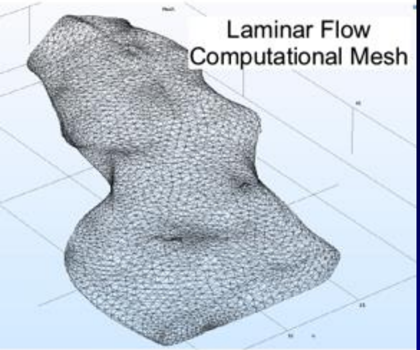
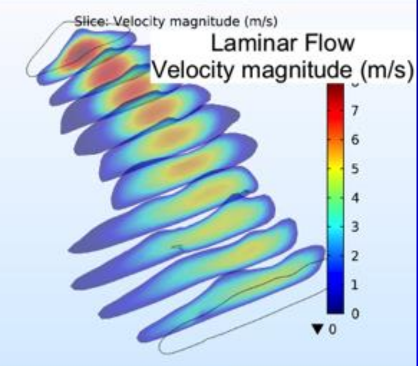
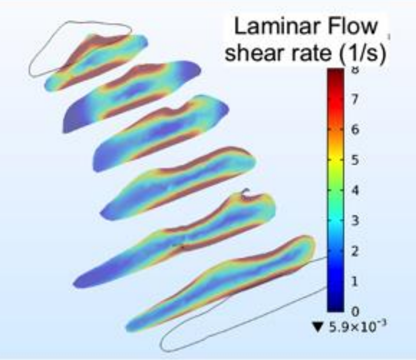






Reanimation of a Lava Tube Using LIDAR Cave Scan Data and COMSOL Multiphysics

Susan E. H. Sakimoto

Department of Geology, University at Buffalo, USA and

Space Science Institute, Boulder, Colorado, USA

With thanks to the NASA Goddard Instrument Field Team for LIDAR data and discussions, especially P. Whelley, K. Young

Motivation

- Lava tubes are a primary mode of lava emplacement in non-explosive volcano eruptions
  - *Most prior models are simple laminar sheet flow analytic solutions and yield poor estimates of flow parameters*
  - *Need better understanding of tubes in general for hazard and emplacement studies on Earth.*

- Lava tubes are also high priority exploration sites for the moon, as they are prospective habitat sites.
  - *Need models for comparing planetary and terrestrial emplacement*
  - *Need to model structural integrity*

Objectives

- Improved general model for lava tube flow
- Specific model for particular terrestrial lava tube

Approach

- COMSOL model of lava flow in elliptical cross-sections for general approximations
- COMSOL model of flow from LIDAR cave scan data to assess accuracy of general approximation

Wait, what?

- We are going to use COMSOL to model lava flow through the LIDAR data defined cave system.

- Because we can.

Note:
Topography Scales and Lava Flow

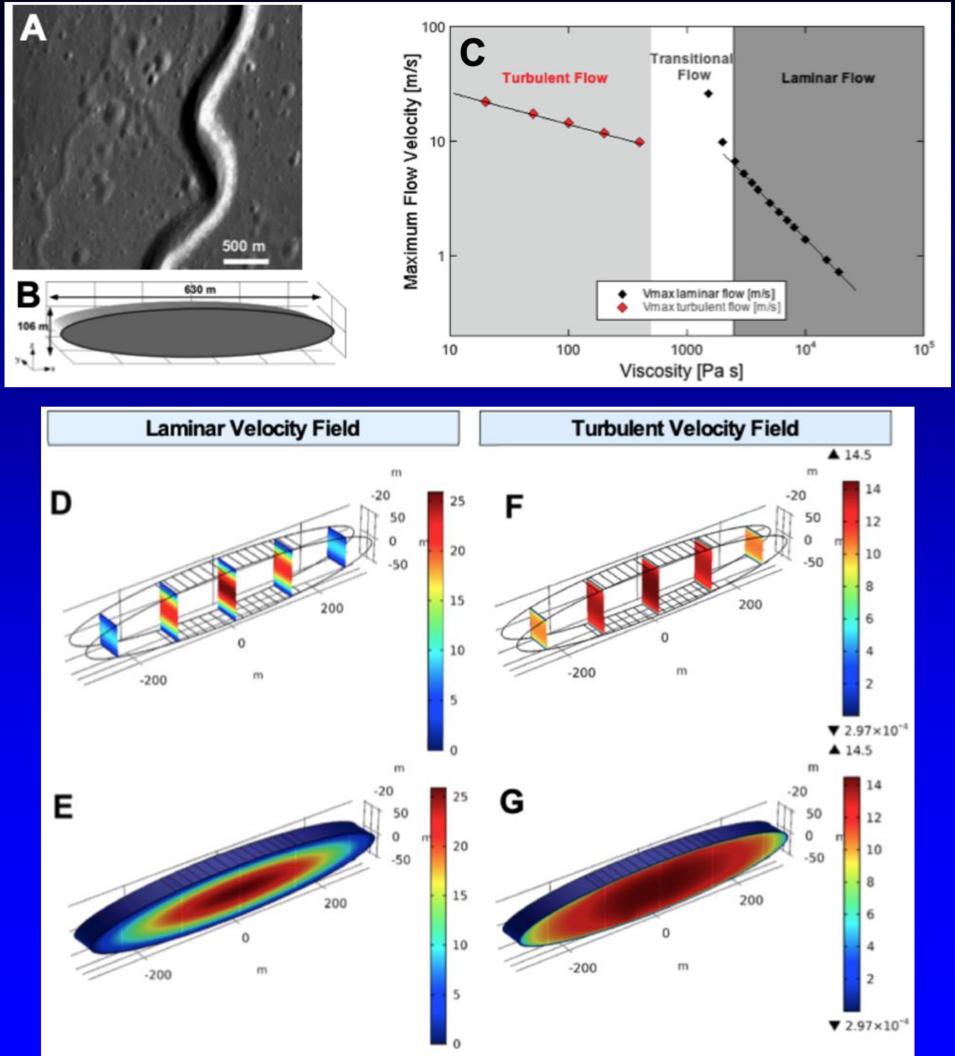
- At a large topographic scale (1 km), the underlying slope is the flow driving force.

- At mid topographic scales (tens of m), tube dimensions control velocity distributions.

- At smaller scales (cm to m), the tube branching, roof presence (or lack), directional changes, and dimension changes are expected to have an effect on flow parameters such as velocity and pressure and thus tube structure.

Step 1: General Model Approach for Elliptical Cross-Sections

- Model a range of lava tubes on Earth and other planets for different parameter ranges.
- Use dimensional analysis to generalize results for elliptical cross-section tubes

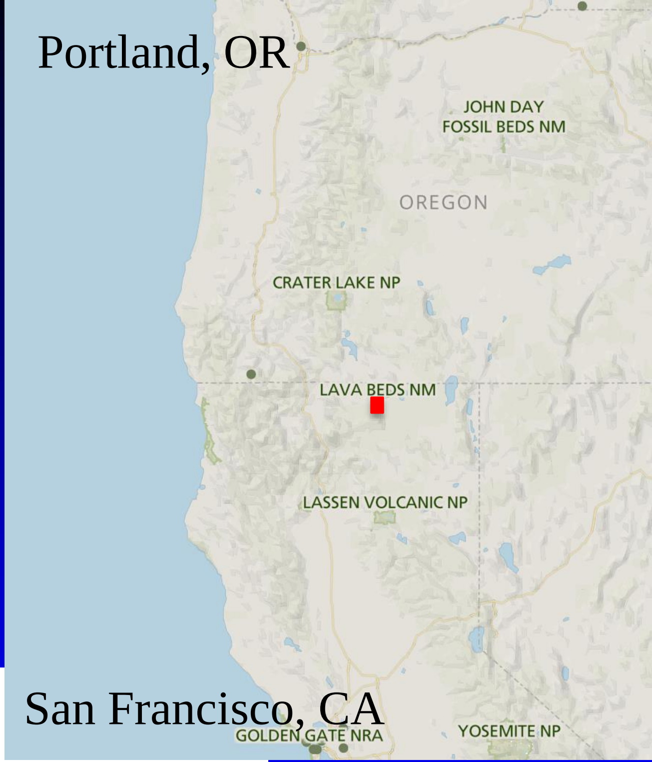


Sakimoto and Gregg, 2019, LPSC

Step 2: Approach for Specific Tube Model

- Model several lava tubes in Lava Beds National Monument where we have new NASA LIDAR scan data of several caves.

- Compare results to elliptical cross section model



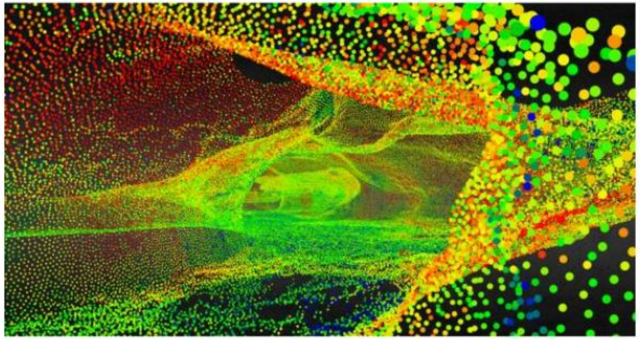


Figure 1: Snapshot of the LiDAR point cloud from inside Valentine Cave, LBNM.

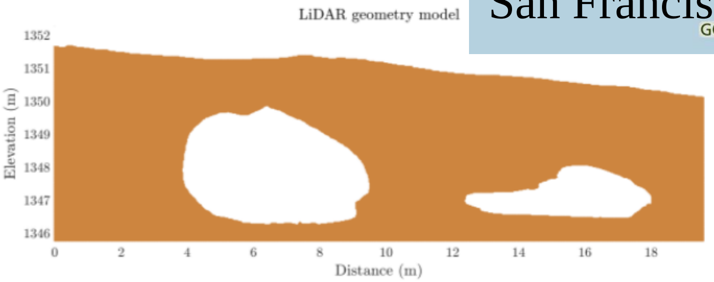


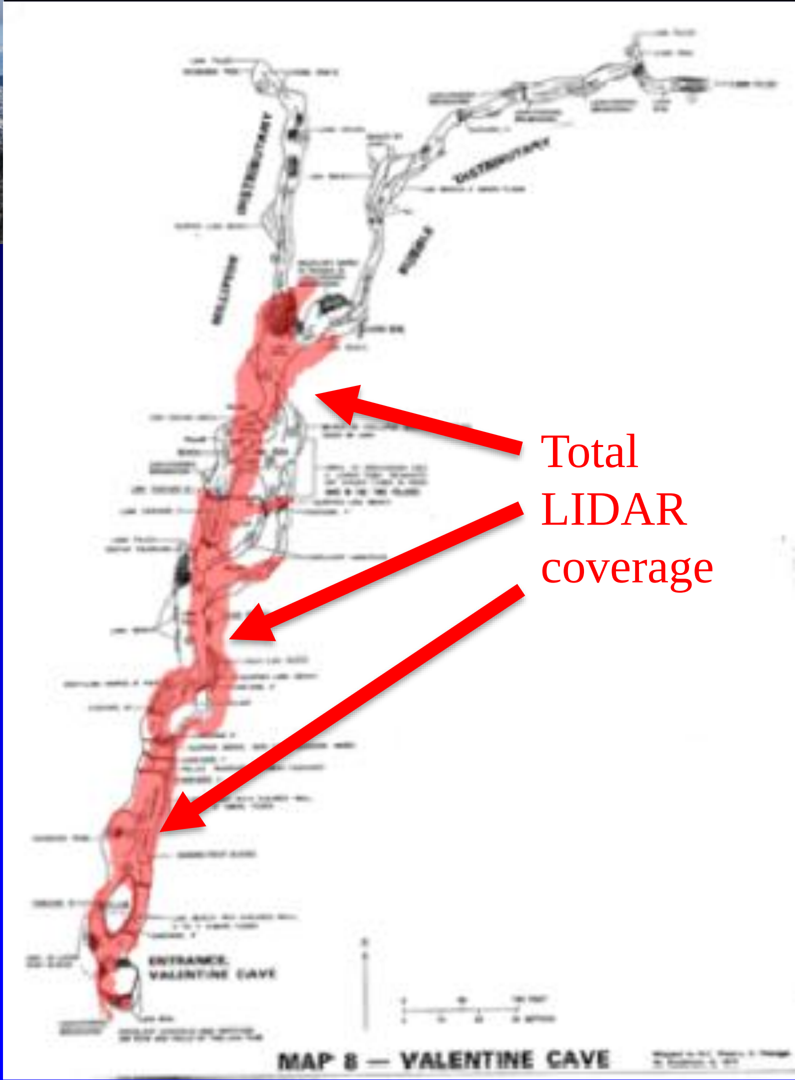
Figure 2: LiDAR geometry model across one GPR transect line at Valentine Cave, LBNM.

Whelley et al. 2018, LPSC

Valentine Cave

- One of ~>500 lava tube caves in monument
- 10,850 year old lava flow
- ~1650 foot long cave (drained part of lava tube)
- Diameters from several feet to several tens of feet
- Several roof collapses- during flow and after
- Lava “bathtub rings” left as flow receded
- Lava tube completely full for part of eruption
- Ave. Internal slope 0.004 deg., locally up to 3 deg.

… *a complex natural flow system*



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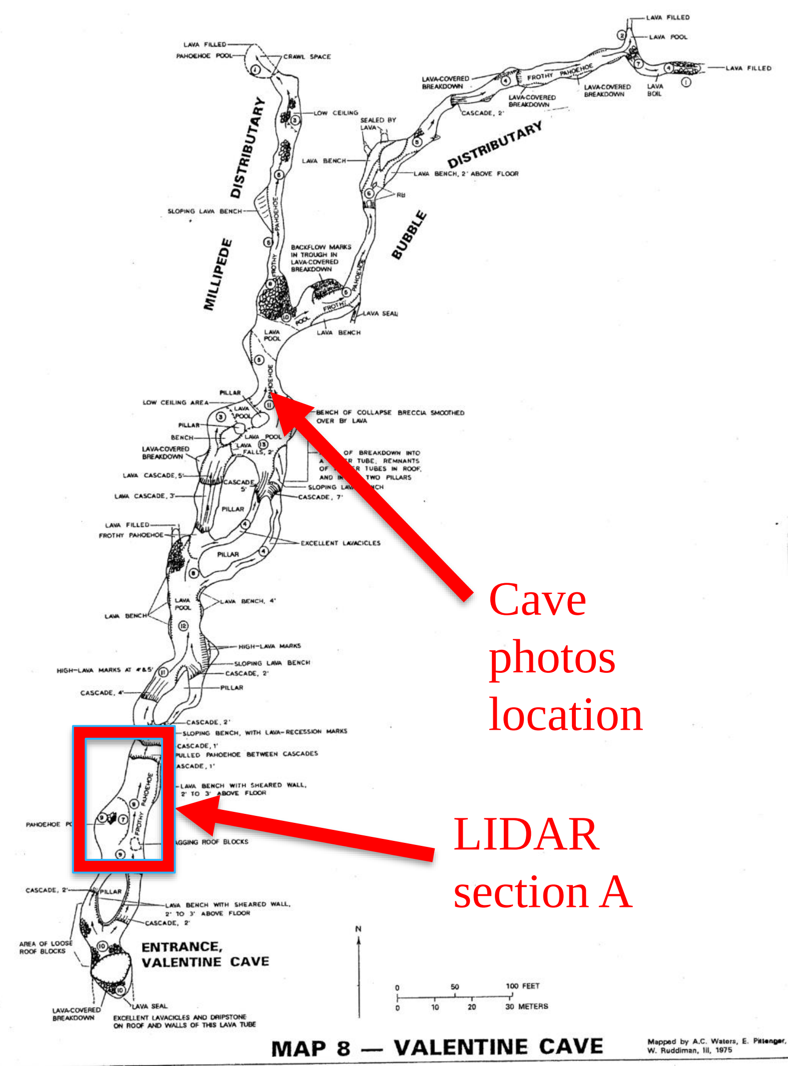
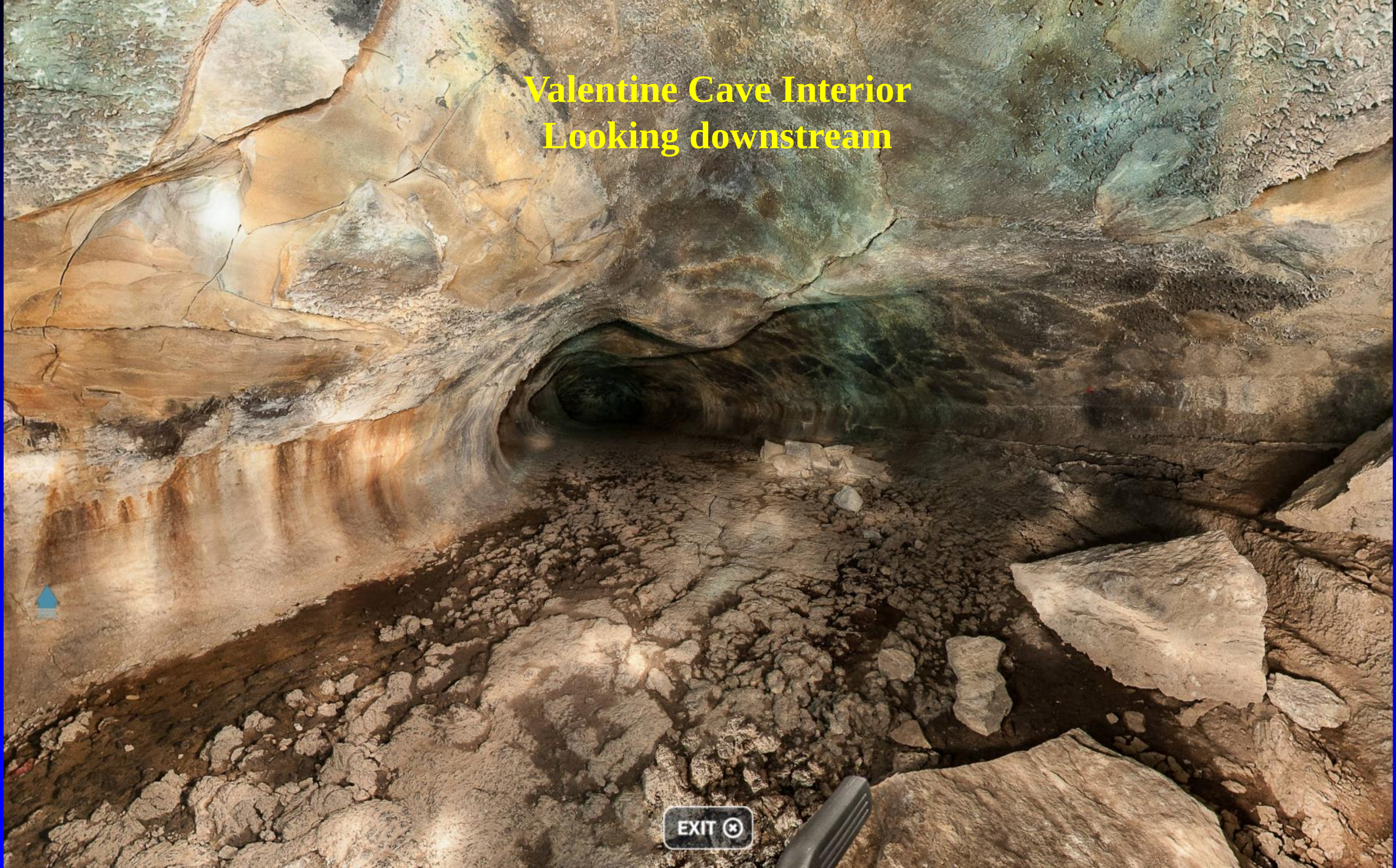


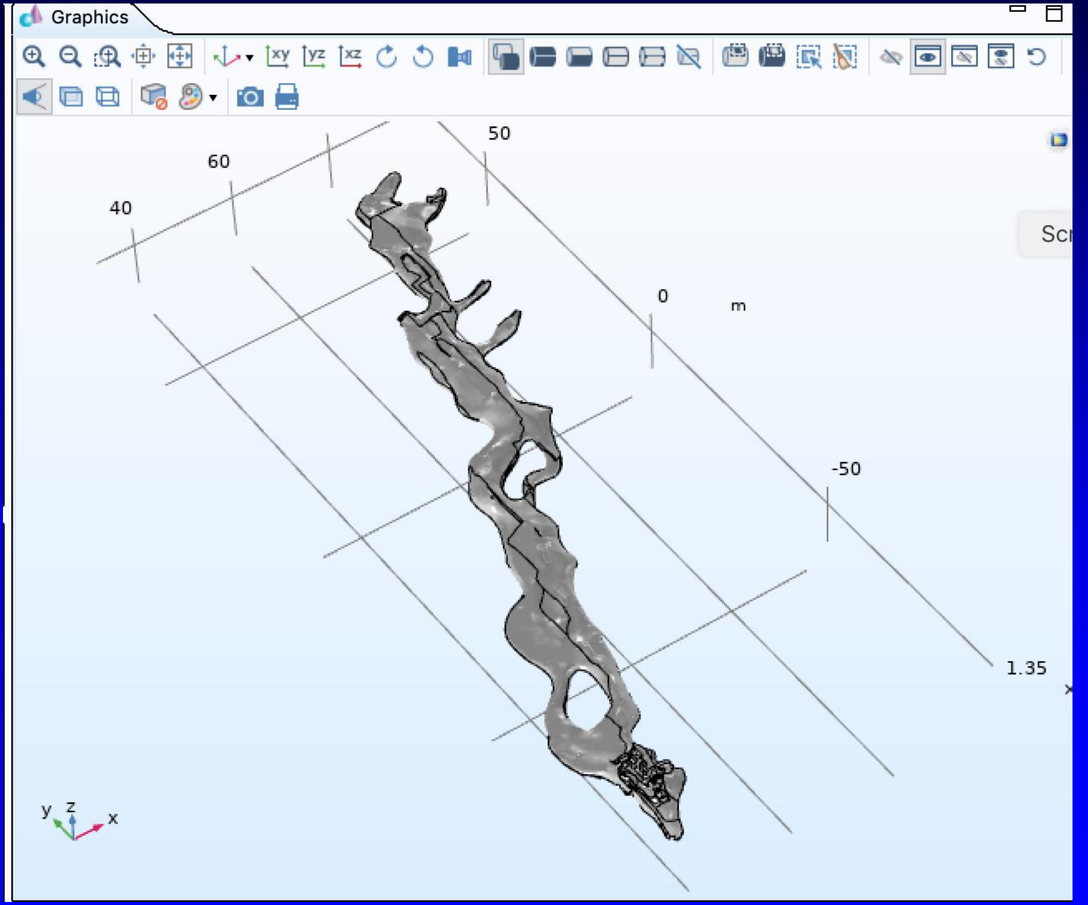

Valentine Cave Interior
Looking upstream
EXIT

Valentine Cave Interior
Looking downstream

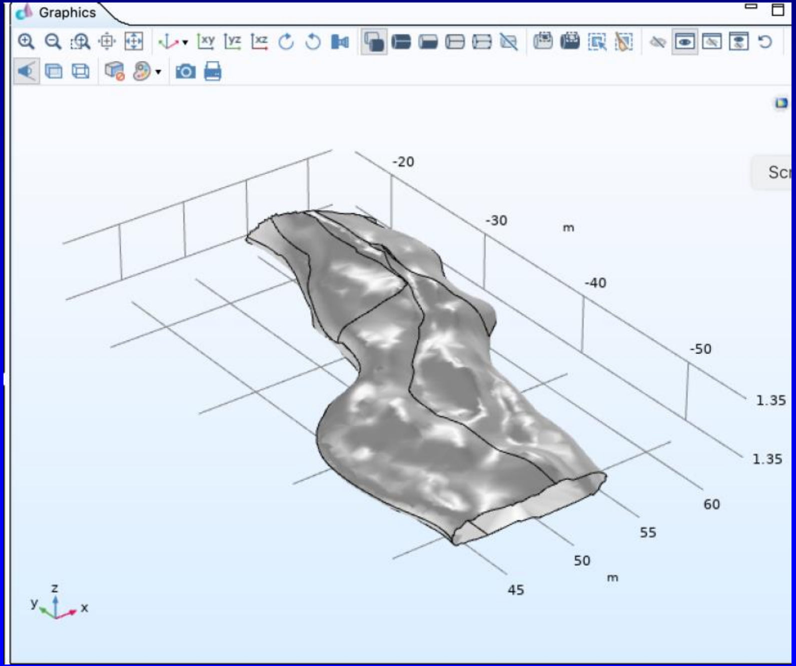


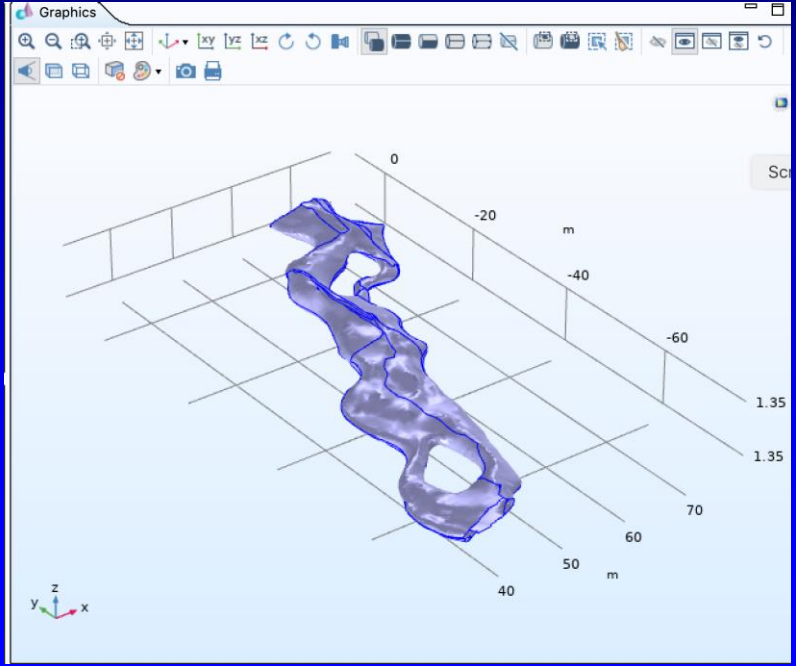
Importing the .stl file into COMSOL

- LIDAR data
- 5 mm point spacing (~750 million points per 50 m of flow)
- CloudCompare to generate .stl file
- Data cleanup proved to be time-consuming…



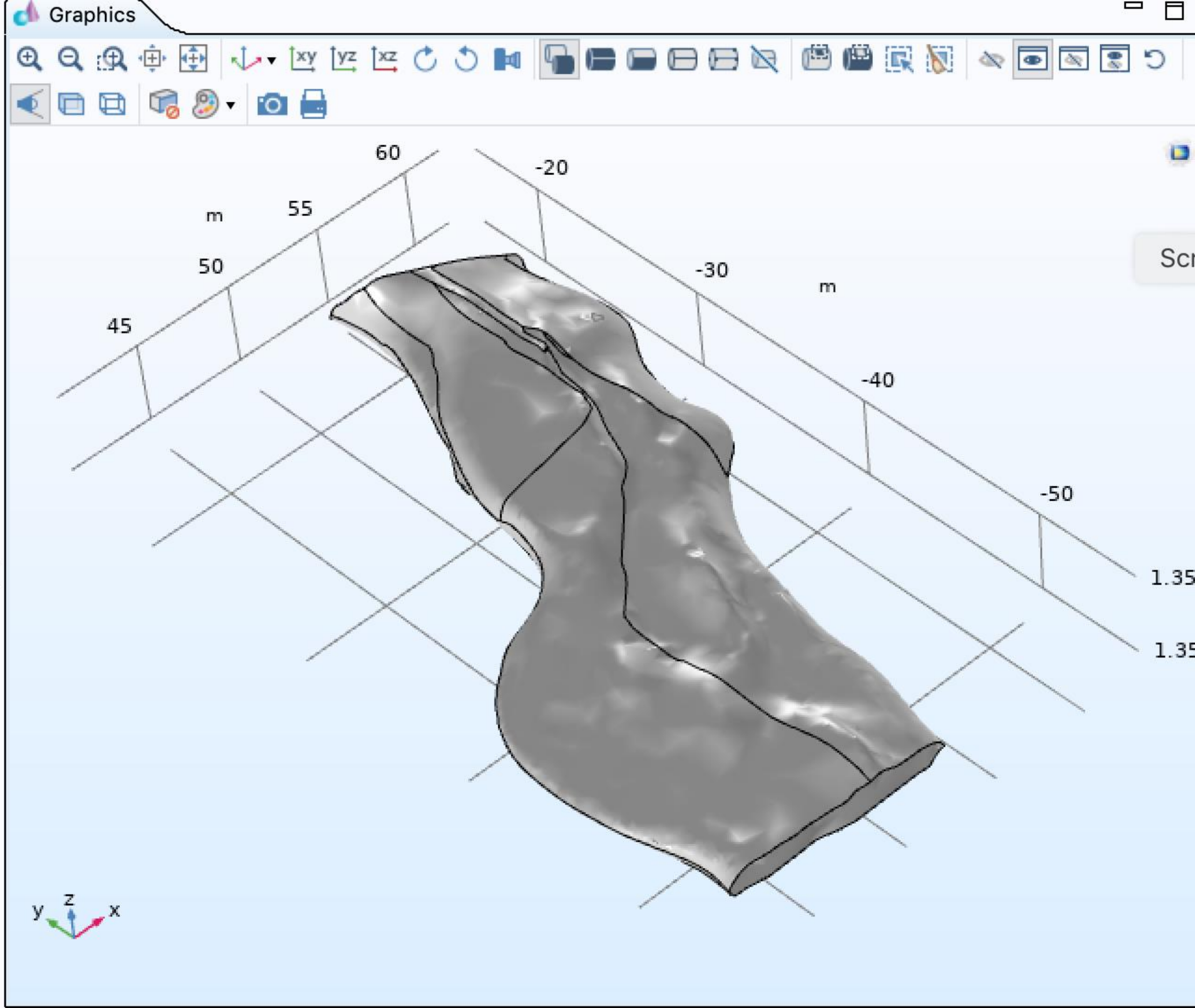
Intermediate Step:
Subsets of the original data file





Lava Tube Subset A

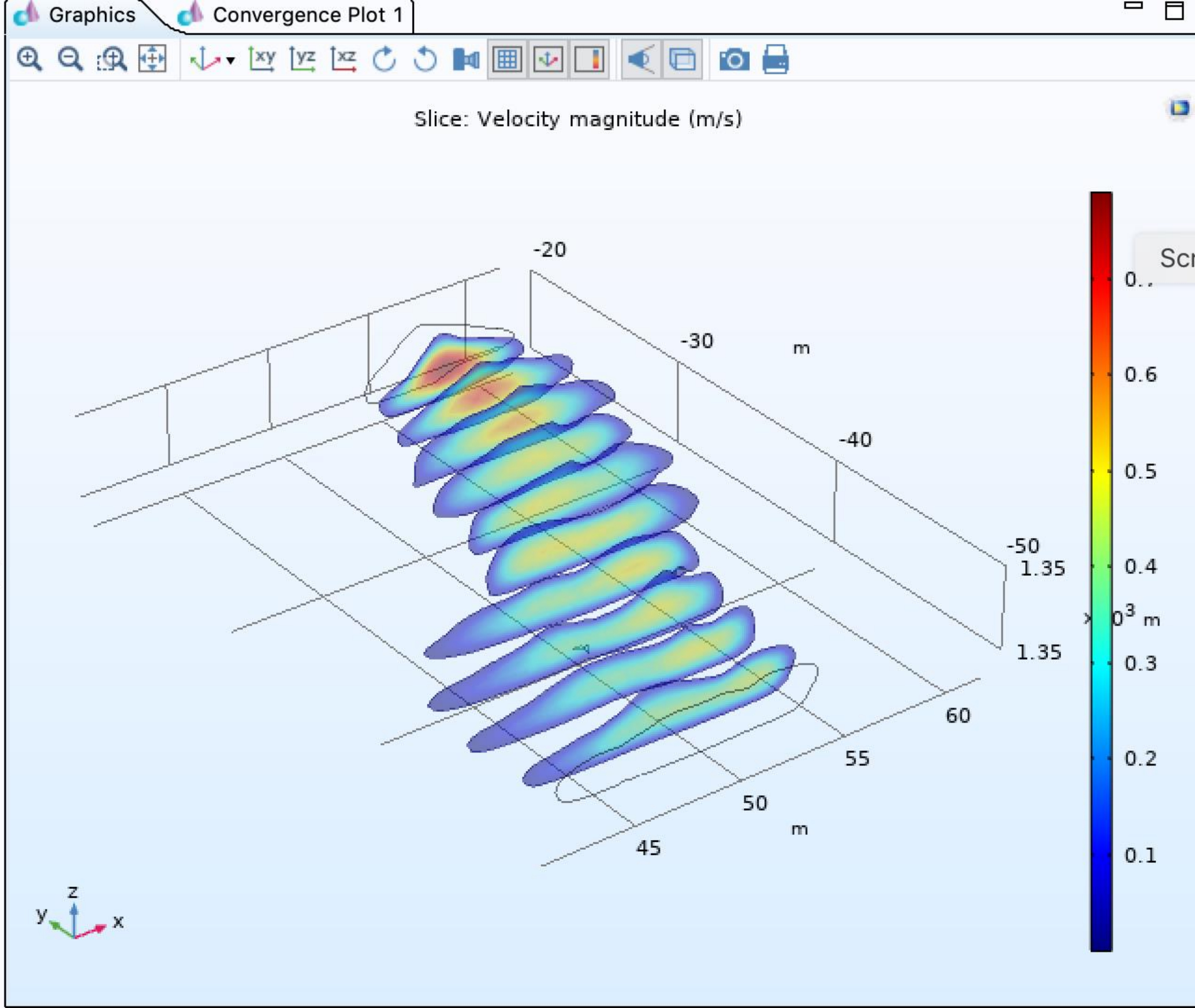
- ~35 m long section
- Capped ends
  - (Thanks COMSOL support!)
- Form solids from surface objects
- No mesh simplification
- **Minimal .stl file repairs**
- Height 2.2-3.25 m
- Average slope 2.23°



Laminar Flow Velocity Field Example

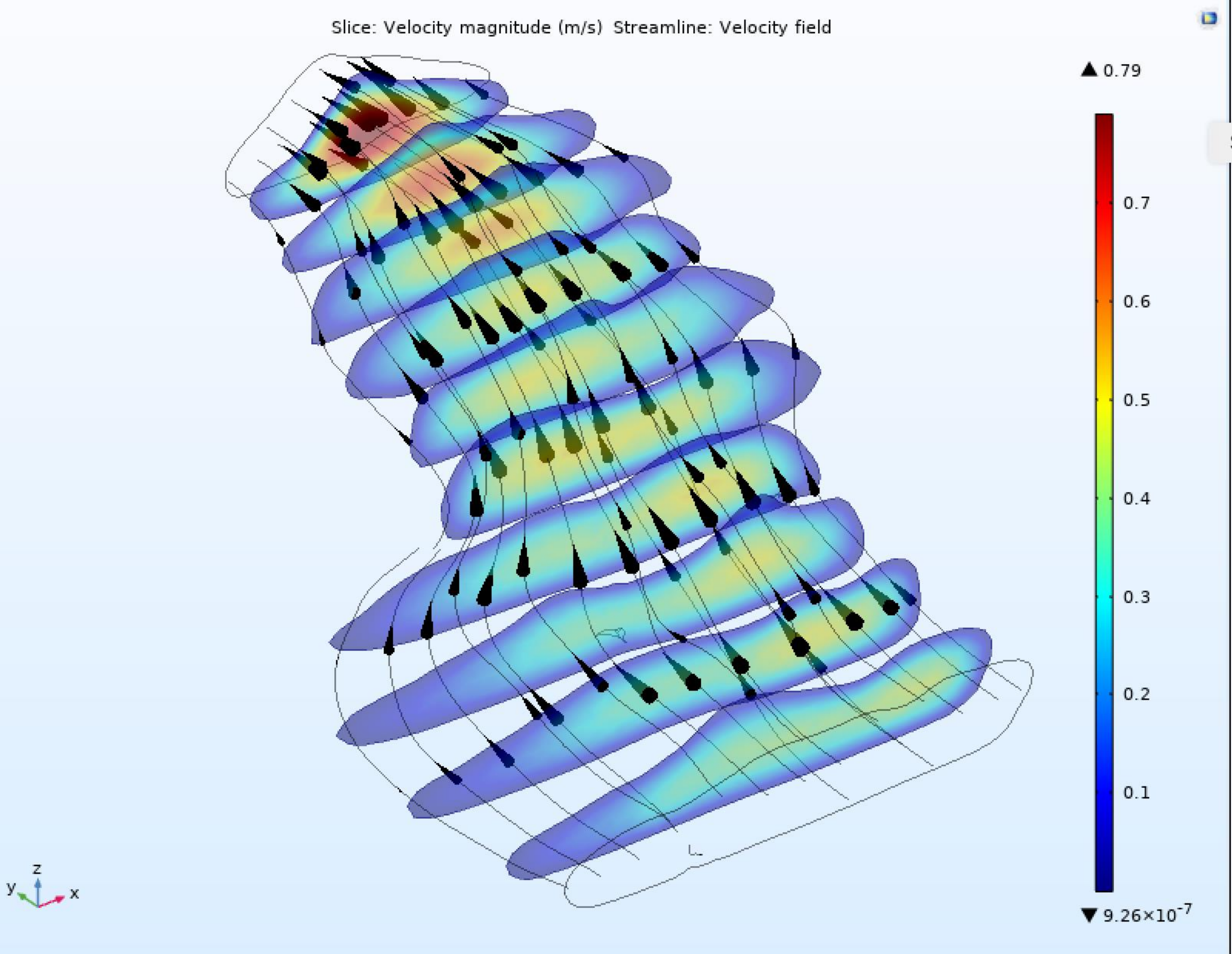
Modeled for range of viscosities

This result from viscosity =200 Pa s



Streamlines

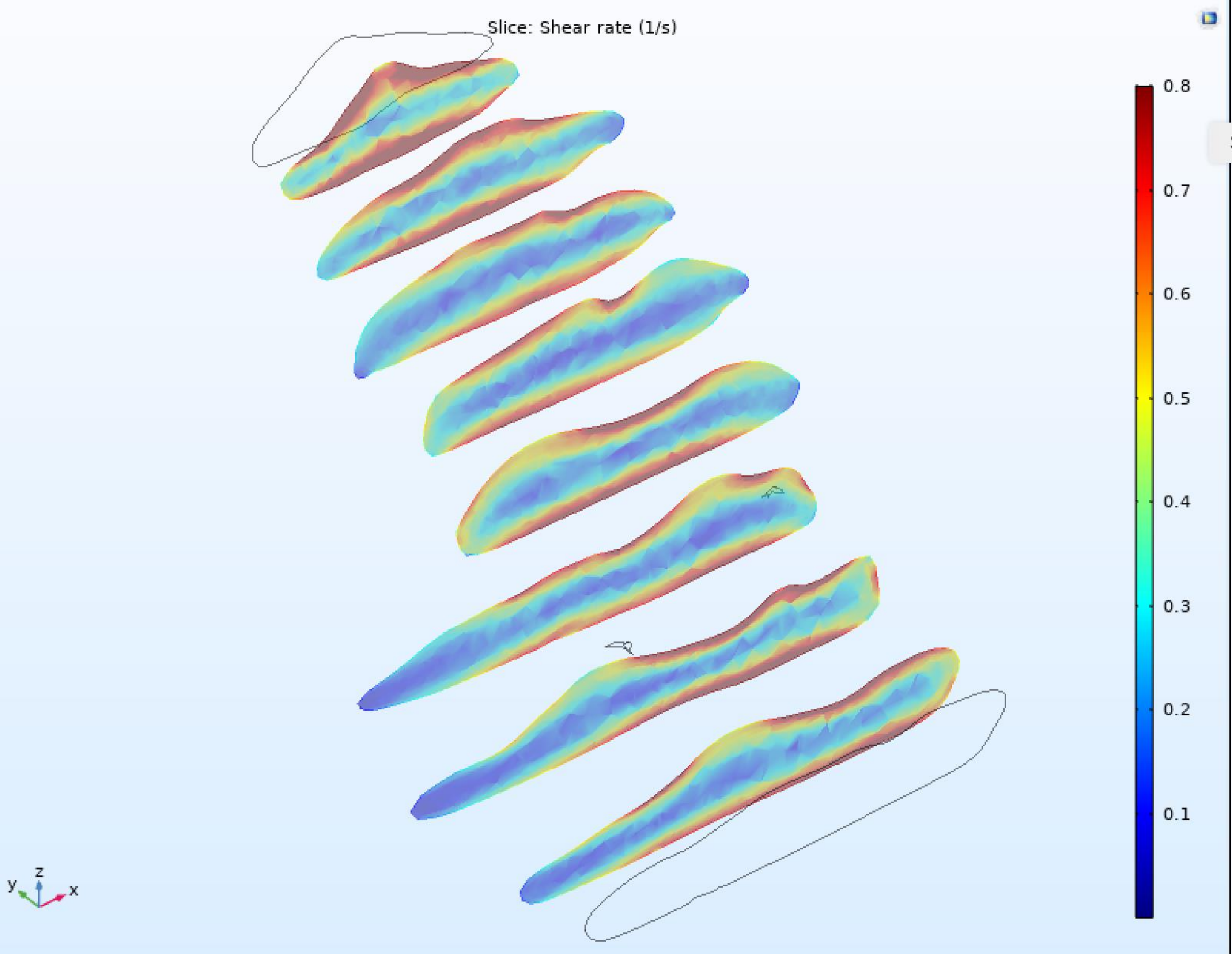
- Flow velocity maximum can be significantly off center
- Changing aspect ratio and cross section significantly changes velocity distribution and magnitude



Shear Rate

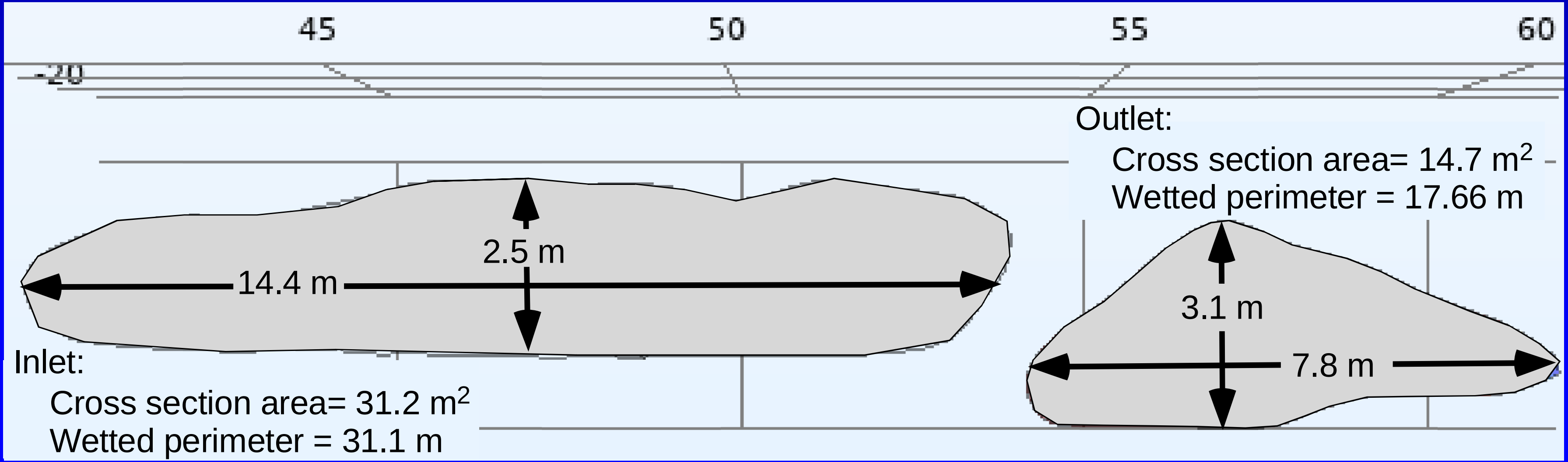
- Shear rates do not generally exceed the strength of the heated margin

- Implications for thermal versus mechanical erosion of surrounding rocks



How do we assess results ?

- Highly irregular cross section
- But can use best ellipse approximation



Valentine Cave Inlet versus Matched Ellipse Approximation

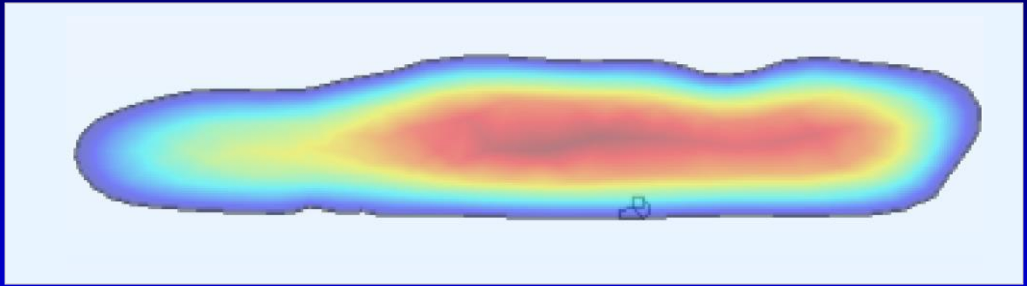
Valentine Cave Inlet

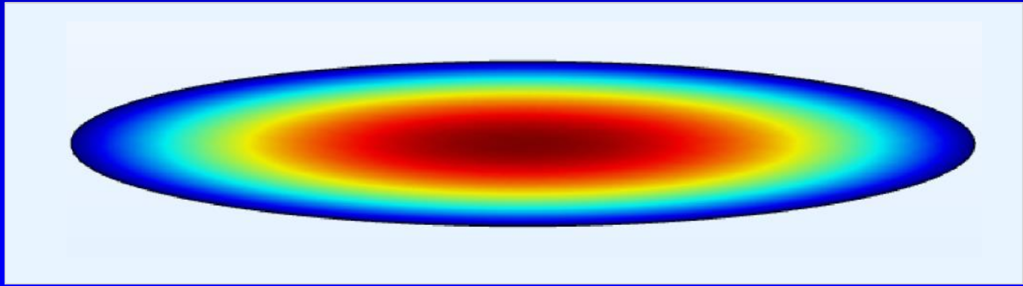
Max velocity 0.8 m/s

Matched Ellipse

Max Velocity 0.85 m/s

Maximum velocities for matched cross section areas are within ~ 10%, but elliptical flow rates are >20% larger, depending on location and local slope





Also assessing flow rate comparisons for different cross sections

Immediate Next Steps

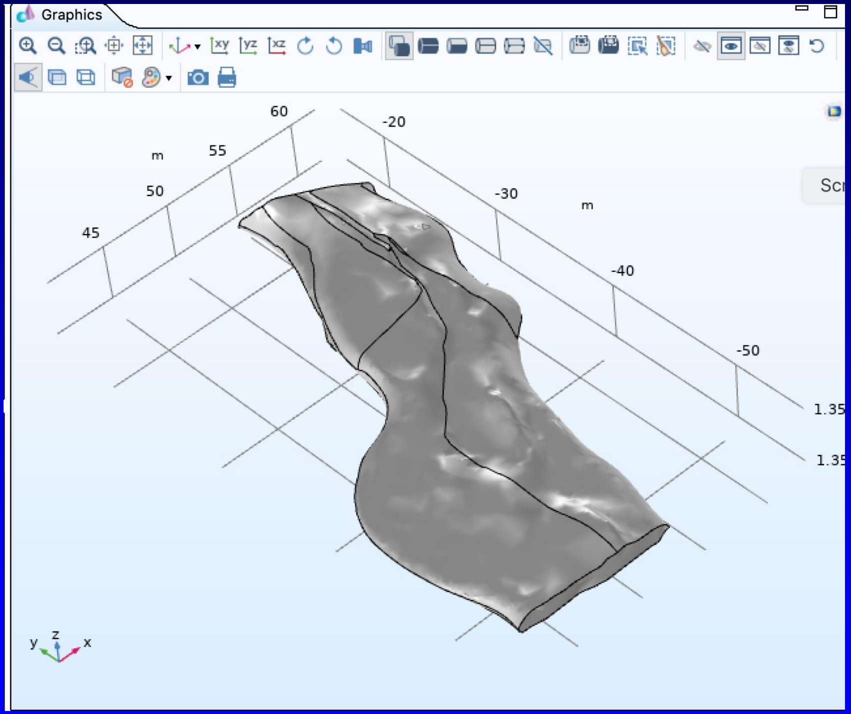
- Laminar flow results plausible for 1st effort

- Turbulent flow results show significant mesh-generated errors

- Use COMSOL Design Module to repair .stl file generated from data points
  - remove slivers, edges
  - remove fallen roof blocks
  - fix narrow elements, short sides

- Rerun laminar flow analysis

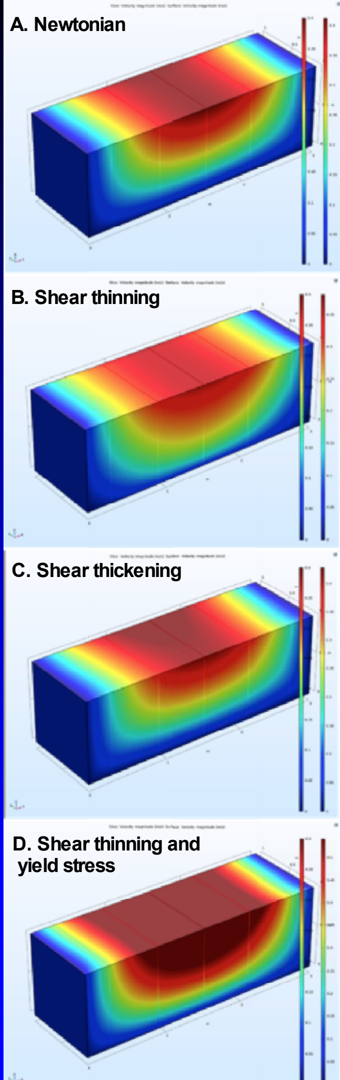
- Rerun turbulent flow analysis



Ongoing Work:
Adding Heat Transfer and Rheology

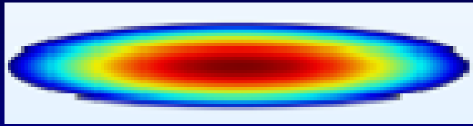
- Cooling is thought to be very strongly coupled through rheology to flow velocities.

- Real lava rheologies may start Newtonian, but evolve to include a yield strength and shear thinning as they cool.

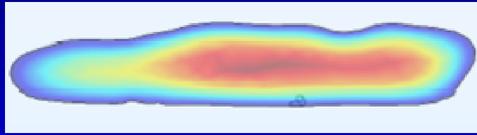


Conclusions

- COMSOL modeling has enabled a new general solution for flow in elliptical cross-section lava tubes



- Re-animating lava flow through specific lava tube scans likely improves velocity and flow rate estimates by 10-20% or more, depending on fit quality of ellipse in general solution to actual lava tube shape.



- Adding cooling and more complex rheologies will allow better understanding of lava tube formation and evolution

- Adding mechanical modeling of lava tube CAVE void may allow stability assessment of caves