DynEarthSol3D: unstructured finite element method to model visco-elasto-plastic ice *dynamics*

Liz Logan | Luc Lavier | Euneo Choi | Eh Tan | Ginny Catania
logan@ig.utexas.edu

INSTITUTE FOR GEOPHYSICS
JACKSON SCHOOL OF GEOSCIENCES

1. Do we really need another numerical model?

Glacier and ice shelf retreat remains an important problem in the numerical modeling community. Calving occurs through the brittle failure of ice in the form of rifts and crevasses.

Motivation: how do rifts and crevasses *form and develop* as they are advected through a glacier or ice sheet?

This poster: presents and shows preliminary model results of the formation and development of features of brittle deformation (like calving blocks and surface and basal crevasses) using *visco-elasto-plastic* rheology.

3. Visco-elasto-plastic rheology (VEP)

Take-away idea: Ice is brittle for high strain rates, and ductile for low strain rates (Schulson and Duval, 2009)*.

In the code, this means:

Viscoelastic (VE) for all $\dot{\varepsilon}_{xx} < 1 \times 10^{-7}\ s^{-1}$

Elastoplastic (EP) for all $\dot{\varepsilon}_{xx} \geq 1 \times 10^{-7}\ s^{-1}$

If it (the element) is Elastoplastic (EP)
It fails in tension for all $\sigma_{xx} \geq 1$ MPa
Otherwise no failure

* Of course, brittle ice failure stress depends on many things (e.g., temperature, grain size, brine, damage/pre-strain, etc) but the overall behavior shows a rheological transition at $O(10^{-7}\ s^{-1})$ strain-rate.
Note: plasticity is not fracture.

4. "Benchmark performance"

Take-away idea: DES preforms comparably well with the dimensionally scaled results of other Stokes (purely viscous) simulations for a freely sliping bed. Differences between DES and Stokes (FS) models are due to the boundary conditions (which are not periodic in our simulation).

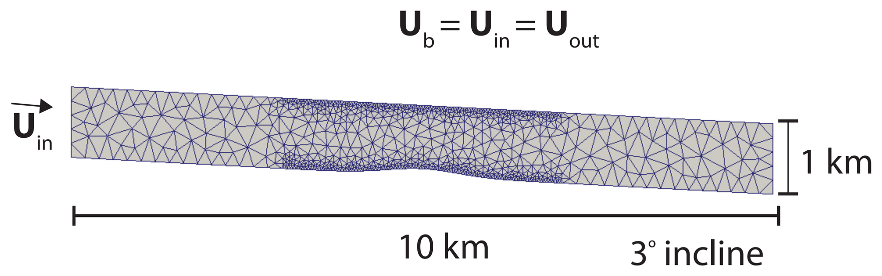
DES is by its nature a "prognostic" model. It has already been benchmarked for the rheologies listed in Section 2 here (Choi et al., 2013). Performing the only prognostic test put forth by the ISMIP-HOM (Pattyn et al., 2008) is difficult with DES because it is designed for **very large strain** problems and has adaptive remeshing. Another way to say this is that in DES there is no steady state. But we tried anyway.

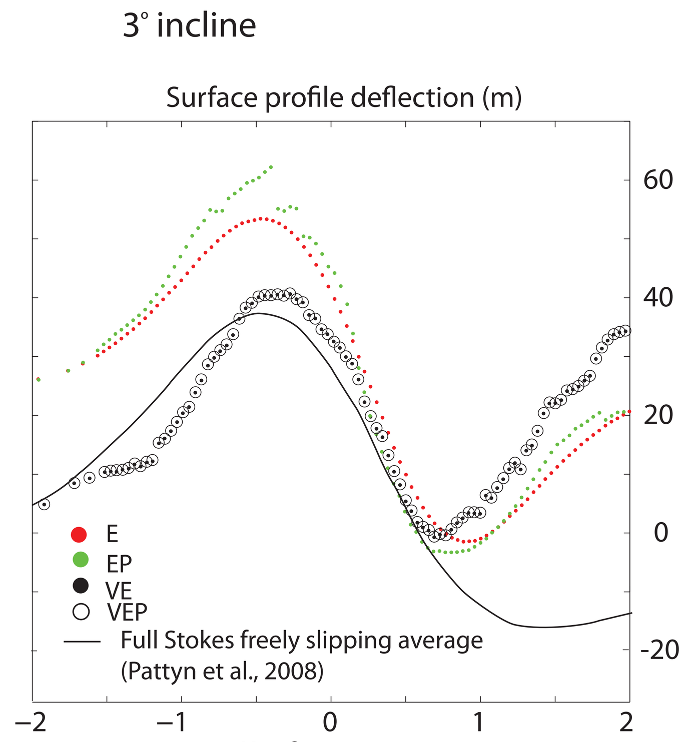
Experiment 1: Ice on a plane with a Gaussian bump, free slip

Basal velocity = $U_b = \rho$ c A $H^2 \sin\alpha \cdot g$ 200 to 40 m resolution

$U_b = U_{in} = U_{out}$ $T_{surface}$ = 240 K

T_{bed} = 273 K

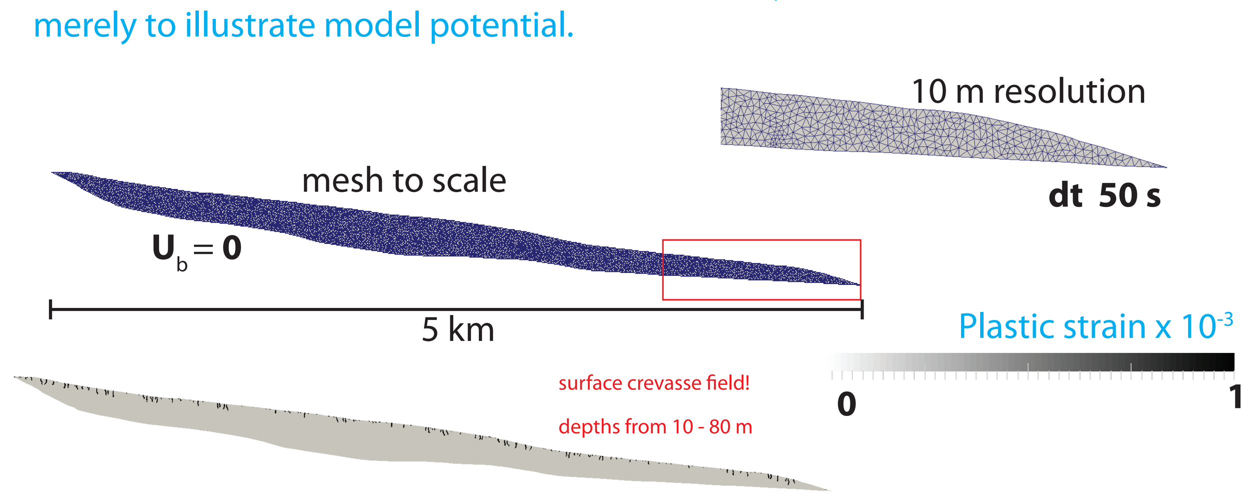




[Right] After 27 months of model run time, the surface of the ice is perturbed around the bump. We have scaled the Full Stokes suite of results from Pattyn et al., 2008 to the center 40% of the domain for comparison.

Benchmark 2: Haut Glacier d'Arolla, no slip: crevasse field!

We ran a VEP simulation of Arolla Glacier simply to show its meshing ability and potential to simulate crevasse development. Again, there is no "steady state" in these models, so we show results after 3 years of run time merely to illustrate model potential.



2. What is DynEarthSol3D (DES)?

I. Conservation equations and physics (no dimensional simplifications):

a. Conservation of:
- Momentum (*time dependent!*)
- Energy
- Mass enforced via elasticity

b. Constitutive law (options):
- (E) Elasticity
- (VE) Maxwell visco-elasticity
- (EP) Mohr-Coulomb elasto-plasticity
- (VEP) Visco-elasto-plasticity

c. Boundary conditions
- Stress or velocity (e.g., to study basal processes)
  - Free surface evolution through time
  - Accumulation / melting capable

II. Computational aspects

d. Solution scheme & implementation
- Equations are solved EXPLICITLY
- Variable time step follows CFL condition
- Paralellized (OMP)

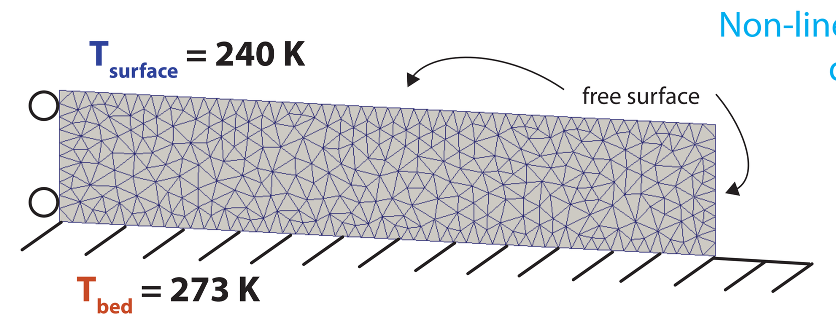
e. Mesh
- Unstructured, Voronoi nodes
  - provided by TetGen
- Adaptive remeshing!
  - helps focus on zones of interest

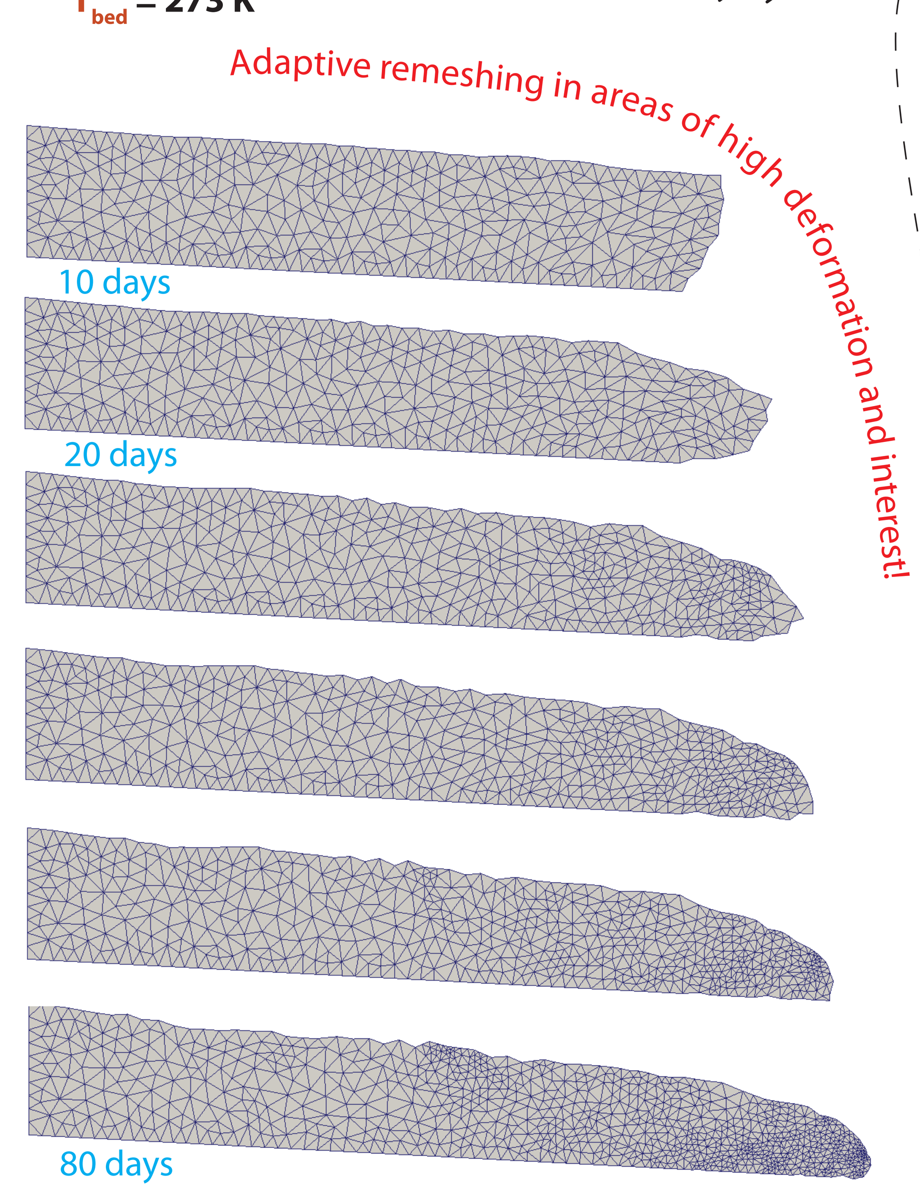
III. Previous work with model
- Validated and verified (Choi et al., 2013)
- Multi-phase
  - e.g., could study till rheology

5. Calving block: visco-elastic vs. visco-elasto-plastic

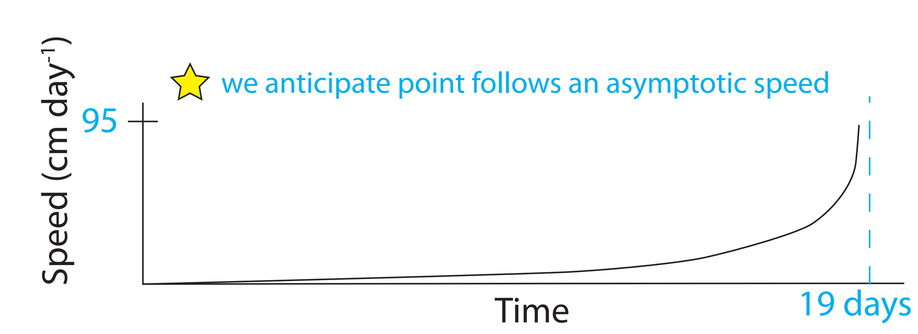
Take-away idea: "hanging" glacier fails in asymptotic fashion much like Mönch, Bernase Alps, Switzerland (Pralong et al., 2003). A lot of potential to explore the thresholds which lead to failure, as well as more complicated boundary conditions, including accumulation and melt.

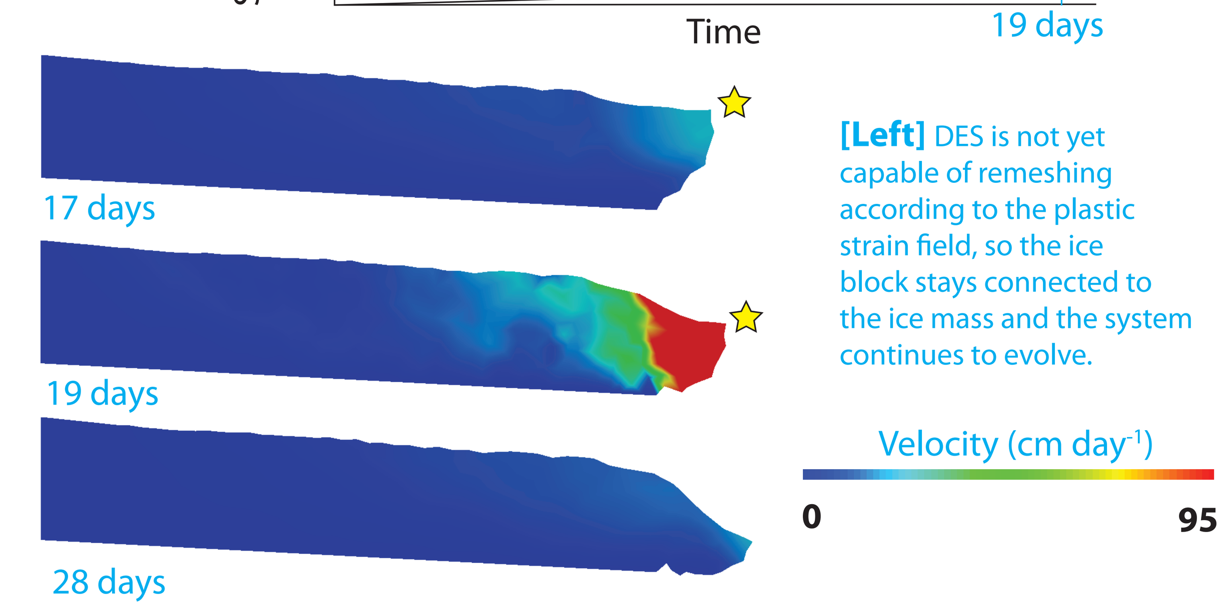
Visco-elastic case (VE)
(no failure)
Non-linear viscosity
$dt^{stable} \leq 50$ s
dx = 100 m





(VEP) Visco-elasto-plastic case
(failure, same as left in every other way)

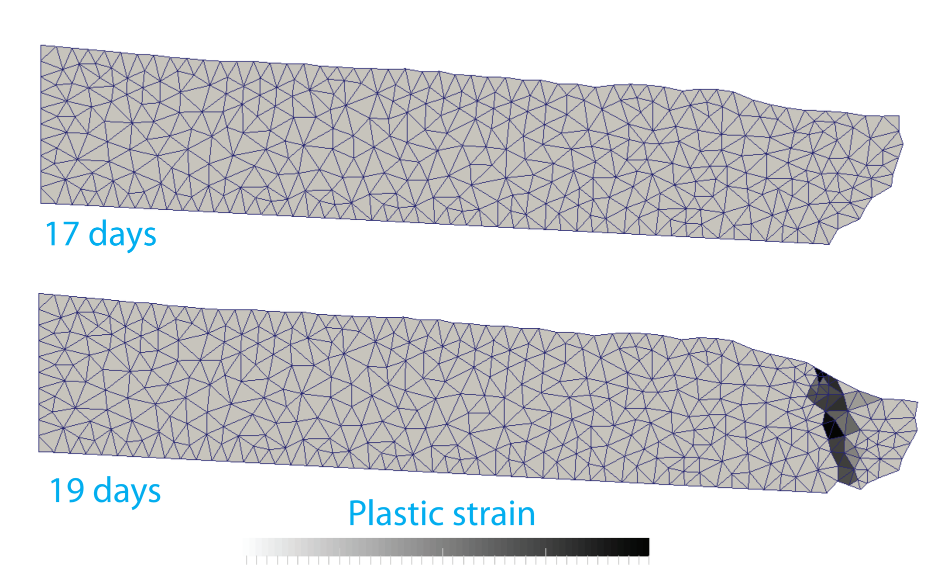




[Left] DES is not yet capable of remeshing according to the plastic strain field, so the ice block stays connected to the ice mass and the system continues to evolve.

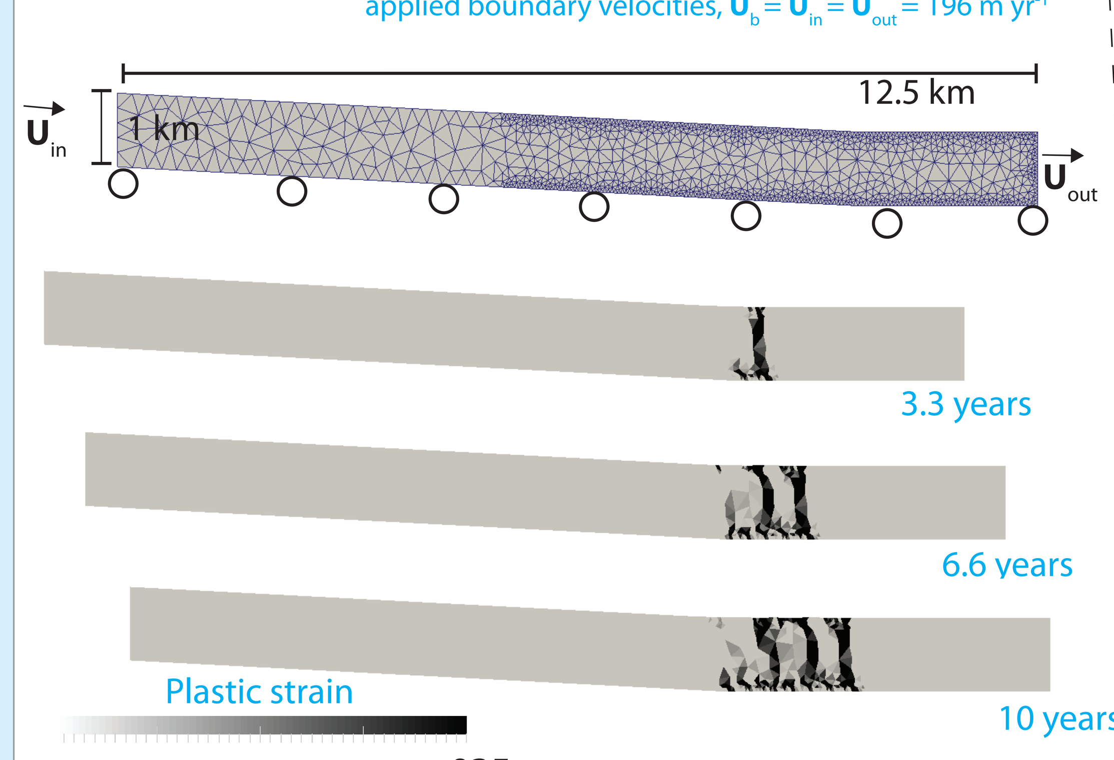
[Right] Mesh refines around the area of brittle deformation.

Plastic strain shows us the broundaries of the chunk of ice falling off.



6. Formation and advection of grounding line basal crevasses

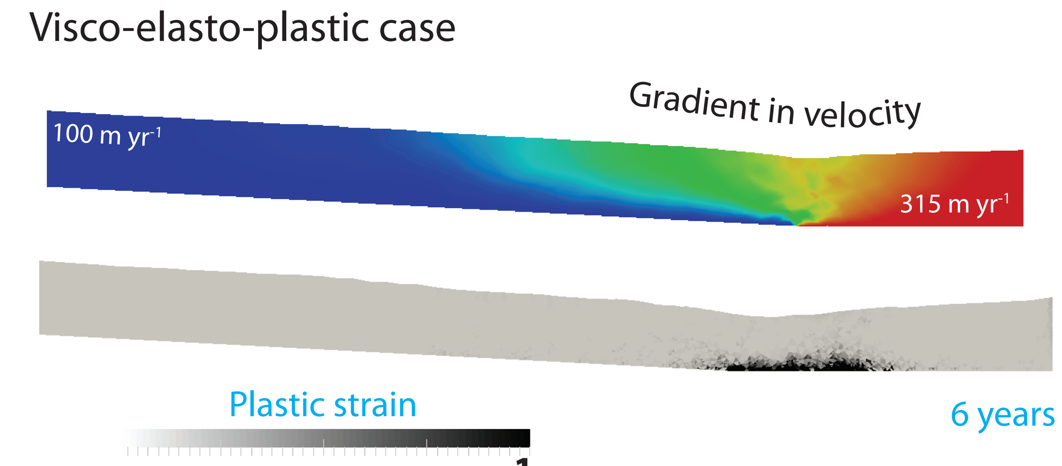
Elasto-plastic case
(failure when $\sigma_{xx} \geq 1$ MPa)
variable resolution, initial dx_{min} = 40 m
applied boundary velocities, $U_b = U_{in} = U_{out}$ = 196 m yr^{-1}



Take-away idea: because the elasto-plastic case is always "primed" to be brittle, the extra stress of bending the glacier is enough to form features that go the whole way through the ice. The VEP material needs something extra to transition into the brittle regime, however. So we apply a gradient in velocity (shown below) to produce brittle failure.

Another way to do this would be to add tides.

Visco-elasto-plastic case



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