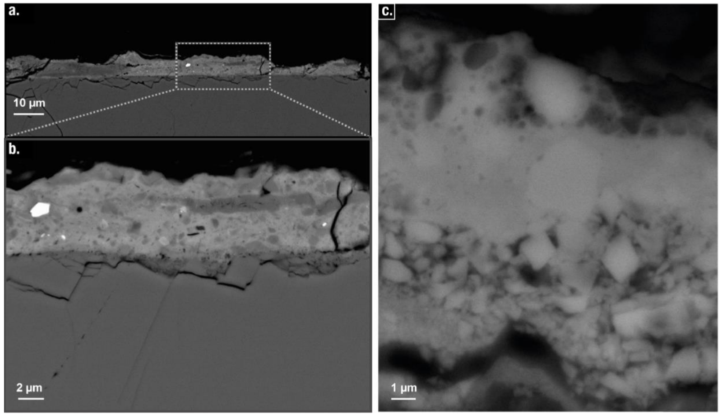
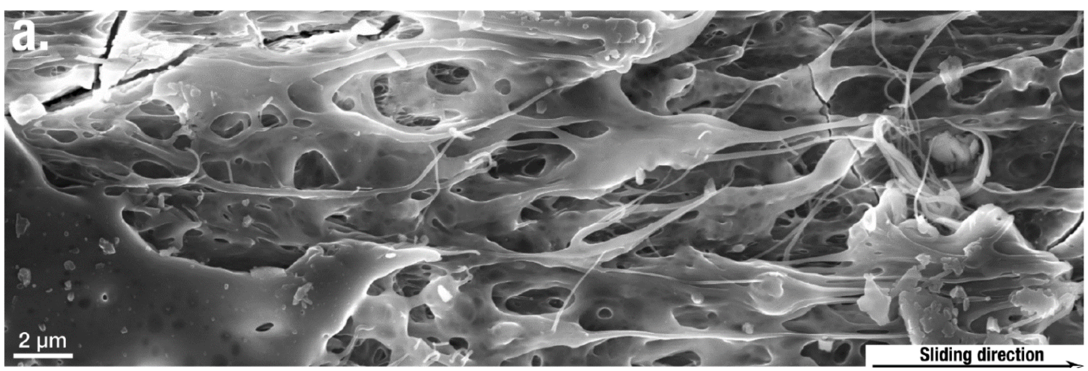
-SEM–TEM observation showed partial or total melting of the gouge layer



Initial gouge particles
Size ~ 1µm

Cross section of amorphous melt layer with micro/nanometric gouge particles





Completely established layer of melt

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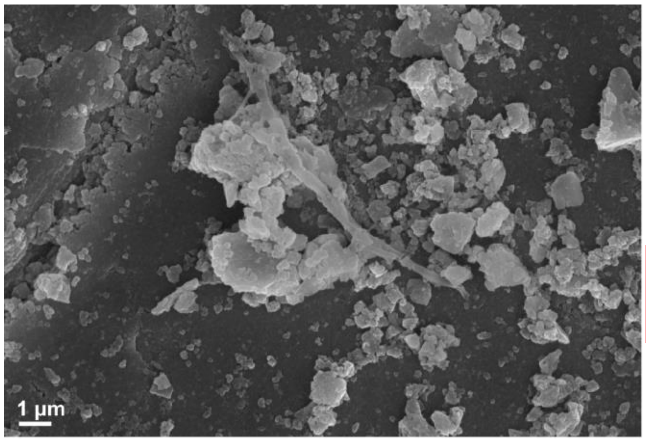

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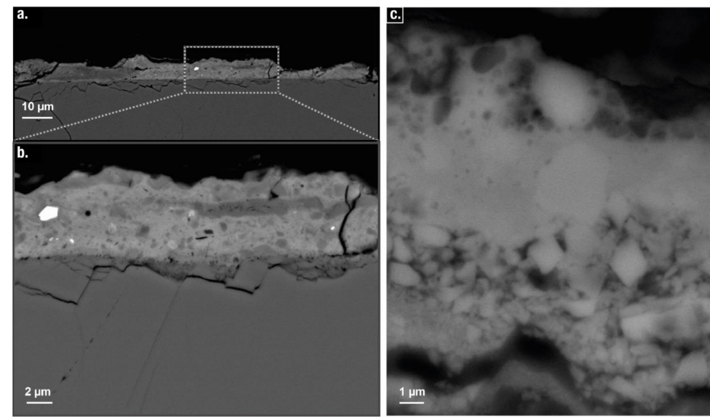
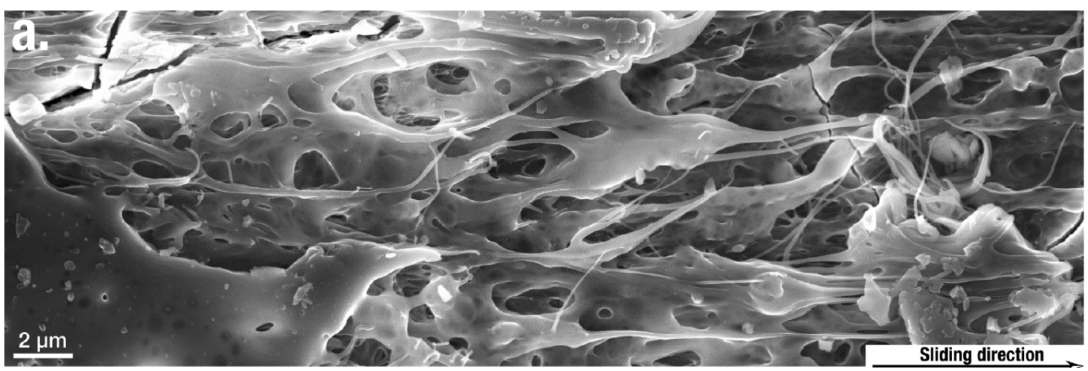




Completely established layer of melt

How does this layer appear, and what are its implications on friction? Can we model this?

I – Introduction

II – Simulations

III – Influence of Fault Thickness

IV – Molten Gouge

V – Influence of Melt Proportion

VI – Perspectives

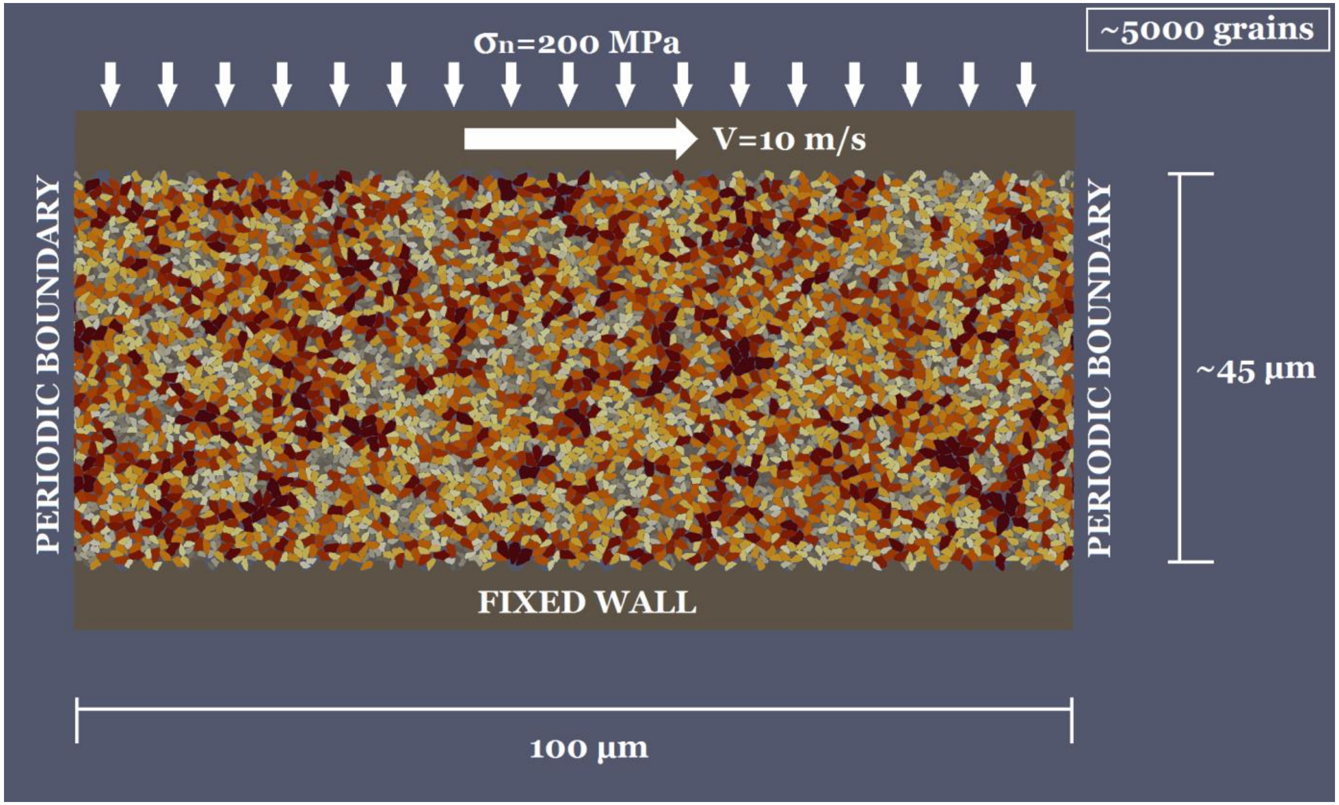
Discrete Element Modelling (DEM, Newtonian dynamics) simulation protocol:

-We assume a perfectly established comminuted gouge with ~1µm angular grains.

-Sample width of 100µm, thickness can vary.

-Normal stress σ_n=200 Mpa, sliding velocity V=10m/s, periodic lateral boundaries.

-Code MELODY2D; plane strain; Simulated time: 20-50 µs; time step ~1ps.

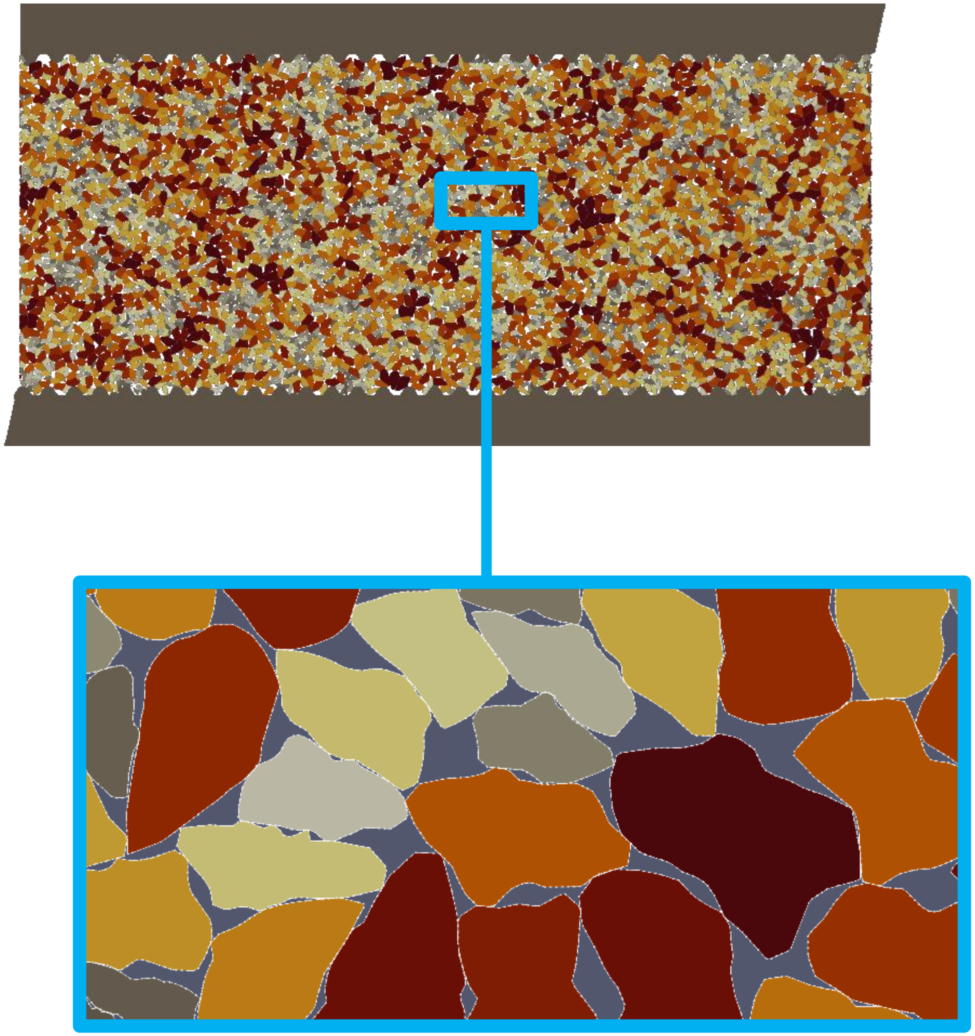


Mollon (2018), Comp. Part. Mech, 5

Local contact conditions:

-Contour of the particles described by a piecewise linear function. Two-pass node-to-segment algorithm.

-Angular shapes and penalized frictional contact between gouge particles, μ=0.8 (calibrated in Mollon et al. 2020).



Angular grains

Mollon et al. (2020), Granular Matter, accepted

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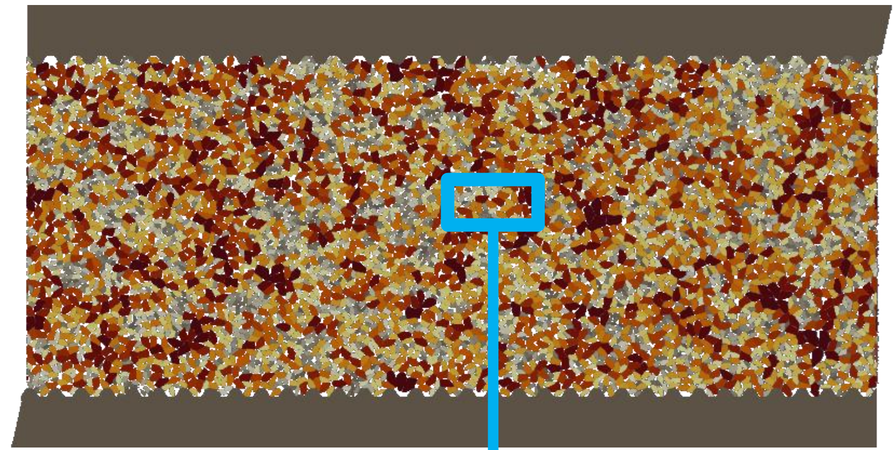
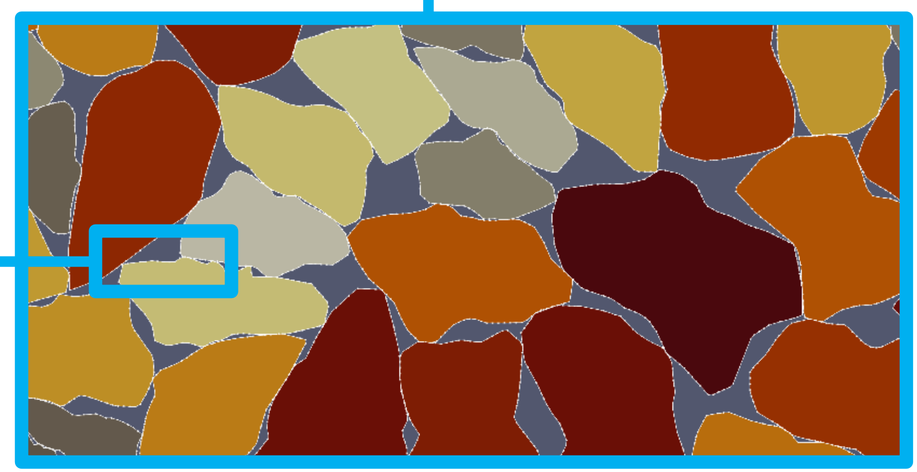
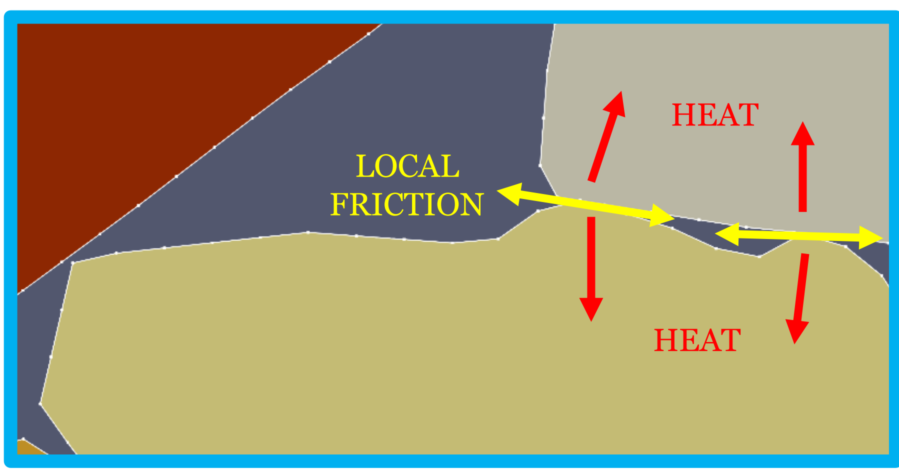
-Any mechanical energy dissipated by intergranular friction is converted in heat and shared between the contacting grains.

-Temperature of each grain increases. No heat diffusion by contacts (yet).







Node-to-segment contact

Angular grains

Mollon et al. (2020), Granular Matter, accepted

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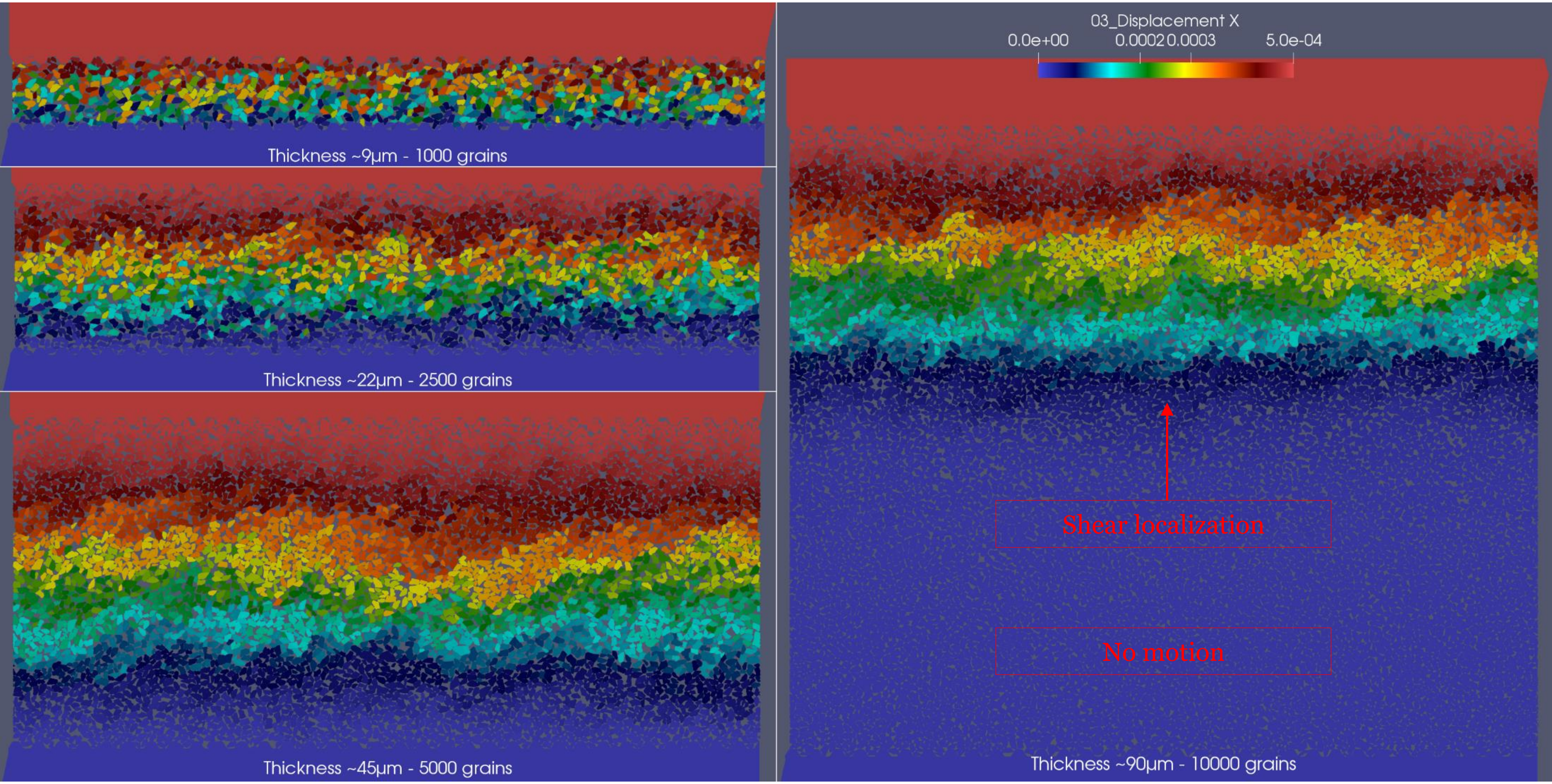
We first vary the thickness of the gouge layer, from ~9µm to ~90µm.

-Shear distributed in the whole thickness for 9µm, 22µm, and 45µm, but localized for 90µm.

Final X-displacement after 50µs shearing



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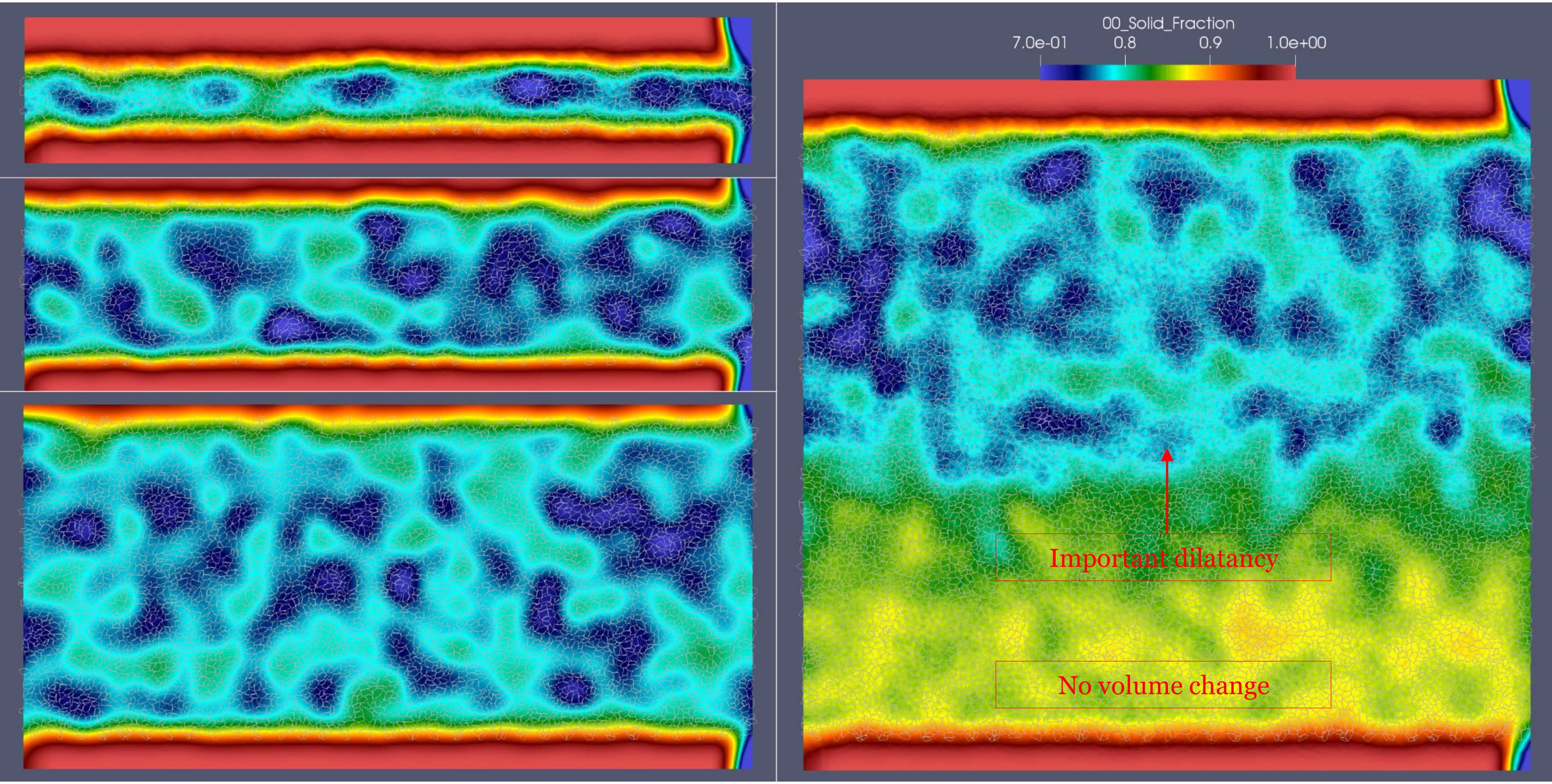
-Shear distributed in the whole thickness for 9µm, 22µm, and 45µm, but localizes for 90µm.

-Confirmed by final distribution of the Volume Fraction of the granular packing



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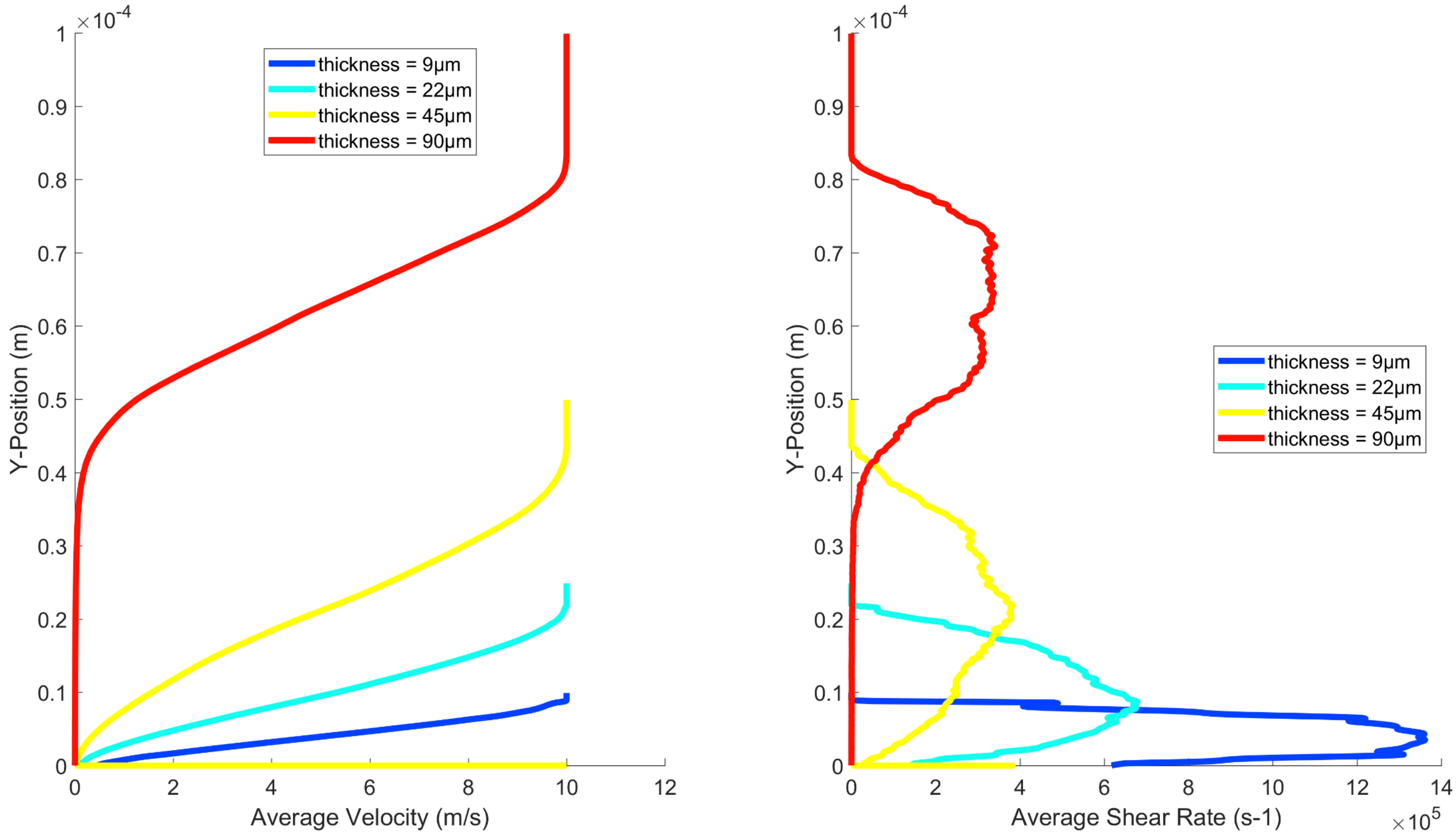
-Shear-rate is thus very high for small layer thickness, but stabilizes above a thickness of 45µm



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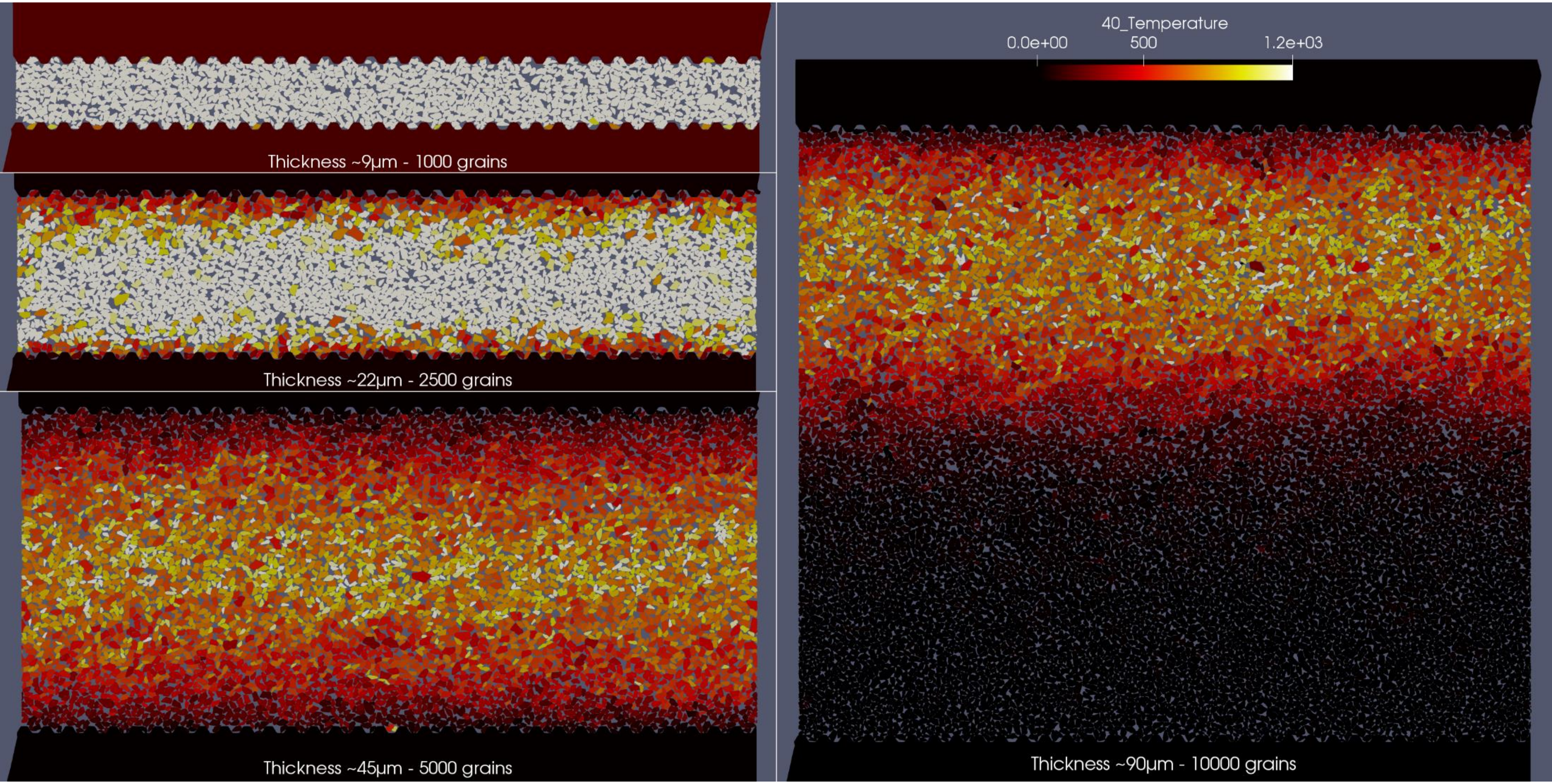
- -Shear-rate is thus very high for small layer thickness, but stabilizes above a thickness of 45µm
- -Temperature increase of the grains follows the same logic



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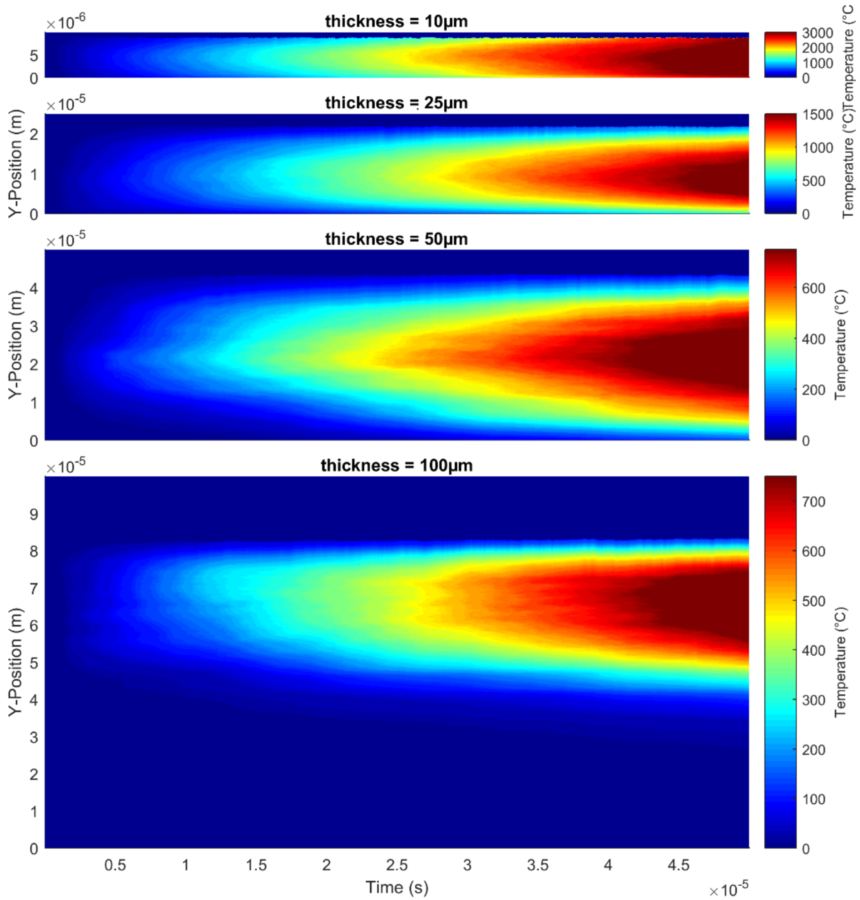
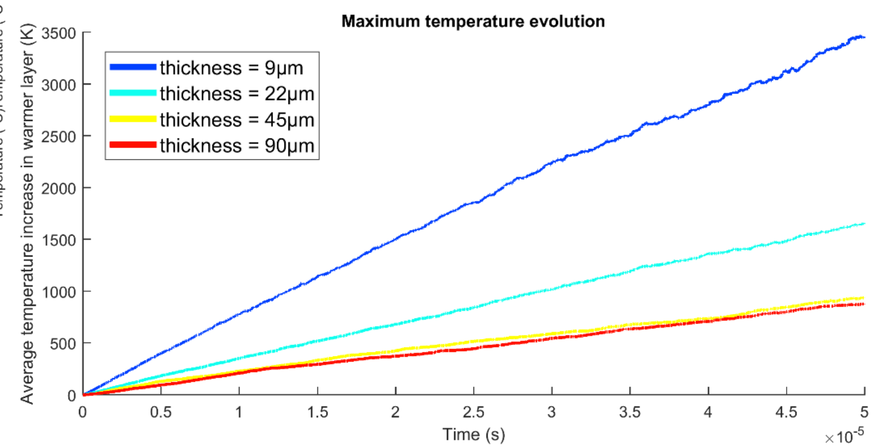
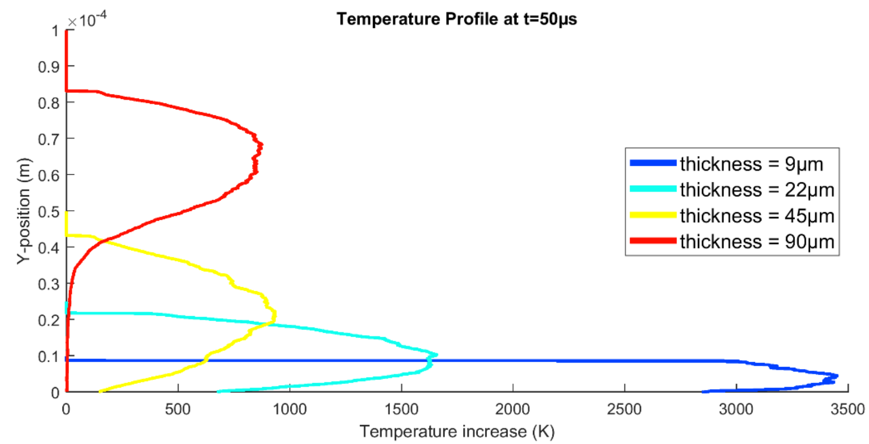
-Temperature increase of the grains follows the same logic

-Temperature maps show a linear increase with time, with a maximum value at the center of the sheared layer





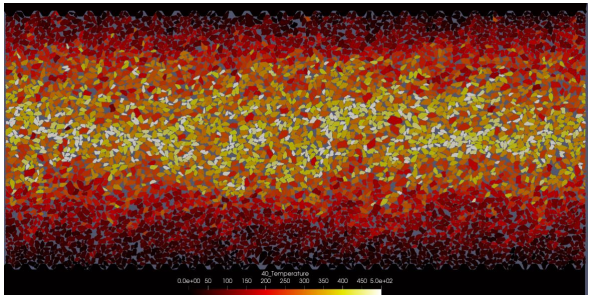


IV – Molten Gouge

Statistics on the temperature increase for each grain

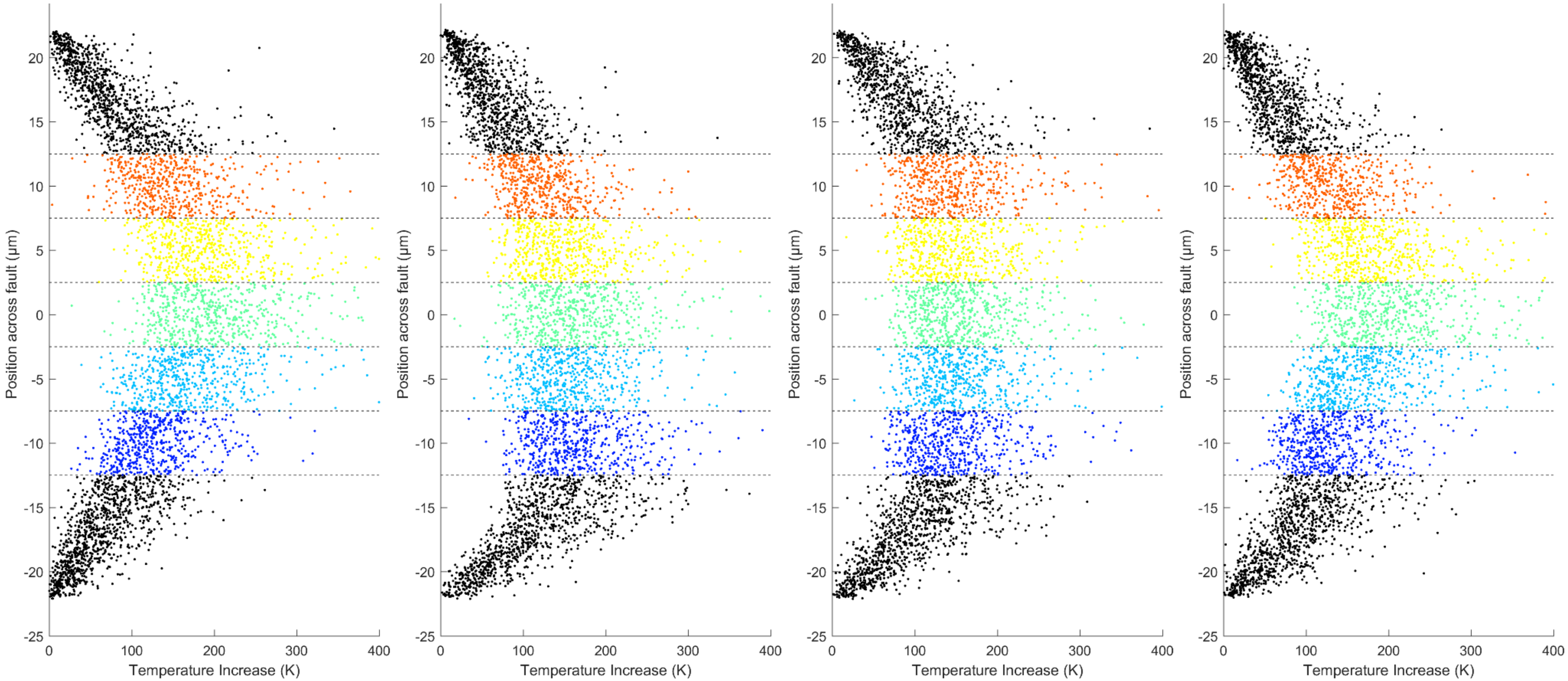
-We focus on the ~45µm-thick sample

-Divided in 5µm horizontal layers for sub-sampling



Temperature increase in each grain as a function of its position in the sheared layer:

From 100 to 200µm of sliding | From 200 to 300µm | From 300 to 400µm | From 400 to 500µm



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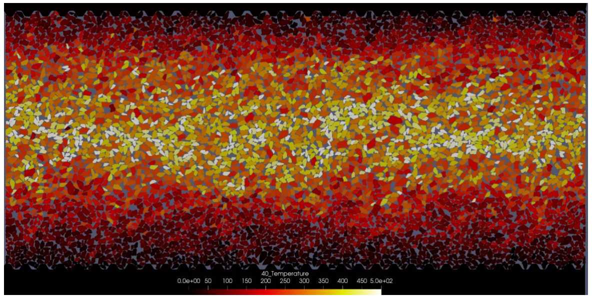
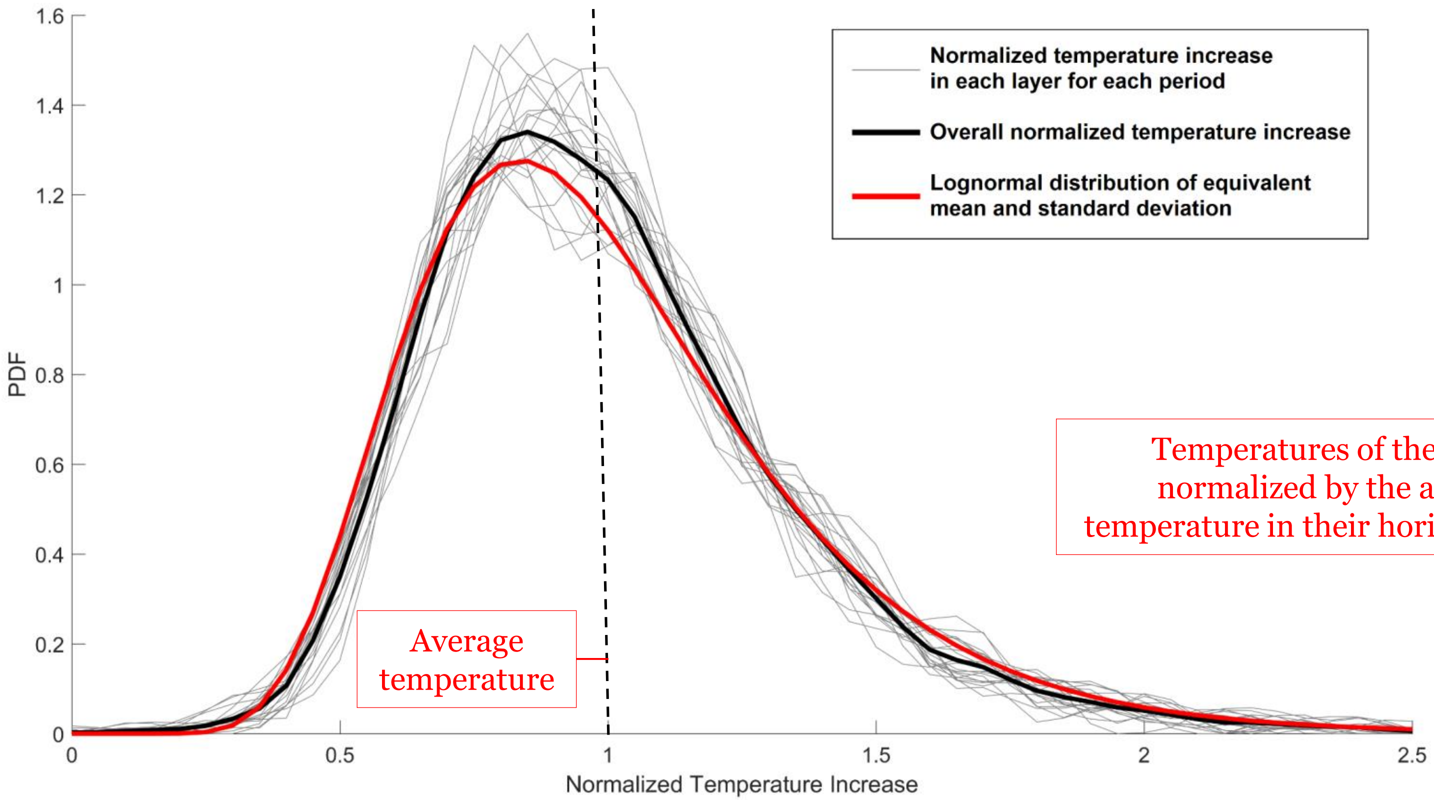


-We focus on the ~45μm-thick sample.

-Divided in 5μm horizontal layers for sub-sampling.

-If temperature of each grain is normalized by the average temperature in its horizontal layer, probability distributions of grains temperature elevations collapse to a lognormal distribution.

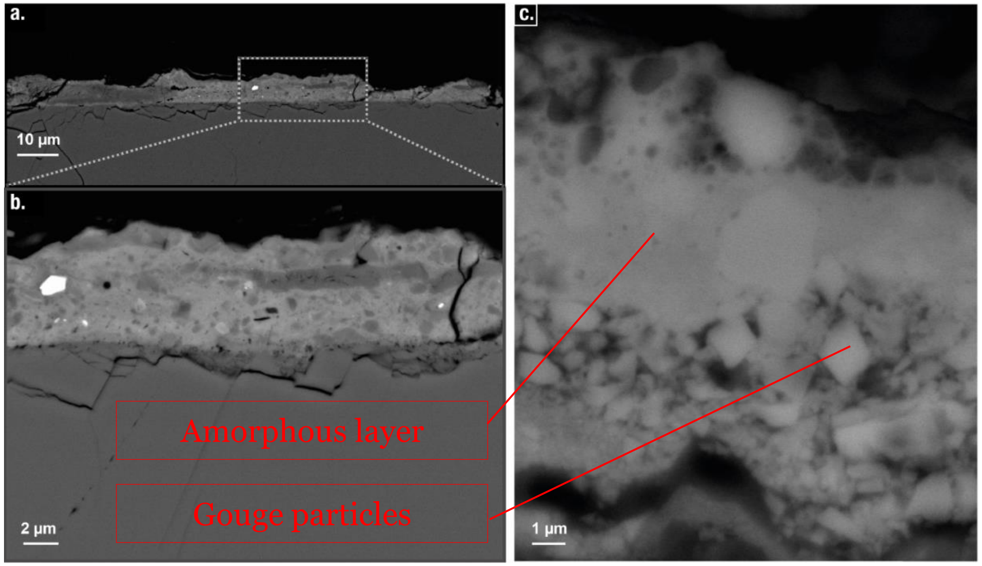


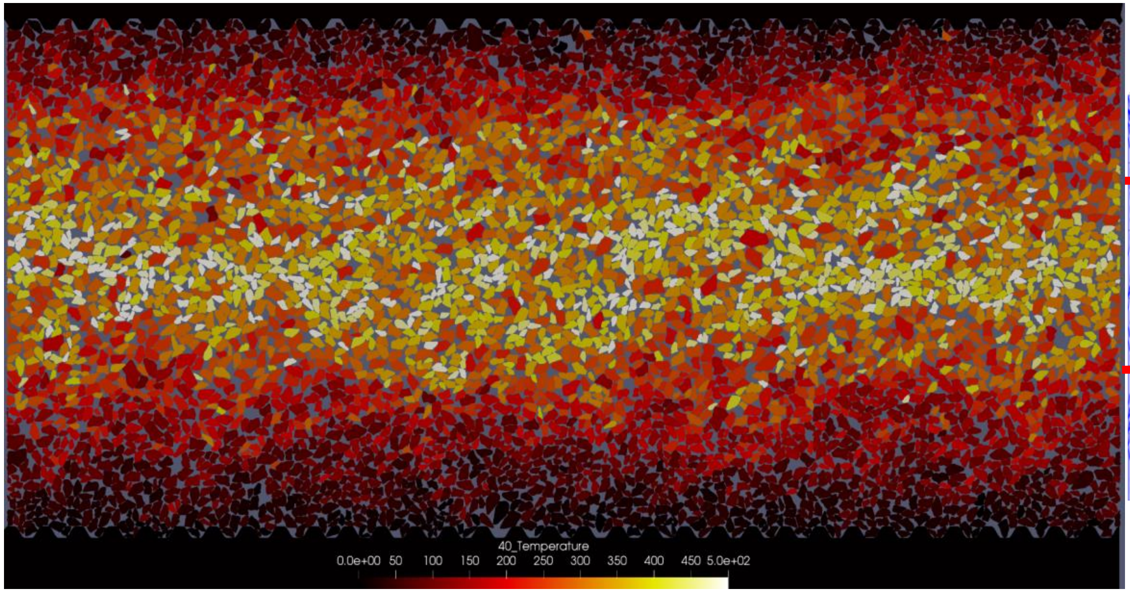
Temperatures of the grains normalized by the average temperature in their horizontal layer

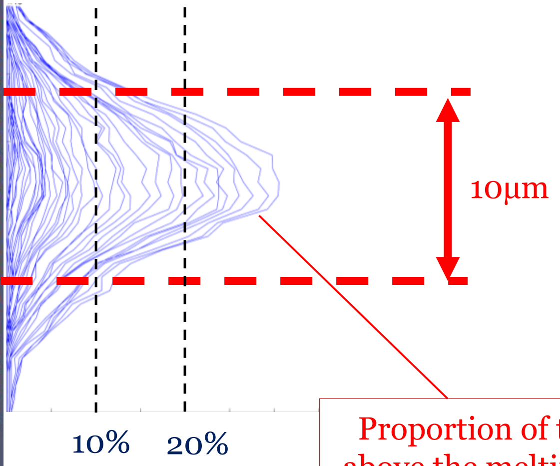
Melt layer:

-Temperature statistics indicate that most of the melt will initially form in a ~10µm thick central layer.

-Good agreement with experimental observations (8-16µm melt layer)





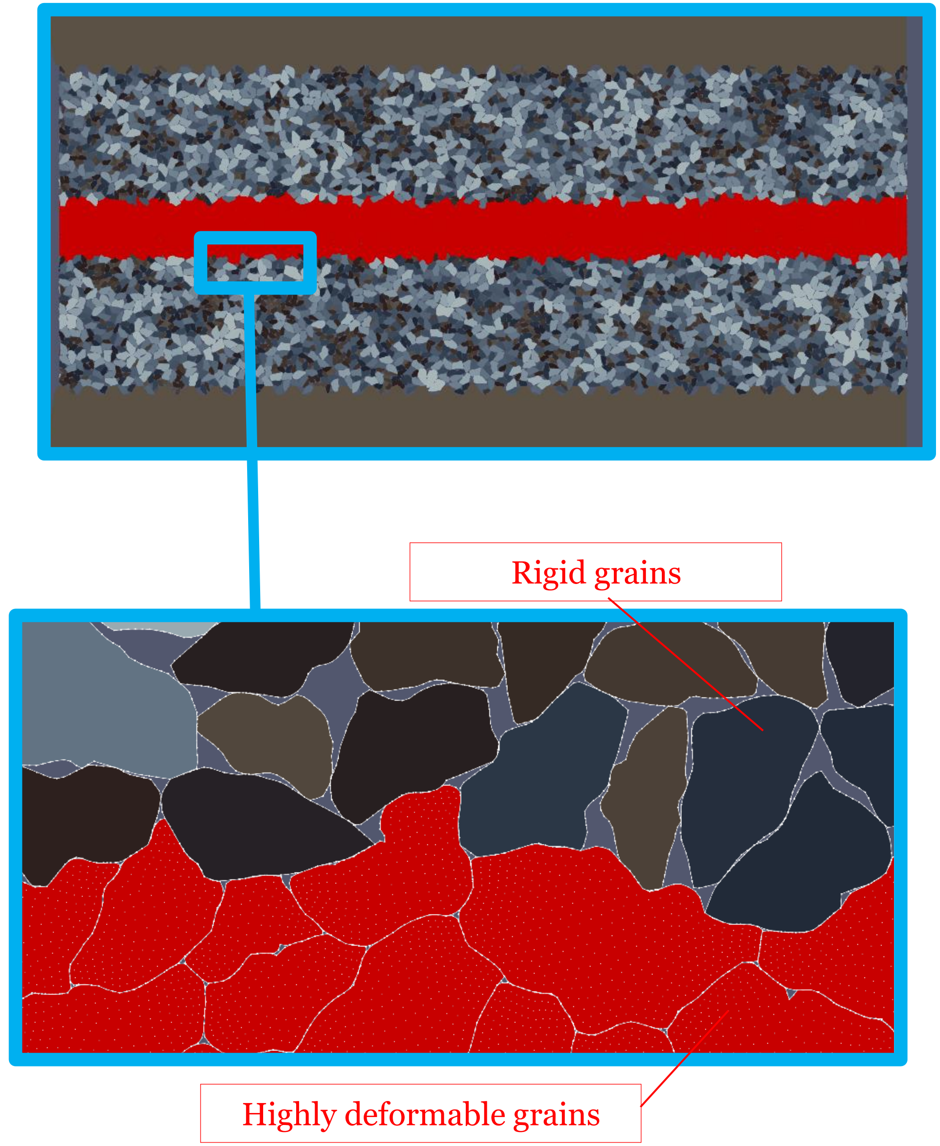


Proportion of the grains above the melting point at several simulated times.

Simulation of a fully molten central layer

-Proxy for the melt rheology: highly deformable, incompressible, viscoelastic grains (Mollon 2018)

-Deformability simulated by a multibody meshfree method (DEM enriched with continuum mechanics), in the code MELODY2D



Mollon (2018), Granular Matter, 20(39)

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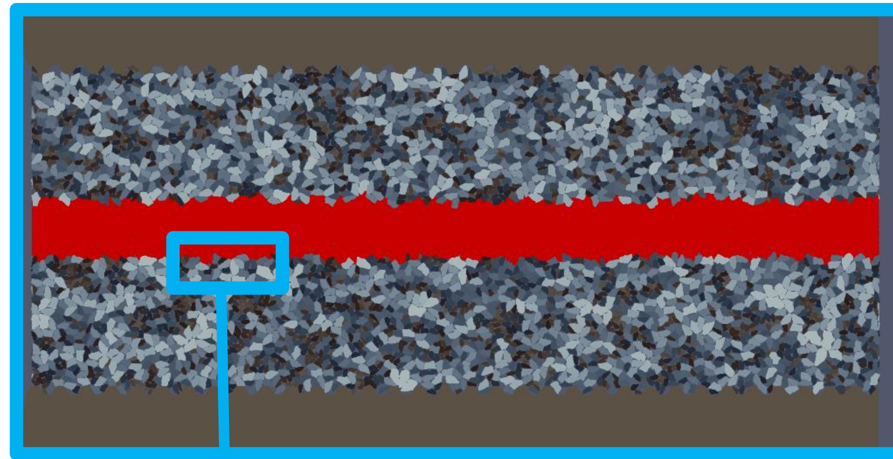
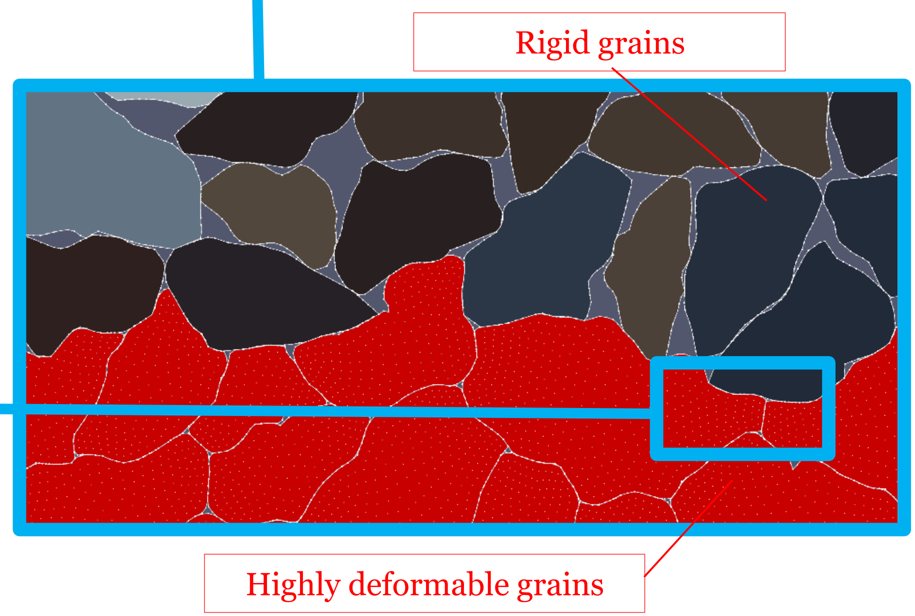
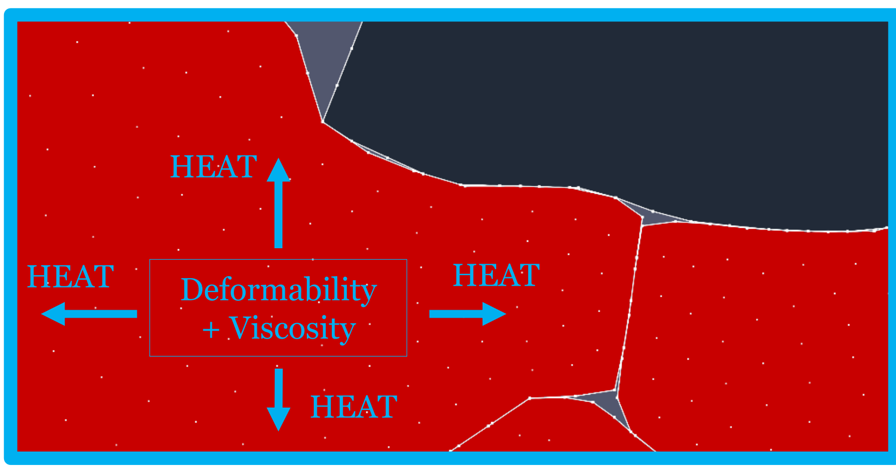
-No friction and no cohesion at contacts, but energy dissipation by internal viscosity and subsequent heat creation.

-Still no heat diffusion through contacts

-Equivalent viscosity: ~12.1 Pa.s (in the low range for molten silicates, Wallace et al. 2019)







Mollon (2018), Granular Matter, 20(39) ; Wallace et al. (2019), Geoc. and Cosmo. Acta 255

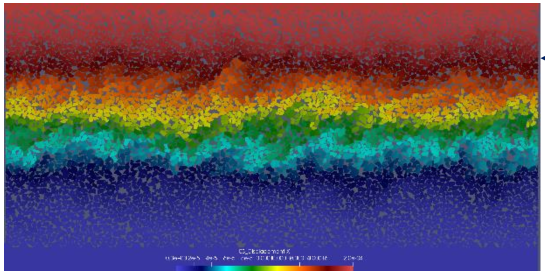
Simulations Results

X-displacement (µm)

200

0

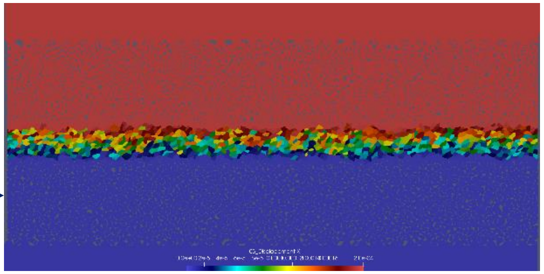
Only solid grains: **µ=0.48**



Distributed shear in the whole granular layer

Localized accommodation in the central melt layer, solid grains unaffected

Fully molten central layer: **µ=0.08**



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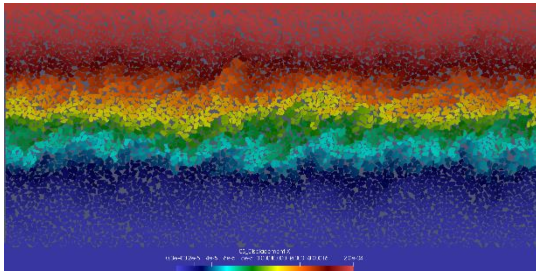

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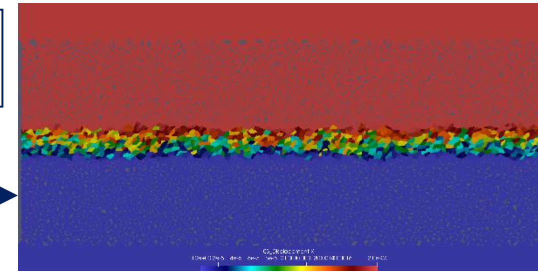
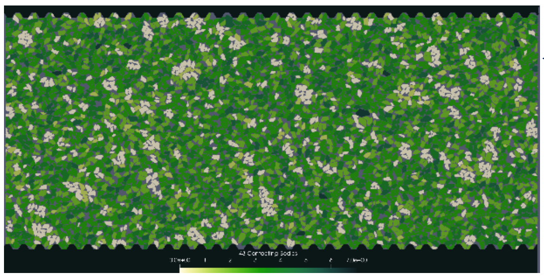


Number of contacting grains

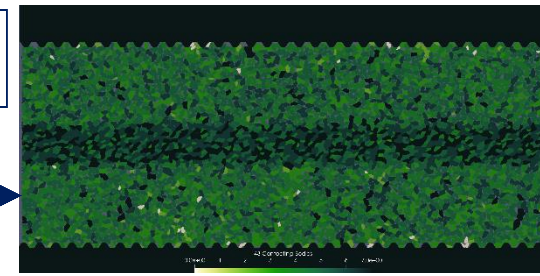
7

0



Low and heterogeneous connectivity

Large and homogeneous connectivity, especially in the melt layer



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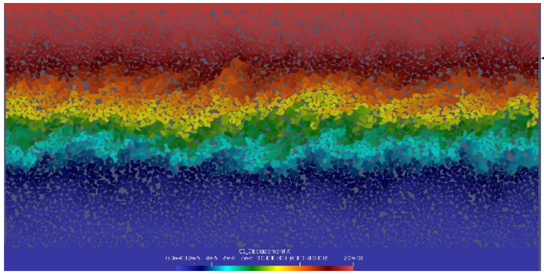
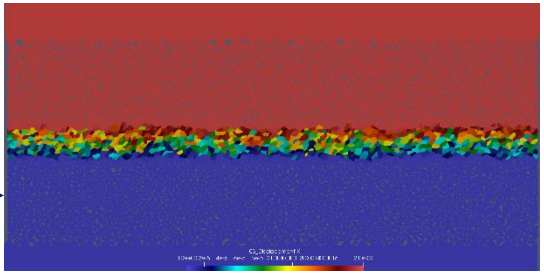
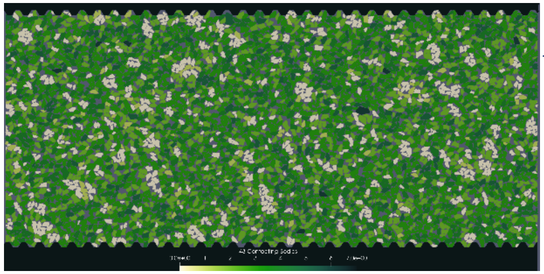
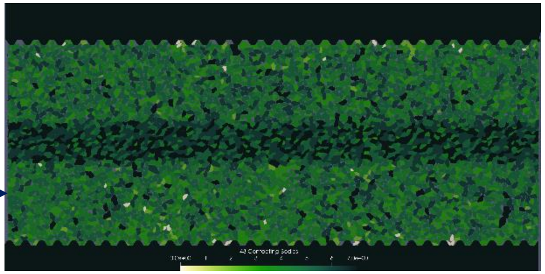
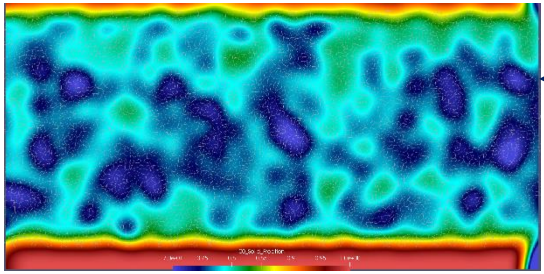
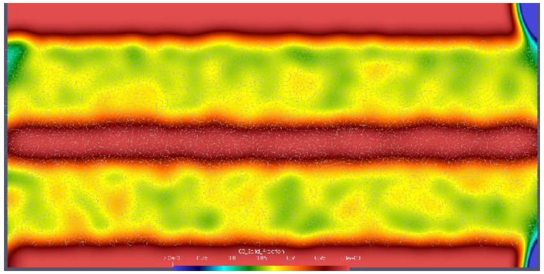
X-displacement (μm) 200 – 0		Distributed shear in the whole granular layer (←) Localized accommodation in the central melt layer, solid grains unaffected (→)	
Number of contacting grains 7 – 0		Low and heterogeneous connectivity (←) Large and homogeneous connectivity, especially in the melt layer (→)	
Volume fraction of the granular packing 1 – 0.7		Important dilatancy (←) No volume change in solid grains, Volume Fraction close to 1 in the melt layer (→)	

Simulations Results

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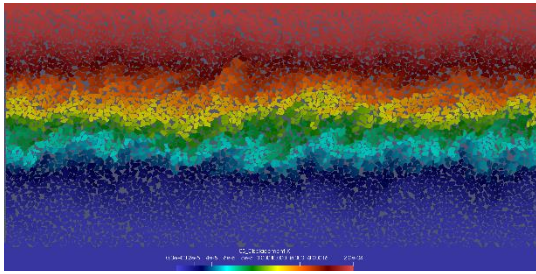
Fully molten central layer: μ=**0.08**

X-displacement (µm)

200

0



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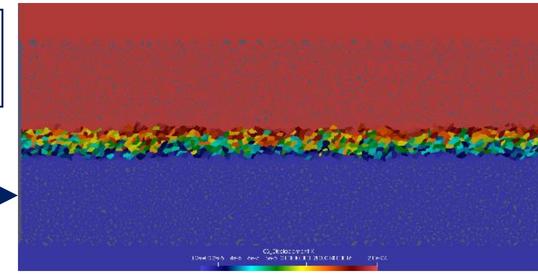

Number of contacting grains

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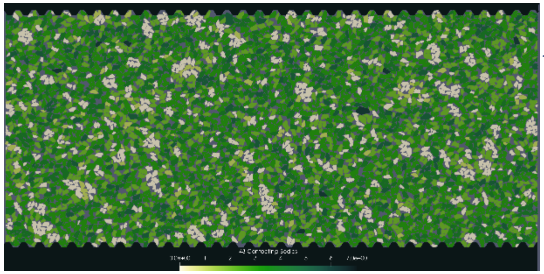
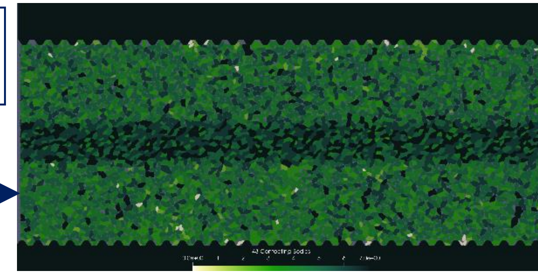


Low and heterogeneous connectivity

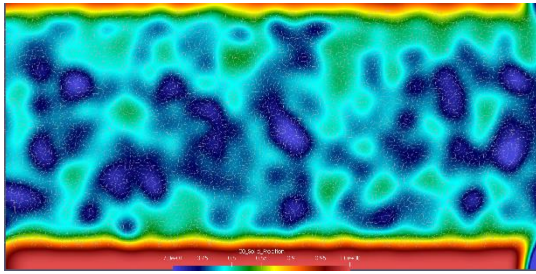
Large and homogeneous connectivity, especially in the melt layer



Volume fraction of the granular packing

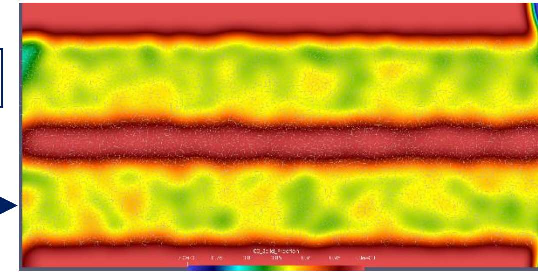
1

0.7



Important dilatancy

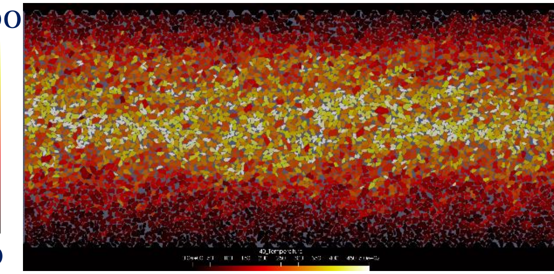
No volume change in solid grains, Volume Fraction close to 1 in the melt layer



Temperature elevation (K)

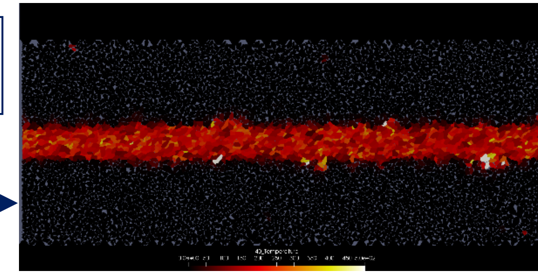
500

0



Distributed and important temperature elevation

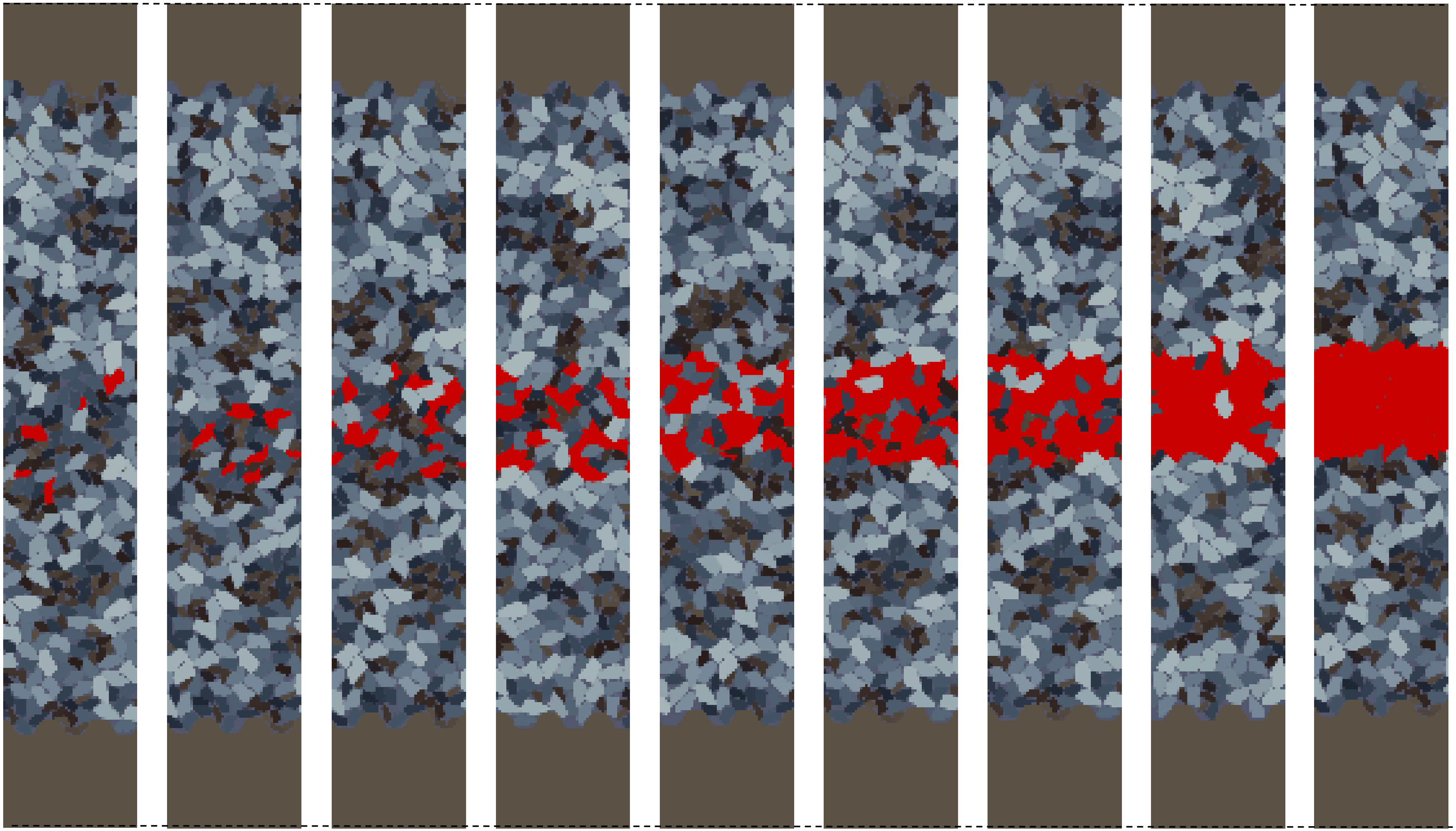
Only moderate temperature elevation in the melt layer



V – Influence of Melt Proportion

Investigation of the progressive creation of the melt layer:

9 simulations with increasing proportions of melt Φ_M in the central layer (5% to 100%, partial views)

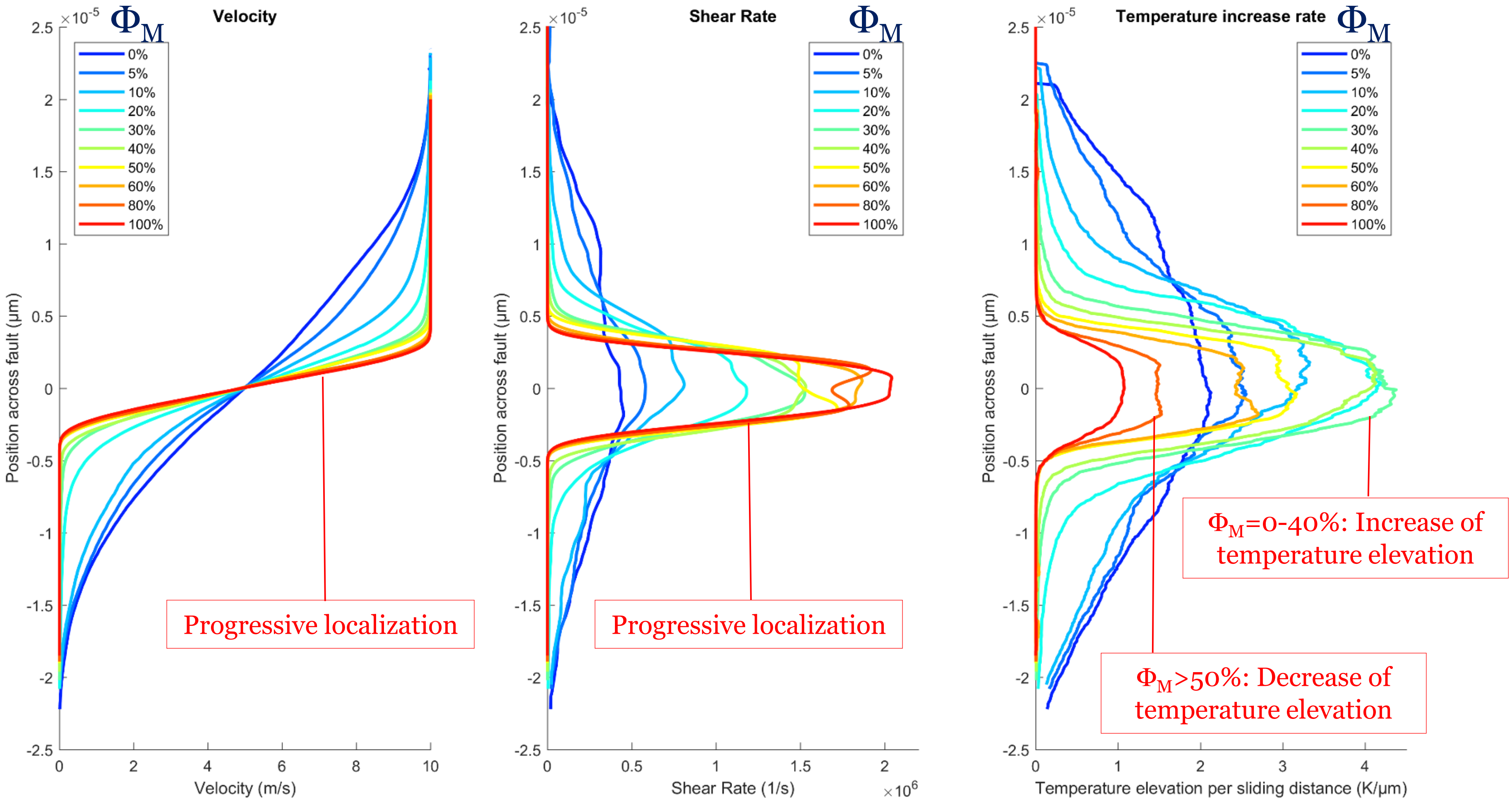


5% | 10% | 20% | 30% | 40% | 50% | 60% | 80% | 100%

Large influence of Φ_M on the flow regime:

-A larger proportion of melt in the central layer promotes localization and increases local shear rate

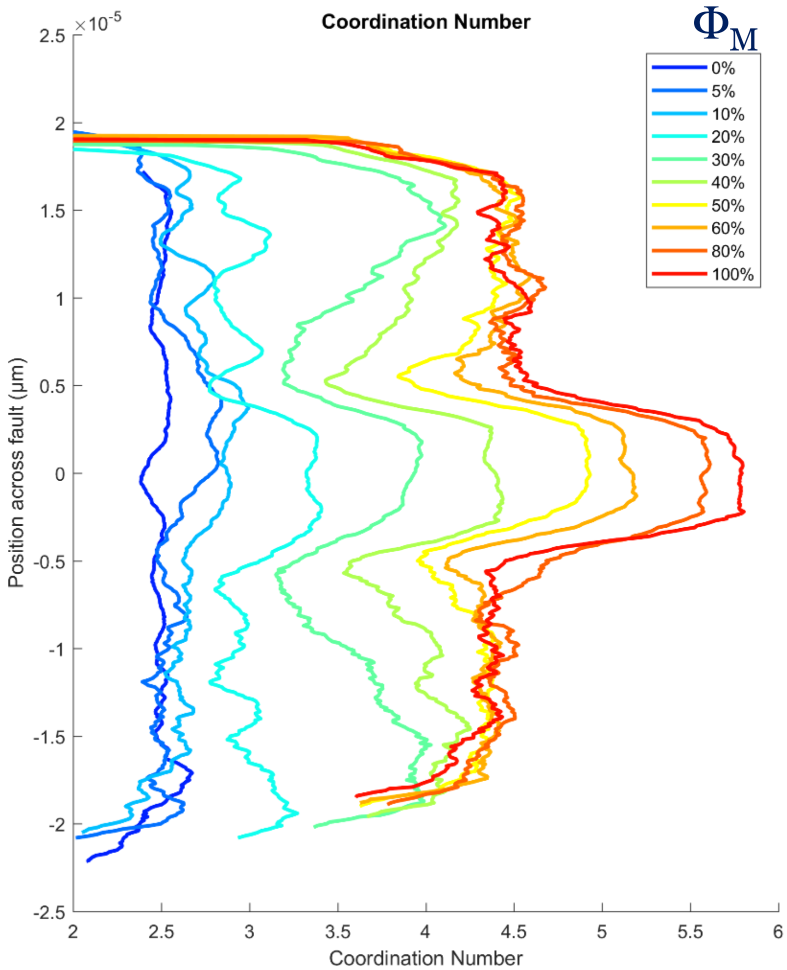
-With increasing Φ_M, temperature elevation first increases in the central layer (due to localization) and then decreases (fluidization of the central layer)

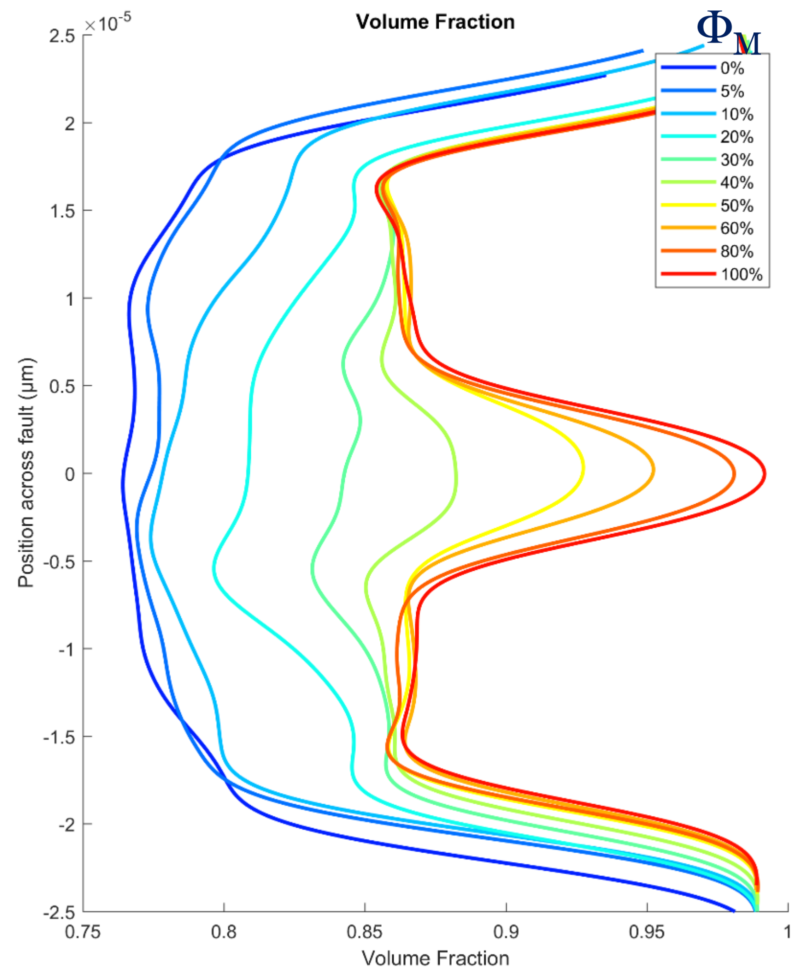


Large influence of Φ_M on the flow regime:

-A larger Φ_M also increases the connectivity of the grains, especially in the central layer

-It also increases the density of the granular packing, especially in the central layer

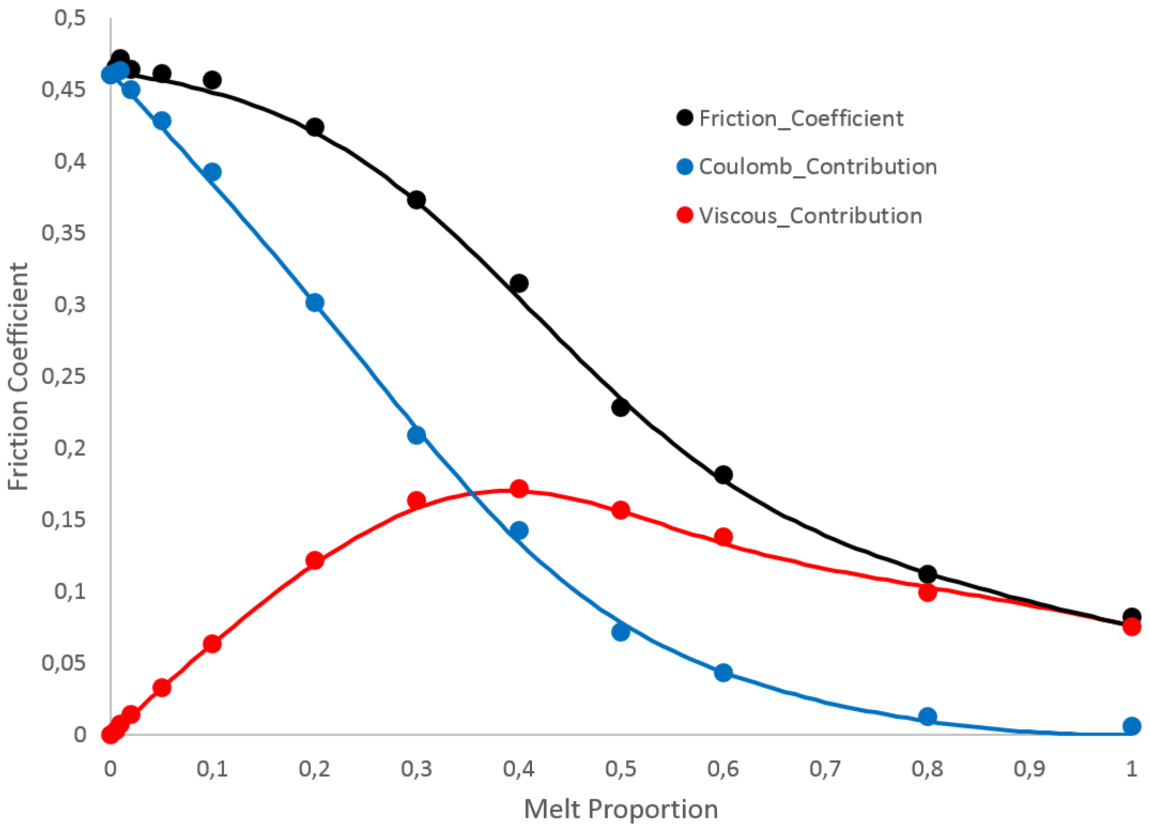




Friction and energetic budget

-Friction coefficient of the interface decreases non-linearly with Φ_M

- Based on the type of energy dissipation (solid or deformable grains), friction is decomposed into two contributions: a Coulomb term and a viscous term.

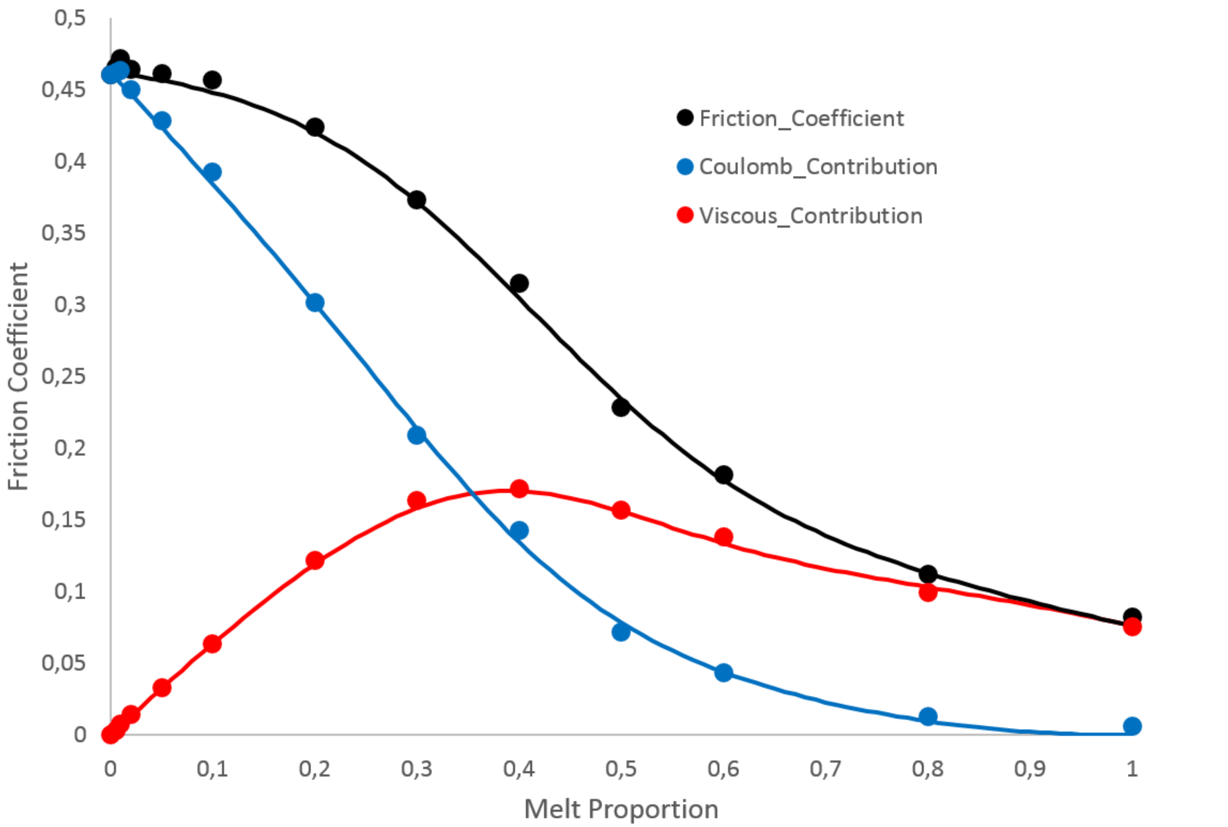


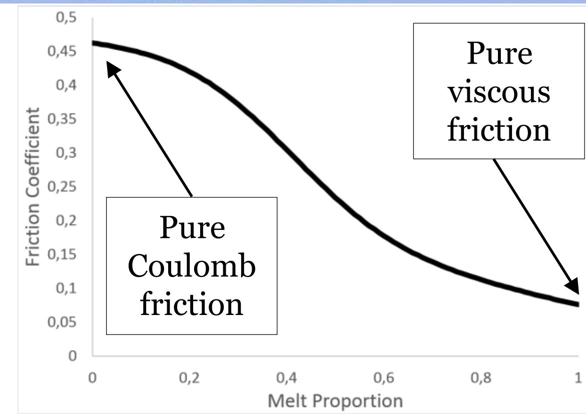
Friction and energetic budget

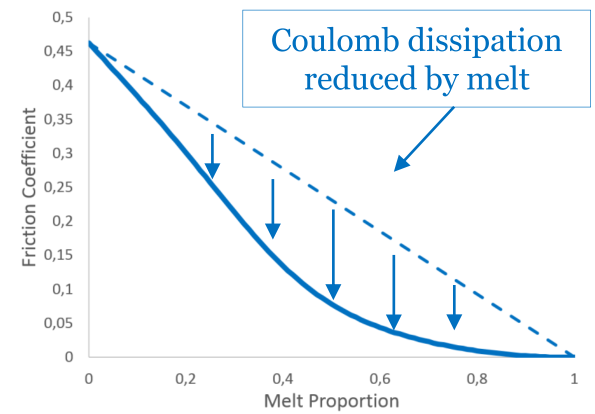
-Friction coefficient of the interface decreases non-linearly with Φ_M

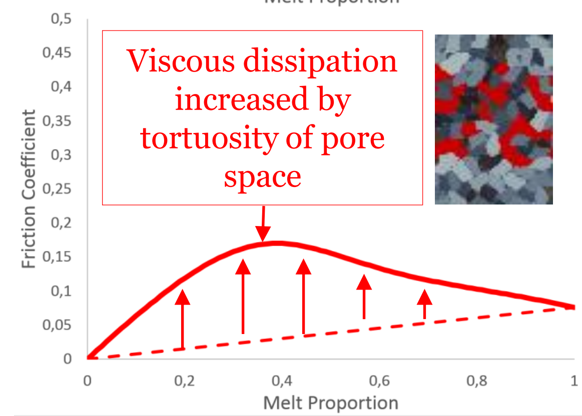
- Based on the type of energy dissipation (solid or deformable grains), friction is decomposed into two contributions: a Coulomb term and a viscous term.

-These contributions do not evolve linearly with Φ_M









VI – Perspectives

Future work will consist in writing a friction law for melting-related dynamic weakening:

-Adding the contributions of:

-a Coulomb term (related to normal stress and granular properties of the gouge)…

-a Viscous term (related to sliding velocity, layer thickness and melt viscosity)…

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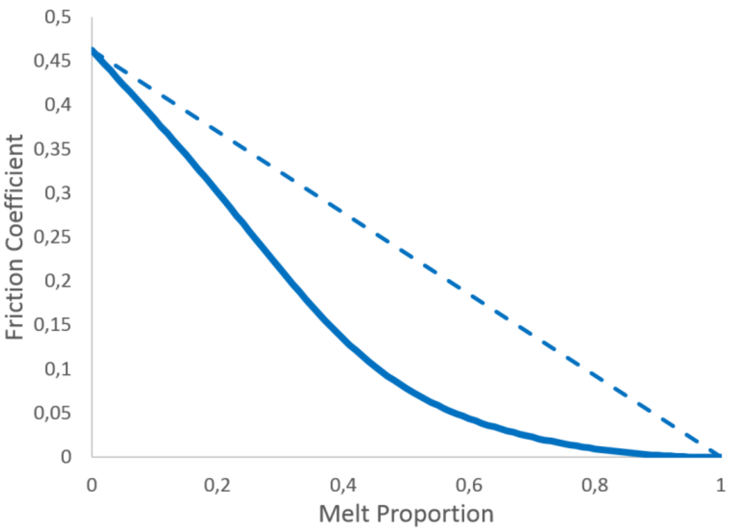
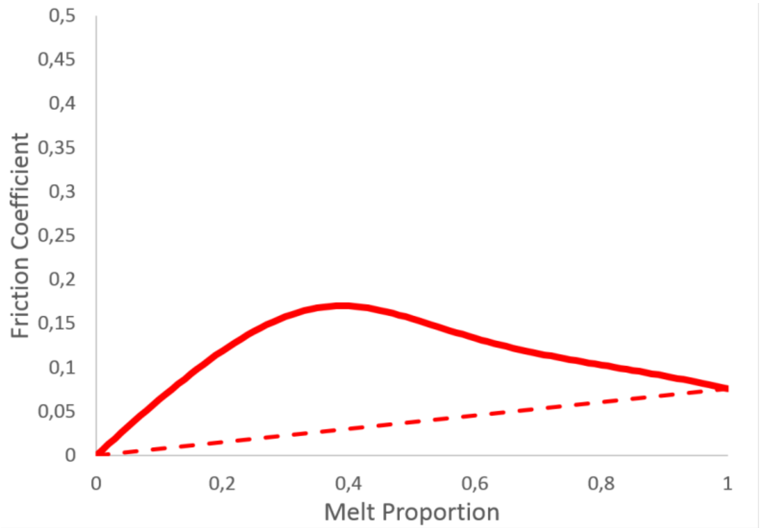
… both of them being functions of the melt proportion…

… which is a function of temperature elevation and shear localization !





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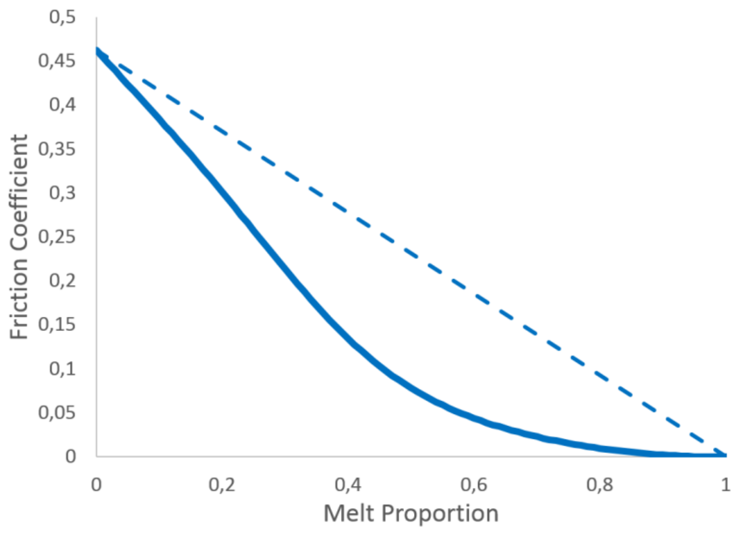

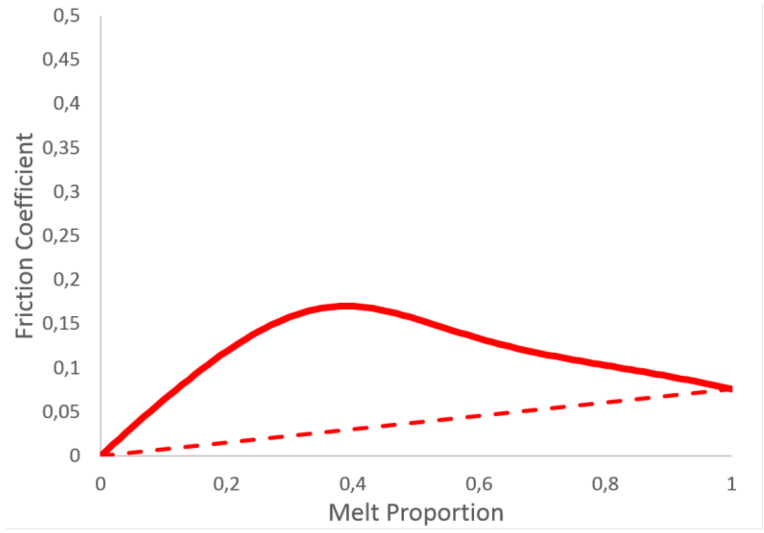

-Formulation of the weakening law in terms of sliding distance.

-Dialog and comparison with existing models, e.g. flash weakening.

-Introduction of heat diffusion in the surrounding medium.

Thank you

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