Multi-sensor monitoring of rock glacier deformation sheds light on dynamic surface processes

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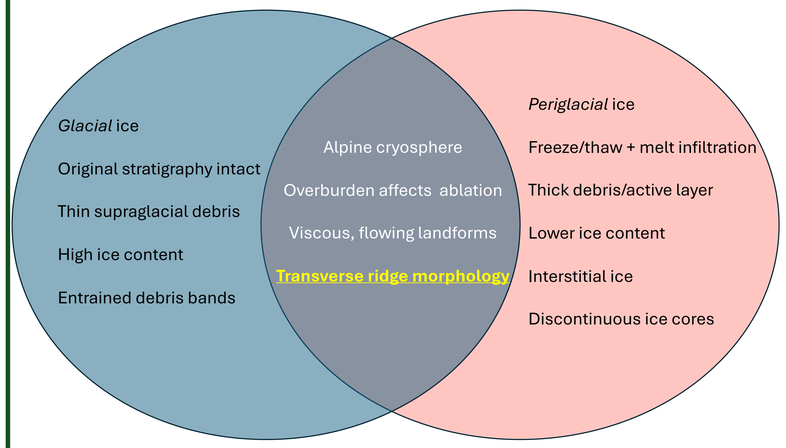
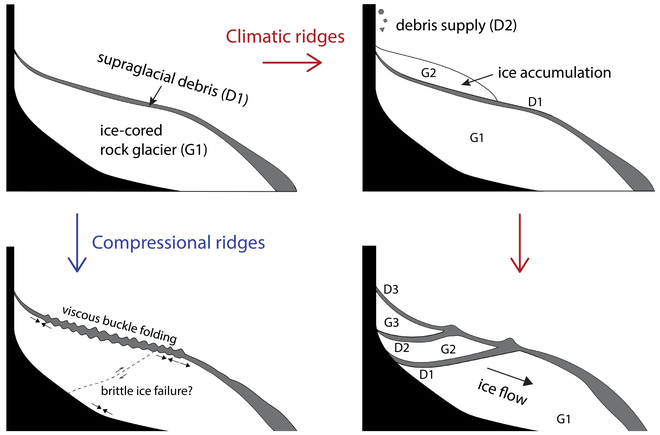
Debris-covered glacier — Rock glacier



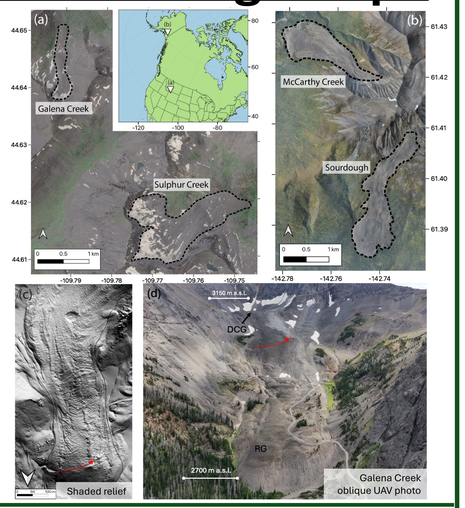
Transverse ridge morphology records stress/strain history and ice/debris accumulation variation



Parameters, Processes & Knowledge Gaps

- Surface morphology, micro-topography (cm scale)
- Debris and ice thickness, total ice volume
- Internal structure, correlation to ridge morphology
- Preserved paleoclimate signals
- Elevation change (surface melt, ~10 cm/year)
- Horizontal velocity (active ice flow, < 2 m/year)
- Seasonality of motion? Flow acceleration?
- Rheological effects of entrained debris?
- Thermokarst, slope destabilization, hazards?
- Active layer processes? Local variability?
- Role in changing ecological systems?

Which complementary measurement techniques provide the most complete understanding of processes modifying the alpine cryosphere?

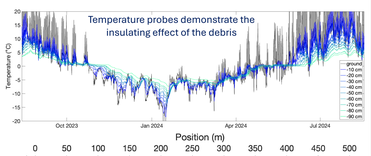


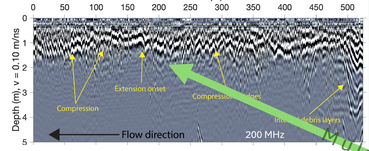
Ground-based Fieldwork

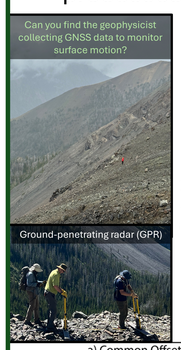
Spatial resolution: Very high
Spatial extent: Very limited
Temporal resolution: Sparse
Accessibility: Difficult

Measurements:

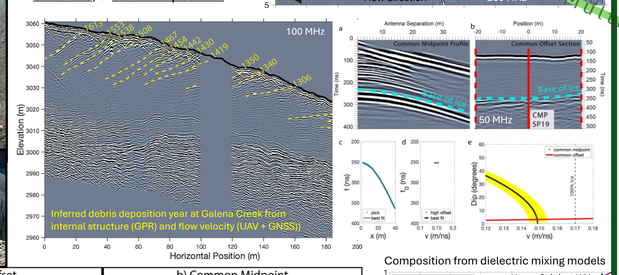
- Subsurface geometry and composition (GPR)
- Morphological mapping
- High-precision validation for remote sensing data (GNSS)
- Direct observation of physical processes

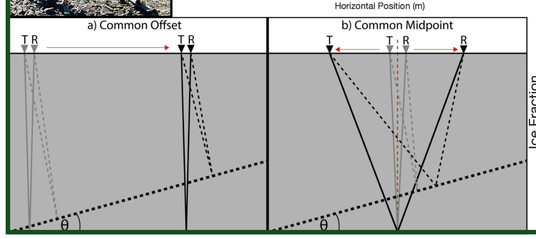


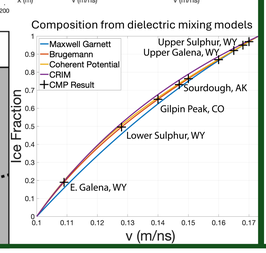




Multi-offset, multi-frequency GPR allows for constraints on debris thickness, ice thickness, internal structure, & bulk composition.







UAV/Piloted Photogrammetry Surveys

Spatial resolution: High/moderate
Spatial extent: Landform scale/regional
Temporal resolution: Moderate
Accessibility: Moderate

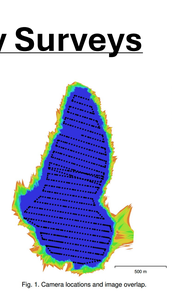


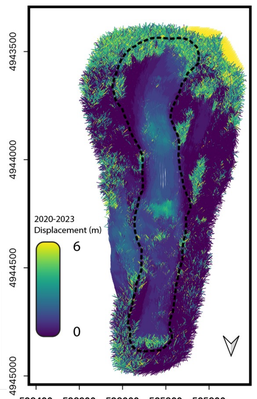
Fig. 1. Camera locations and image overlap.

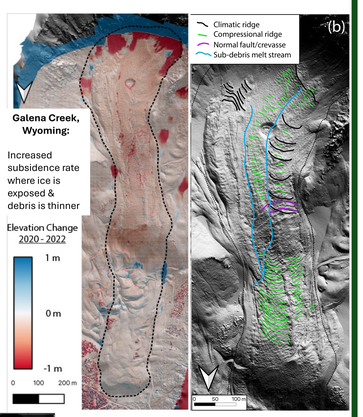
Measurements:

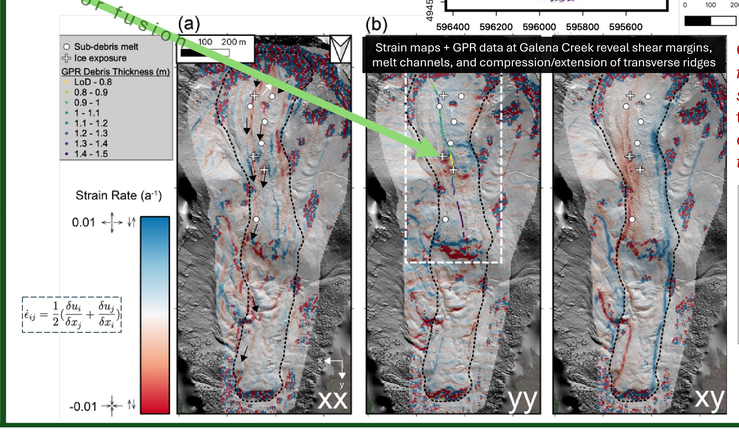
- High-resolution orthomosaics & DEMs (2-20 cm/pixel)
- Topographic change
- Optical feature tracking
  - ➢ Surface velocity
  - ➢ Strain maps
  - ➢ "Kinematic age"

Ground-based control points are extremely valuable for remote data uncertainty characterization!

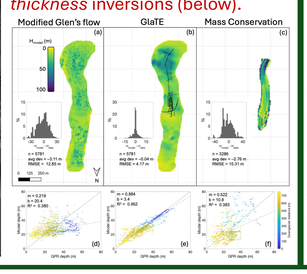
Multi-sensor fusion







Combined datasets permit *ridge formation* interpretation, *subsidence* estimates with thermal modeling, *paleoclimate* characterization, and *3D glacier thickness* inversions (below).



Orbital/Commercial SmallSat

Spatial resolution: Moderate/low
Spatial extent: Global
Temporal resolution: High
Accessibility: Mission cost

Open-access resources:

Meng et al., 2022 (*Journal of Glaciology*)

Meng et al., 2023 (*Remote Sensing*)

Data/code for "Effects of rock glacier dynamics on surface morphology and deformation" (in review)

Measurements:

- *Optical imaging*: limited by resolution and georeferencing due to slow flow
- *InSAR*: high line-of-sight displacement sensitivity, consistent temporal resolution (12 days with Sentinel-1)
  - ➢ Flow variability detection is limited by pixel size
  - ➢ Coherence in high-relief terrain can be sporadic
- Error & bias inhibit precise subsidence estimates

Ongoing goal: characterize error sources to leverage multi-sensor methods for minimizing geophysical uncertainty propagation.

Right: Multi-sensor topographic change at Alaskan field sites showing how resolution/bias affects surface process observation.

Below: Small baseline subset (SBAS) time series analysis consistent with *increased summer deformation rates for both rock glaciers*.