MATLAB® as a Tool for Research in the Geosciences

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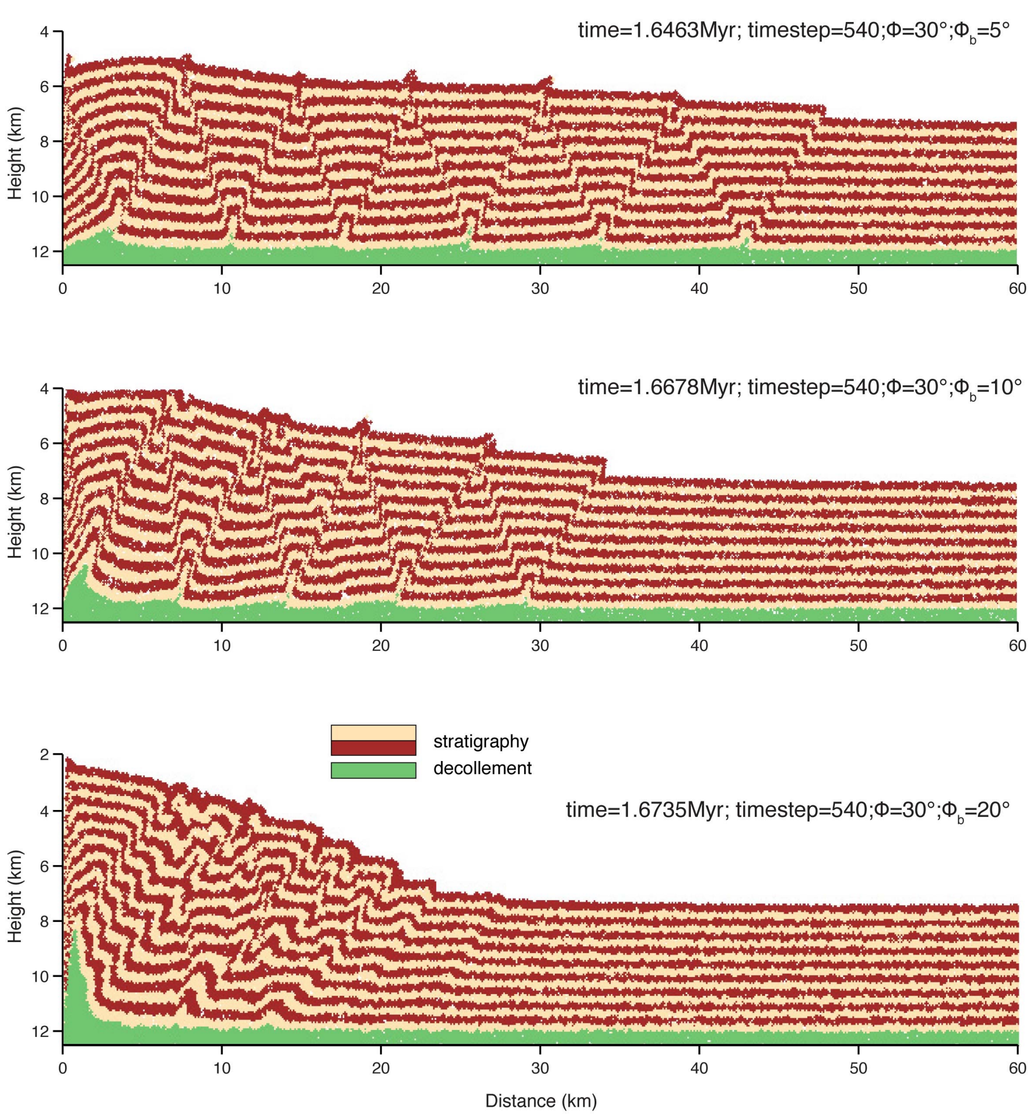
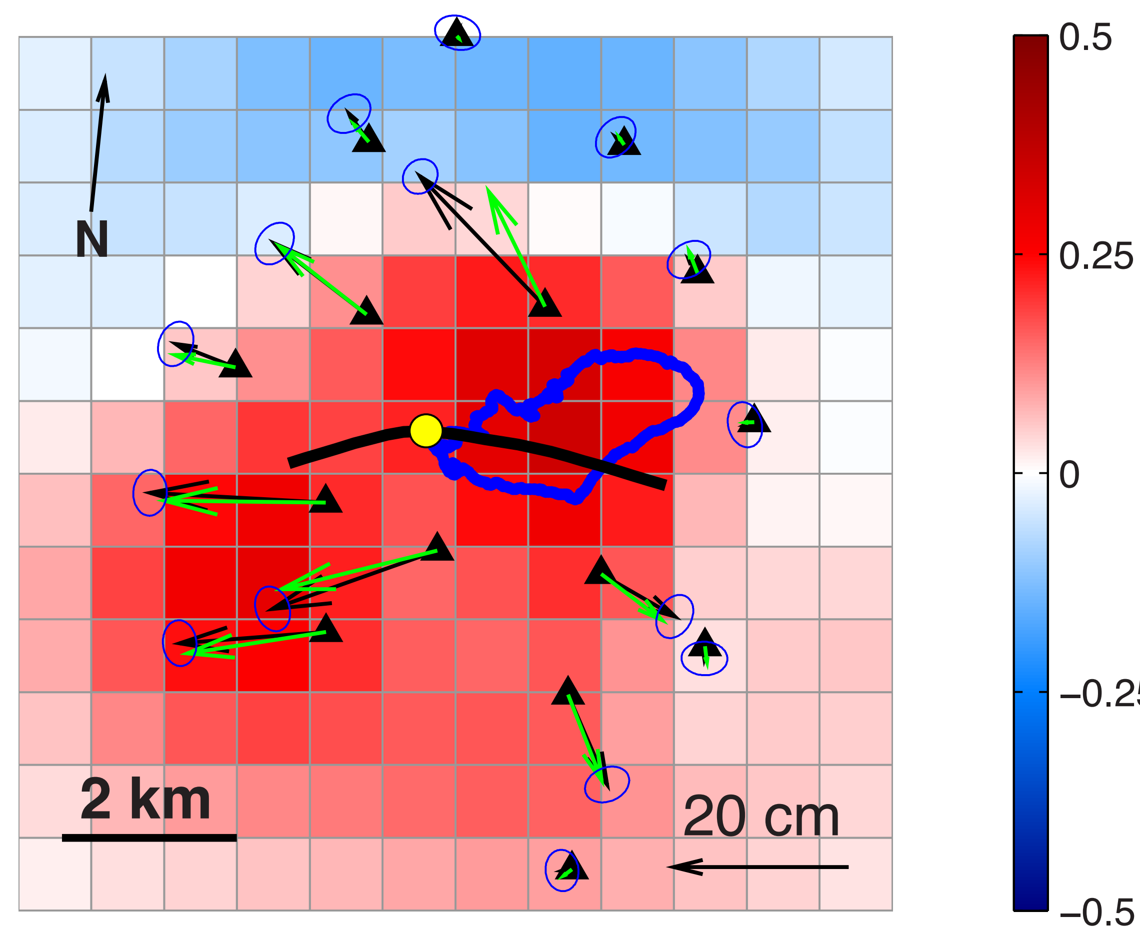
Jean-Arthur Olive, Laura Stevens (*MIT/WHOI Joint Program*)

Modeling Long-term Tectonic Deformation



Ice Sheet Dynamics



WHOI Geodynamics Group

The WHOI Geodynamics Group investigates the dynamics of deformation in glacial, marine, and terrestrial environments.

The group is composed of WHOI scientists, MIT/WHOI Joint Program graduate students, post-docs, and undergraduate Summer Student Fellows.

Our work involves analysis of geophysical/geologic/geochemical datasets, development of forward and inverse models, and data/model visualization.

MATLAB

Why MATLAB®?

1) Easy to learn and use—*many (most?) students entering our group have not used MATLAB® before*.

2) Can interact directly at the command line — *easy to debug*.

3) Widely available at most academic institutions (and is used throughout the geosciences community).

4) Allows data analysis and visualization to be performed within a single program.

5) Provides tools for handling geophysical datasets and displaying them using geographical projections.

6) Powerful enough for computationally intensive numerical modeling (e.g., Parallel Computing Toolbox, Distributed Computing Server).

MATLAB

Examples of MATLAB® in the WHOI Geodynamics Group

Example 1: Dynamics of the Greenland Ice Sheet

- Field program monitoring the response of the Greenland Ice Sheet to the drainage of supra-glacial lakes.
- MATLAB® implementation of the Network Inversion Filter (NIF) for GPS datasets
- Visualization of the NIF model.

Example 2: Modeling long-term lithospheric deformation

- Developed a 2-D particle-in-cell finite-difference model that can handle visco-elasto-plastic rheologies
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- Application to the interaction between faulting and surface processes.

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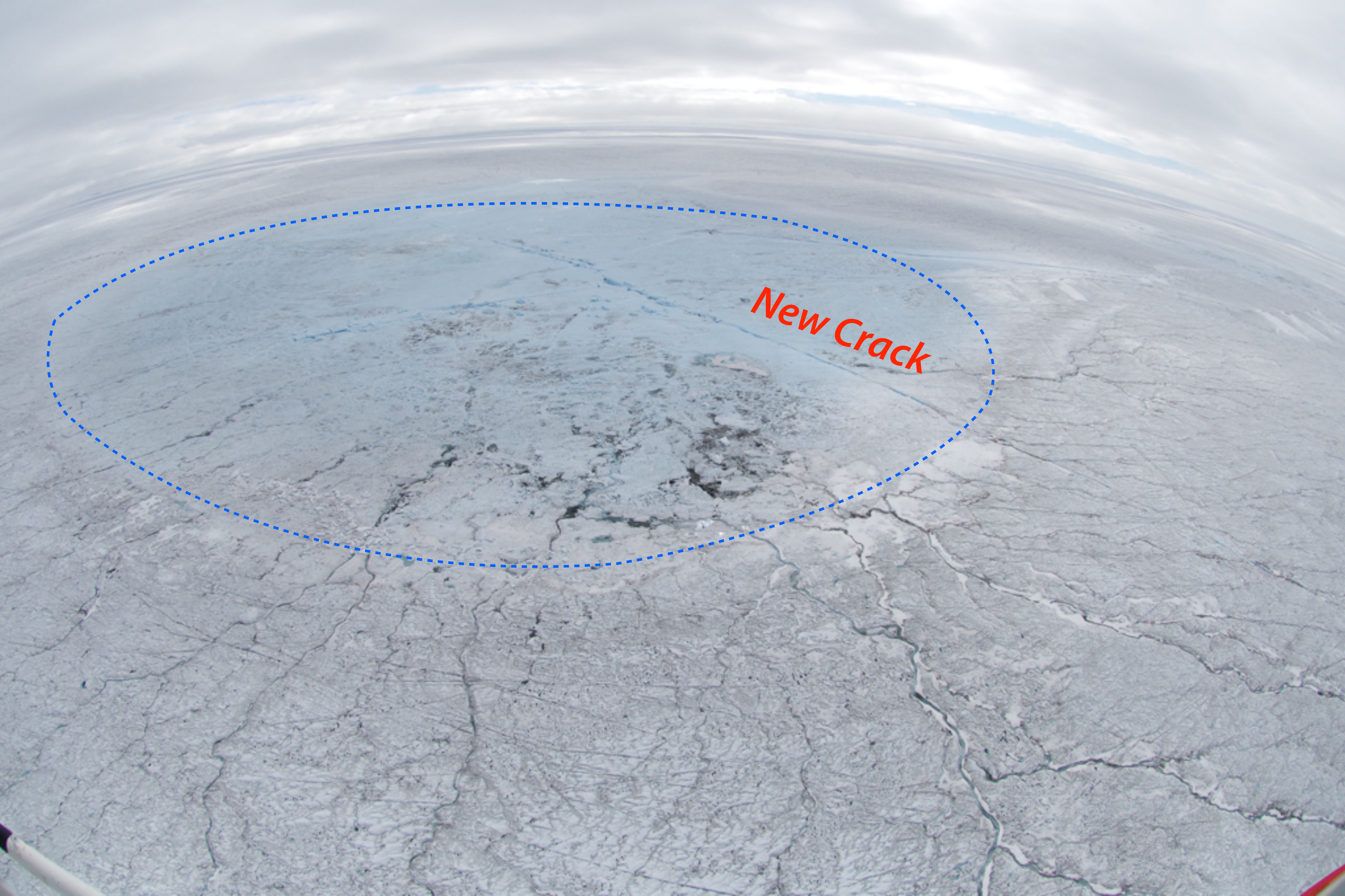
A distinctive feature of the Greenland Ice Sheet is presence of 1–5 km diameter supra-glacial lakes that fill with melt water during summer months.

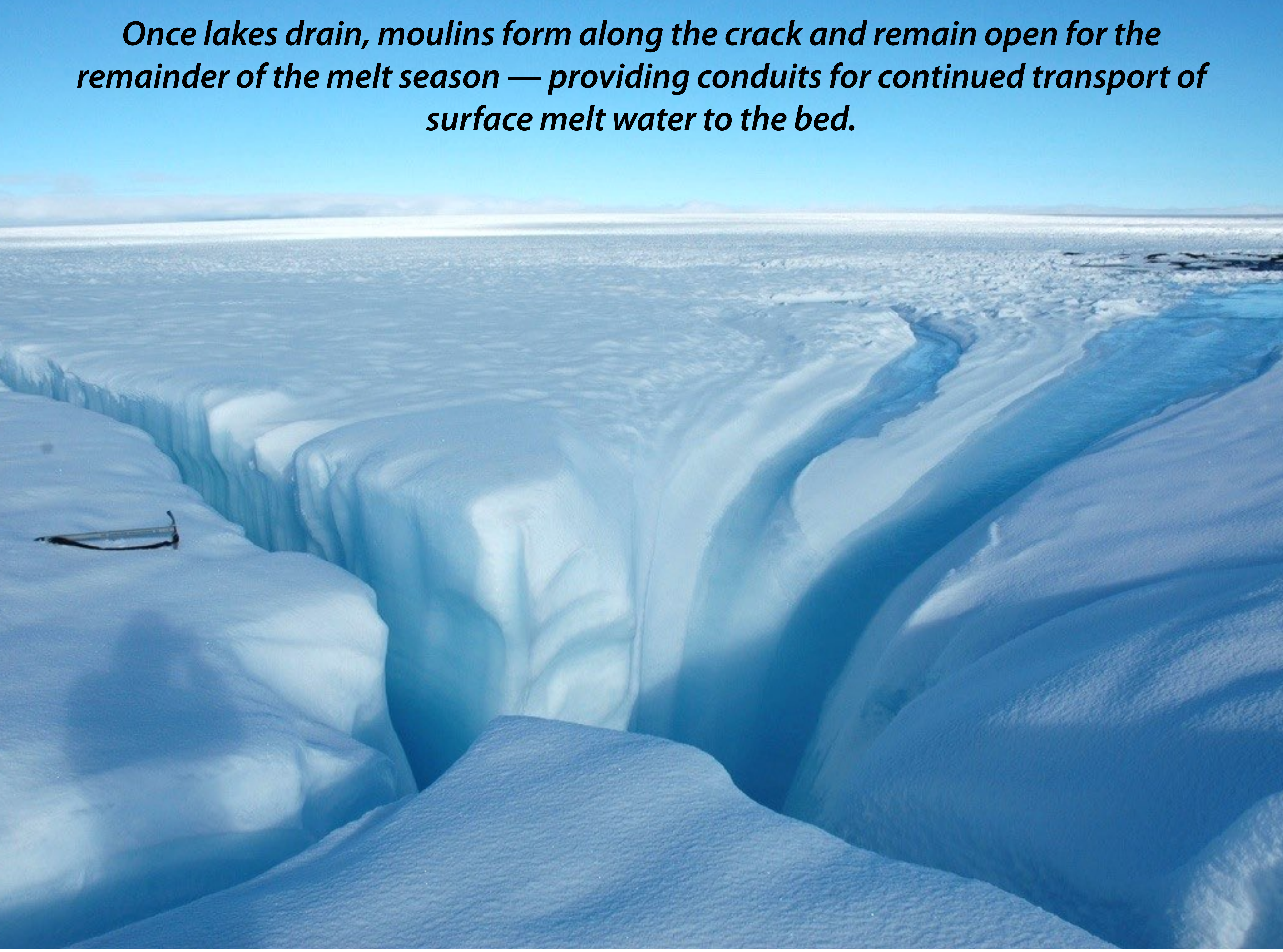
Sarah Das & Jeff McGuire (WHOI),
Ian Joughin (UW),
Laura Stevens(WHOI/MIT)

Field and instrument support from CPS, UNAVCO, PASSCAL/IRIS

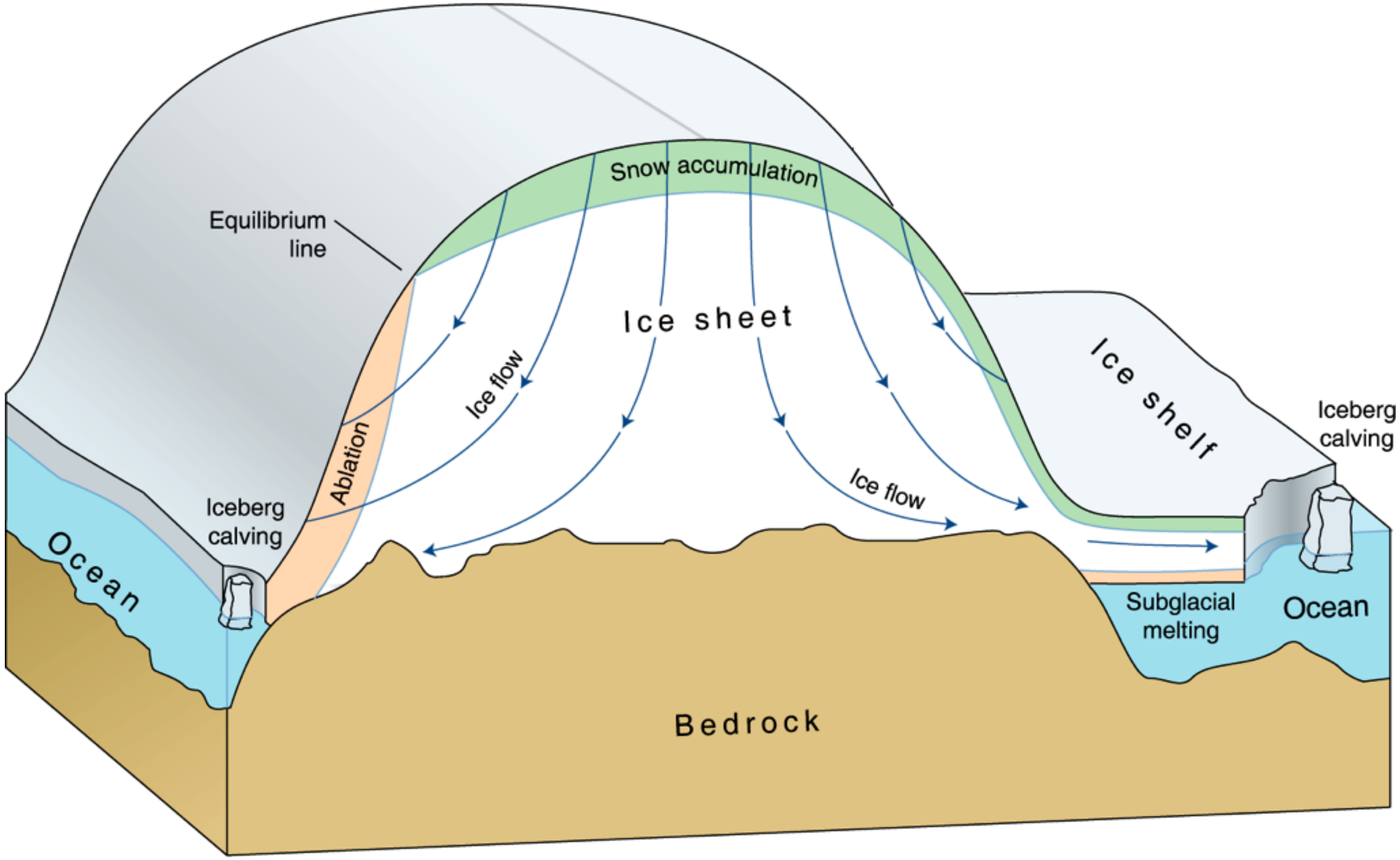
These lakes can drain in minutes to hours through kilometer-long cracks that form beneath the lakes.

South Lake in Summer 2008
(2 Days Post-Drainage)




Once lakes drain, moulins form along the crack and remain open for the remainder of the melt season — providing conduits for continued transport of surface melt water to the bed.

Schematic Illustration of Ice Flow within an Ice-sheet



UNEP/GRID-Arendal

Rate of ice flow will be strongly affected by the material properties at the ice-bedrock interface.

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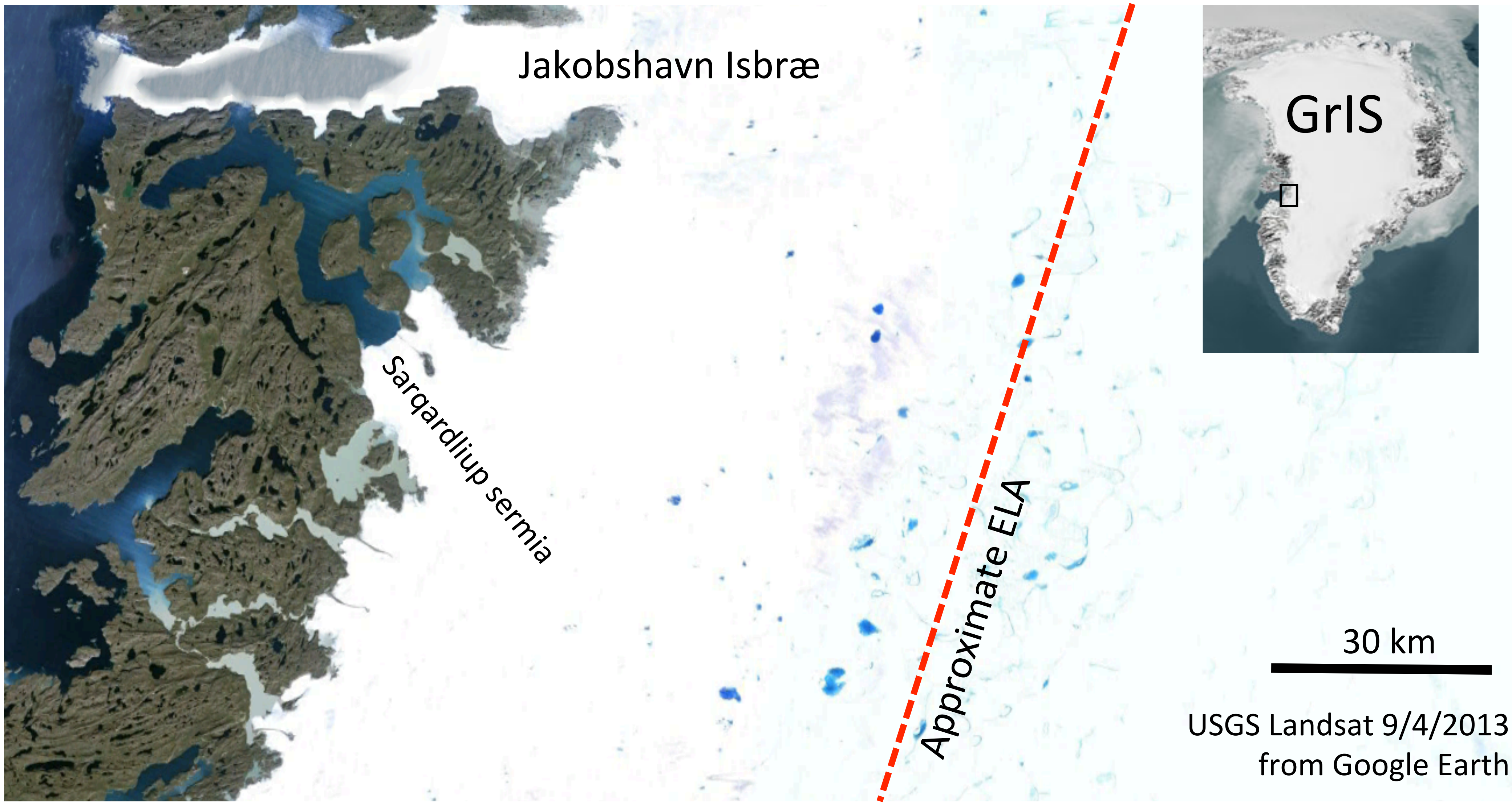
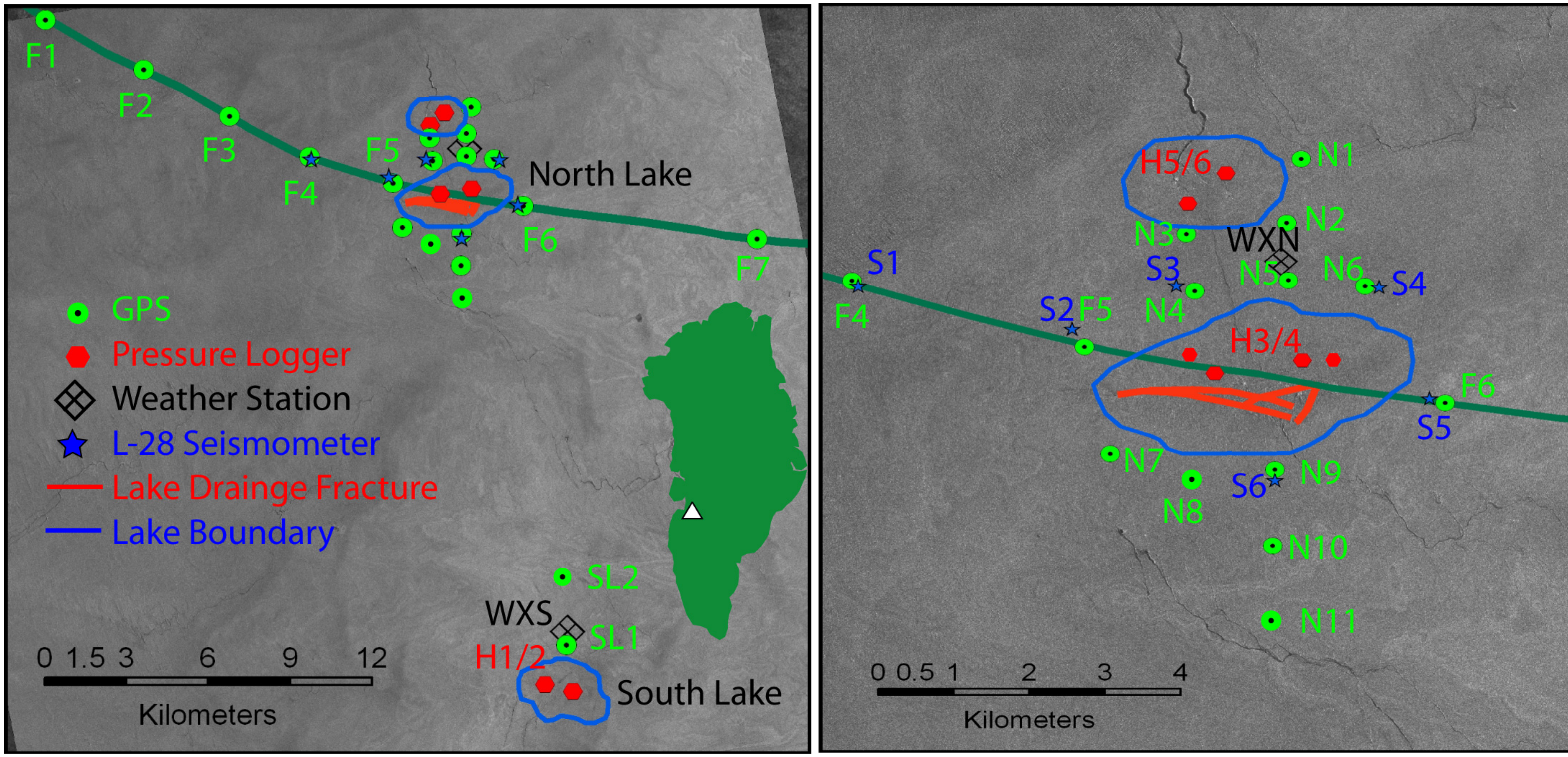
Outstanding Questions



- ***What are the conditions for drainage initiation? What is the geometry of the crack during opening?***
- ***What is fate of melt-water once it reaches the bed? Over what spatial and temporal scales does it influence sliding behavior?***
- ***How will lake drainages migrate inland in a warming climate?***

2011–2014 Field Program at North Lake Site on the GrIS



GPS Network:

- *6 Flow line stations*
- *15 stations surrounding lake site*

Seismic Network:

- *6 short-period seismometers*

Pressure sensors

- *3–4 sensors a year in each lake*

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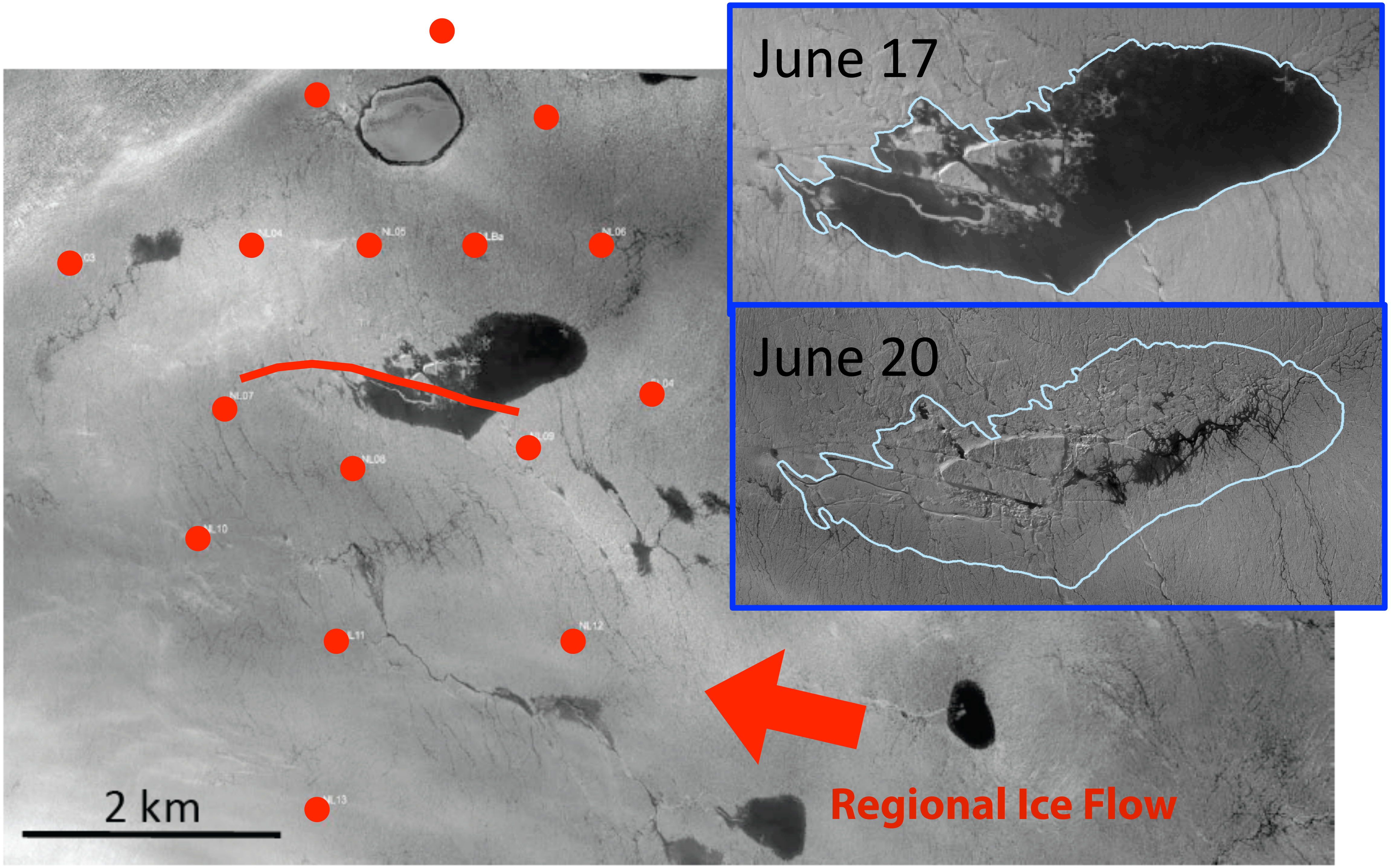
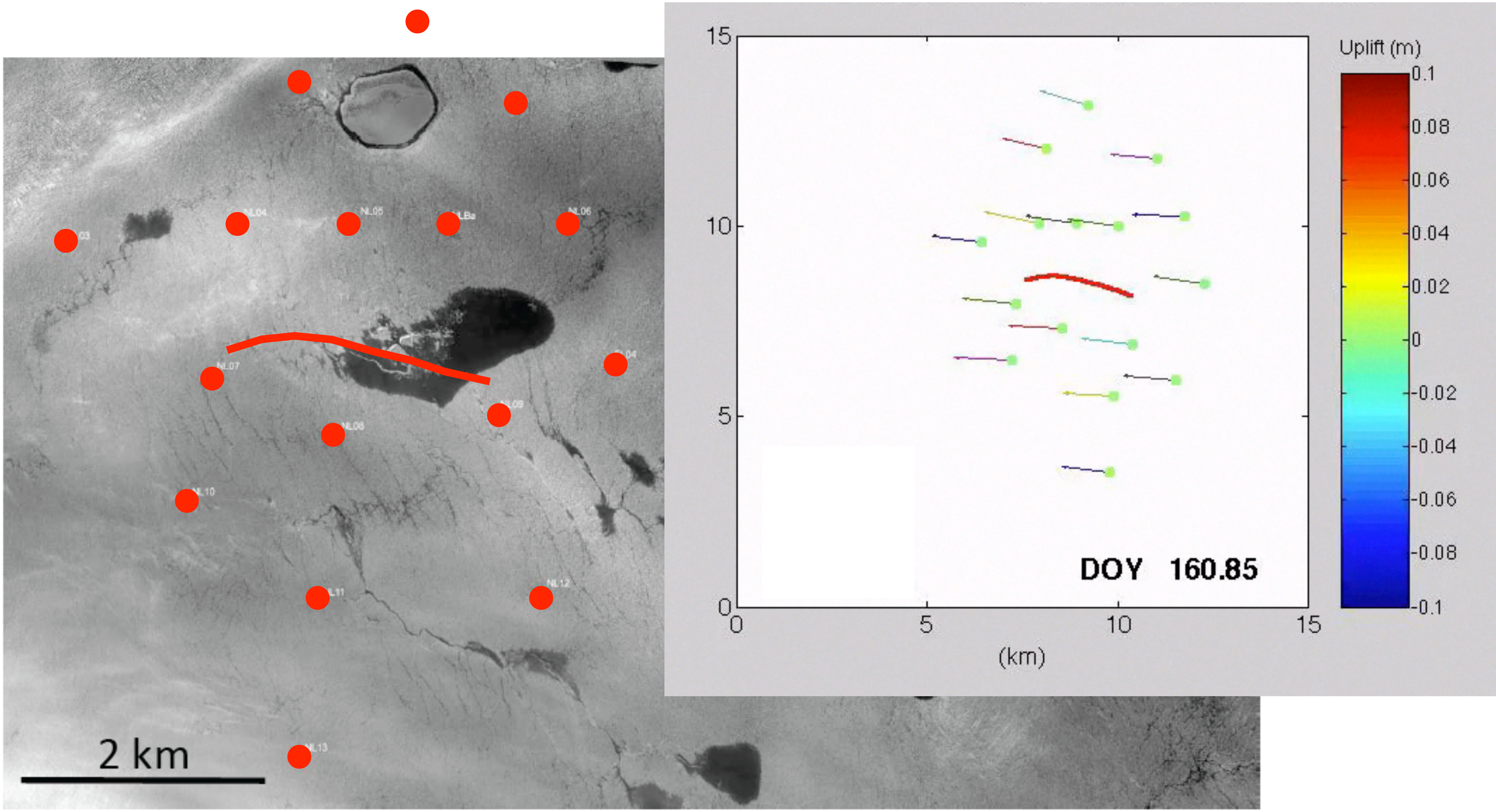
Setup of “Rapid-Install” GPS Station

High Resolution GPS Network from 2011-2014



GPS network from 2011-2014 captured 3 rapid lake drainage events, all of which occurred early in the summer melt season (early to mid June).

High Resolution GPS Network from 2011-2014



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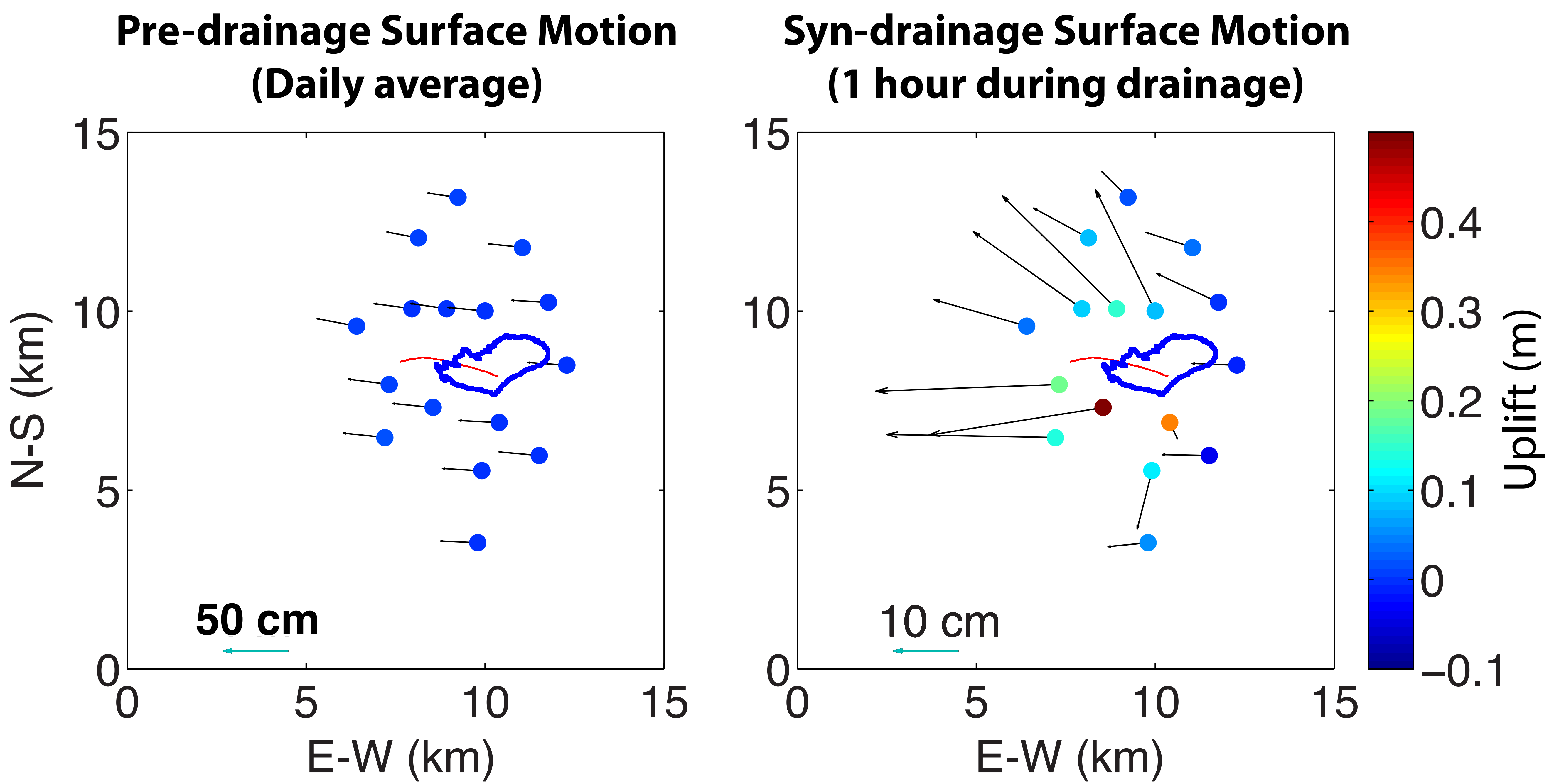
Surface Motions Associated w/ 2011 North Lake Drainage



Rapid lake drainages are associated with (1) surface uplift, (2) crack normal motions, and (3) downstream acceleration of the ice-sheet.

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Time-Dependent Inversion of GPS Data using MATLAB®

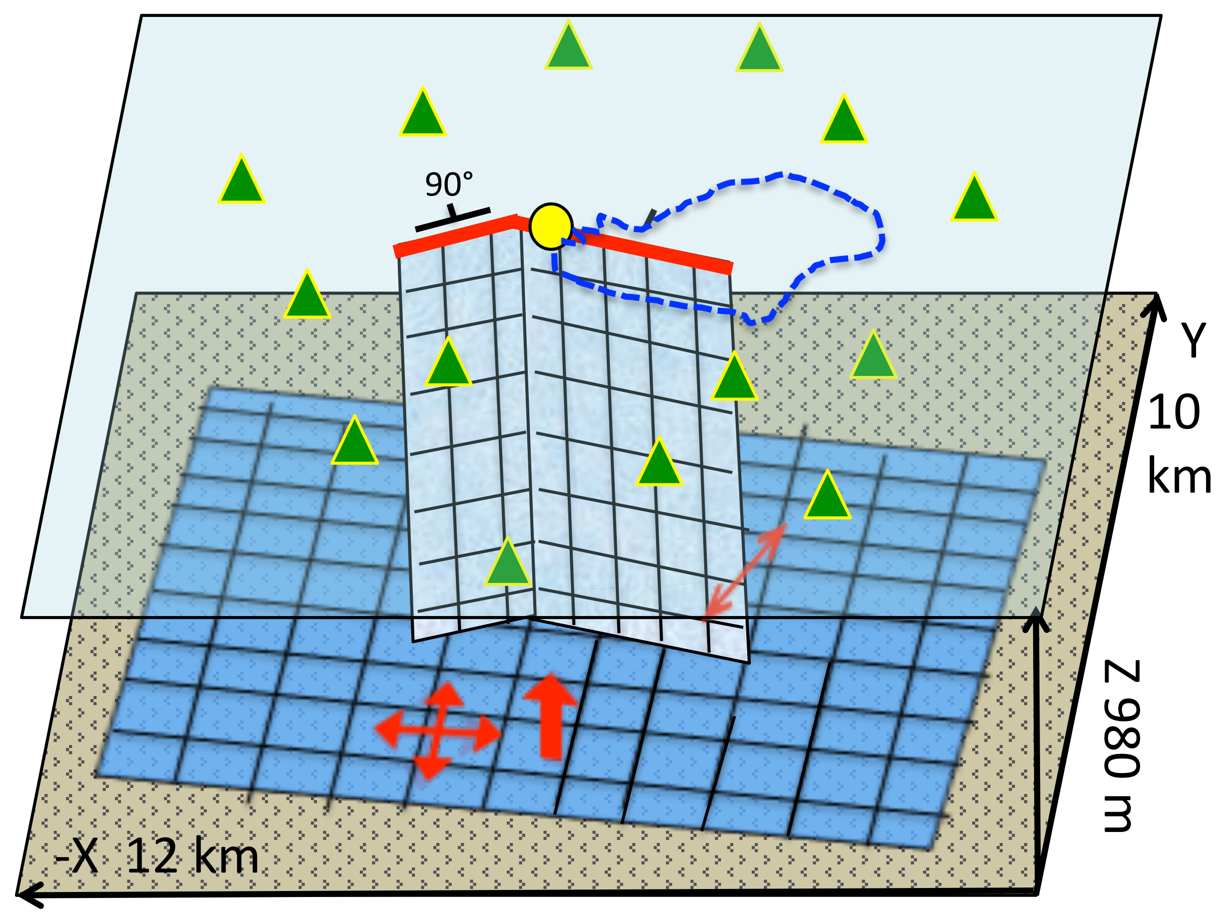
Ice Surface GPS Time Series

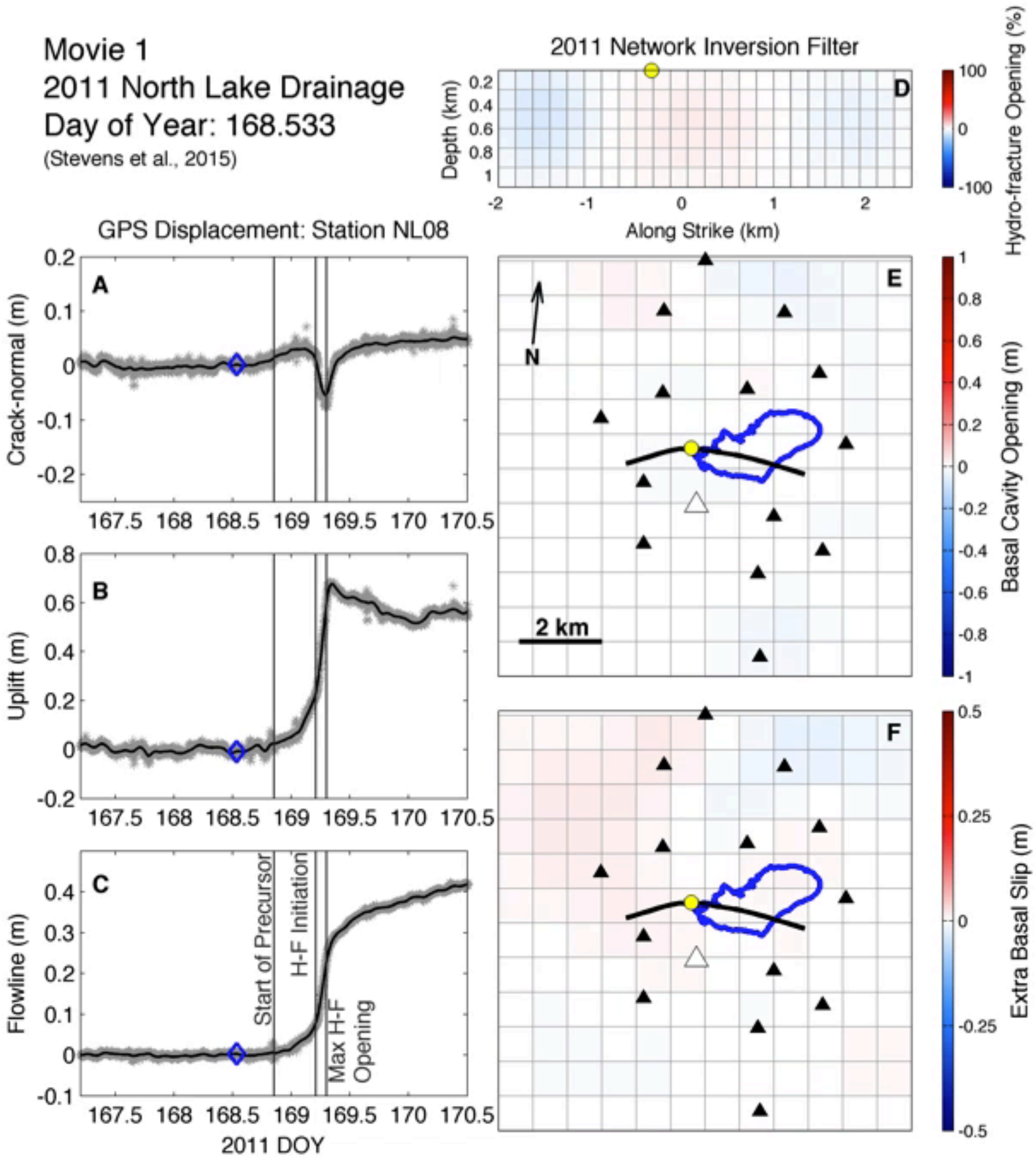
Green's functions for dislocations in an elastic half-space [*Okada*, 1985]

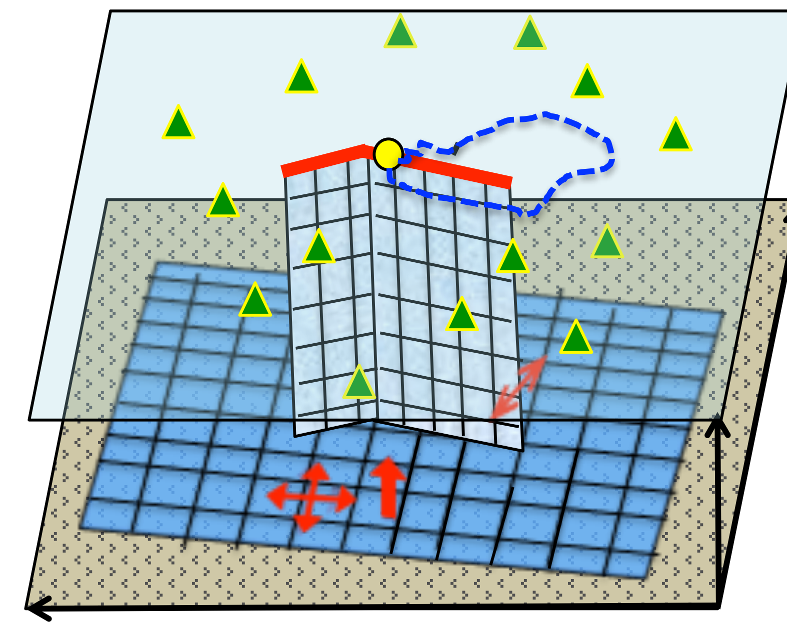
Invert using recursive linear (Kalman) filter

Output temporal and spatial distribution of slip and opening on crack and at bed

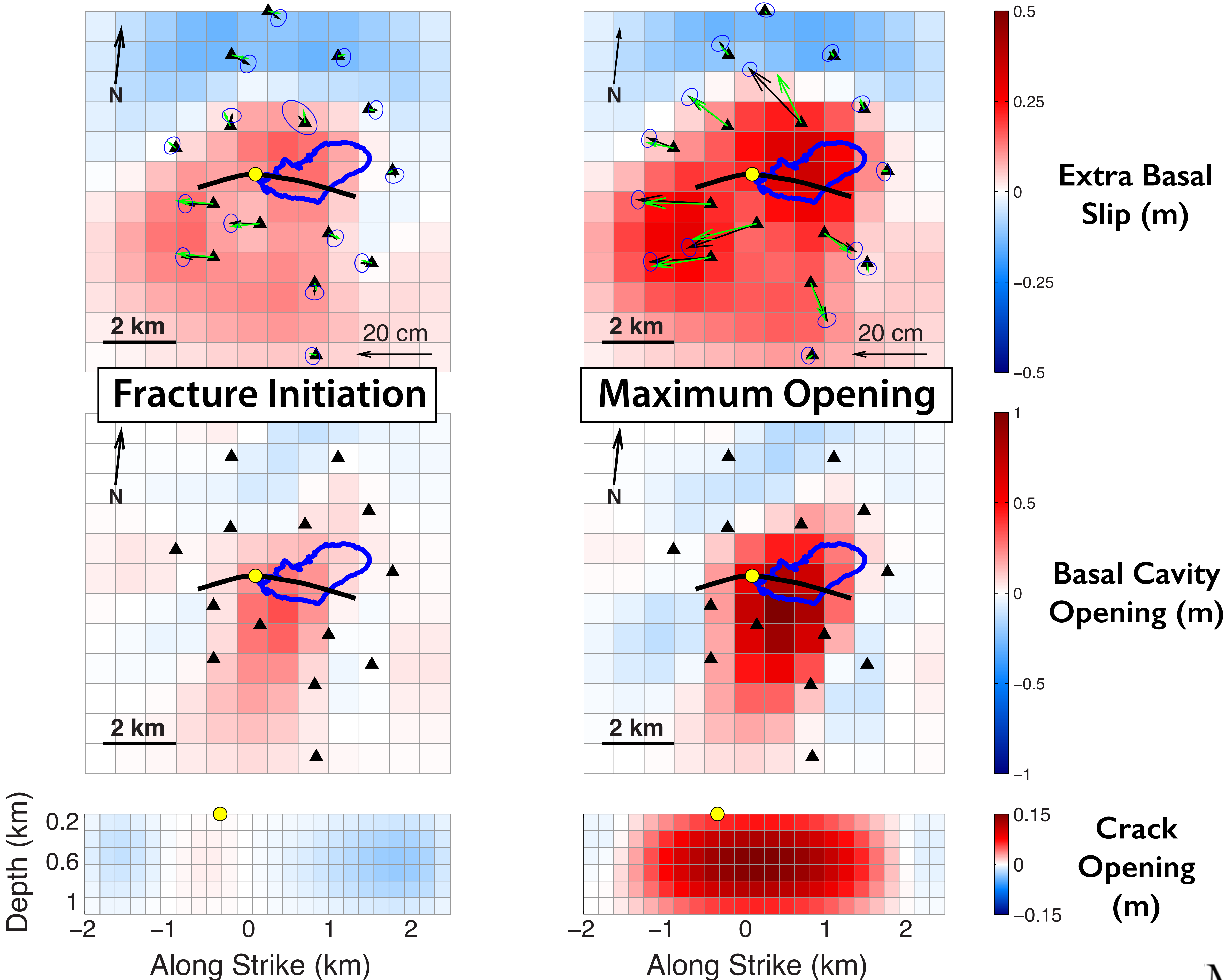
GPS Network Inversion Filter [*Segall & Matthews*, 1997]







Work of MIT/WHOI Joint Program Student Laura Stevens


Fracture Initiation
Maximum Opening
Extra Basal Slip (m)
Basal Cavity Opening (m)
Crack Opening (m)
N
2 km
20 cm
0.5
0.25
0
−0.25
−0.5
1
0.5
0
−0.5
−1
0.15
0
−0.15
Depth (km)
0.2
0.6
1
−2
−1
0
1
2
Along Strike (km)

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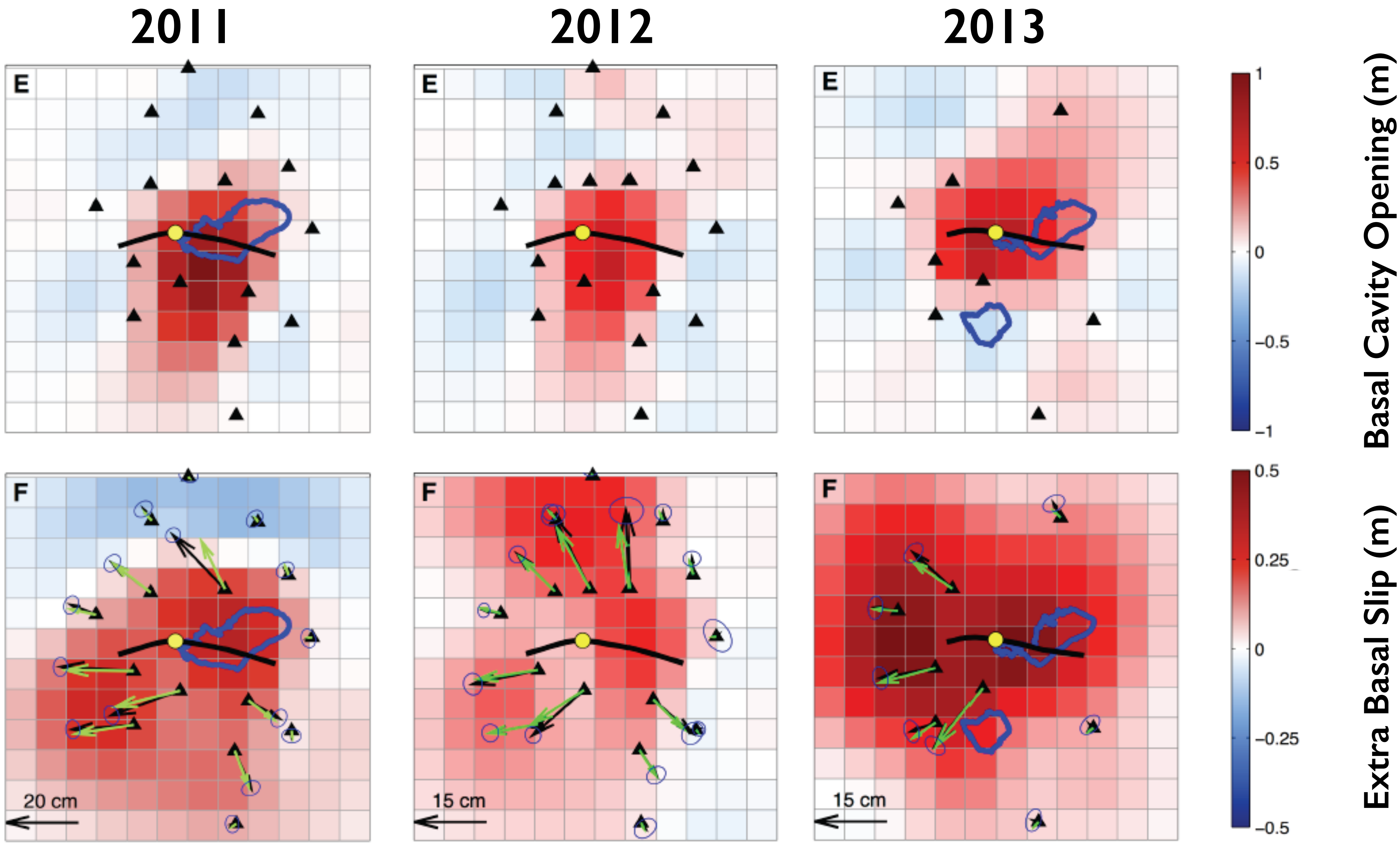
Comparison of 2011–2013 Drainages at Maximum Opening



All 3 drainage events show similar patterns of basal cavity opening and enhanced basal slip.

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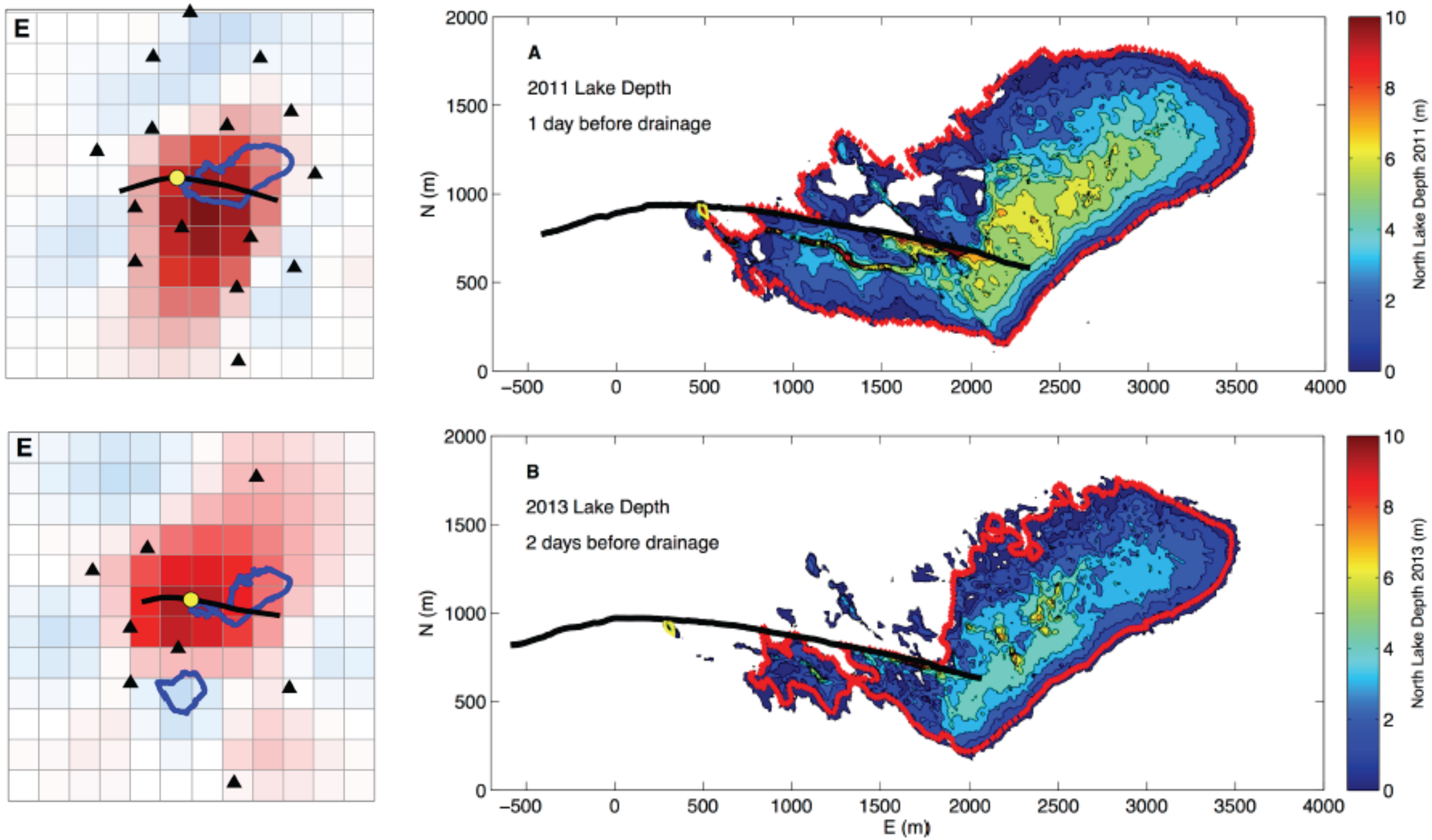
Time-Dependent Inversion of GPS Data

2011

2013



Total basal cavity opening immediately after drainage matches the amount of water in the lake immediate before drainage.

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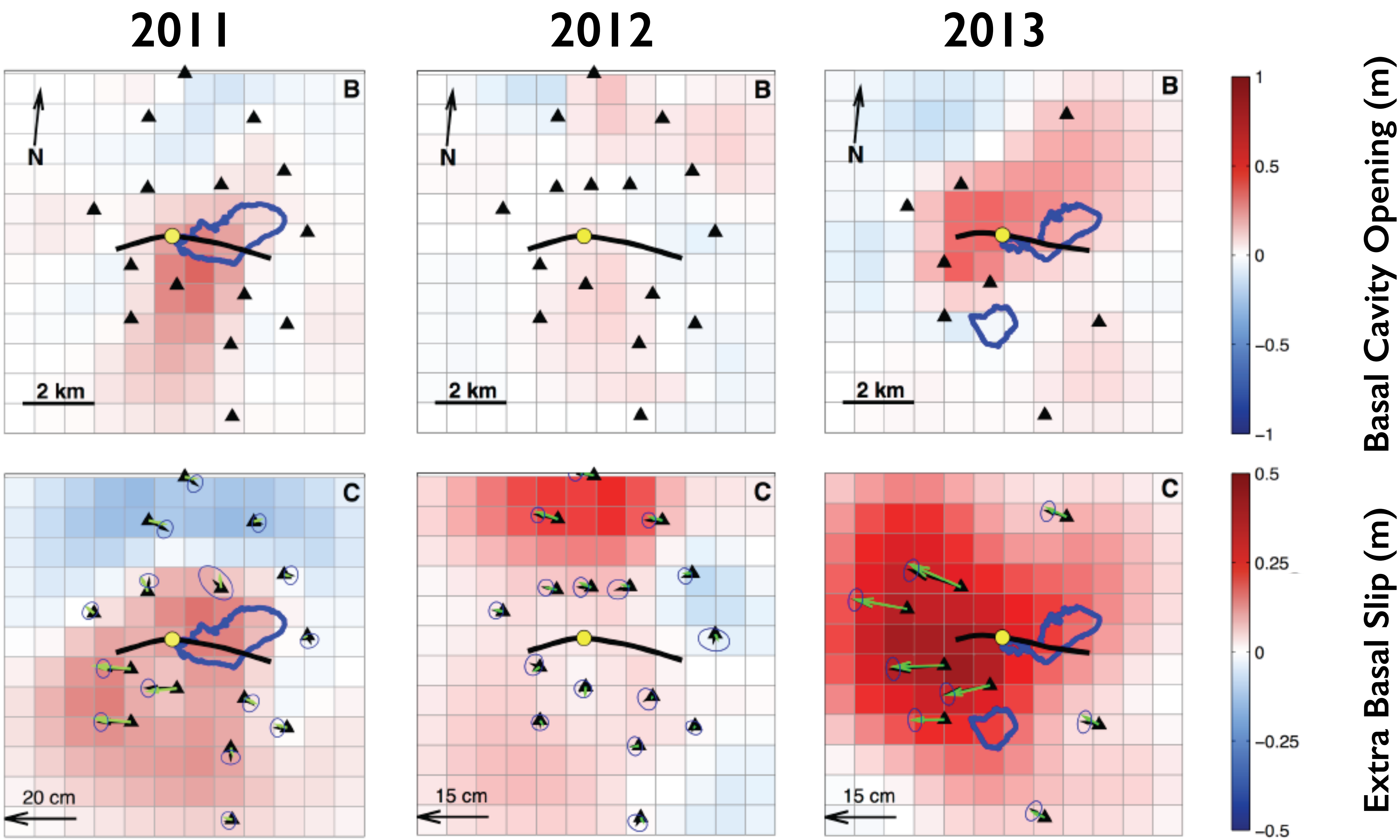
Comparison of 2011–2013 Drainage Precursors



All 3 drainage events show uplift precursors — however, 2012 appears to initiate in the north rather than immediately below the lake.

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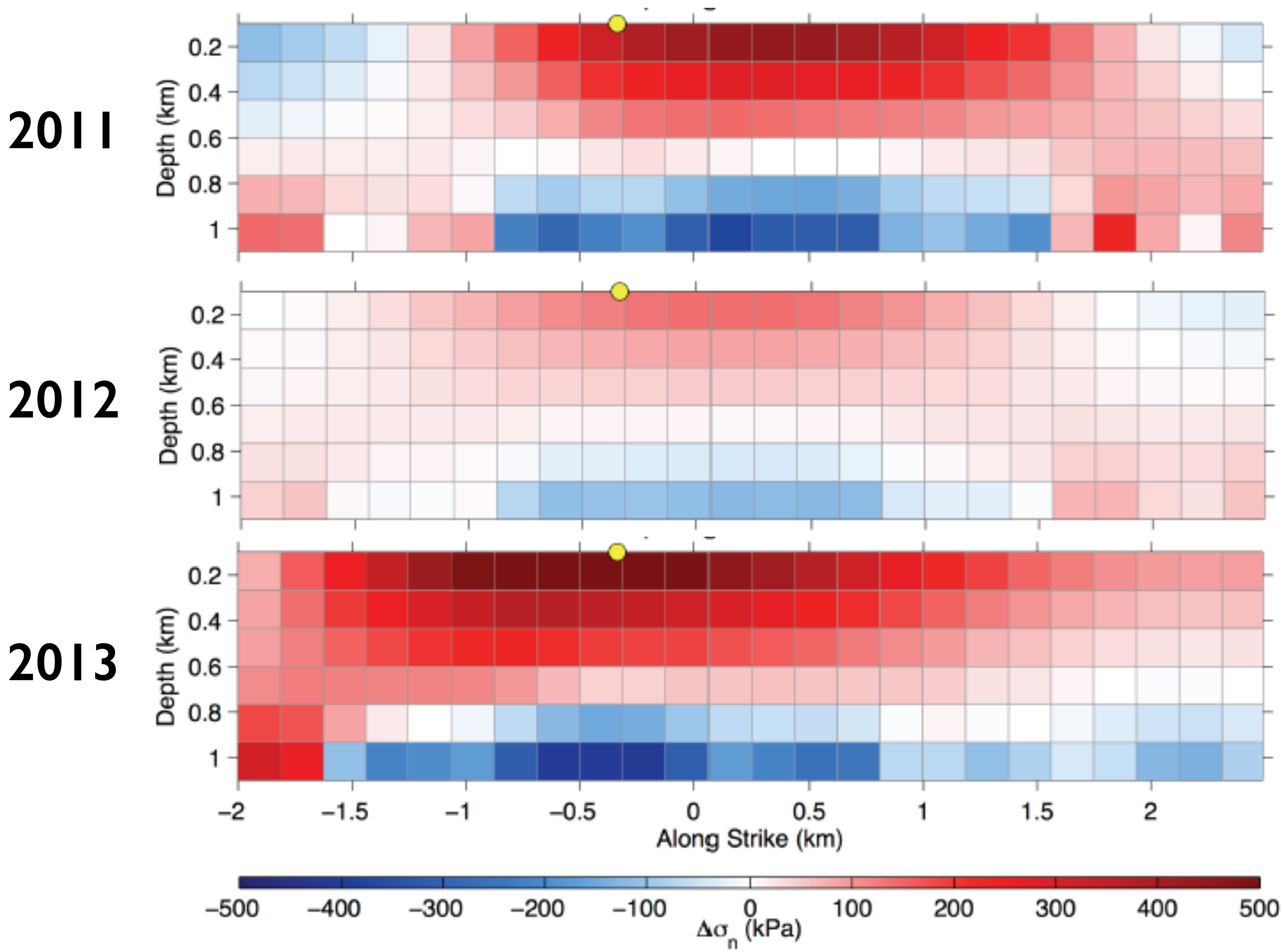
Stress Perturbations Associated with Drainage Precursors



Red = tension

Blue = compression

Precursors put the upper half of the crack in tension, over-coming the compressive stresses in the lake basin and triggering drainage.

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Example 1: Dynamics of the Greenland Ice Sheet

Scientific Take-Aways:

- Meltwater propagates rapidly (~hours) to the bed of the Greenland Ice Sheet via hydro-fracture beneath supraglacial meltwater lakes.
- Drainage events generate elastic deformation at the surface of the ice sheet that corresponds to (i) opening and closing of the hydrofracture, and (ii) opening of a meltwater "pond" at the bed.
- Inversion of geodetic data indicates that rapid drainage is preceded by a precursory event — suggesting that meltwater is reaching the bed through pre-existing crack systems before primary lake drainage.

Comments on the use of MATLAB®:

- MATLAB® was used for both the inverse modeling as well as the visualization of the results.
- L. Stevens had relatively little MATLAB® (or modeling) experience before beginning this project.
- We are beginning to consider MATLAB® for real-time processing of geophysical data while we are in the field.

MATLAB

Examples of MATLAB® in the WHOI Geodynamics Group

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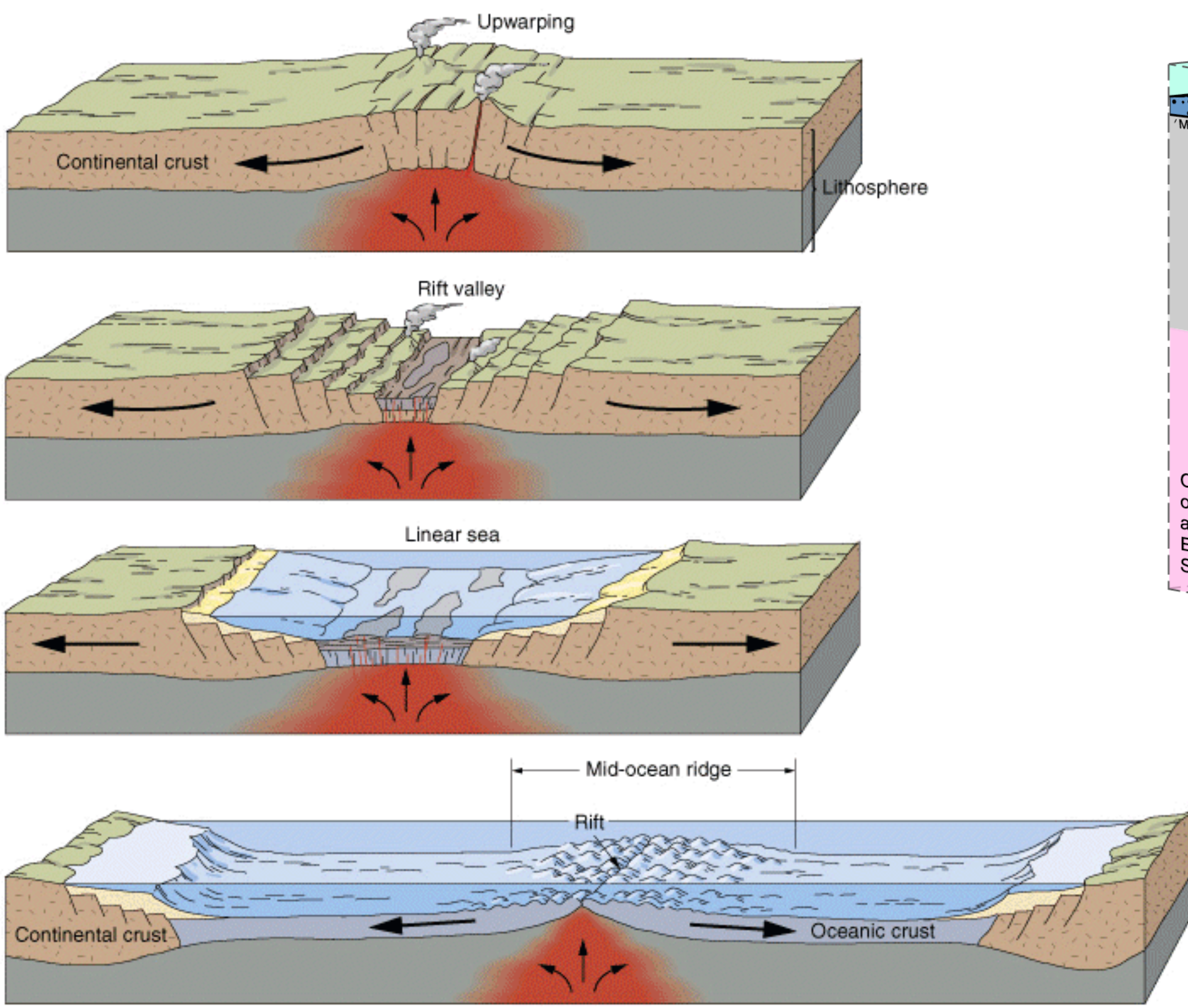
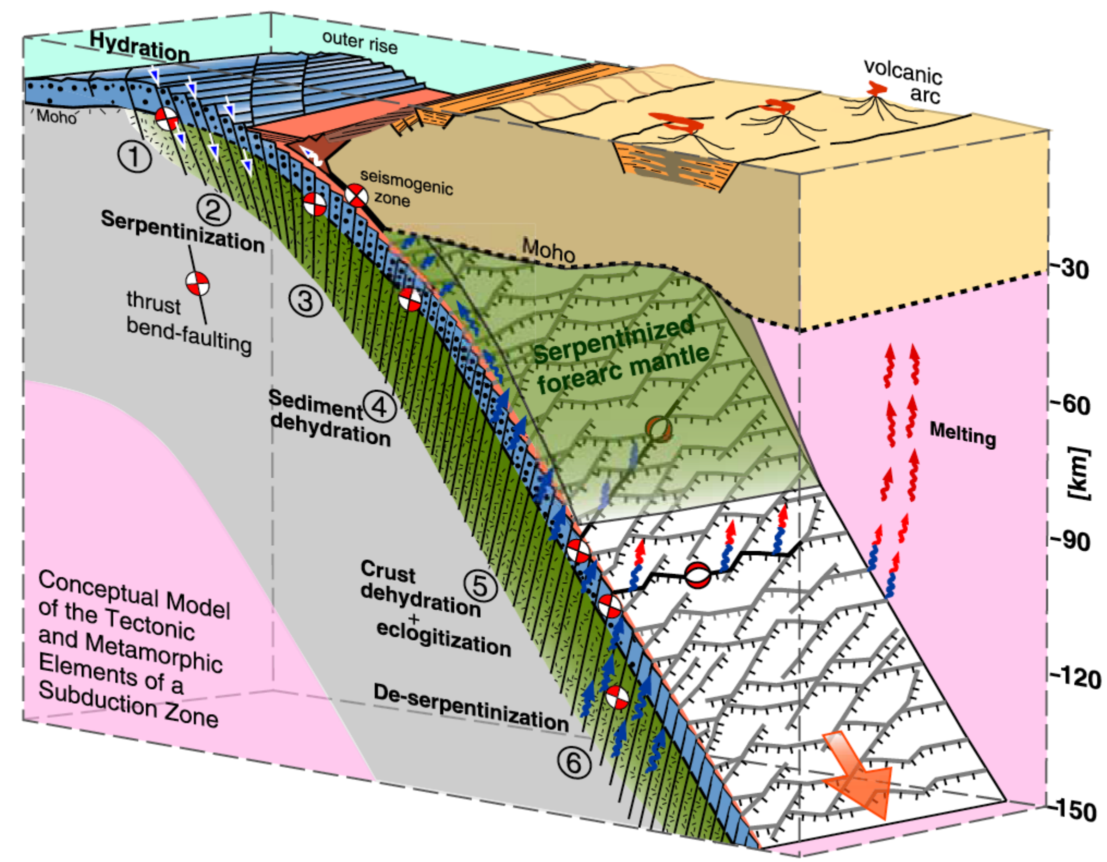
Modeling Long-term Lithospheric Deformation

Continental Rifting



Pearson Education Products

Subduction Dynamics



Ranero et al. [2005]

Model Development

Modeling Needs

- Solve for conservation of mass, momentum, and energy
- Ability to handle visco-elasto-plastic rheologies
- Ability to include compositional heterogeneity (e.g., sediments, crust, mantle)
- Must be computationally efficient (typically we are modeling deformation over time-scales of 10^6 years)
- Would like to be able to do this in a 3-D geometry. Still a work in progress…

Model Development

SiStER: Simple Stokes for Exotic Rheologies

- Primarily developed by J.-A. Olive (former MIT/WHOI JP Student)
- 2D particle-in-cell finite difference code
- ~4000 lines of code
- Publicly available at bitbucket.org/jaolive/sister
- Originally designed as a learning tool or "stepping-stone" to 3D code developed in C^{++} and PETSc. (Older "SiStER" of HiPStER). *However…*
- Applications to date include:
    - model tectonic faulting in extension systems and subduction zones
    - interaction between faulting, magmatism, and surface processes
    - ascent of buoyant sediment diapirs in subduction zones
    - accretionary wedge dynamics
    - descent of slabs through the transition zone
    - ice-sheet flow

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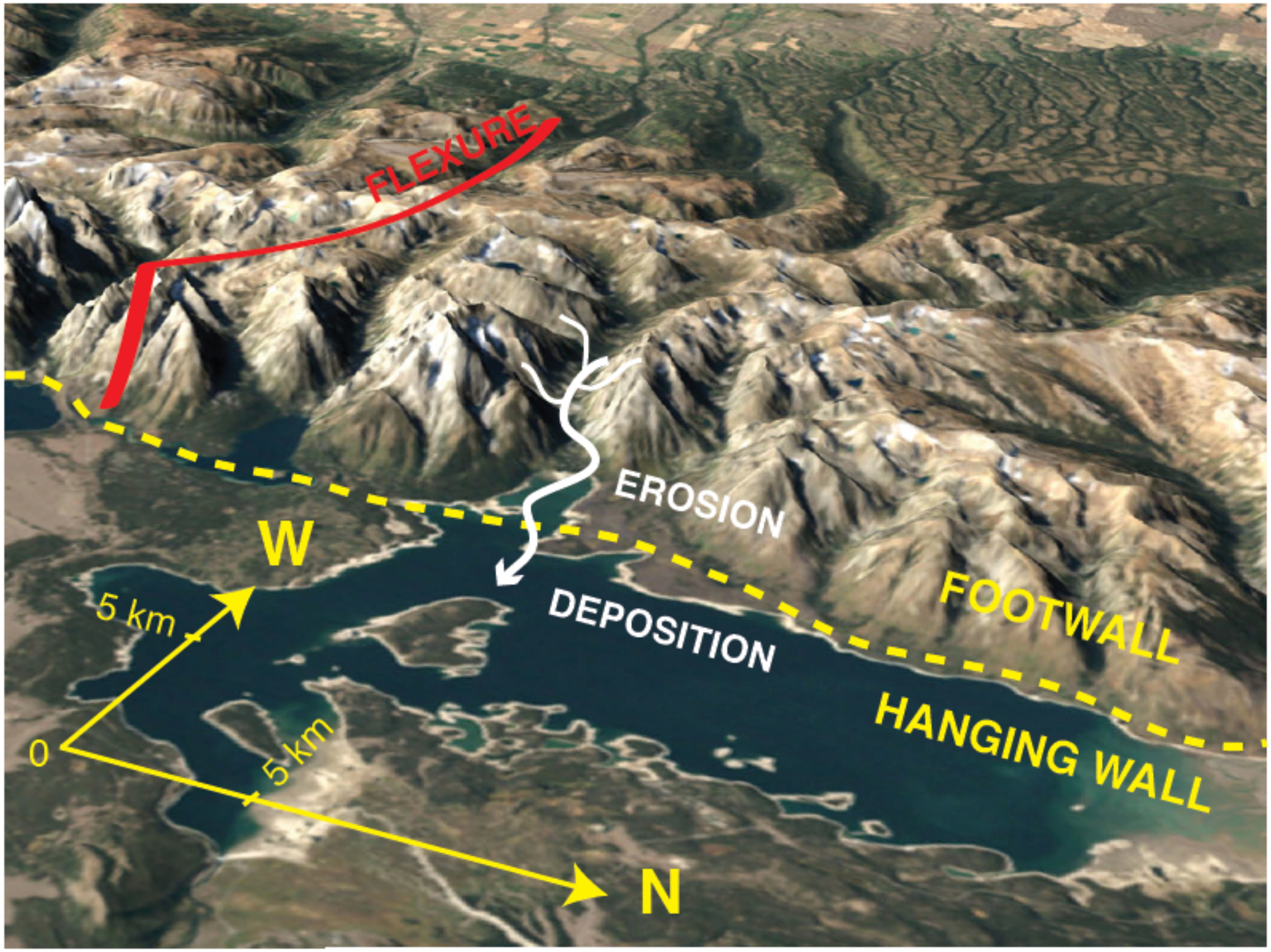
Feedbacks between Surface Processes and Normal Faulting



Surface processes shape extensional landscapes and have the potential to feedback on the evolution and lifespan of normal faults by influencing topographic stresses.

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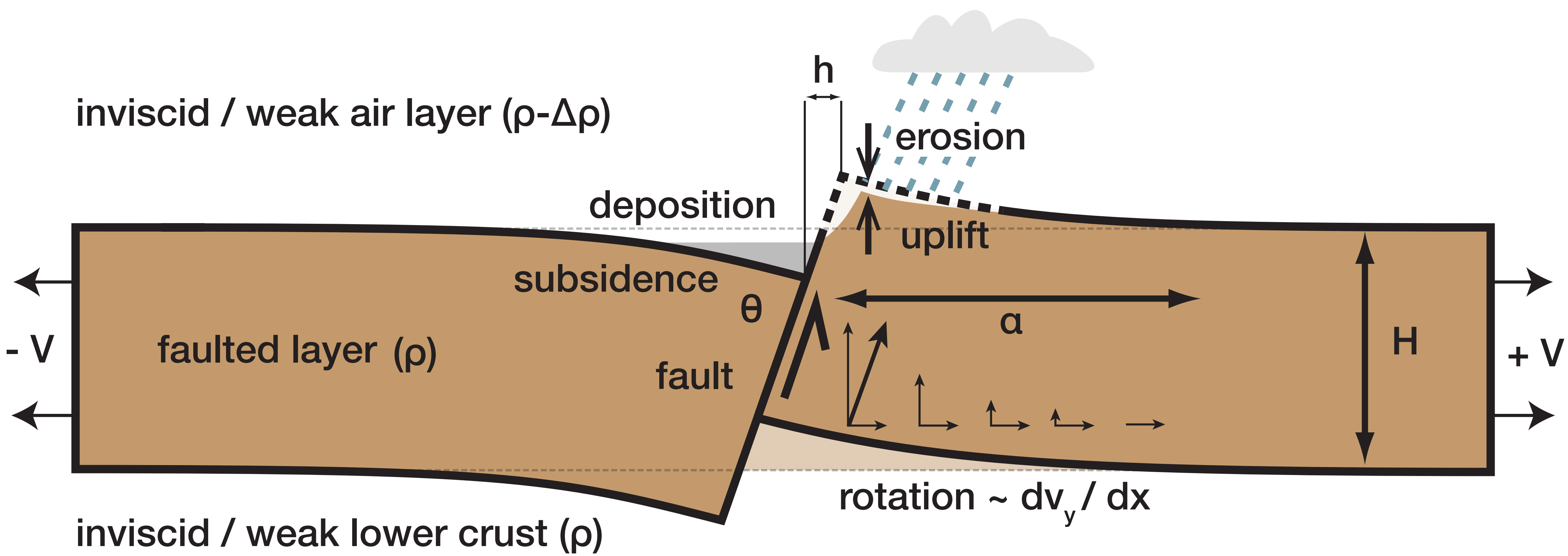
Coupled Geodynamic – Surface Processes Model

Geodynamic Model Setup

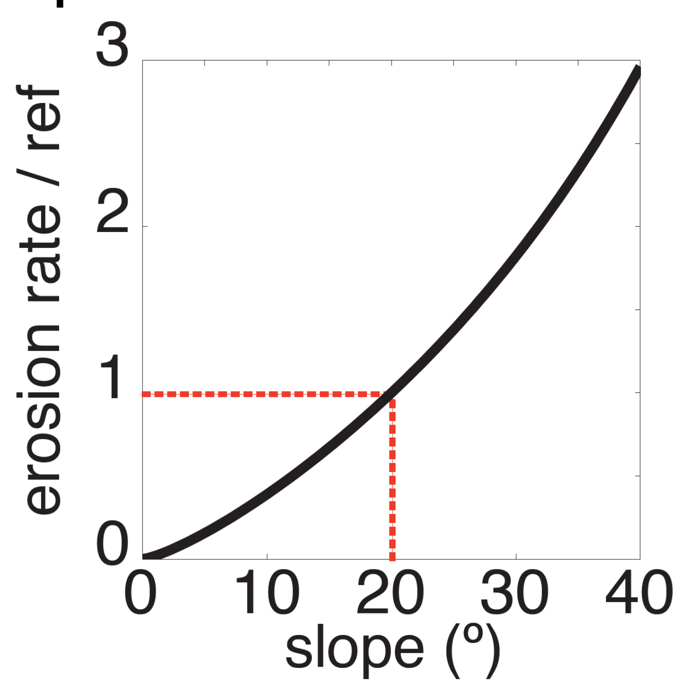
- **Strong brittle layer** (thickness **H**) with seeded fault subjected to stretching at half-rate **V**.
- Fault evolution monitored as offset **h** increases.
- All calculations performed using FD-PIC code **SiStER**.



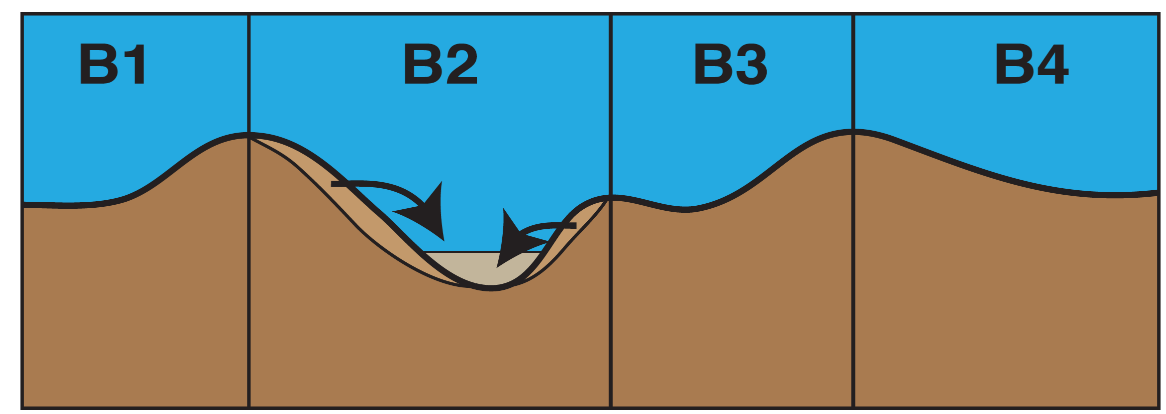
Coupled Geodynamic – Surface Processes Model

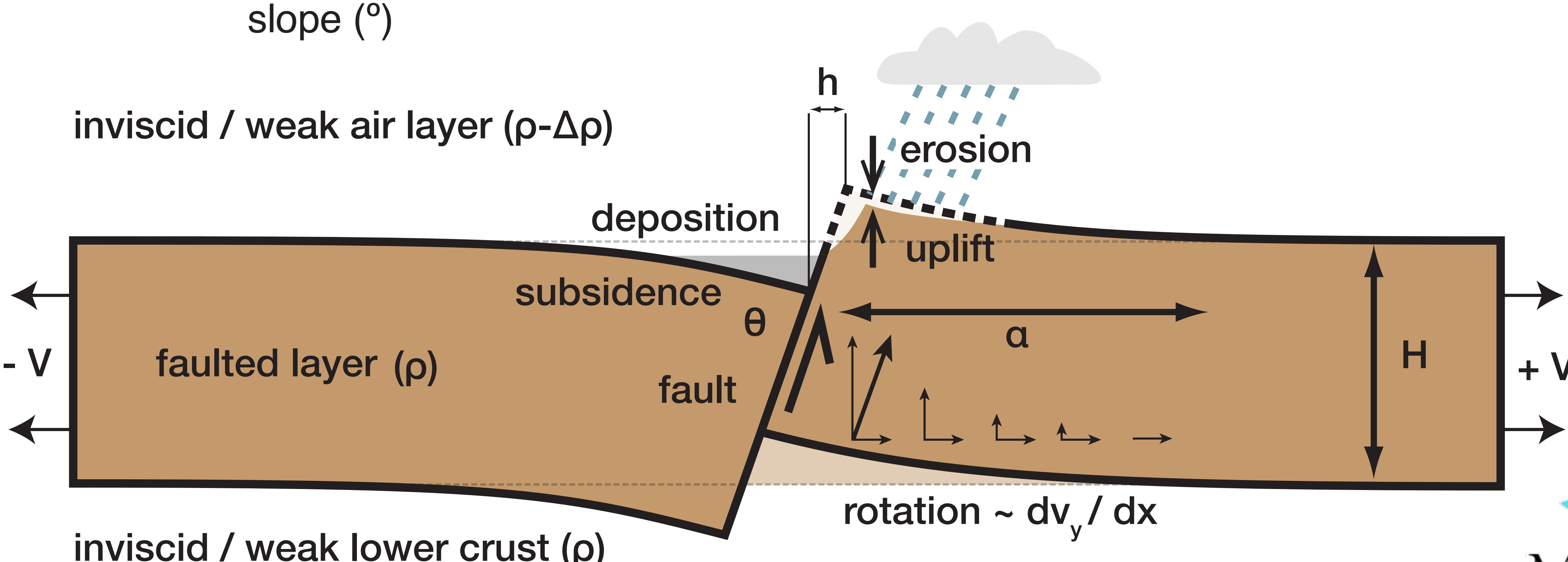
Surface Processes Model Setup

Step 1: **erode** material



Step 2: **deposit** material flat in corresponding watershed





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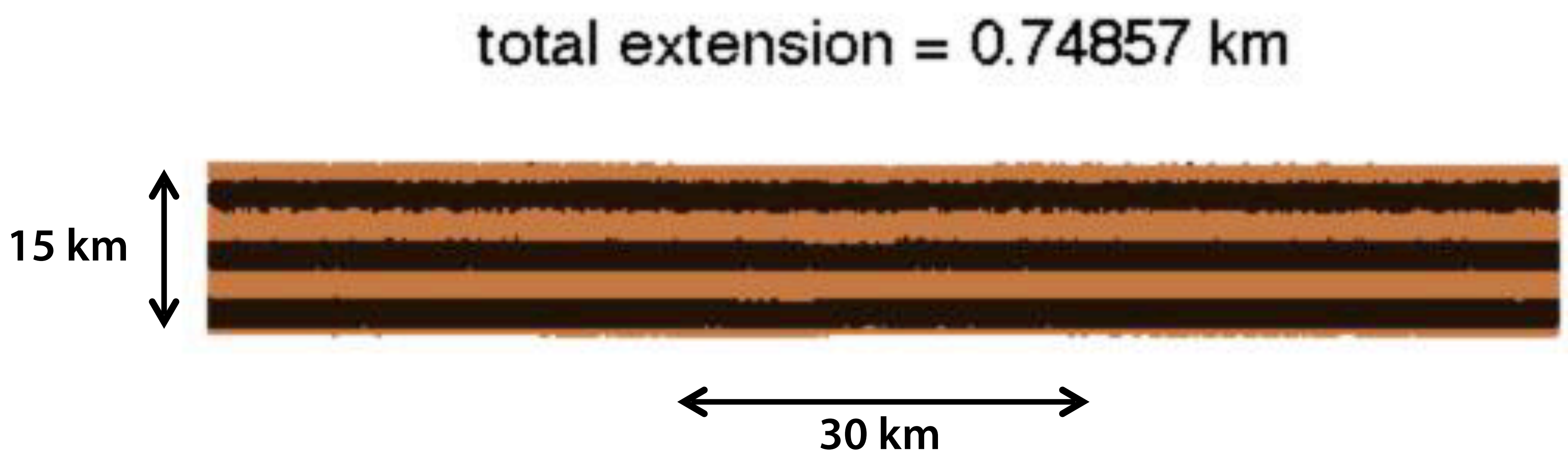
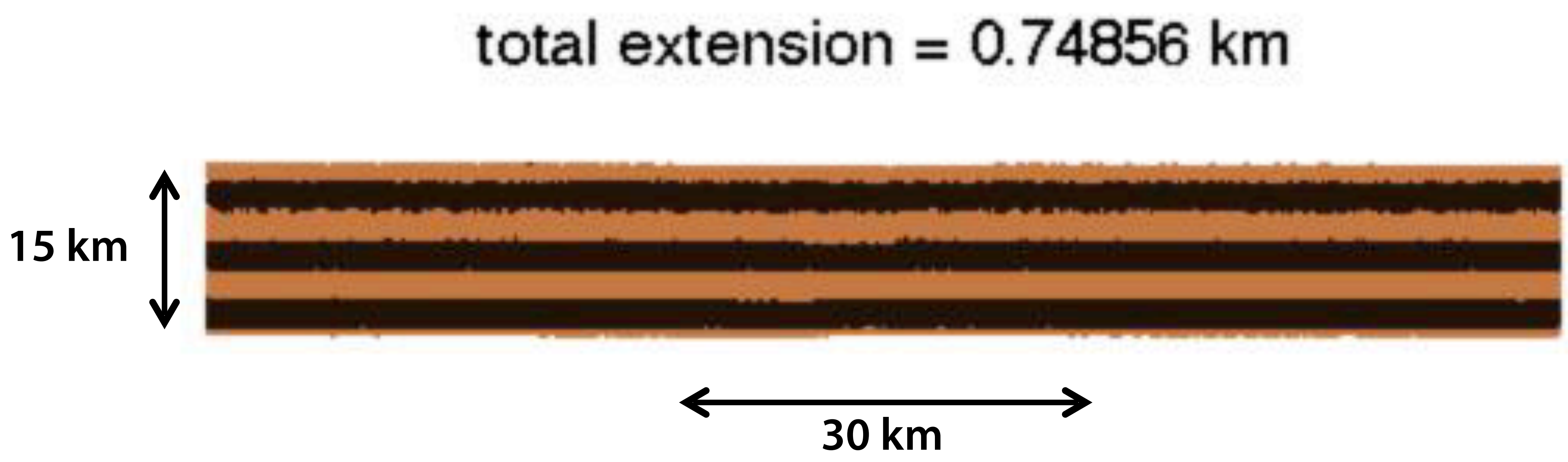
Sequence of Faulting with Slow Erosion

Extending a **15 km thick** layer at **2 mm/yr** (full rate).
Ref. erosion rate = **0.05% of fault slip rate.**



Sequence of Faulting with Fast Erosion

Extending a **15 km thick** layer at **2 mm/yr** (full rate).
Ref. erosion rate = **35% of fault slip rate**.



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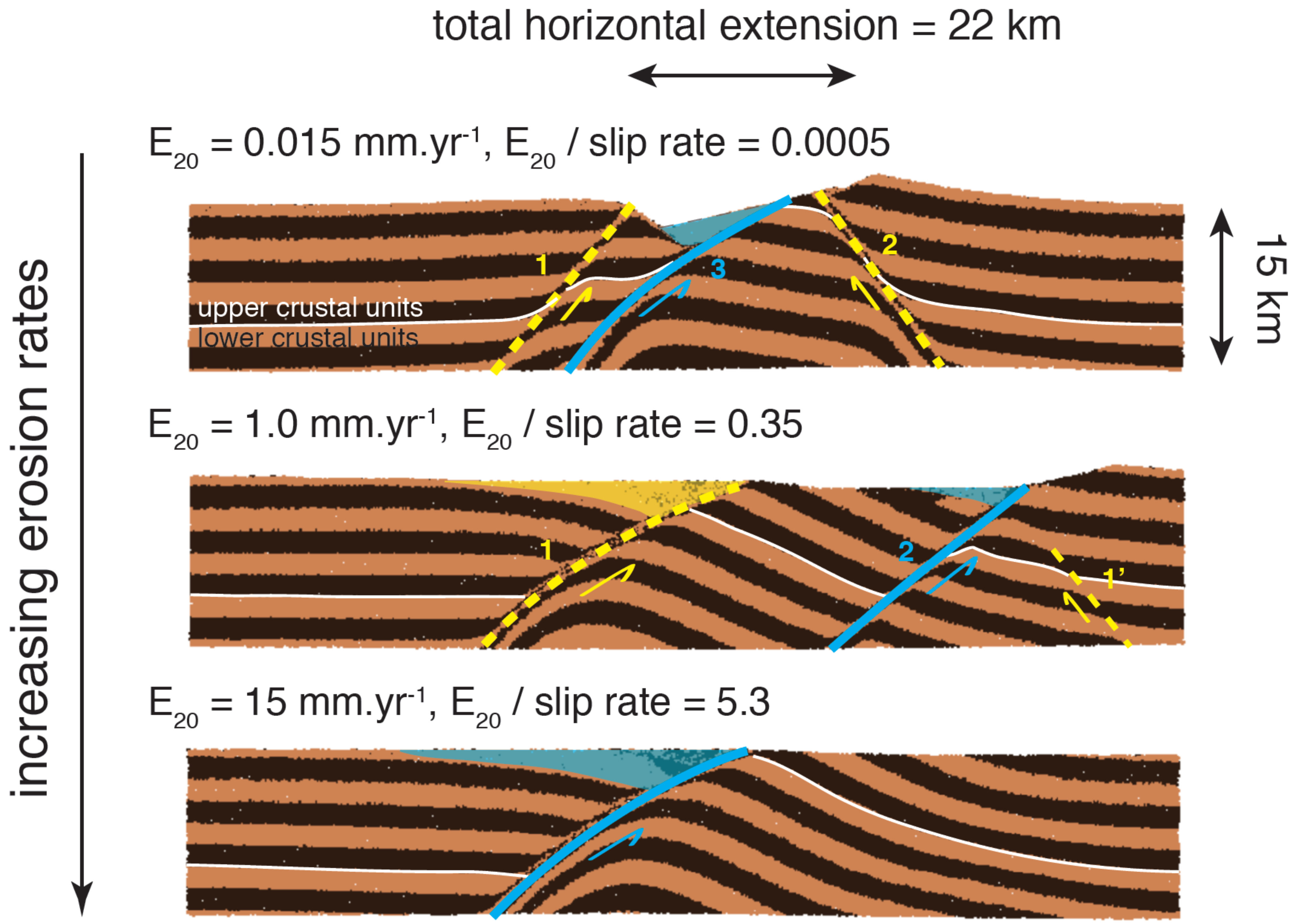
Relationship between Erosion Rate and Fault Lifespan



Faster erosion rates lead to longer normal fault lifespan.

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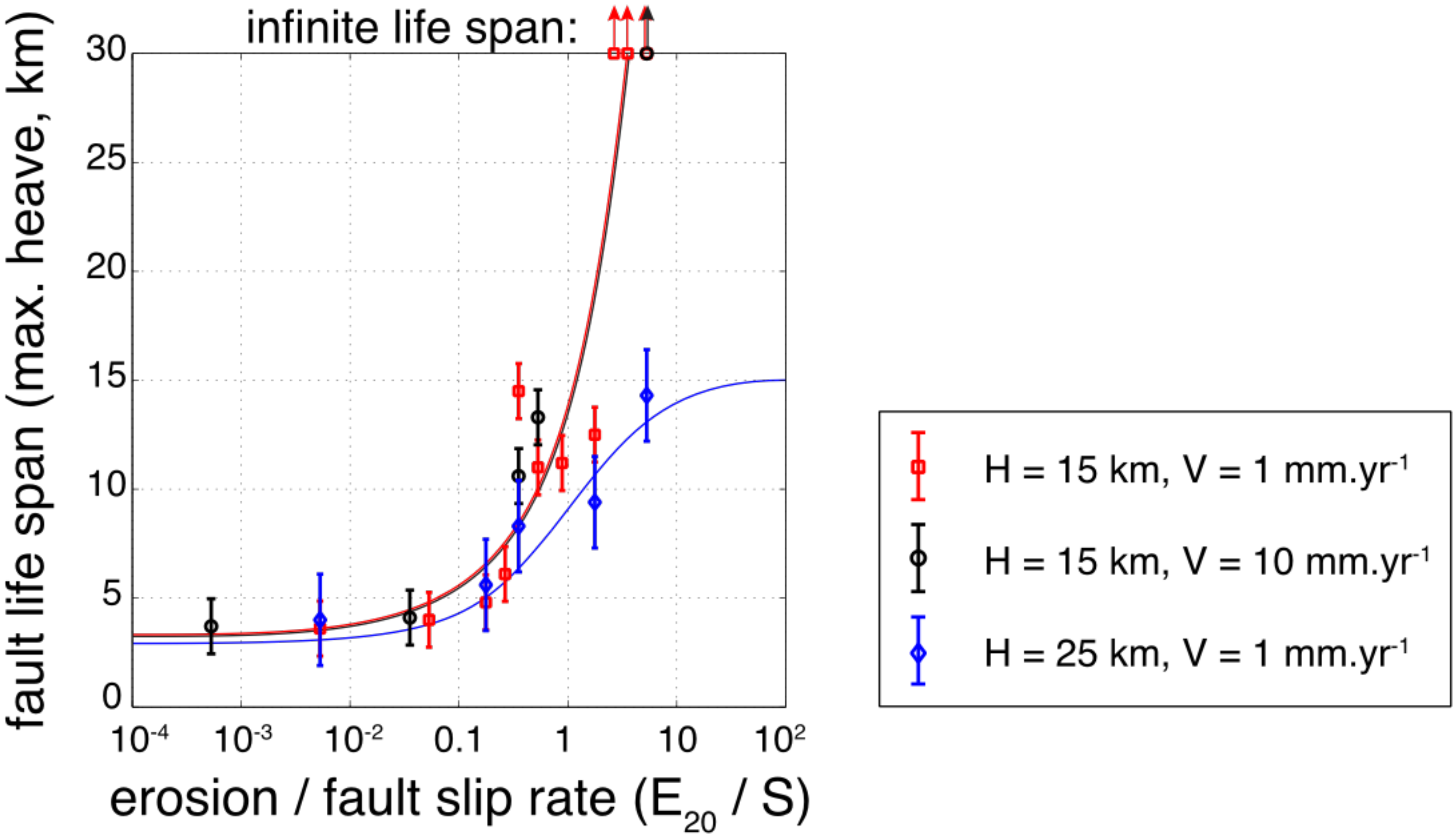
Relationship between Erosion Rate and Fault Lifespan



Surface processes further enhance fault life span in thinner faulted layers for a given erosion / slip rate.

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Example 2: Modeling Long-term Lithospheric Deformation

Scientific Take-Aways:

- Efficient erosion can enhance normal fault lifespan by relieving the energy cost associated with building rift-flank topography.
- Surface processes may therefore enable the development of the large offsets (10+ km) observed on major range-bounding normal faults.

Comments on the use of MATLAB®:

- MATLAB®'s ease of use has allowed *SiStER* to be adapted for a wide number of research problems by students and other researchers.
- MATLAB® "backslash" solver is highly efficient for 2D problems.
- Future work is needed to determine if MATLAB® will be competitive with other codes for 3D simulations that require parallel processing.

MATLAB

Concluding Thoughts

MATLAB® is an excellent tool for research in the geosciences due to its ability to seamlessly integrate data analysis and visualization.

Students learn the most from other students — teamwork is key!

Issues with using a "proprietary code" do exist at funding agencies and within the community…

MATLAB