Invited speaker of GFR 2024

In-situ viscosity measurements of active lava

Oryaelle Chevrel

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Lava viscosity have predominantly been constrained from analyzing flow dynamics and measuring re-melted rocks in the laboratory. Laboratory viscometers have been used extensively to establish the viscosity-temperature relationship of lava at super and subliquidus conditions (900-1400°C). Laboratory measurements are well-constrained in temperature, shear rate, and oxygen fugacity but are unable to fully reproduce the complexities and dynamics of the natural emplacement environment (predominantly due to the inability to retain bubbles over experimentally relevant timescales). In situ viscosity measurements of lava in its natural state, during active flow emplacement, have been an underutilized method largely due to a lack of reliable field instruments but also due to the hazardous volcanic environments. Yet, it is the only method able to capture natural lava's multiphase rheology and map the rheological properties along lava flows that is needed to validate and implement accurate lava flow properties in numerical modeling efforts for hazard assessment.

Here we present two new field viscometers: a lava penetrometer (Harris et al. 2024) and a rotational viscometer (Chevrel et al. 2023). The lava penetrometer is able to measure a force of 10 to 500 N, and has been calibrated for a viscosity range of ~10^2 to 10^5 Pa s. The rotational viscometer covers a wide range of stress (30 to 3870 Pa) and strain rate (0.1–28 s^{-1}), and, with that, viscosity range of 10 to 10^3 Pa s. Both instruments are designed to be easy to operate, highly mobile, and capable of measuring multiphase lavas temperature up to 1200°C. These instruments were deployed during the 2023 Litli Hrútur eruption, Iceland, generating the first in-situ rheological map along a complete lava flow. Viscosity measurements were combined with temperature measurement and sampling for textural characterization. The resulting data represent an extensive contribution to the very limited database of natural lava viscosity.

Collaborators: M.A. Harris, S. Kolzenburg, T. Latchimy, J.T. Parsons, R. Delpoux, L. Batier, M. Payet-Clerc, T. Thordarson, A. Höskuldsson, W.M. Moreland, I. Sonder

Probing the frictional-viscous properties of collapsing mountains

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Preference : Talk, session S3: Rheology of geophysical fluids

Keywords (5 max): non-Newtonian flow; tectonics; friction; faulting

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Abstract : Mountain ranges are areas of high gravitational potential energy, which spontaneously collapse in the absence of tectonic support (compression). Recent studies have identified a power law relationship between the surface deformation rate of collapsing mountain ranges and their local relief, with exponents of 3–3.3. These are classically interpreted as the stress exponent of a quartz-rich, non-Newtonian lower crust, which flows to relax topographic stresses. These studies however overlook the fact that to produce any observable surface deformation, deep viscous flow must somehow trigger shallow brittle faulting.

Here we design a simple analytical model of topography-driven lower crustal flow coupled with frictional slip on upper crustal faults. We show that mountains can collapse in two regimes characterized by the ratio of the upper crust's frictional resistance to the gravitational driving force. If this ratio is small, flow in the lower crust is Poiseuille-like, and measured power law exponents exactly match the stress exponents of the lower crust. If this ratio is large, the observed relationship cannot be a true power law because it involves an intrinsic length scale: the minimum relief required to overcome the crust's frictional strength. In this case, apparent power law exponents may significantly exceed the stress exponent of lower crustal materials. In practice, fitting our analytical model to available measurements of extensional strain rates vs. relief in the Apennines and the Eastern Tibetan Plateau places novel constraints on the composition, viscous strength and thickness of the ductile lower crust, as well as the effective friction coefficient of the brittle upper crust.

On modelling a solid, fluid, granular and cold geomaterial: sea ice

Véronique Dansereau* and members of the Scale-Aware Sea Ice Project (SASIP)

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Preference : TALK

Keywords (5 max): *Sea ice modelling, transitions in mechanical behavior (brittle-granular-fluid)*

Abstract :

The thin ice that covers the polar oceans is a very complex geomaterial that exhibits various mechanical behaviors - brittle solid, fluid, granular - depending on its local state and on the time and space scales at which it is observed. Between these different behaviors, the intensity of energy, gas and momentum exchanges between the ice, the overlying atmosphere and the underlying ocean are widely different, hence the importance of capturing their essence in large scale, climate models.

This talk will present past and ongoing efforts to develop numerical models for the dynamics of sea ice. It will discuss associated challenges, for instance, formulating rheologies that can capture the multi-scale, multi-mechanics behavior of this geomaterial while keeping a continuum framework that incorporates a minimum number of observationally-relevant state variables. It will also discuss similarities between the deformation mechanisms present in sea ice and in other geophysical systems - the Earth crust in particular - and how these similarities could be exploited to develop transversal and numerically-efficient models.

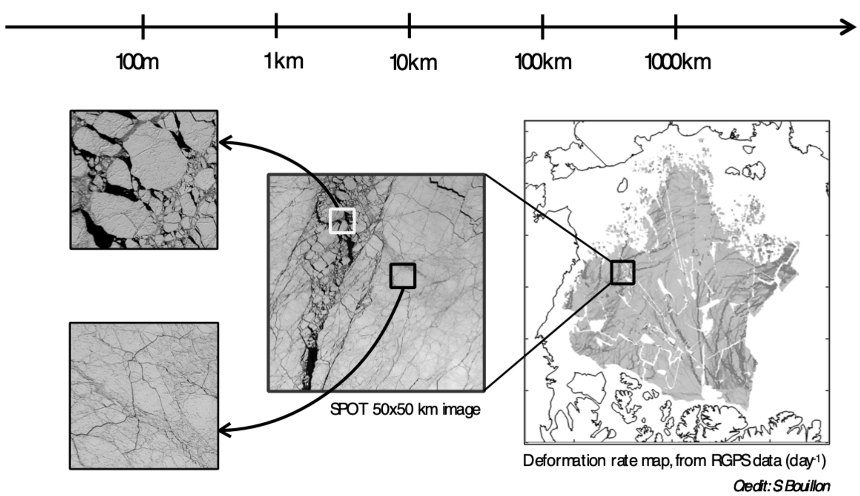

Figure: Representation of sea ice in the Arctic: at different scales and in different mechanical regimes.

Viscoplastic free-surface flows over topographies

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Preference: TALK

Keywords: yield-stress fluid, geophysical flows, natural hazards, experiments, numerical simulations

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Abstract :

Geophysical processes such as avalanches and debris flows involve free-surface flows of viscoplastic materials over topographies. The interplay between inertia, rheological effects and topographical features give rise to specific flow patterns, such as flow splitting, unyielded accumulations ahead of obstacles, dry zones downstream of obstacles, etc. We report on laboratory experiments specifically designed to study these complex processes. Finite volumes of a model viscoplastic material (Carbopol) are released from a rectangular reservoir onto 3D-printed topographies. The evolution of flow thickness over time is monitored with a temporal resolution of 250 Hz and a typical accuracy of 0.5 mm through a Moiré projection technique. The influence of release position, release volume, and fluid rheology on flow dynamics are investigated. In all case, an abrupt transition is observed between an inertia-dominated regime at short times, and a regime mainly controlled by plasticity and rheological effects at longer times. Interactions with the topography affect this transition by either promoting or delaying the deceleration of the flow. Experimental results are compared to numerical simulations based on depth-averaged shallow-flow models. In this approach, which is largely used for risk-related applications, the vertical structure of the flow is not resolved. Systematic cross-comparisons with the experimental data provides a unique benchmark to assess the predictive capabilities of the models. Lastly, recent developments to better account for complex rheological effects in these models will be discussed.

Ultrasound-induced Softening of Nuclear Sludges

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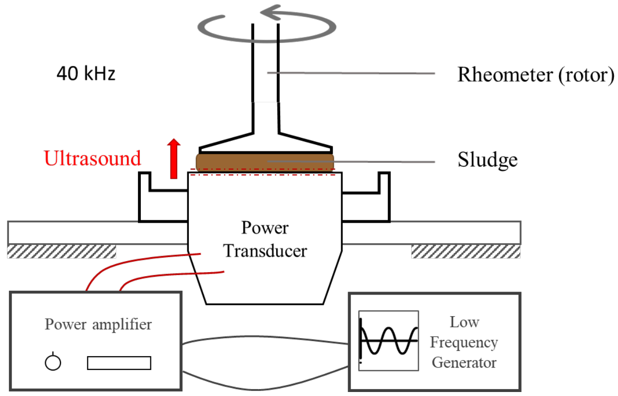
Preference: TALK in S3/ Rheology of geo-physical fluids

Keywords (5 max): Sludge, Power Ultrasound, Rheology

Abstract: (250 Words Max) The nuclear industry produces radioactive waste of various typology. Nuclear sludges require specific attention as they must be pumped, conveyed, and mixed safely and efficiently. To aid in processing, they often need to be fluidized. High-power ultrasonic fields exhibit interesting interactions with liquid suspensions by modifying their microstructure and subsequently reducing their viscosity and yield stress. In this work, a set-up coupling rheological measurements with high-amplitude ultrasound generated by an ultrasonic transducer has been assembled. This set-up consists of a stress-imposed rheometer equipped with a parallel plate geometry, where the static lower plate of the geometry has been replaced by a 40 kHz plane transducer. The impact of ultrasound on a model carbon black gel is first studied and compared to previous results [1] in order to validate the setup. Special attention is given to separating the thermal and acoustic effects on the gel rheology. A surrogate sludge, mimicking a real nuclear sludge, then allows us to safely study the rheological properties of industrial sludges under ultrasonic waves. Additionally, different model suspensions are characterized in order to identify the individual roles of each constituent on the sludge behavior under ultrasound. While a drop in the storage modulus is observed in all cases, we find that the various samples behave differently under ultrasound depending on the size of the primary particles and aggregates. Furthermore, some samples exhibit significant restructuring after ultrasound is turned off, suggesting the formation of a denser microstructure due to the application of ultrasonic vibrations.

[1] T. Gibaud *et al.*, "Rheoacoustic gels: Tuning mechanical and flow properties of colloidal gels with ultrasonic vibrations", *Physical Review* X, **10**, 011028 (2020)



Experimental set-up coupling rheometry and power ultrasound

Continuum modeling of cohesive and compressible granular flows with elasto-viscoplasticity

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Preference: TALK, Session S3

Keywords: granular flow, elasto-viscoplasticity, cohesion, critical state, material point method

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Abstract:

Modeling the mechanical and rheological behavior of granular media is a challenging task as such systems can exhibit characteristics of both solids and fluids under different conditions. Thus, a complete model should account for, e.g., elastic forces, shear band formation, internal friction and varying bulk density depending on the rate of the flow. In addition, some systems may also display a varying degree of cohesion due to attractive forces between the particles. Recently, the topic of cohesion in granular flows has gained significant interest, and this is particularly relevant for snow avalanches as climate has and will contribute to an increasing proportion of wet and cohesive avalanches in many areas.

With the $\mu(I)$-rheology originally developed for dense granular flows and critical state soil mechanics developed for granular solids, we present here an elasto-viscoplastic constitutive model based on the combination of the two theories, thus offering the “best of both worlds” in the appropriate flow rate limits. In the fluid transition, this “critical state $\mu(I)$-rheology” model recovers the dependence of the apparent friction on the inertial number, while a Modified Cam-Clay yield criterion allows for tuning cohesion. In addition, the model permits the direct treatment of dilation and compaction through a hardening law of the yield surface. The model is implemented in a two- and three-dimensional Material Point Method (MPM), providing an uncomplicated approach to handling the free-surface and avoiding mesh-distortion issues. We demonstrate our model on various problems, including flow on inclined planes and granular collapse, comparing with analytic solutions and previous experimental observations. Its applications to full-scale snow avalanche modeling will also be demonstrated.

This work was supported by the Swiss National Science Foundation (grant number PCEFP2 181227).

Effects of friction on MEB model for sea ice

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Preference : Poster

Keywords (5 max): sea ice, granular matter, modelling

Abstract : Sea ice is a complex material that plays a key role in the climate system by strongly regulating heat and momentum exchanges between the ocean and atmosphere. When and where it is dense - during the winter and in the central Arctic mostly - it behaves as a continuous and damageable solid that is well-simulated using a visco-elasto-brittle model of the Maxwell-type (MEB, Dansereau et al., 2016; 2017, Rampal et al., 2019). Where it is highly fragmented and loosened – during the summer and the peripheral Arctic Ocean - it behaves like a granular media. Its mechanical resistance is then dominated by frictional contacts, a behavior that is not well-accounted for in current mechanical sea ice models and harder to quantify using observations.

In this context, this work aims to improve the existing MEB model for sea ice by incorporating in it a parameterization of the effects of friction. To do so, we replicate with the model an annular Couette flow laboratory experiment that has investigated the frictional properties of a fault in floating ice and that, thereby enabling comparisons of the simulations with experimental findings.

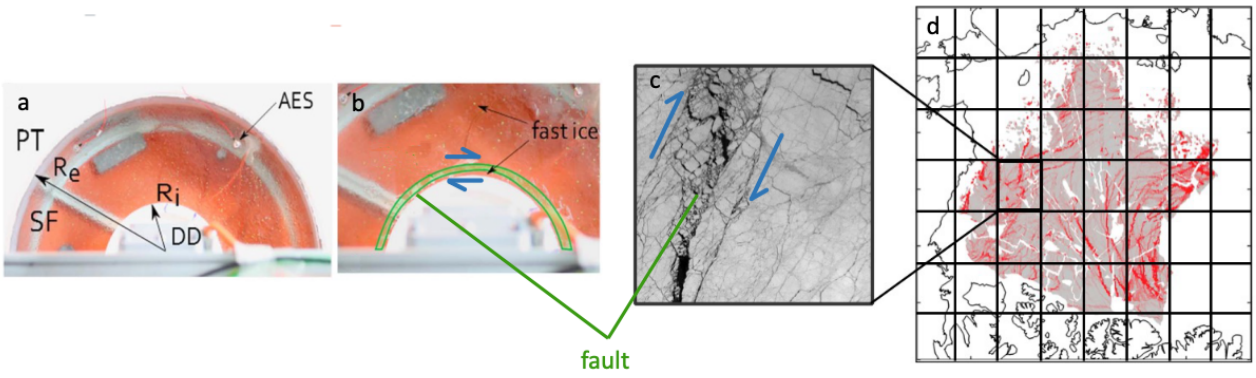

Figure: shear stress in sea ice fracture at lab scale (left), arctic scale (right)

From microstructural heterogeneity to macro- and mesoscale shear zones: a recipe for strain localization on Earth

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Preference : TALK, Session S3

Keywords (5 max): Viscoplastic behavior, strain localization, shear zones, geodynamics

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Abstract :

Strain localization is the rule rather than the exception in the lithosphere. Yet, modelling strain localization in the ductile field, which represents on average 90% of the lithosphere, remains a real challenge. Analysis of observations of ductile (viscous) strain localization at various spatial scales in nature and experiments shows that heterogeneity in the mechanical behavior is key for strain localization. This heterogeneity exists at all scales, in particular at small ones, and evolves in response to the mechanical fields. In the ERC RhEoVOLUTION, we posit that poor representation of this heterogeneity and its evolution during deformation is the locking point for generating strain localization in geodynamical models and examine how strain localization may arise in rocks deforming by ductile processes by associating a stochastic description of the mechanical properties of the medium with simple laws describing how these properties evolve in response to the resulting spatial variations in stress and strain rate. These models show that initial heterogeneity in the rheological behavior and damage/healing due to evolution of the microstructure leading to spatial variations in the mechanical behavior controlled by the mechanical energy dissipation field (local work rate) are necessary, but not sufficient conditions to produce strain localization during viscous deformation. An additional condition is that the rate of energy consumption by the damage process is within a range from the average mechanical energy dissipation in the system. These results are used for defining a regime diagram for viscous strain localization.

This work was supported by the European Research Council (ERC) under the European Union Horizon 2020 Research and Innovation programme [grant agreement No 882450 – ERC RhEoVOLUTION].

Investigating the relation between elastic and relaxation properties of dry, frictional granular media

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Preference : TALK

Keywords (5 max): Friction, Numerical Simulations, Elastic Properties, Relaxation

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Abstract : The mechanical behavior of dry frictional granular media is dominated by collision and friction between individual grains. Depending on packing fraction and external applied shear, these media can either exhibit a solid-like or a fluid-like behavior. The transition from a liquid-like to a solid-like behavior is reminiscent of a “jamming transition”. If, in the dense granular flow regime, the behavior is well captured by the μ(I) rheology, the local approach cannot account for non-local effects resulting from elastic long-ranged interactions between microplastic events. One way to take these elastic effects into consideration and to characterize the state of the granular medium at a mesoscale is to define a damage parameter that measures the progressive softening of the sheared granular assembly, which results from topological rearrangements. In the meantime, these granular media, even in their jammed state, are known to relax with time as soon as loading vanish, a behavior reminiscent of a remaining viscous-like behavior.
Here we present a series of molecular dynamics simulations of the shearing of frictional granular media, in a range of inertial numbers corresponding to the transition from the critical state to the dense flow regime. In the course of shear deformation, we track concomitantly the elastic properties of the medium from oscillatory tests, i.e. its level of damage, as well as its relaxation behavior and residual stress from relaxation tests, in order to link elastic and viscous-like properties, and to establish their dependence on the applied shear rate, applied pressure and, eventually, granular packing fraction.

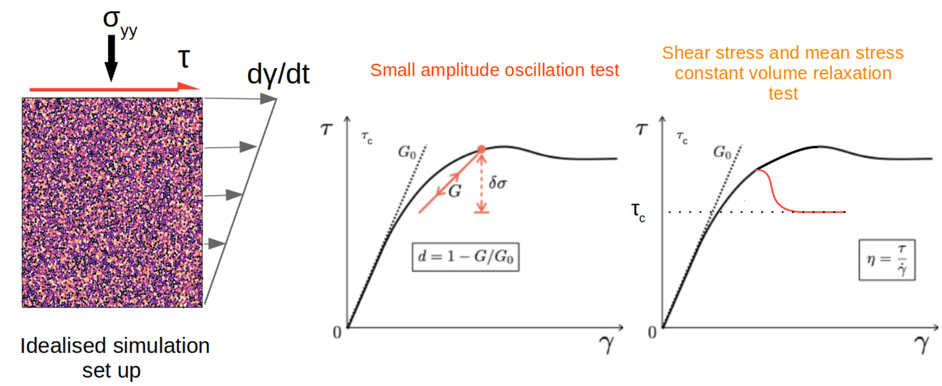

Figure: Schematic representation of simulation done to estimate evolution of elastic and viscous properties

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Microstrucural and rheological analysis of silica colloids: a DEM study

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Preference: Talk (S2 or S3)

Keywords (5 max): Colloidal suspensions, Numerical modelling, Gelation, Rheology

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Abstract (250 Words Max): Colloidal dispersions of silica nanoparticles have proven to be excellent materials for setting up laboratory mantle convection experiments. Indeed, thanks to their particular rheology, these fluids can reproduce some of the fundamental features underlying the complex dynamics of mantle convection (e.g. plate tectonics). However, the relationship between colloidal properties (particle size, salt concentration, pH, etc.), nanoparticle spatial organization and macroscopic rheological behavior remains poorly understood.

To shed light on this problem, we use dynamic particle-scale numerical simulations to model our colloidal silica dispersions. The evolution of the system is driven by the Langevin equations of motion where the conservative potential accounts for both DLVO interactions (non-touching particles) and granular interactions (particles in contact). Using the experimental data in our possession, we first characterize the microstructural organization of the colloidal dispersions (e.g. void distributions, particle network connectivity, locally favored structures) at different particle volume fractions (ϕ). The computer simulations nicely reproduce the phase diagram obtained experimentally in terms of sol-gel and gel-glass transitions. They show how the competition between electrostatic repulsion and particle concentration fully controls the phase transitions that characterize these colloidal systems. Second, we focus on the rheological characterization of our numerical configurations. This part of the study (still in progress) will lead us to understand how to control the rheological behavior of the colloidal silica dispersions. This results will allow us to better design the laboratory experiments on mantle convection.
