3D Calving in Elmer/Ice

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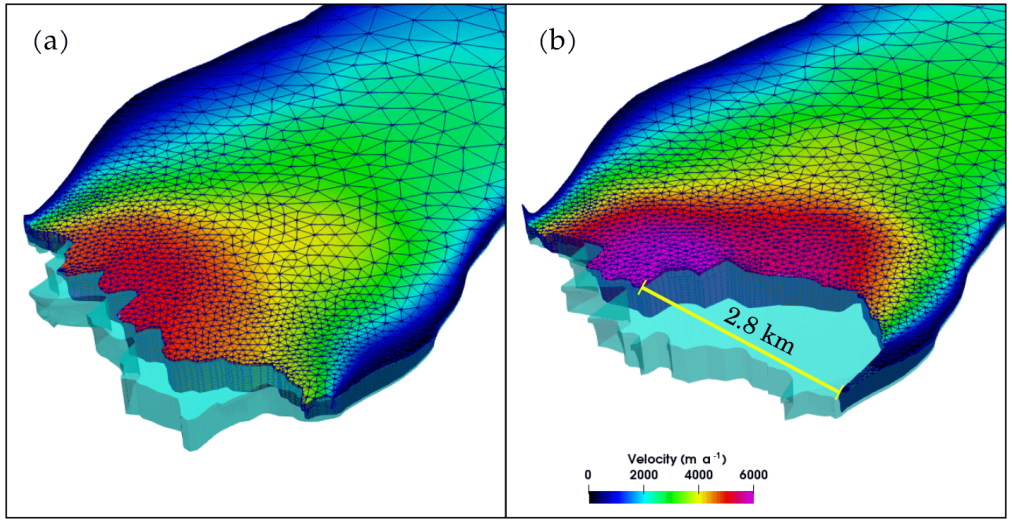
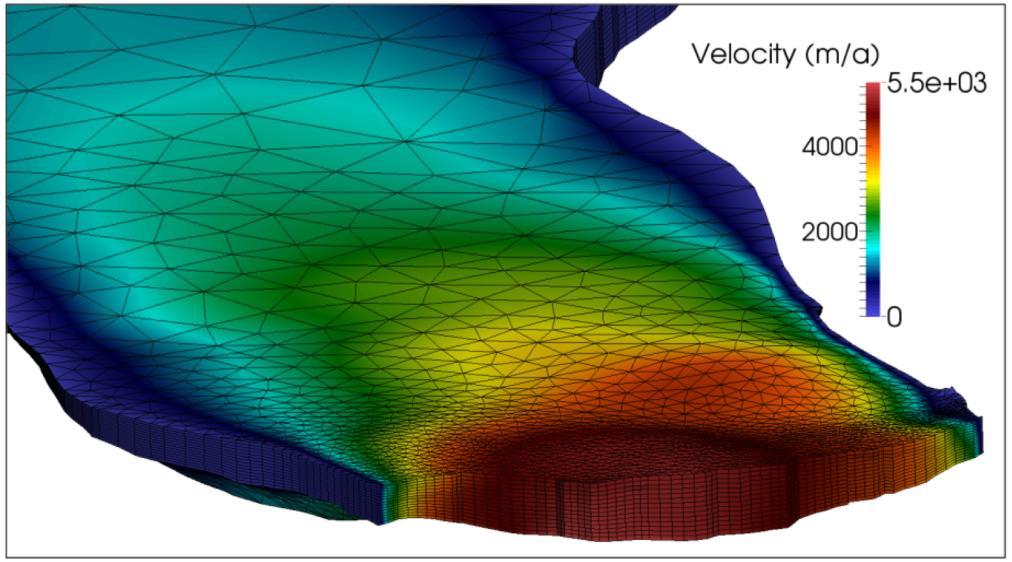
Why a new algorithm?

- Previous calving model from Joe Todd
- Model fast flowing tidewater glaciers
  - Lateral margin advance/retreat
  - Non projectible calving front
- Uses an extruded mesh
- Use of command line calls within the code



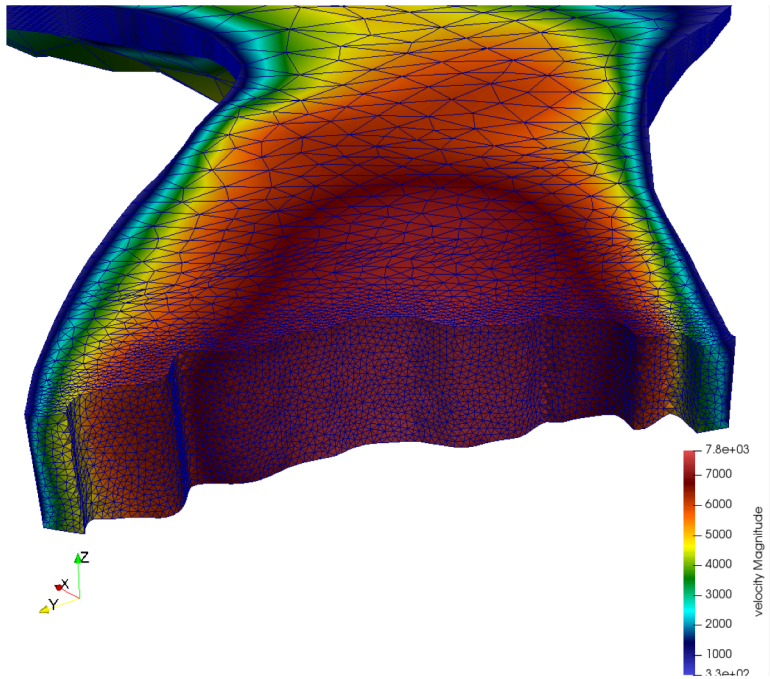
Todd et al., 2019



Todd, 2016

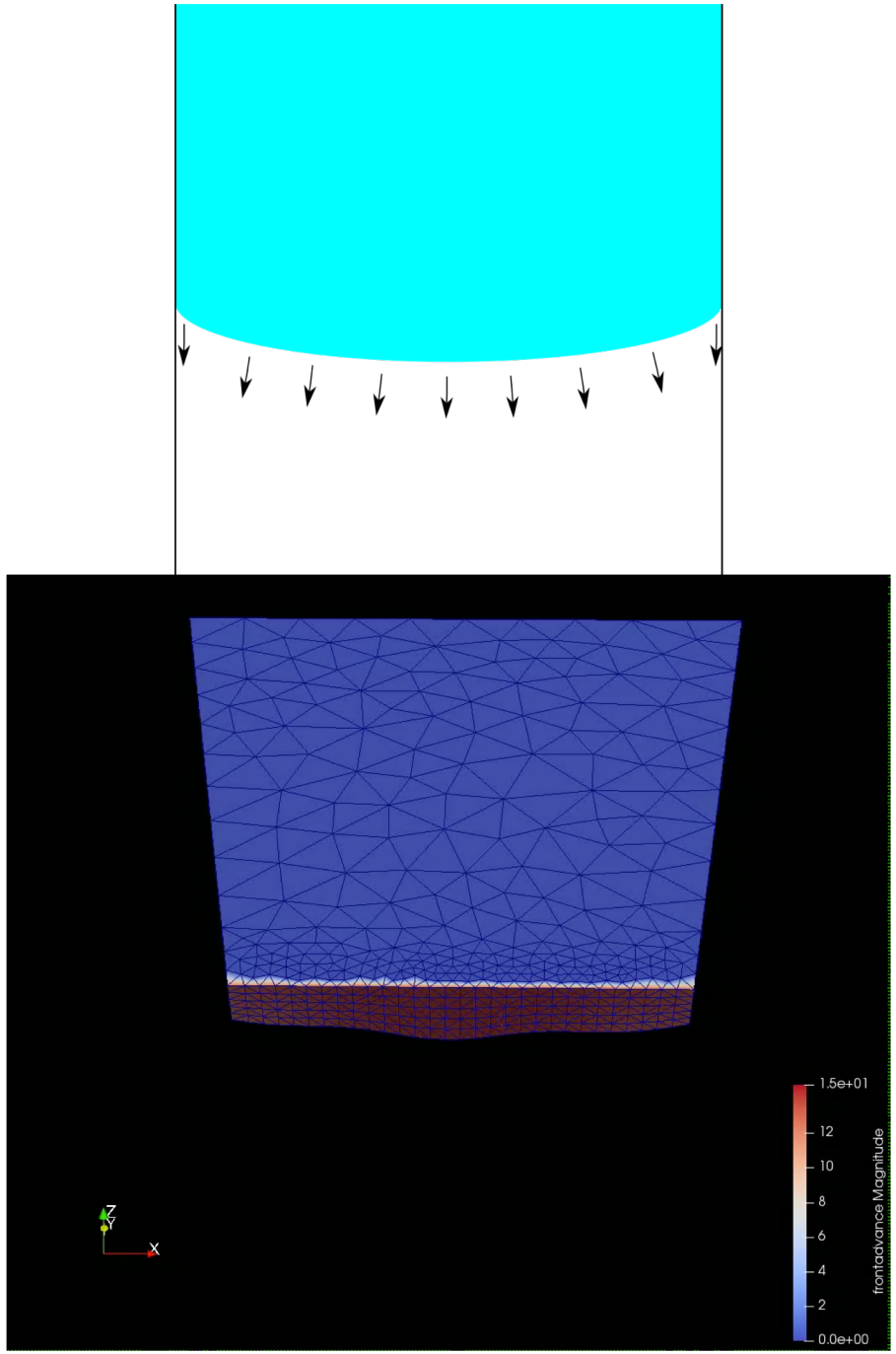
What is in the new algorithm?

- Requires tetrahedral mesh – internal changes in Elmer to compensate
- Terminus advance
- Level set calculation
- Calving law unchanged (CDL) but any could be implemented
- Complete remeshing using Mmg
- Rebalancing using Zoltan



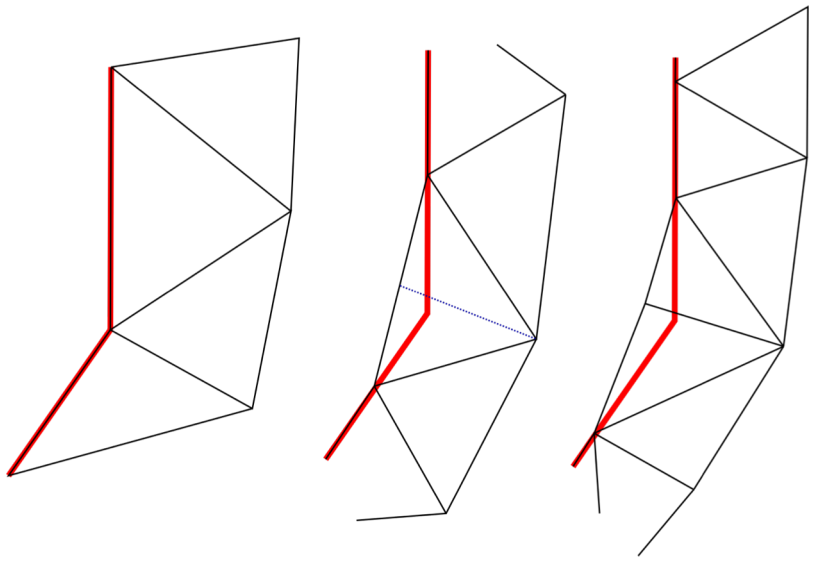
Front advance

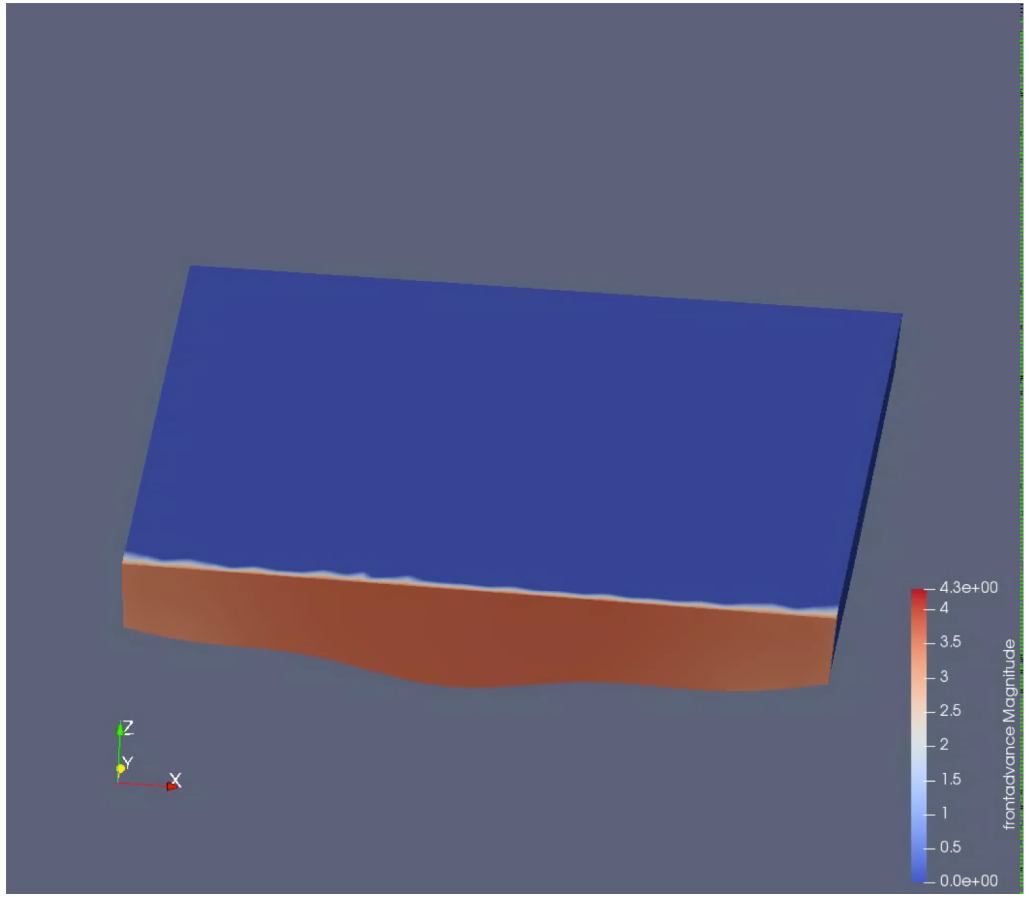
- Originally developed by Eef Van Dongen and Joe Todd
- CalvingGlacierAdvance3D.F90
- Terminus advance Lagrangian except for lateral margins
- Computationally light
- Mesh modified by MeshSolve.F90 (mesh deformation)
- Advance = (velocity – melt) * dt



Front Advance

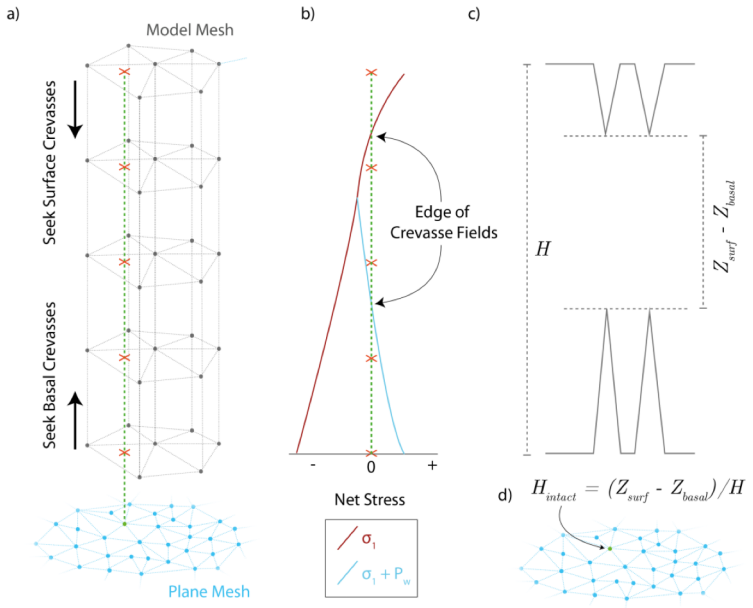
- Modified for boundary element reallocation
- Changes needed for remeshing



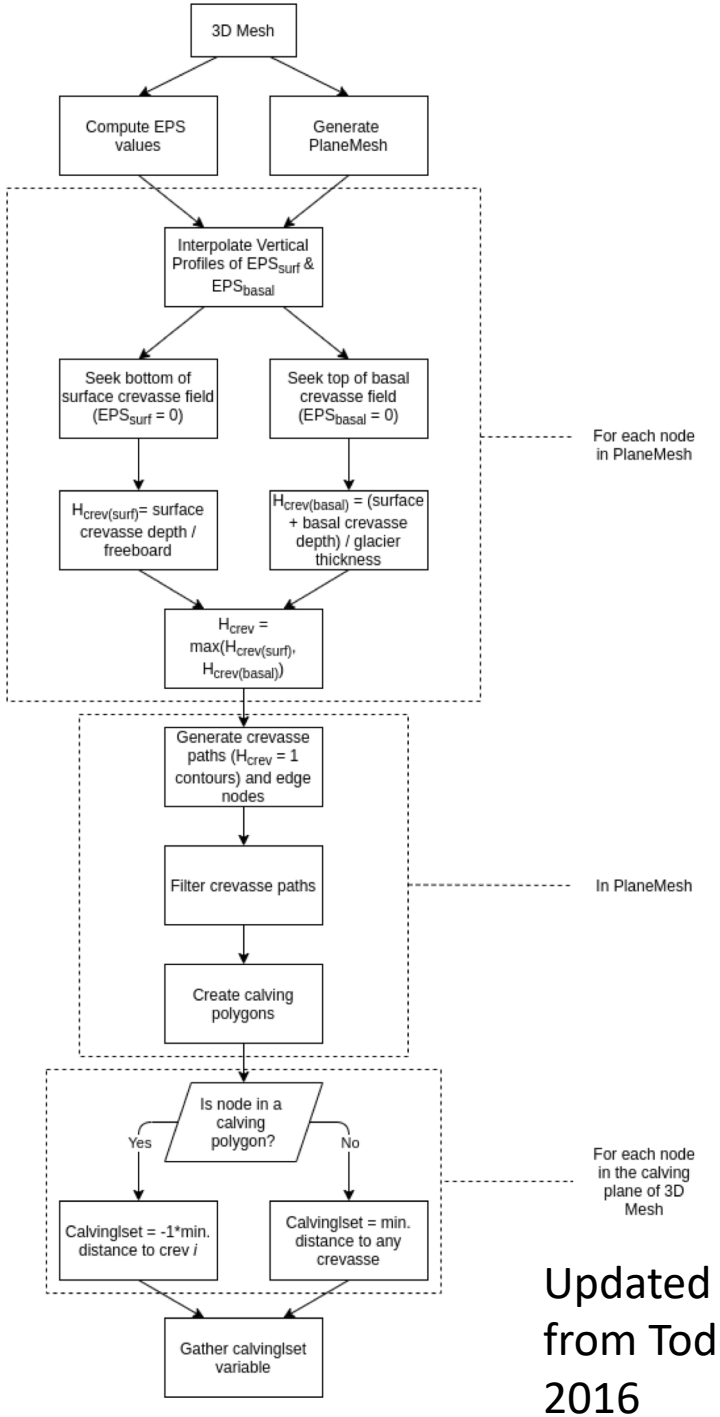


Calving Projection

- Calving law currently unchanged (CDL)
- Calving projected on PlaneMesh (2D) using ProjectCalving.F90
- Translated in level set variable on 3DMesh

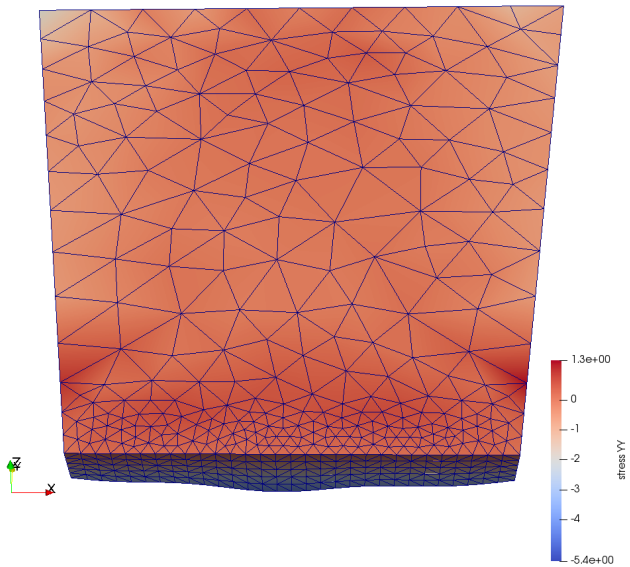


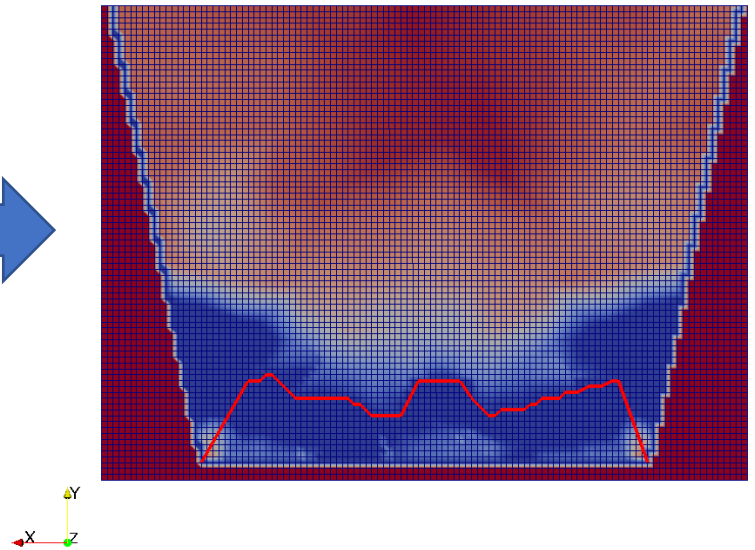
Todd, 2016

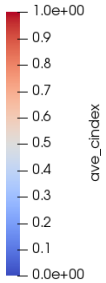


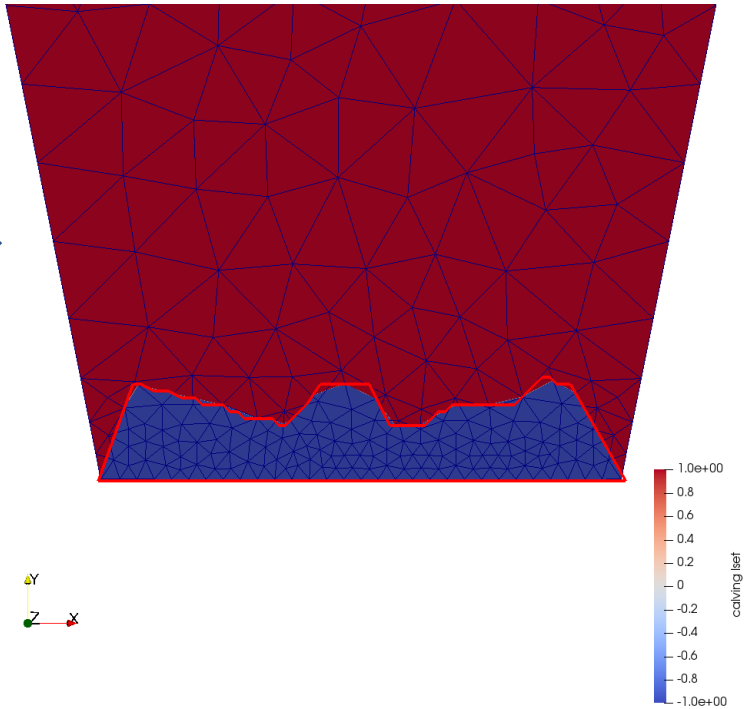
Updated from Todd, 2016

Level set calculation (Calving3D_lset.F90)









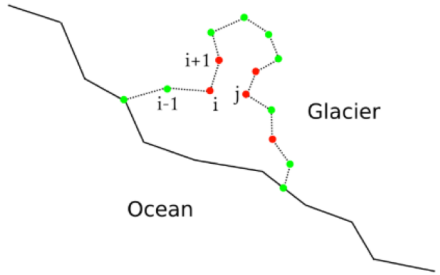
Stress field

Project calving on 2D PlaneMesh -> validate crevasses

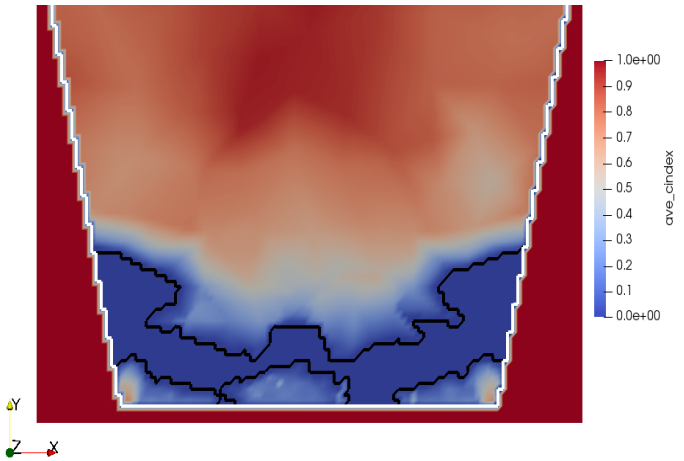
Translate crevasses into level set variable. Calved areas (-1) * distance from nearest crevasse

Crevasse validation

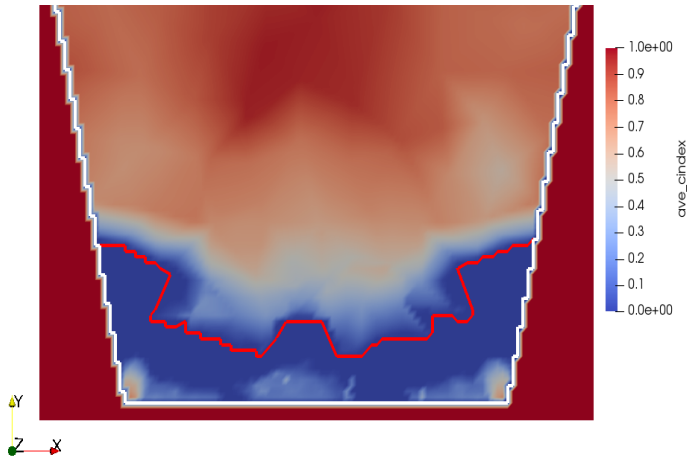
- Updated to work for any front geometry
- Option to add lateral margins to prevent unrealistic calving



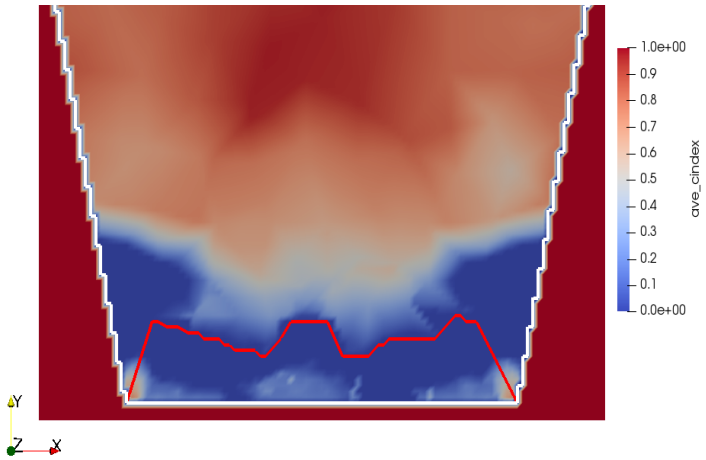
Todd et al., 2018



Unvalidated crevasses



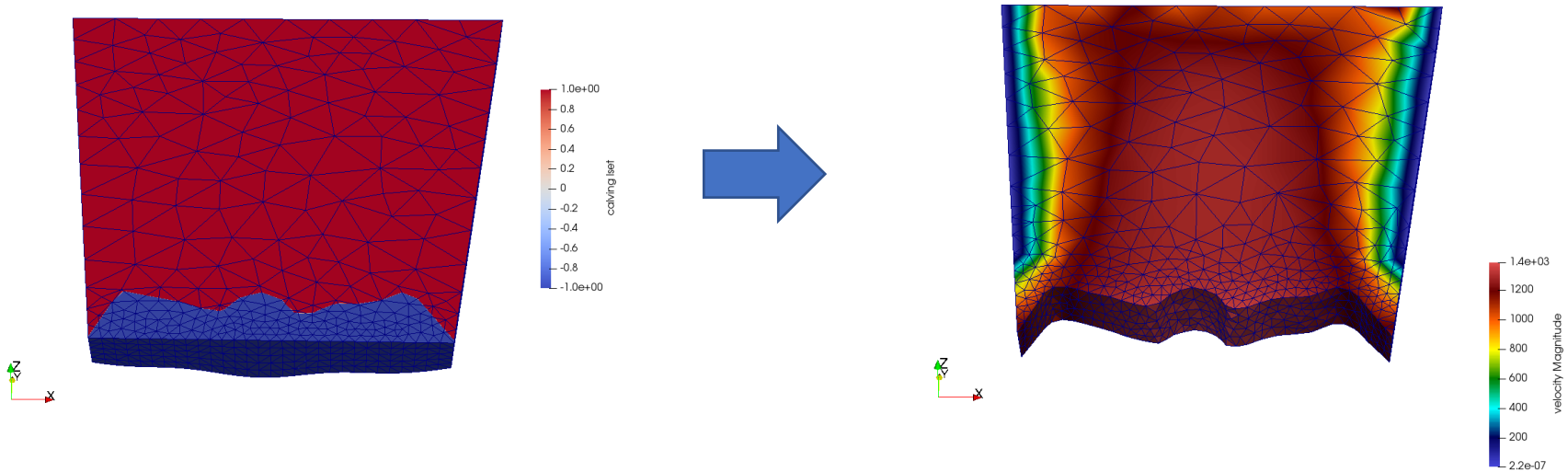
Validated crevasses without lateral margins added



Validated crevasses with lateral margins added

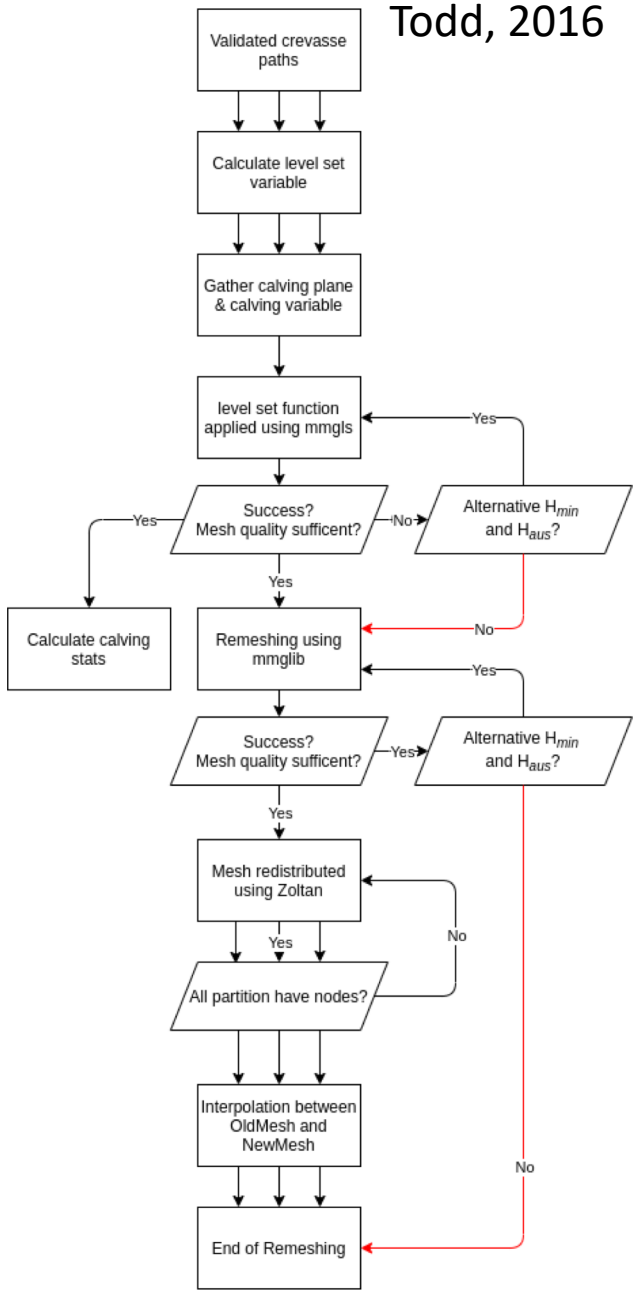
Implementation of calving and remeshing

- Remeshing in two steps



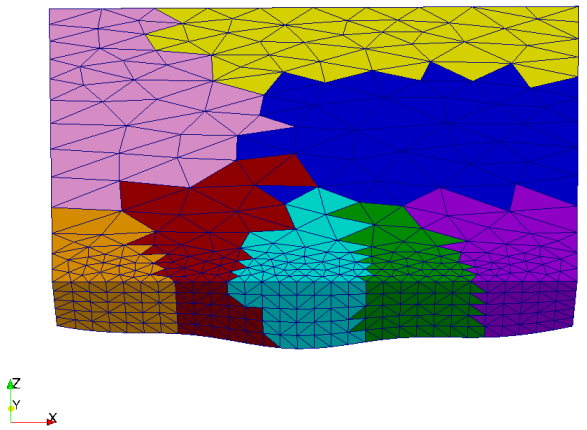
- CalvingRemeshMMG.F90

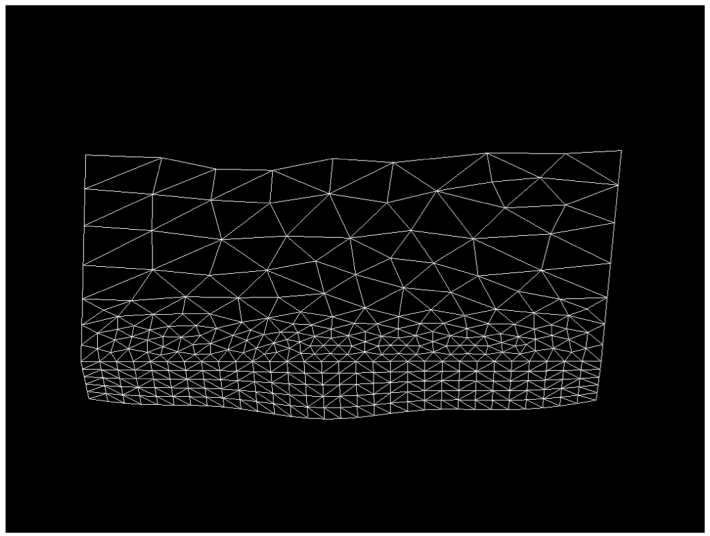
Updated from Todd, 2016



Implementation of calving and remeshing

- Gather mesh on one process for serial remeshing
- User defined calving plane





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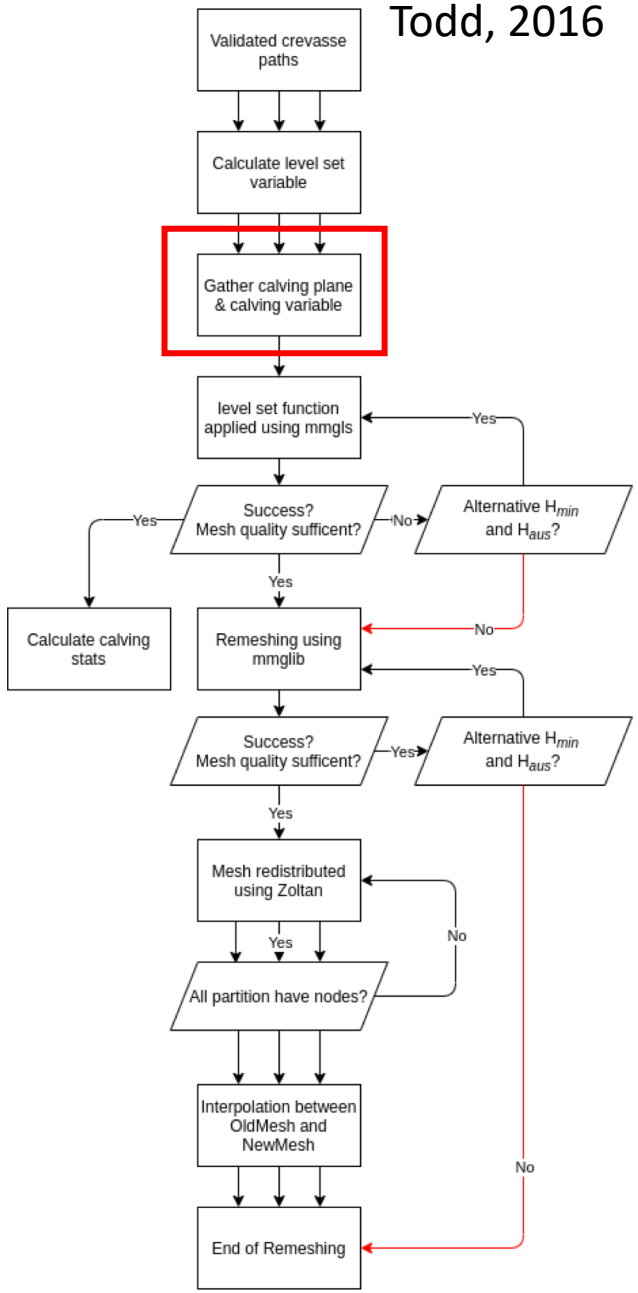
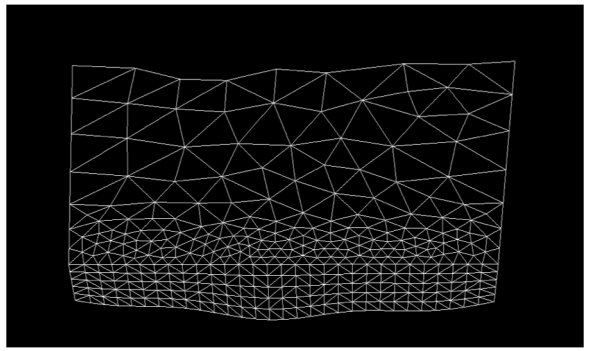
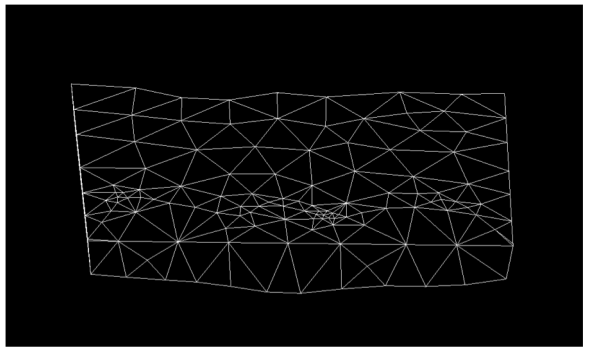


Implementation of calving and remeshing

- Level set variable given as solution file
- Split mesh using mmg3dls (serial)
  - Isotrophic
- Mmg libaries sometimes fail...
  - Multiple options of Hmin and Haus can be provided





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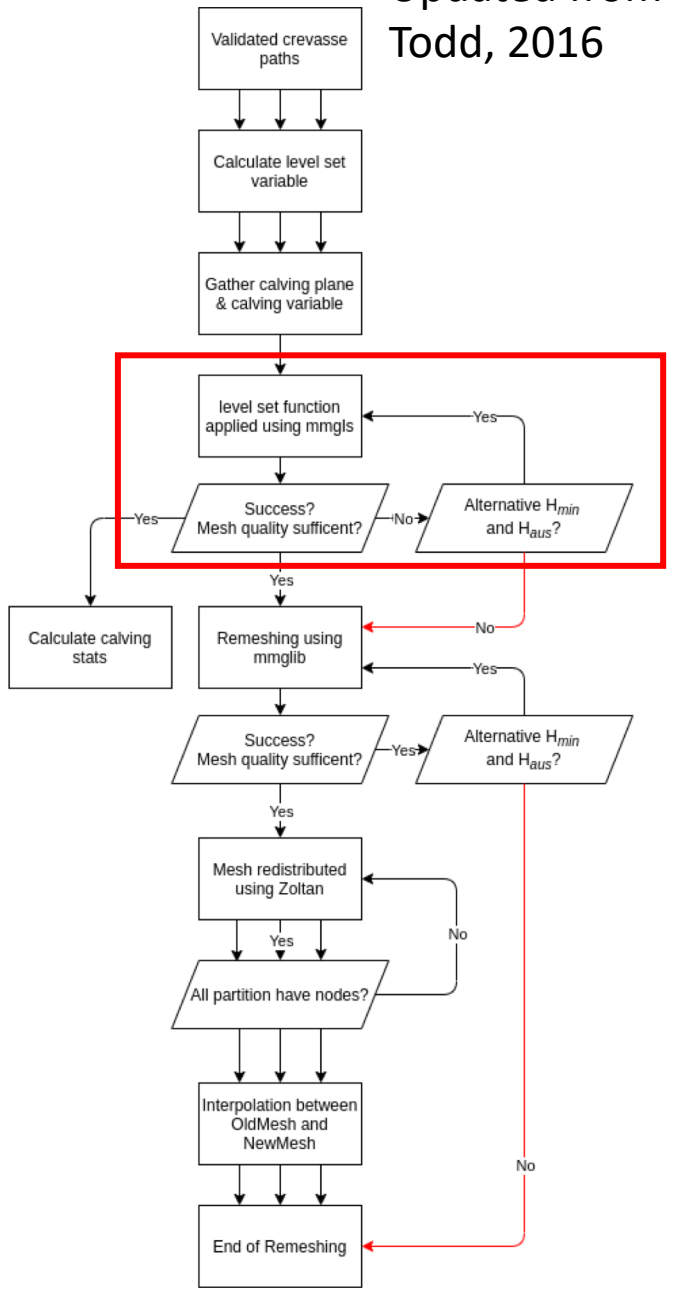
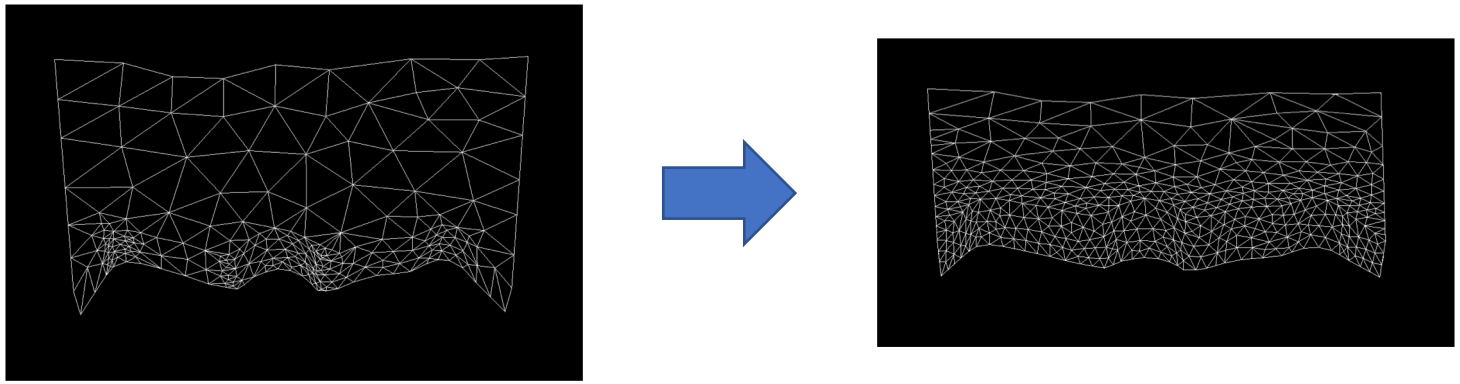


Implementation of calving and remeshing

- Remeshing using mmg3dlib (serial)
  - Anisotrophic based on solution using USF_GlacierMeshMetric.F90
- Mmg libaries sometimes fail...
  - Multiple options of Hmin and Haus can be provided



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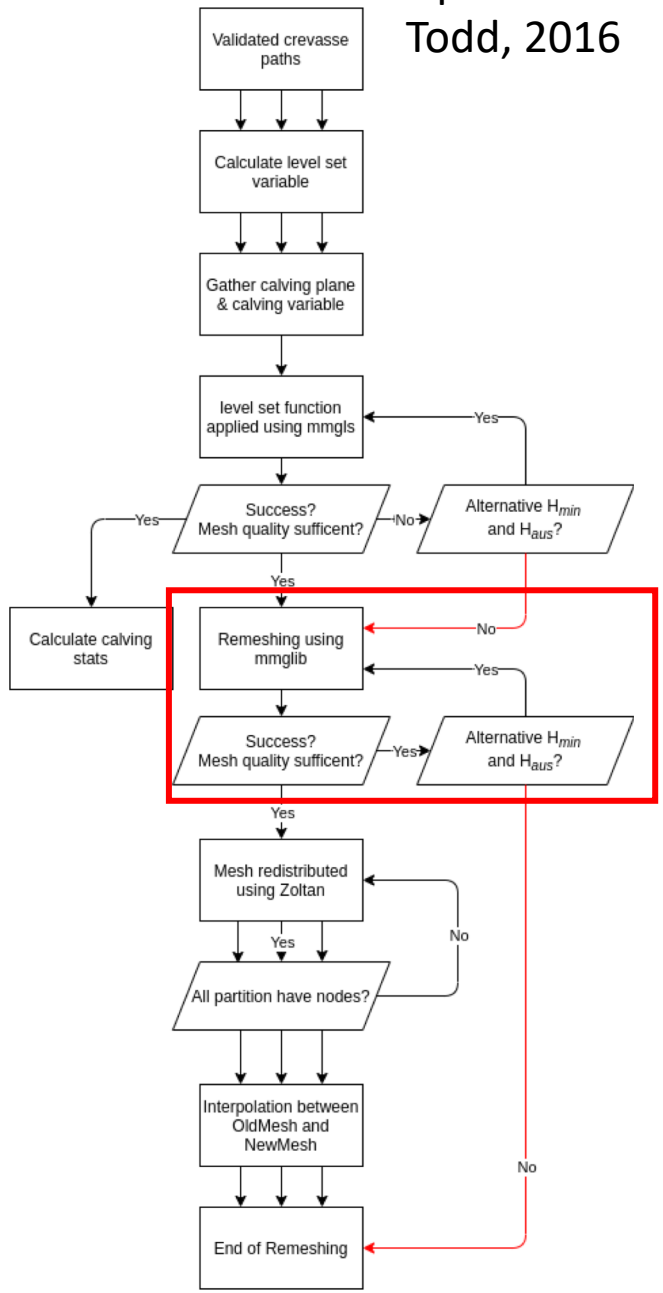
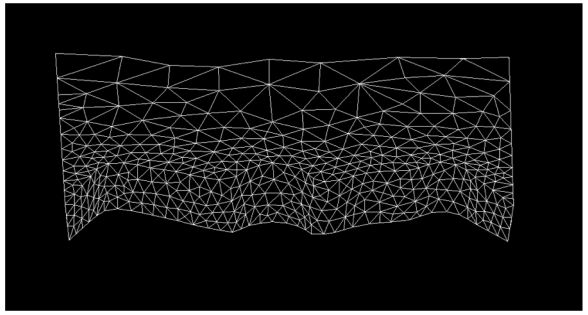
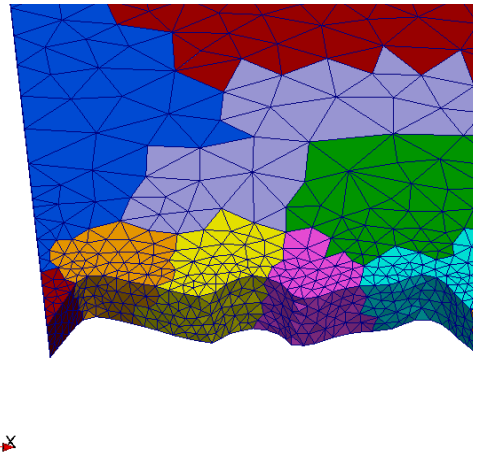


Implementation of calving and remeshing

- Rebalancing using Zoltan
- When massively parallel sometimes parts have zero elements
  - Retry with lower imbalance tolerance





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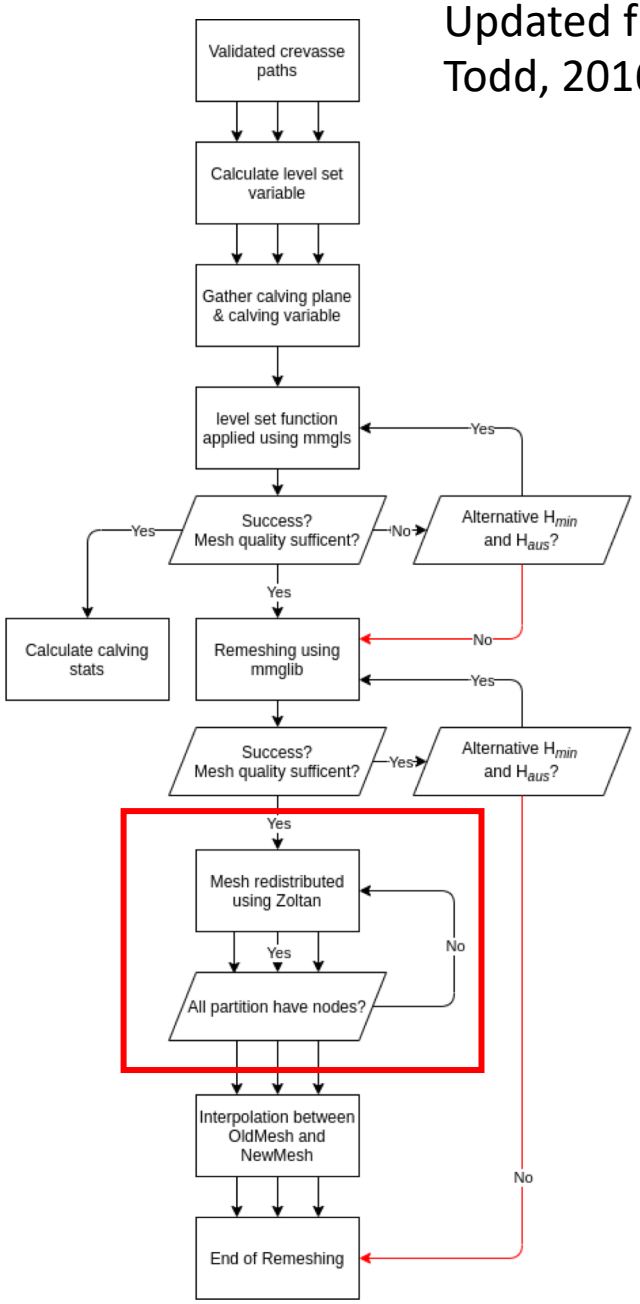
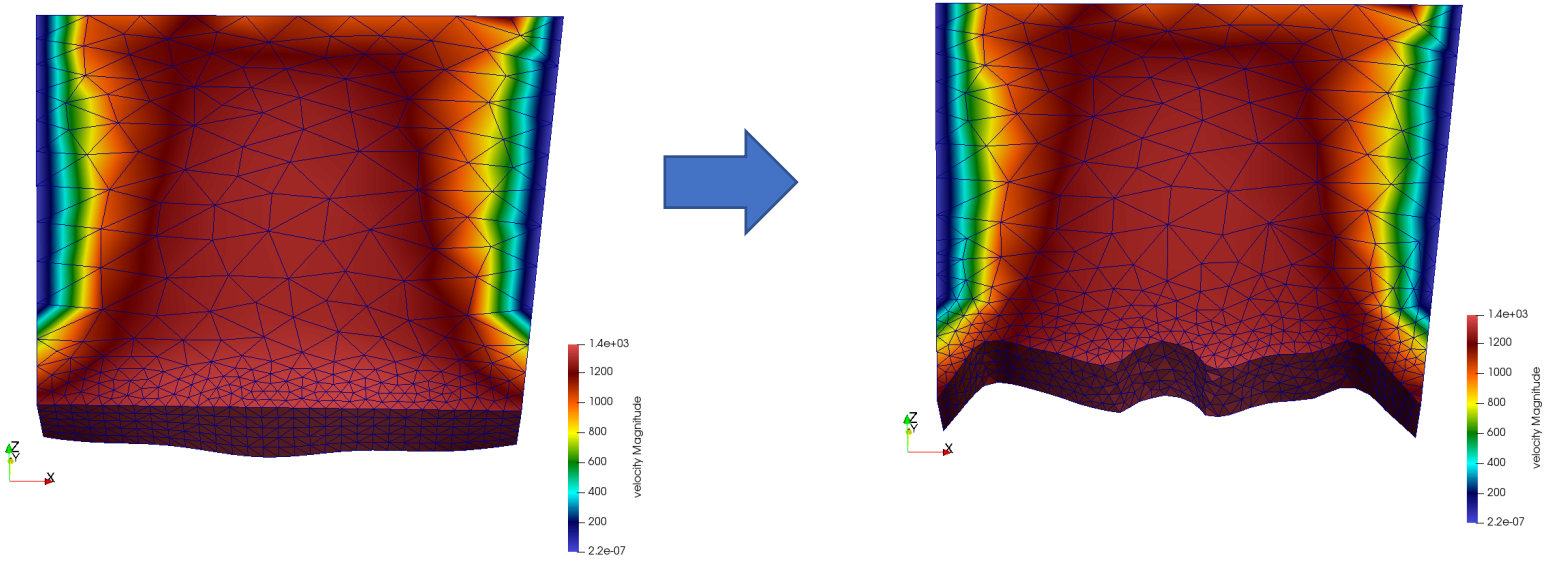


Interpolation to new mesh

- Numerous bugs fixed
- Variables no longer projected onto calving front
- Unfound variables beyond old mesh domain extrapolated



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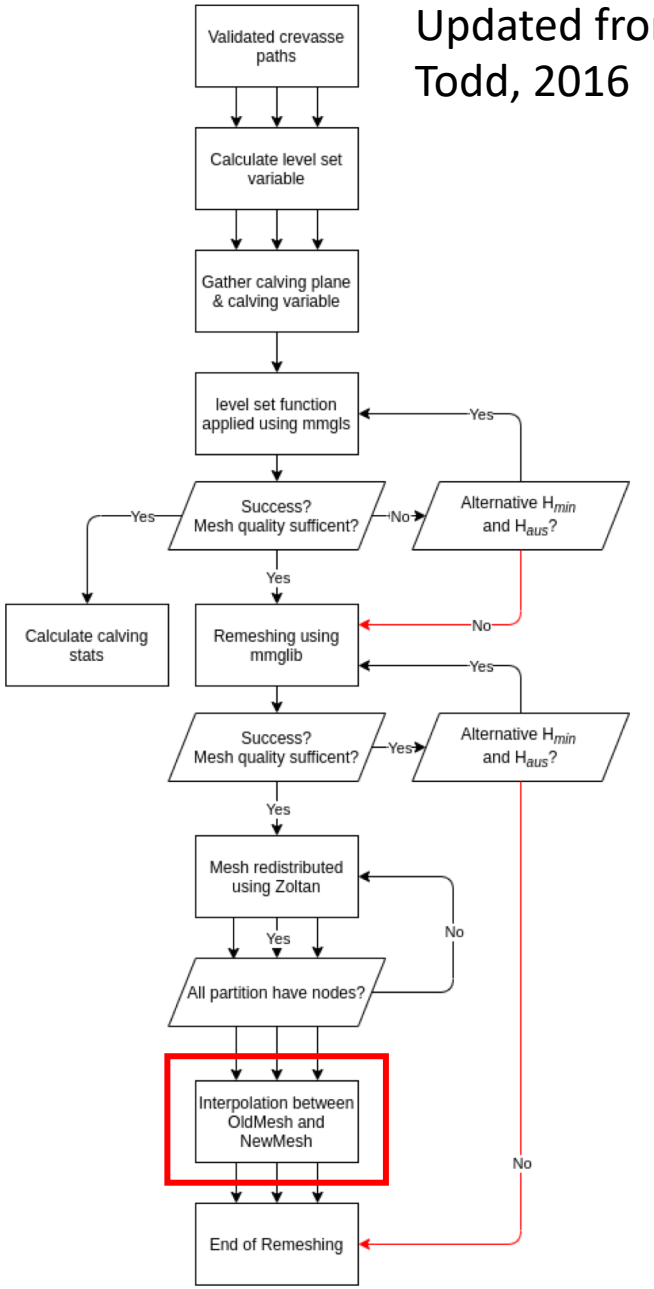
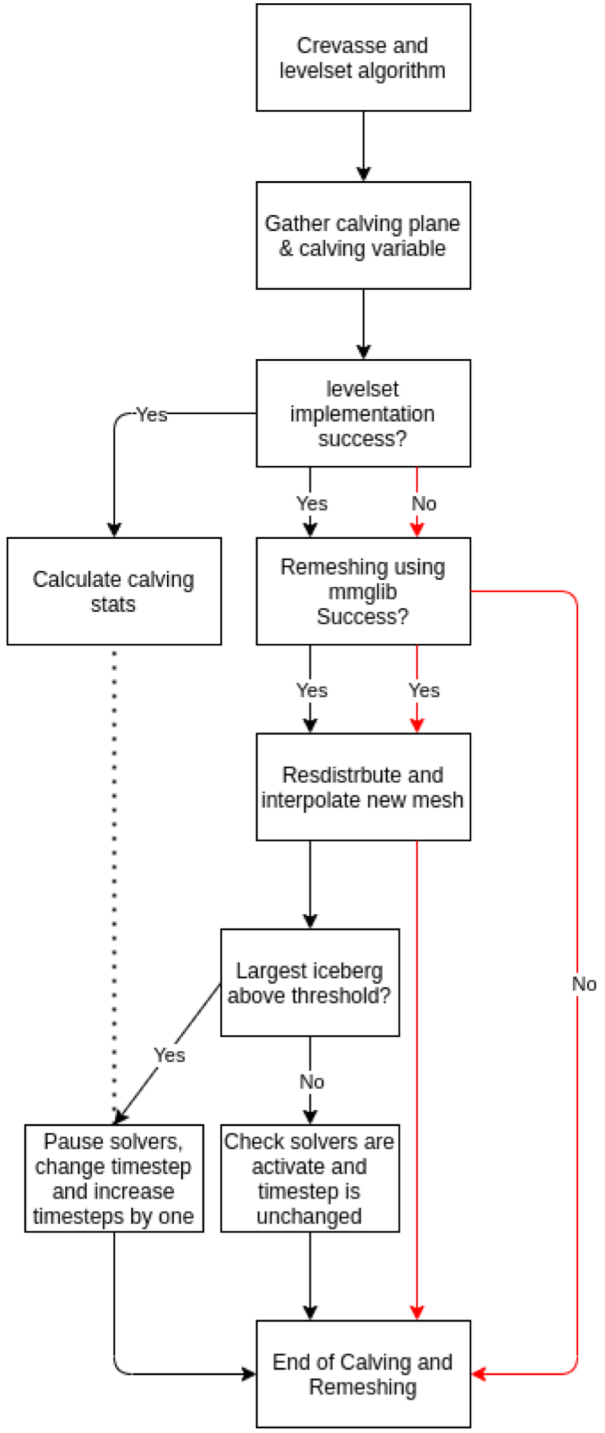


Calving overview

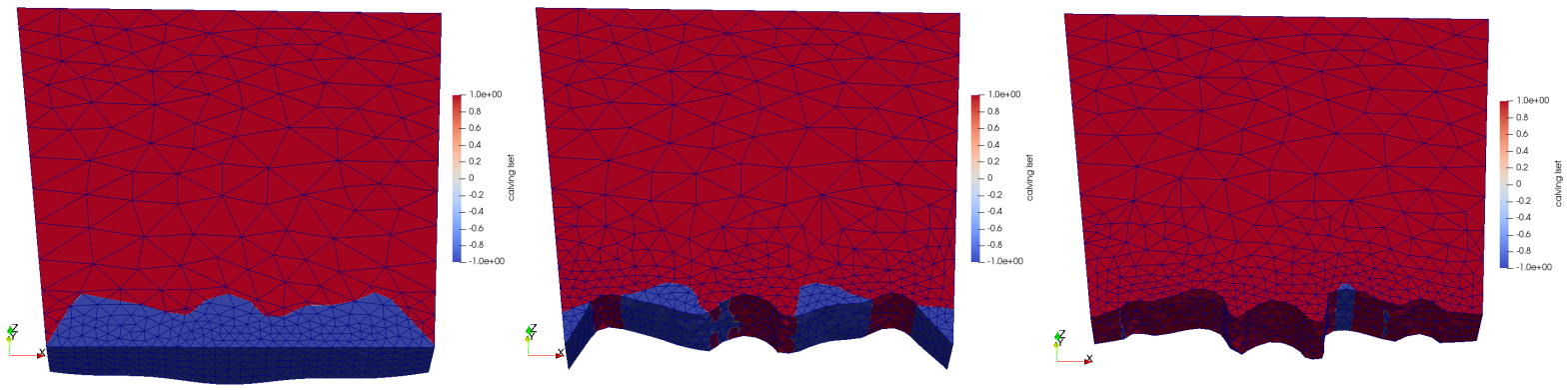
- When is calving prevented?
  - Level set implementation fails
  - Remeshing fails
- Either Mmg break or mesh fails quality test
- Adaptive time stepping
- Calving stats output determines if solvers are paused

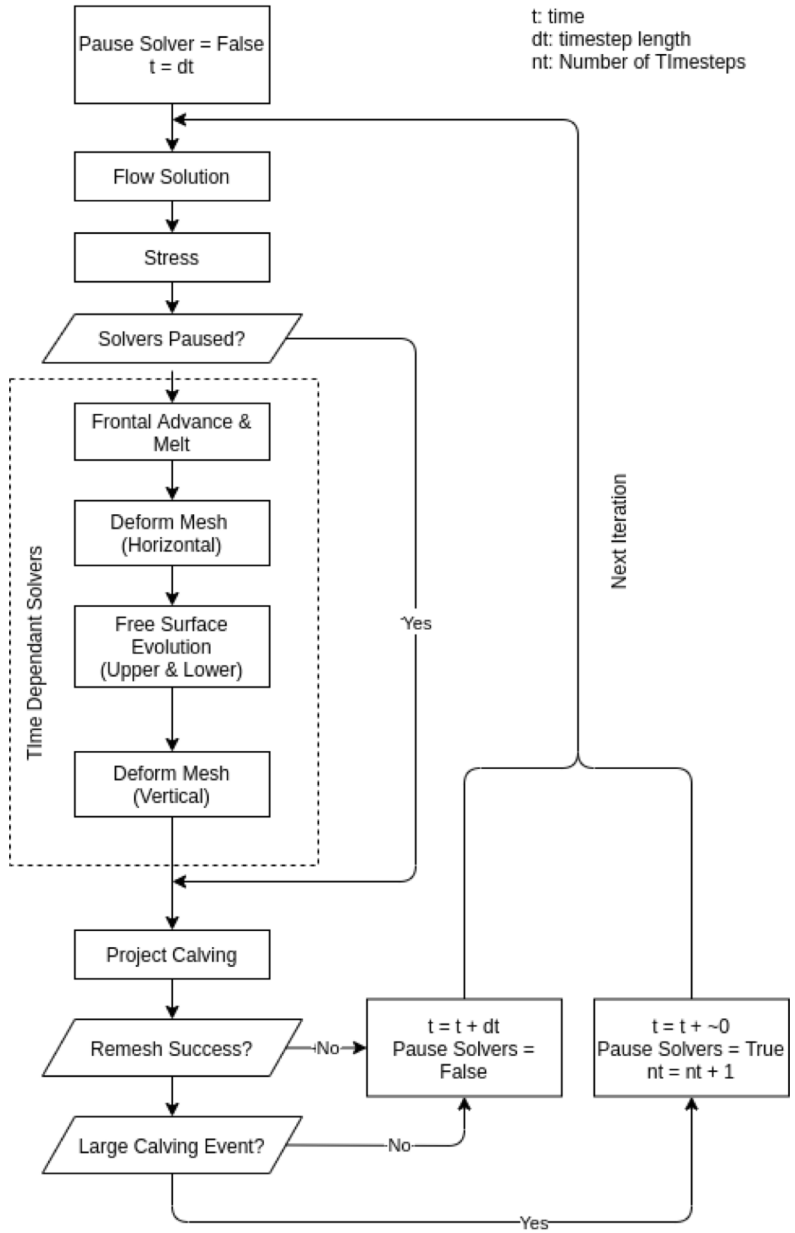


Updated from Todd, 2016

Typical simulation

- Option to pause solvers
- ElmerSolver.F90 modified to add extra timesteps
- Really Stokes should be solved twice

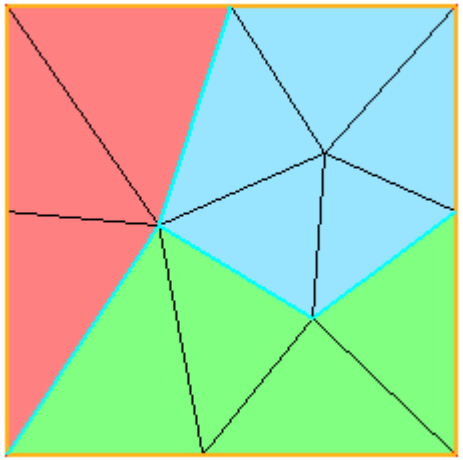


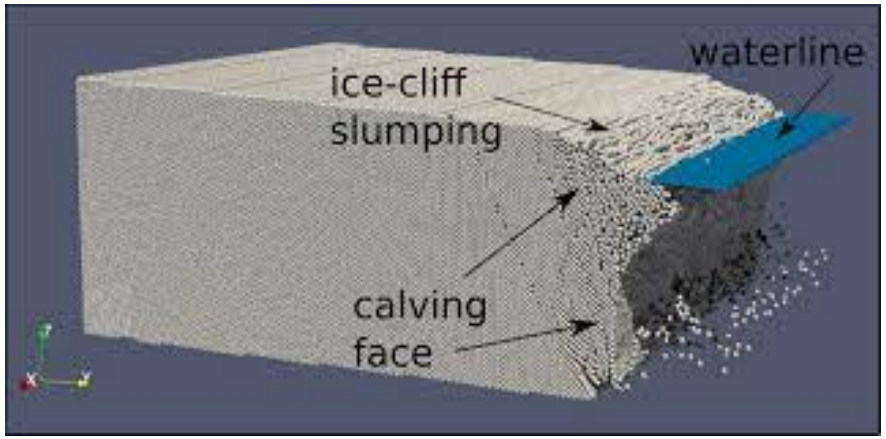


Updated from Todd, 2016

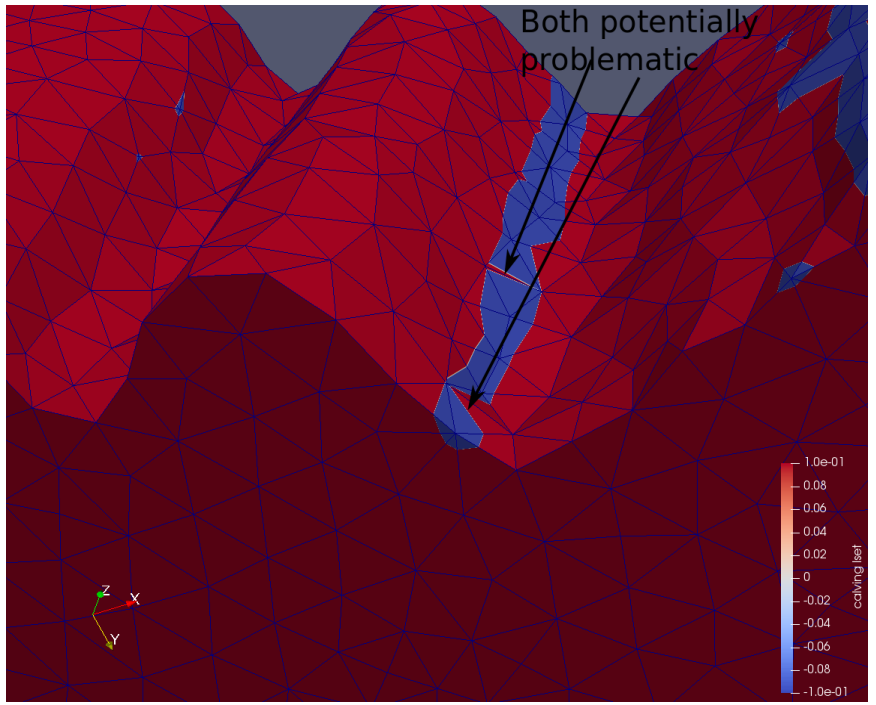
Future developments

- ParMmg – remeshing currently available
  - Level set discretization in the works
- Ice cliff failure
- Clean up level set to improve remeshing



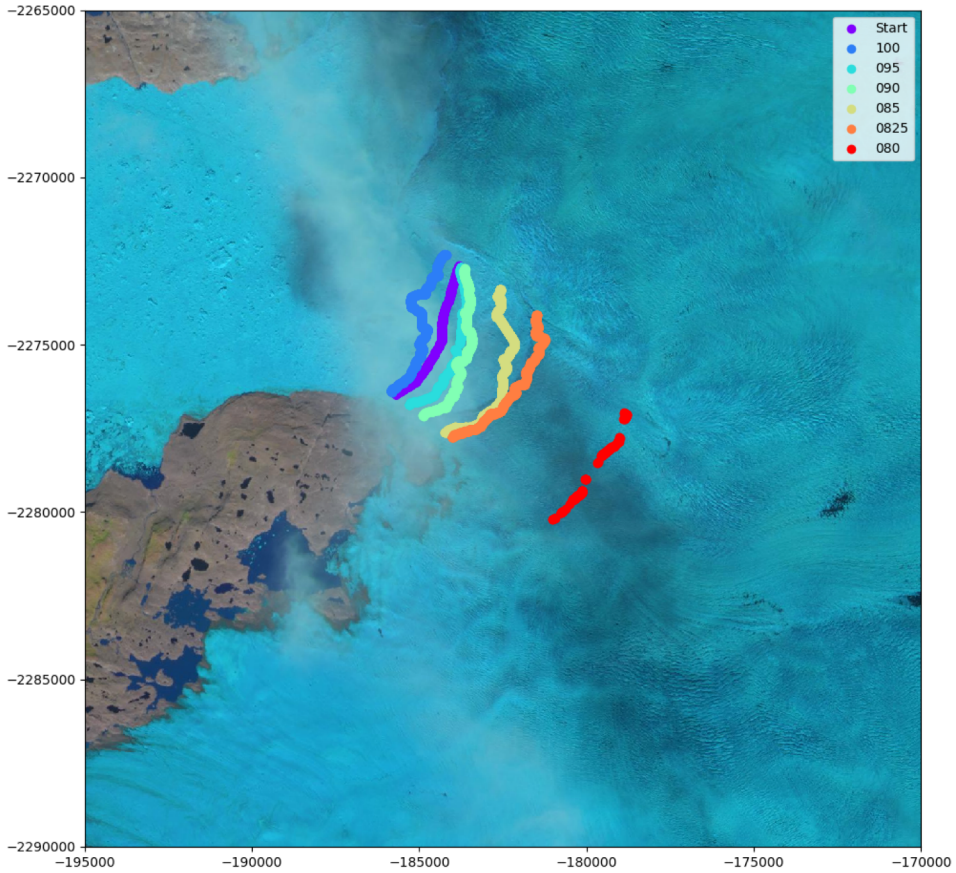


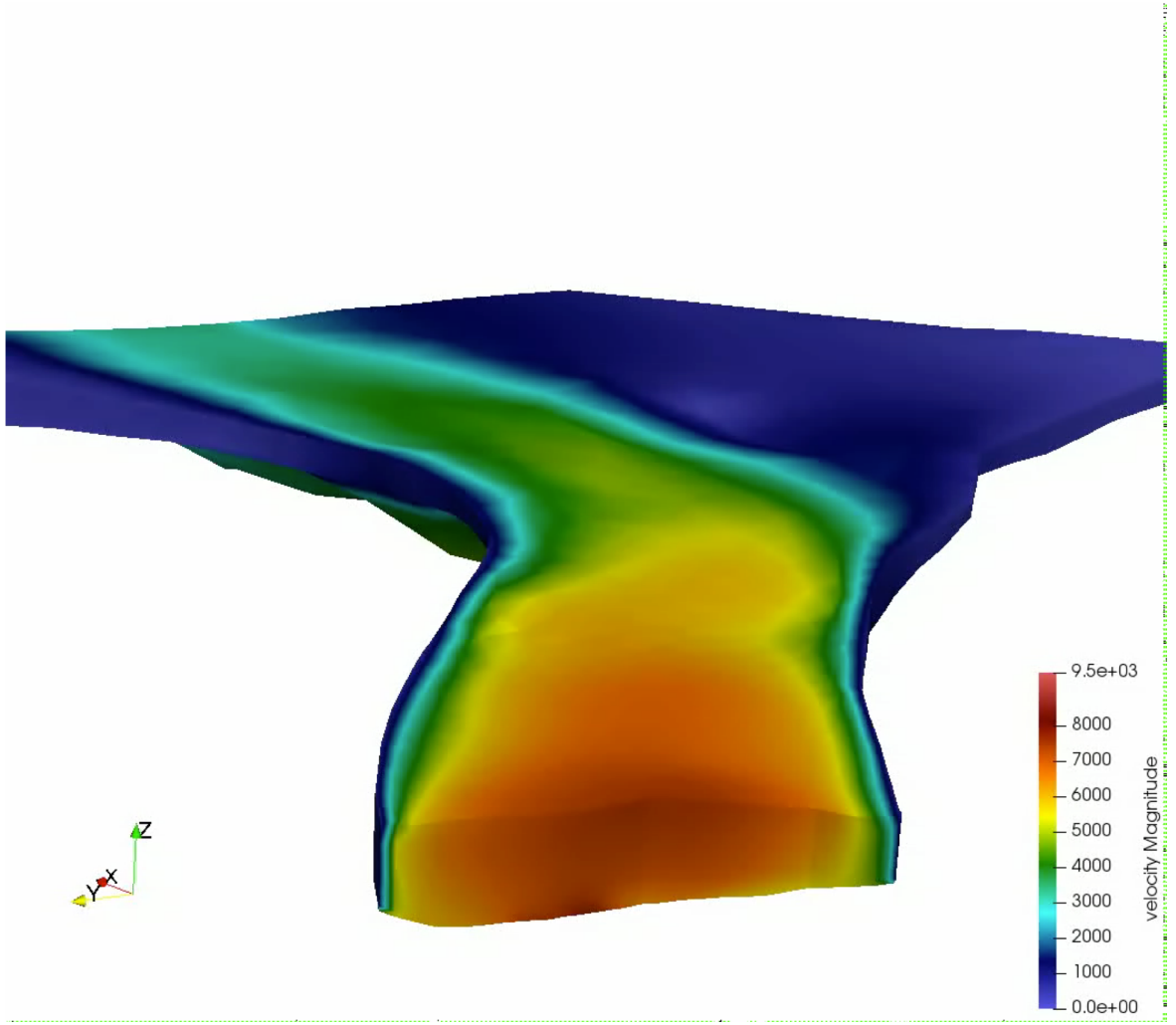
Crawford, 2021



Application at Jakobshavn…

- Summer 2017 altering crevasse depth required to calve





References

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Todd, J, Christoffersen, P, Zwinger, T, et al. 2018, 'A Full-Stokes 3-D Calving Model Applied to a Large Greenlandic Glacier, *Journal of Geophysical Research: Earth Surface*, 123, 410-432

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Crawford, A, Benn, D, Todd, J et al. 2021, 'Marine ice-cliff instability modeling shows mixed-mode ice-cliff failure and yields calving rate parameterization', *Nature Communications*, 12, 2701