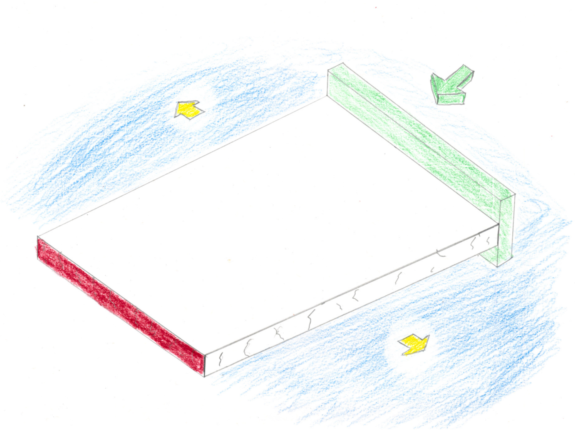
Alternative viscous-plastic rheologies for the representation of fracture lines in high-resolution sea ice models

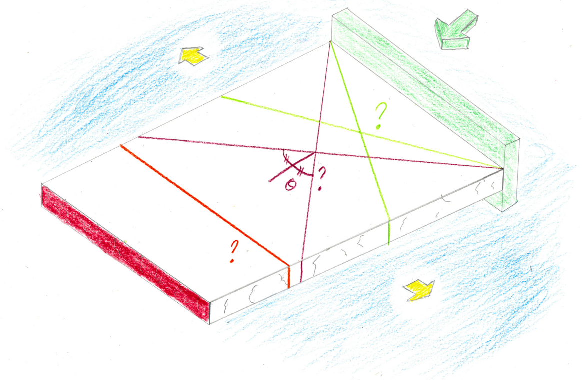
Damien Ringeisen, Martin Losch, and L. Bruno Tremblay

vEGU 2021 — EGU21-1373 — 2021-04-30

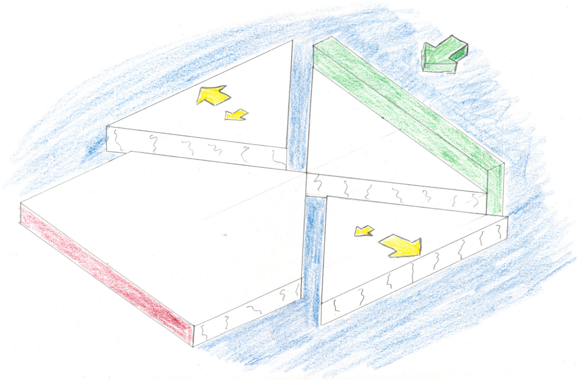
A little thought experiment...



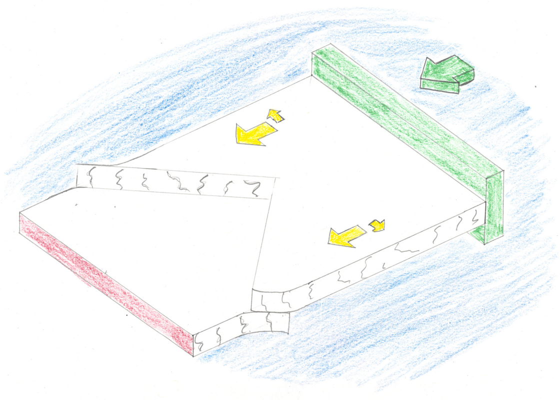
A little thought experiment. . .



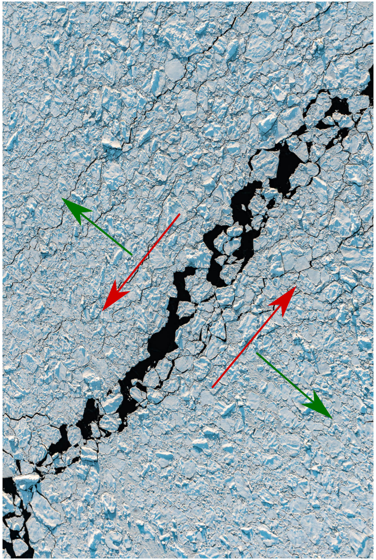
A little thought experiment...



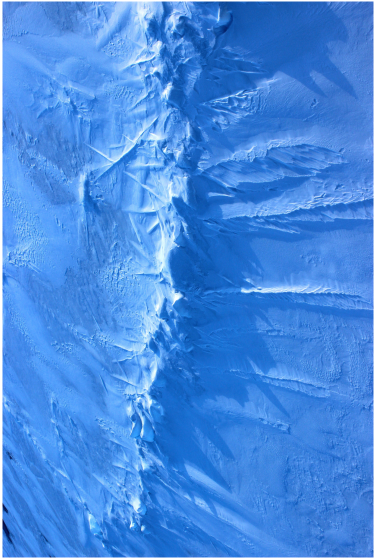
A little thought experiment. . .



. . . which we can observe on the field.



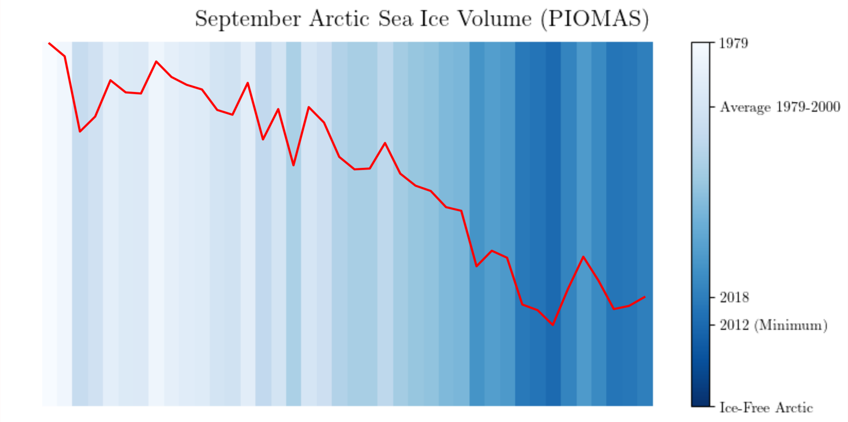
Credit: Lukas Piotrowski



Credit: Grace Shephard (distributed via imaggeo.egu.eu) CC-BY-NC

Motivation?

The overarching motivation



Motivation?

We call these deformation lines *Linear Kinematic Features* or **LKFs**.

LKFs influence

- Exchange of Energy and Moisture
- Creation of new ice → in leads
- Creation of thick ice → in ridges

→ **Influence the mass balance**

We

- Observe the LKFs intersection angles in deformation patterns
- Want to reproduce these patterns in sea ice dynamical models

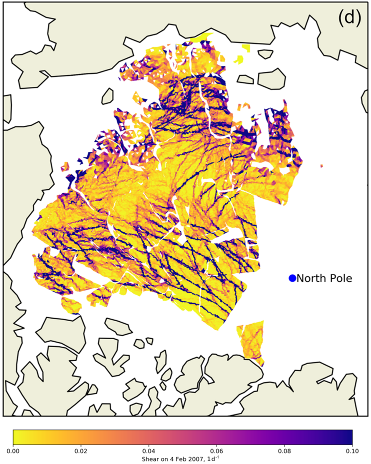


Figure: Shear Deformation — From Rampal et al. (2019) — under CC-BY license.

The sea ice Viscous-Plastic (VP) rheological model

The most widely used sea ice model

- Viscous for small deformations $\rightarrow$ Plastic for large deformations (Hibler, 1977)
- Two main components:

A yield curve

- Transition between Viscous and Plastic in the stress space
- Viscous deformation are slow ($t_{def} \simeq 35\,y$)
  - Almost a purely plastic model

A flow rule

- Post-failure deformation
- i.e. the ratio of shear and divergence or convergence
- Can be **normal** or **non-normal** to the yield curve

We call **rheology** the coupling of a yield curve shape and a flow rule.

VP was designed for resolution of O(100 km)
and is now used at resolution of O(1 km)

Models and observation disagreen on LKFs intersection angles

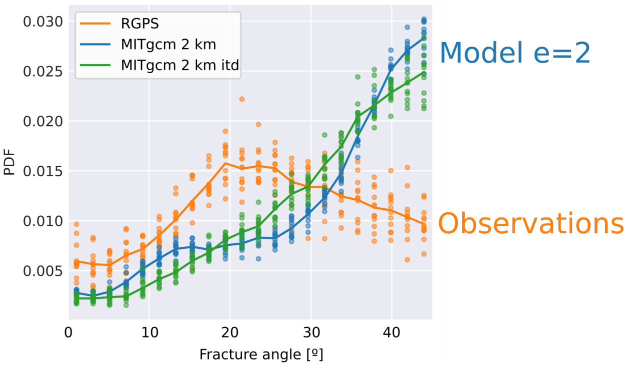


Figure: PDFs of LKFs half-intersection angles — Derived from Hutter and Losch (2020) – under CC-BY license.

See the work of Nils Hutter on comparing sea ice rheological model here at vEGU21: EGU21-9739

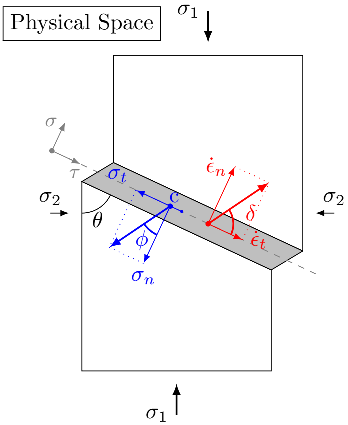
Theory of fracture angles in granular matter

- **Coulomb Angle** θ_C (Coulomb, 1773):
  The fracture angle depends on the slope of the yield curve, i.e., the stress ratio ϕ along the shear line.

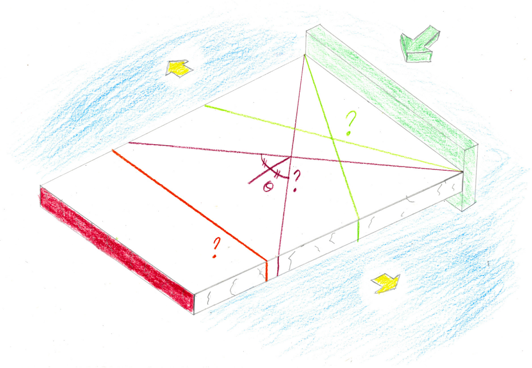
- **Roscoe Angle** θ_R (Roscoe, 1970):
  The fracture angle depends on the orientation of the flow rule, i.e., the strain-rate ratio δ along the shear line.

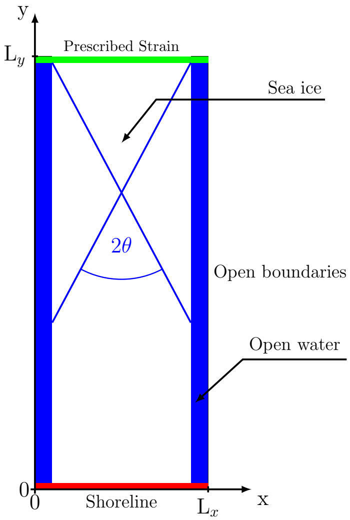
- **Arthur Angle** θ_A (Arthur et al., 1977):
  The fracture angle is the average of θ_C and θ_R.

$\rightarrow$ with a normal flow rule, then $\theta_C = \theta_R = \theta_A$



Experimental setup: Uni-axial compression





Recent results with the same setup

Ringeisen et al. (2019)

- Ellitptical yield curve with normal flow rule (Hibler, 1979)
- Fracture angles depend on the yield curve slope with a normal flow rule
- Cannot create angles smaller than 30° in uni-axial compression

Ringeisen et al. (2020)

- Designed a elliptical yield curve with non-normal flow rule.
- The direction of the flow rule sets the fracture angle → **Roscoe angle**
- Able to create angles smaller than 30° in uni-axial compression

Here we

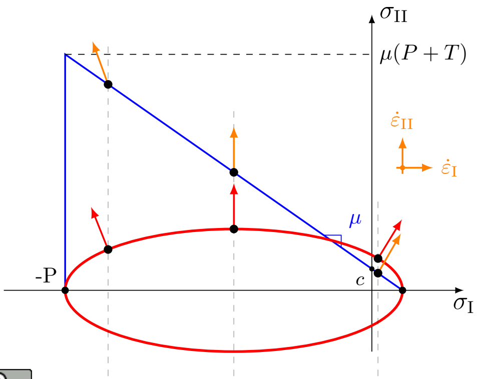
- Investigate yield curves that do not have an elliptical shape.
  - Especially Mohr–Coulomb yield curve, known for the modelling granular materials.
  - Insist on good numerical convergence to explore the precise effects of the rheology.
- Idealized compression experiment
- with the MITgcm sea ice package (Losch et al., 2010).

New yield curves: Mohr–Coulomb & Teardrop

Mohr–Coulomb yield curve (MCE)

non-normal flow rule

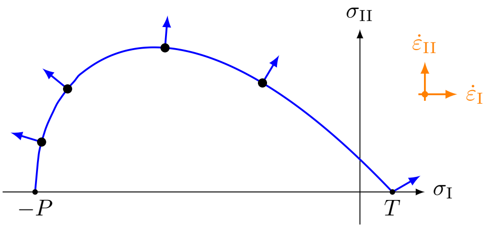
derived from Ip et al. (1991)



Teardrop yield curve (TD)

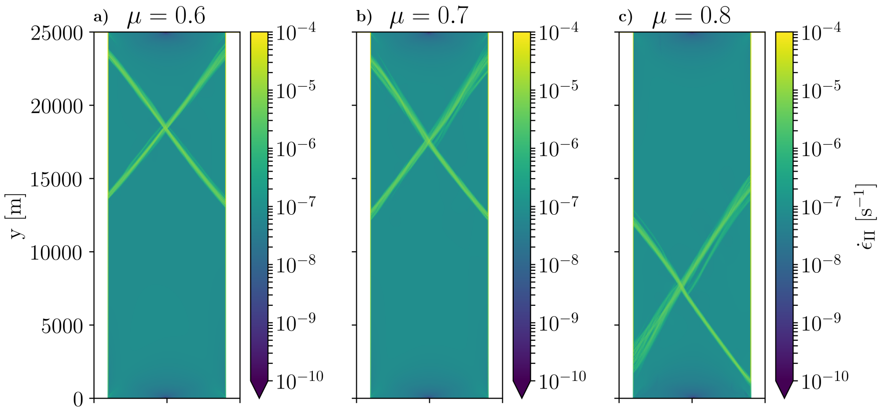
normal flow rule

modified from Zhang and Rothrock (2005)



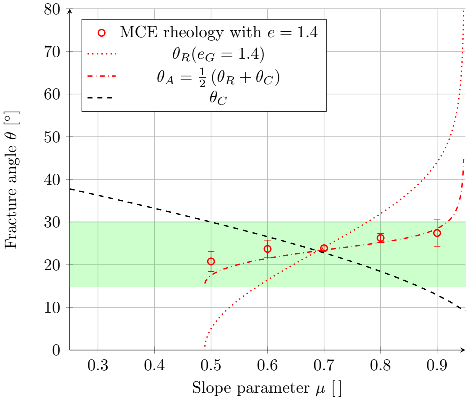
Results: Mohr–Coulomb yield curve

- Creates defined shear lines, unlike the formulation of Ip et al. (1991).



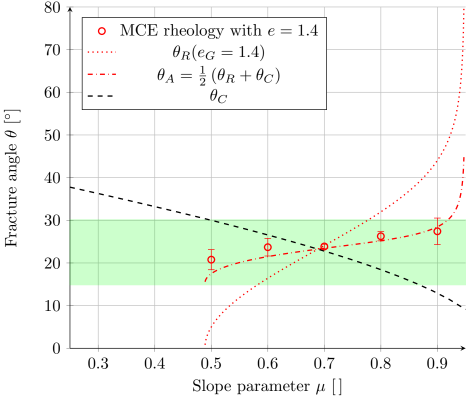
Results: Mohr–Coulomb yield curve

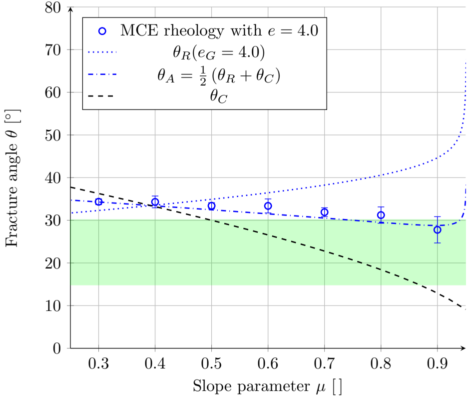
- Creates defined shear lines, unlike the formulation of Ip et al. (1991).
- The fracture angles correspond to the **Arthur angles**.



Results: Mohr–Coulomb yield curve

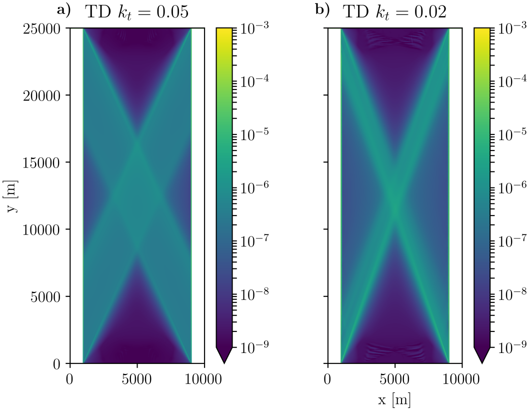
- Creates defined shear lines, unlike the formulation of Ip et al. (1991).
- The fracture angles correspond to the **Arthur angles**.





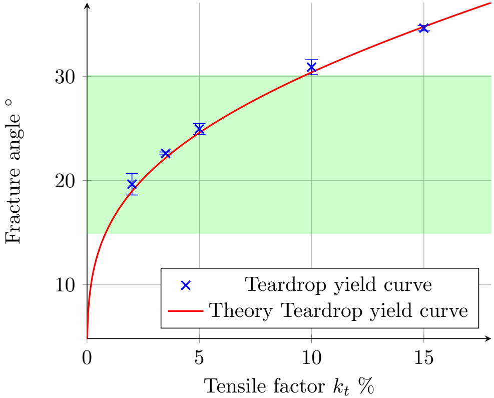
Results: Teardrop yield curve

- Creates defined shear lines with small angles.



Results: Teardrop yield curve

- Creates defined shear lines with small angles.
- Modeled angles fit exactly the theoretical angles with normal flow rule.



Conclusions and Outlook

Mohr–Coulomb

- Surprisingly: Shear lines with Arthur angles
  - Contradicts our previous work (Ringeisen et al., 2020).
  - Unknown reason yet.
- Allows to decrease the fracture angles.

Conclusions and Outlook

Mohr–Coulomb

- Surprisingly: Shear lines with Arthur angles
  - Contradicts our previous work (Ringeisen et al., 2020).
  - Unknown reason yet.
- Allows to decrease the fracture angles.

Teardrop

- Very good agreement with theory
- Clean fracture pattern, with issues fixed.
- Also allows to decrease the angles
- Good candidate to reduce the fracture angles overall.

Conclusions and Outlook

Mohr–Coulomb

- Surprisingly: Shear lines with Arthur angles
  - Contradicts our previous work (Ringeisen et al., 2020).
  - Unknown reason yet.
- Allows to decrease the fracture angles.

Teardrop

- Very good agreement with theory
- Clean fracture pattern, with issues fixed.
- Also allows to decrease the angles
- Good candidate to reduce the fracture angles overall.

Conclusions

- Essential to test our rheological models
- We can reduce the fracture angles with non-elliptical yield curves
- With a yield curve for granular properties

Conclusions and Outlook

Mohr–Coulomb

- Surprisingly: Shear lines with Arthur angles
  - Contradicts our previous work (Ringeisen et al., 2020).
  - Unknown reason yet.
- Allows to decrease the fracture angles.

Teardrop

- Very good agreement with theory
- Clean fracture pattern, with issues fixed.
- Also allows to decrease the angles
- Good candidate to reduce the fracture angles overall.

Conclusions

- Essential to test our rheological models
- We can reduce the fracture angles with non-elliptical yield curves
- With a yield curve for granular properties

Outlook

- Yield curves implemented in the MITgcm sea ice package
- Currently testing their effect in high-resolution pan-Arctic simulations

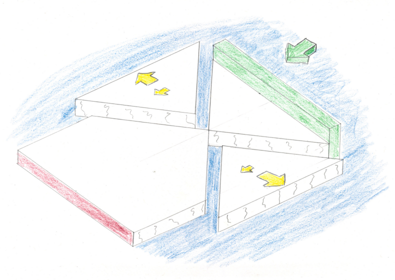
Summary — Contact us for more info

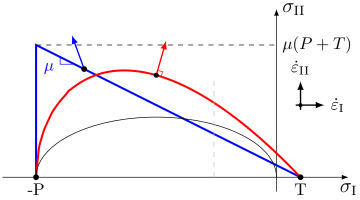
Deformation lines in sea ice

- Intersection angles are larger in models than observed.
- Linked to the Viscous-Plastic rheology

Two modified rheologies

- Mohr–Coulomb yield curve — non-normal
- Teardrop yield curve — normal flow rule





Idealized numerical experiment

- Both rheologies allow for smaller angles
- MCE creates fractures with Arthur angles

- Investigating rheologies is necessary
- Available in MITgcm now
- Next step: test in pan-arctic setups

References I

Arthur, J. R. F., Dunstan, T., Al-Ani, Q. a. J. L., and Assadi, A. (1977). Plastic deformation and failure in granular media. *Géotechnique*, 27(1):53–74.

Coulomb, C. (1773). Test on the applications of the rules of maxima and minima to some problems of statics related to architecture. *Mem Math Phys*, 7:343–382.

Hibler, W. D. (1977). A viscous sea ice law as a stochastic average of plasticity. *Journal of Geophysical Research*, 82(27):3932–3938.

Hibler, W. D. (1979). A Dynamic Thermodynamic Sea Ice Model. *Journal of Physical Oceanography*, 9(4):815–846.

Hutter, N. and Losch, M. (2020). Feature-based comparison of sea ice deformation in lead-permitting sea ice simulations. *The Cryosphere*, 14(1):93–113.

Ip, C. F., Hibler, W. D., and Flato, G. M. (1991). On the effect of rheology on seasonal sea-ice simulations. *Annals of Glaciology*, 15:17–25.

Losch, M., Menemenlis, D., Campin, J.-M., Heimbach, P., and Hill, C. (2010). On the formulation of sea-ice models. Part 1: Effects of different solver implementations and parameterizations. *Ocean Modelling*, 33(1–2):129–144.

Rampal, P., Dansereau, V., Olason, E., Bouillon, S., Williams, T., Korosov, A., and Samaké, A. (2019). On the multi-fractal scaling properties of sea ice deformation. *The Cryosphere*, 13(9):2457–2474. Publisher: Copernicus GmbH.

Ringeisen, D., Losch, M., Tremblay, L. B., and Hutter, N. (2019). Simulating intersection angles between conjugate faults in sea ice with different viscous–plastic rheologies. *The Cryosphere*, 13(4):1167–1186.

Ringeisen, D., Tremblay, L. B., and Losch, M. (2020). Non-normal flow rules affect fracture angles in sea ice viscous-plastic rheologies. *The Cryosphere Discussions*.

Roscoe, K. H. (1970). The Influence of Strains in Soil Mechanics. *Géotechnique*, 20(2):129–170.

Zhang, J. and Rothrock, D. A. (2005). Effect of sea ice rheology in numerical investigations of climate. *Journal of Geophysical Research: Oceans*, 110(C8):C08014.