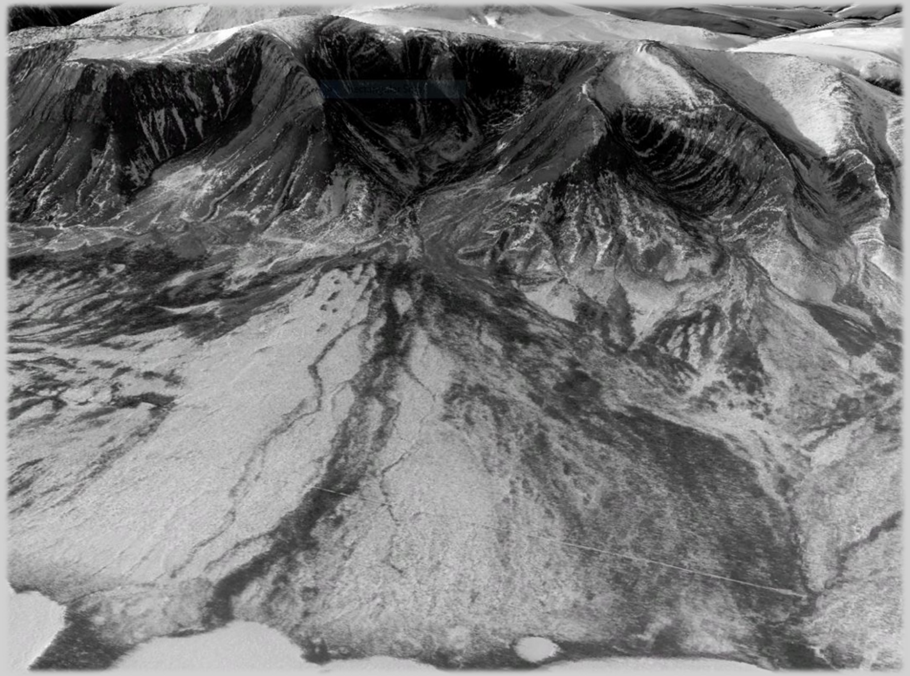
Sediment transport processes in an arctic watershed undergoing climate change



Marisa C. Palucis, Justin V. Strauss, and Jill Marshall

Motivation

Rowland et al., 2010

- Arctic warming ~2x faster than temperate landscapes
- Degradation of permafrost will change water and sediment fluxes (and processes)
- Carbon, nutrients, and trace elements will follow similar pathways

Want to quantify water and sediment fluxes to an alluvial fan (closed system) in an arctic catchment

- What are the dominant processes that build periglacial fans?
  - Low rock-to-water fluvial events
  - High rock-to-water debris flow events

- What are typical flow discharges, grain sizes, and sediment fluxes?

- How does this fan compare to temperate systems?

Field site: Richardson (Aklavik) Mountains (NWT, Canada)

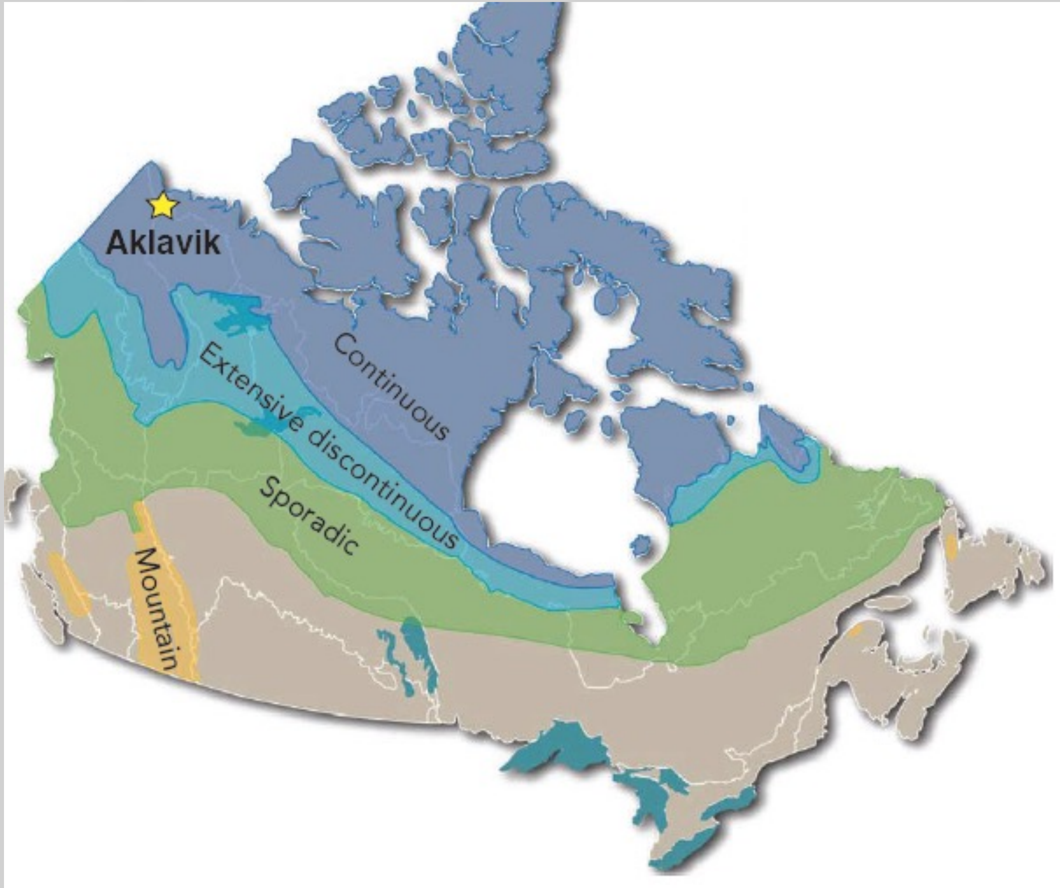
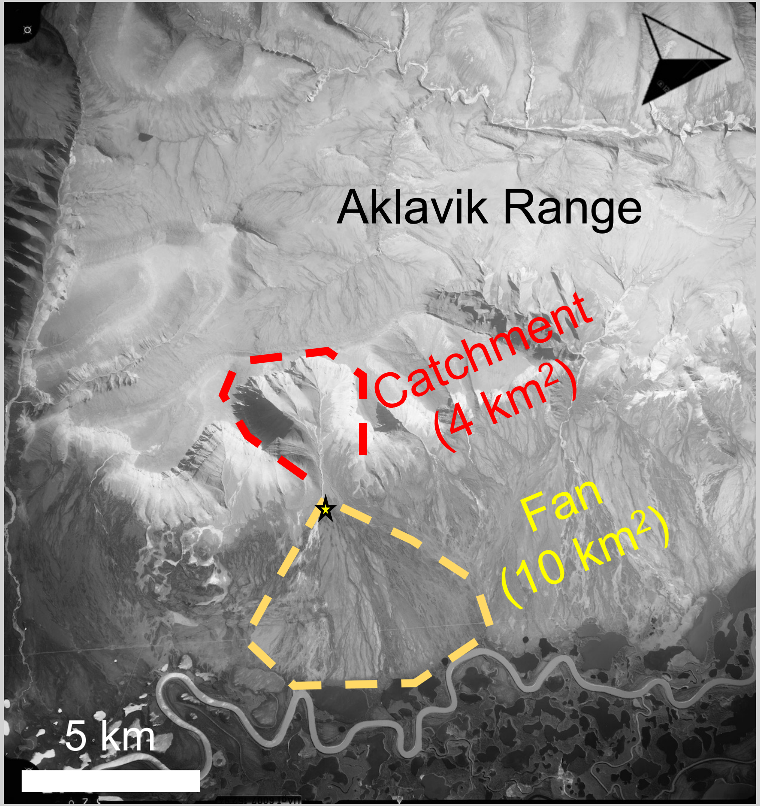


Photo Credit: International permafrost association

Field site: Black Mountain Fan



National air photo library (NAPL, Natural resources Canada)

Field Site: Black Mountain Fan

- **Climate**: semi-arid with cold and dry winters and short summers (12^{o}C mean temp in June and -35^{o}C mean temp in January), mean annual precipitation is ~200-250 mm (>50% snow)

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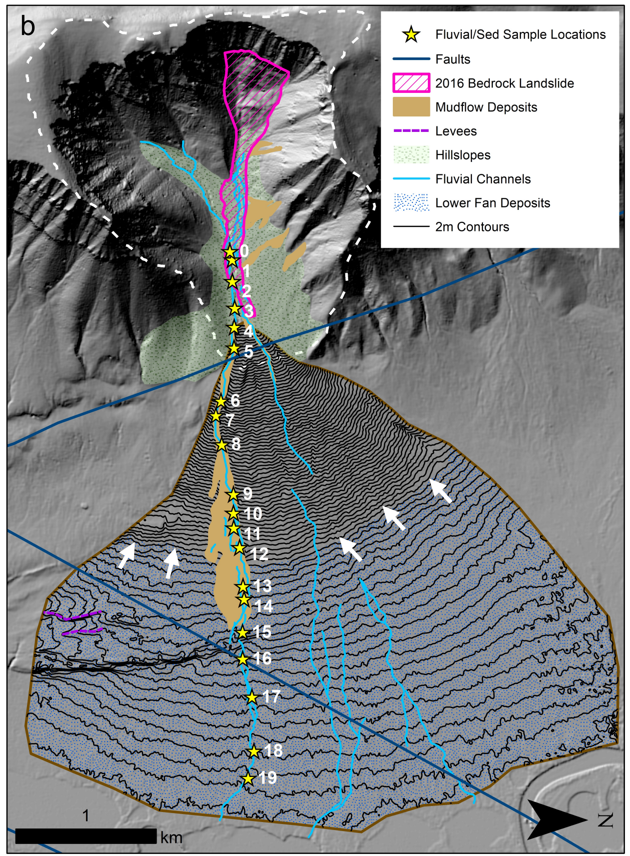
- **Geomorphology**: fan mapped in the 1990s to be a debris flow dominated fan with periglacial modification

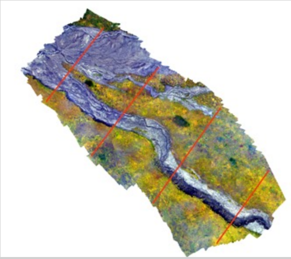
Summer 2019 Field Campaign



Palucis et al., *in press*

Fan sedimentology and geomorphology

Monitor active flow event

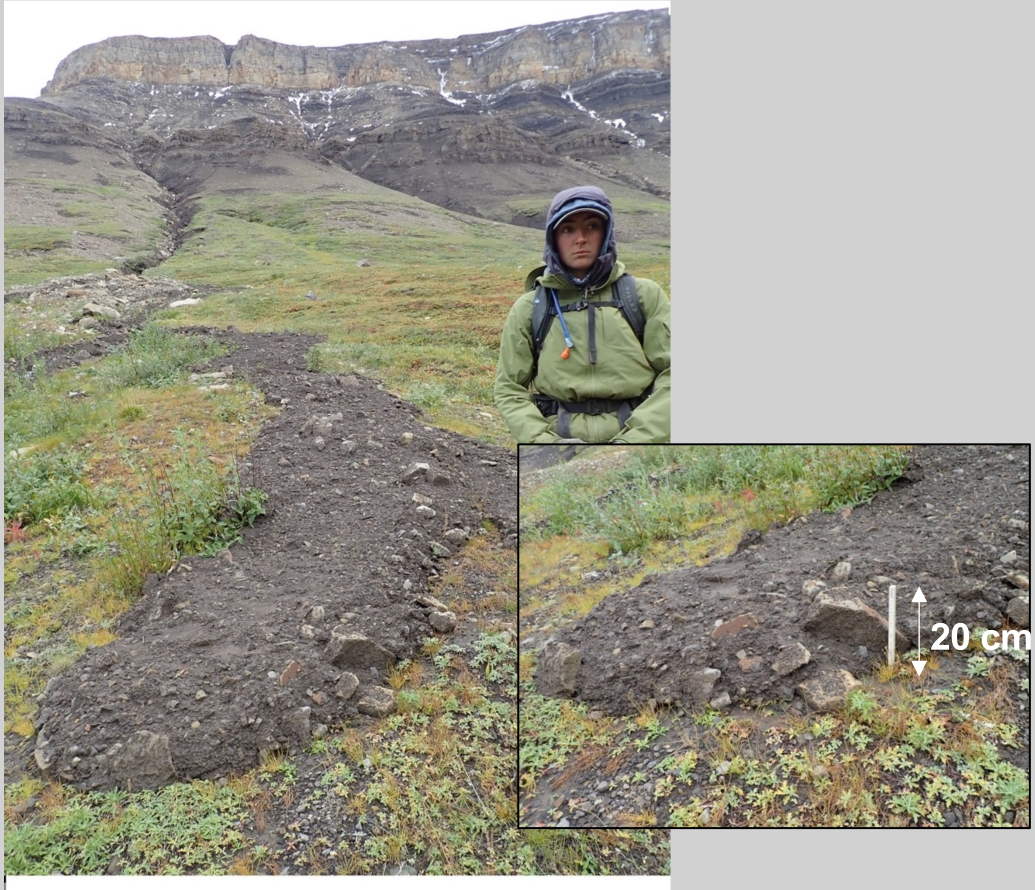


Fan topography

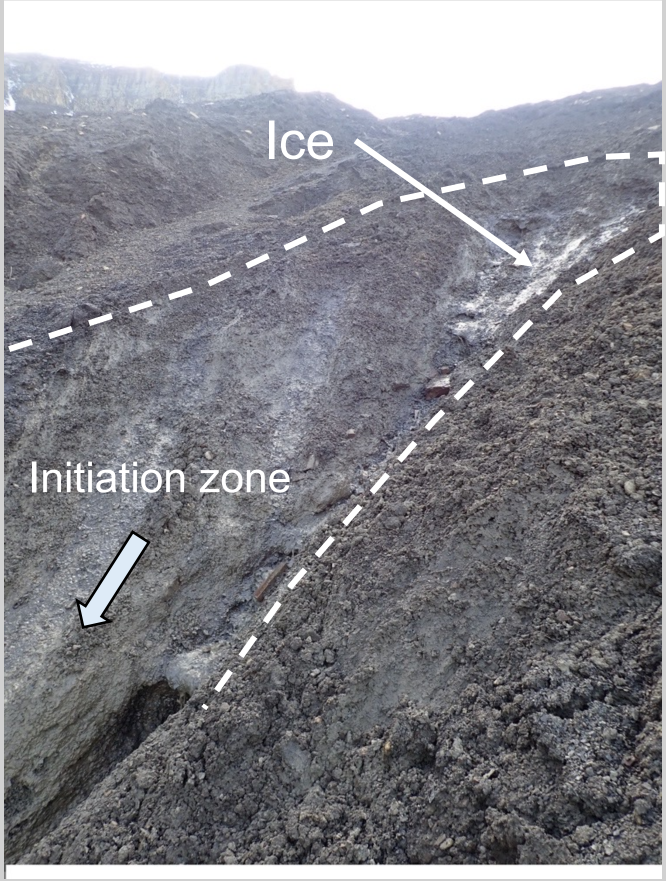
Results

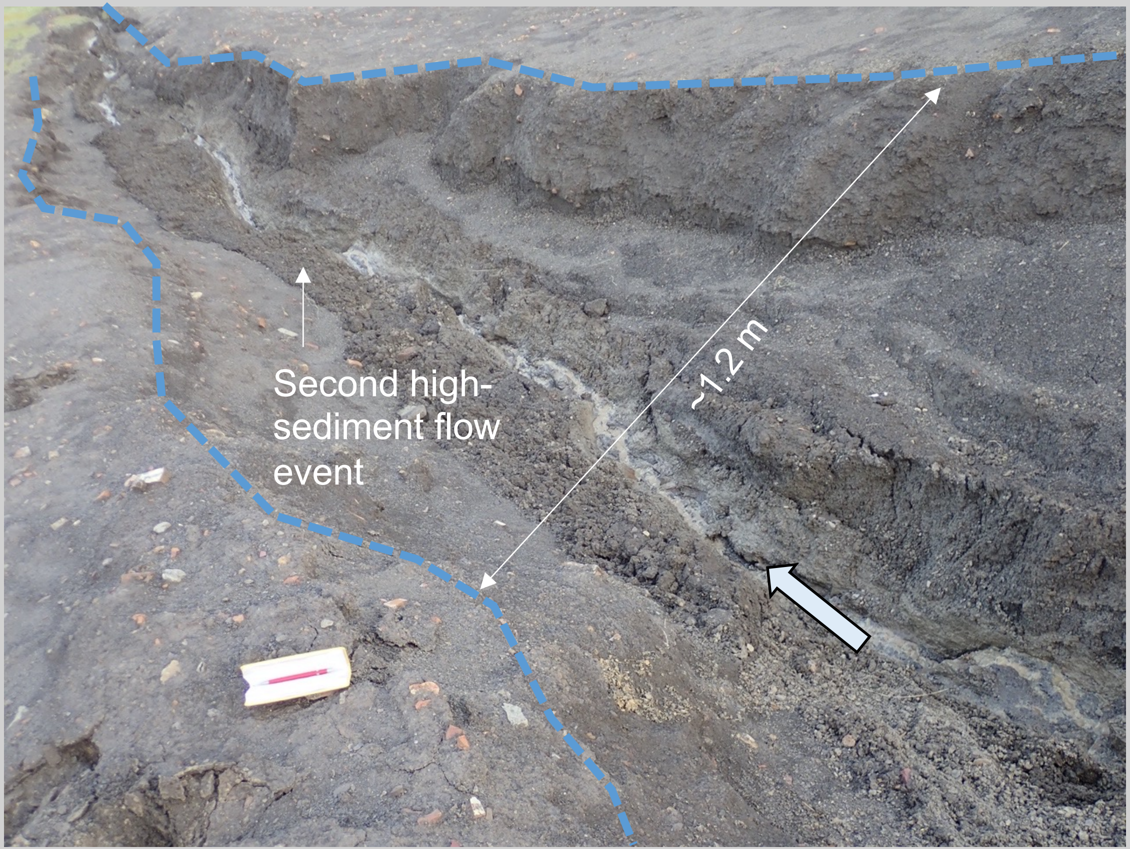
- What are the dominant processes that build periglacial fans?
  - Low rock-to-water fluvial events
  - High rock-to-water debris flow events
- What are typical flow discharges, grain sizes, and sediment fluxes?
- How does this fan compare to temperate systems?

Results: debris flow event from icy gully



Results: debris flow event from ice-melt-induced landslide





Results: Lower fan had active fluvial channels across it

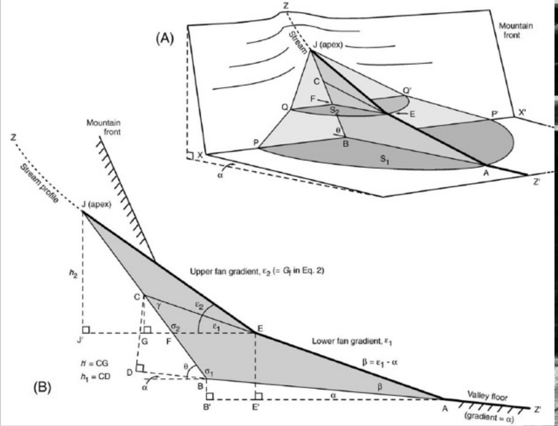
Results: mainly debris flow deposits within incised channel walls of upper fan

- Where we have good exposures, clasts tend to be sub-angular to sub-rounded, poorly sorted, no imbrication or sedimentary structures, occasionally reverse grading

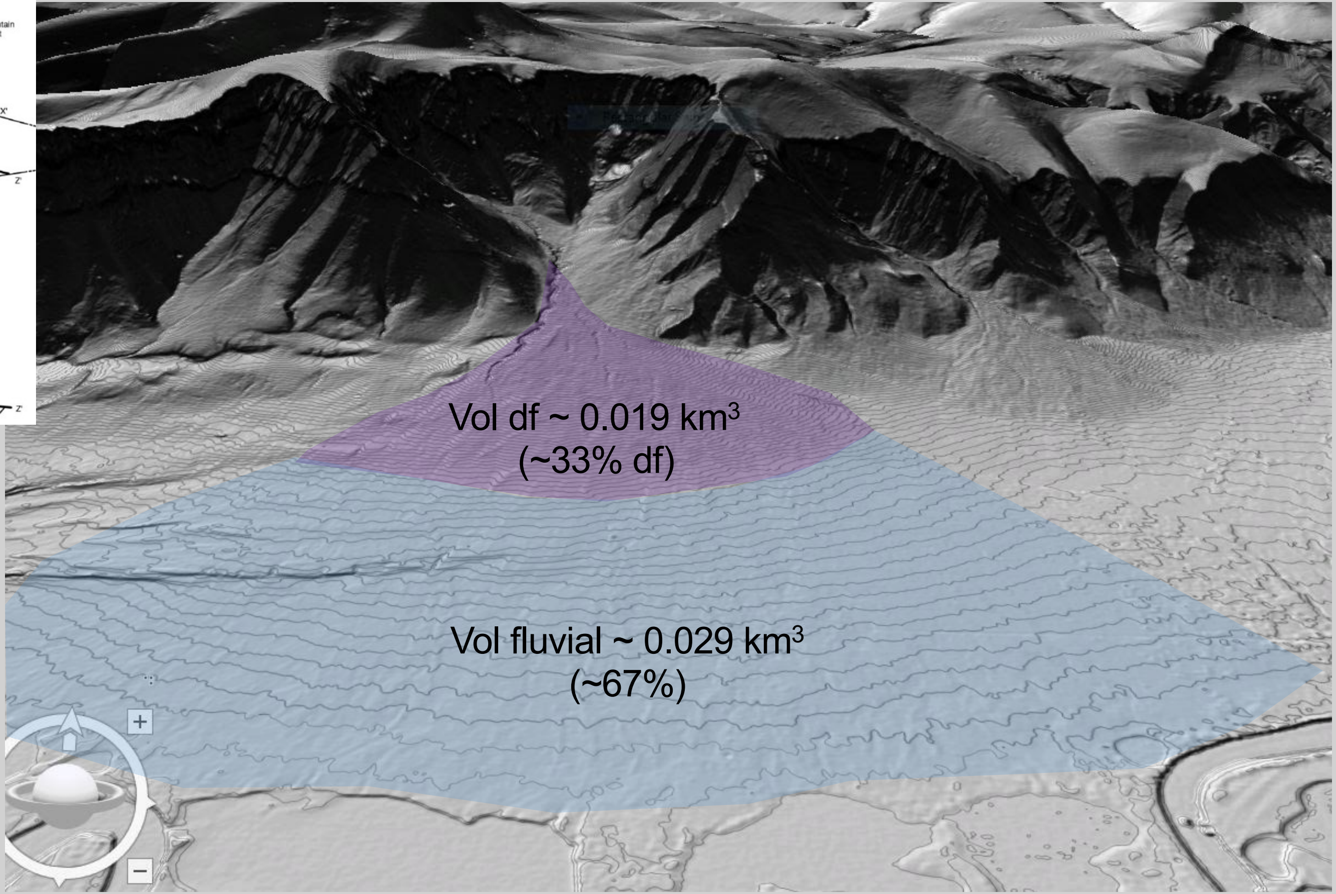
Results: fluvial processes dominate lower fan

- Alternating layers of silt and clay
- Layering is ~5 cm thick, with silt often in lenses with imbricated pebbles
- Lower fan deposits tend to be overlain with ~0.5 to 0.75 m of soil/tundra

Results: % debris flow versus fluvial



Giles et al. (2010)



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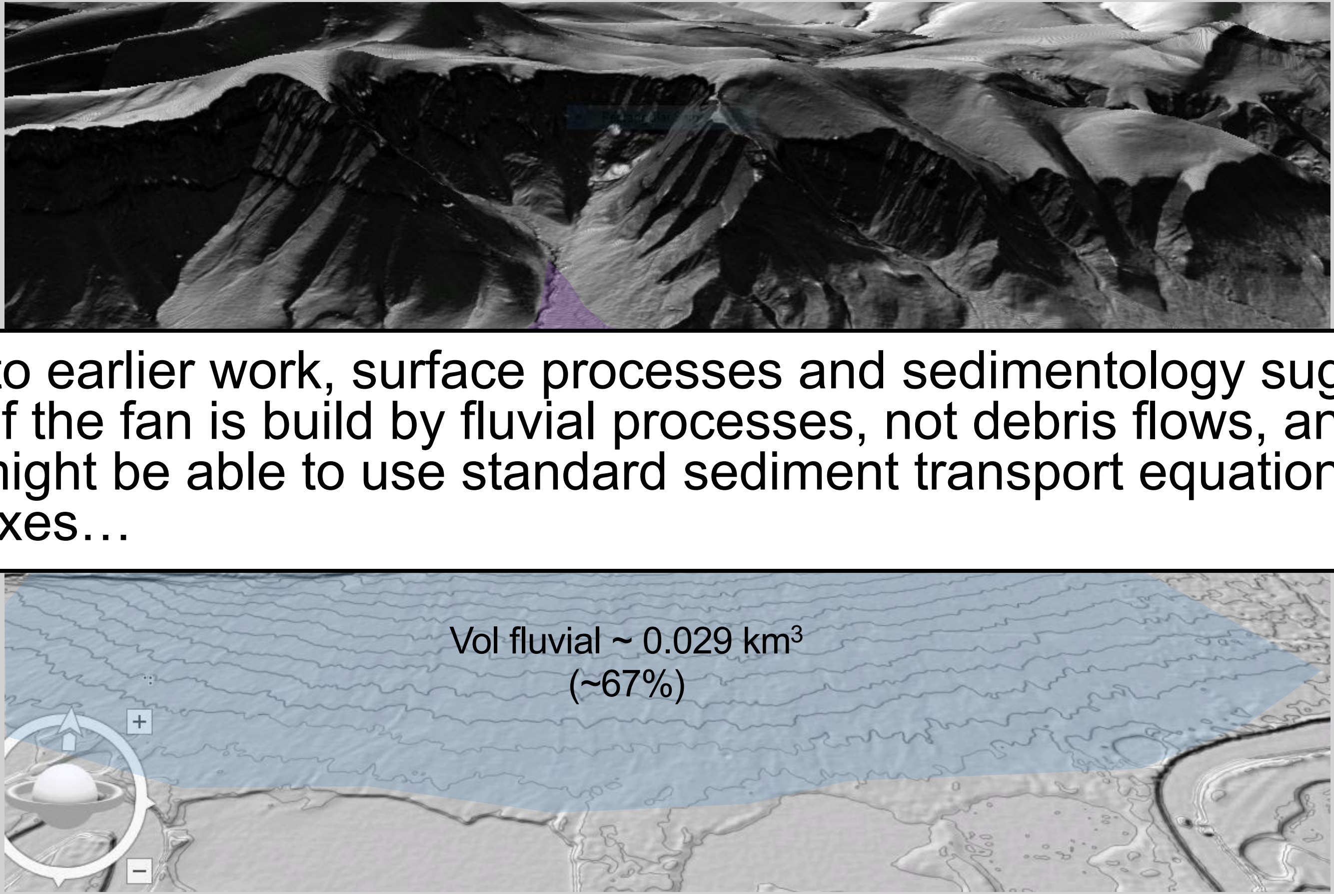
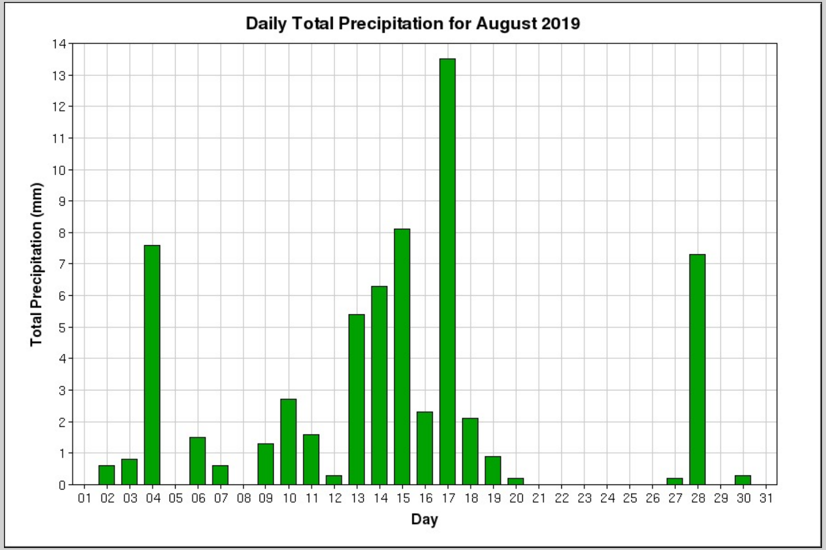


Compared to earlier work, surface processes and sedimentology suggest that much of the fan is build by fluvial processes, not debris flows, and hence we might be able to use standard sediment transport equations to estimate fluxes…

Results

- What are the dominant processes that build periglacial fans?
  - Low rock-to-water fluvial events
  - High rock-to-water debris flow events
- What are typical flow discharges, grain sizes, and sediment fluxes?
- How does this fan compare to temperate systems?

Results: Observed a rain/snow event on Aug 17 2019



- ~14 mm of rain and snow occurred over several hours on the evening of the 17th
- Max rate ~ 1 - 2 mm/hr
- Snow filled the gullies within the catchment; rain occurred lower on the fan (at camp)

Climate.weather.gc.ca

Results: Discharge (Q)

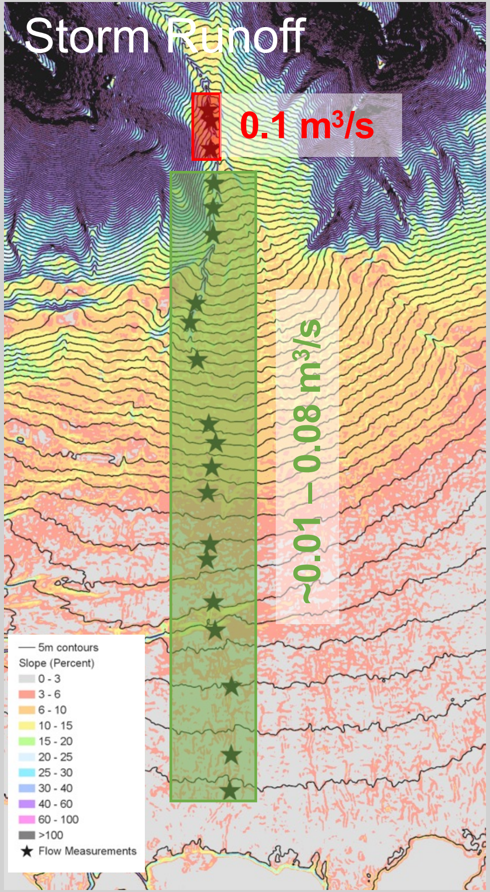
(1) $$U = \sqrt{gHS}\,\frac{6.5(\frac{H}{D_{84}})}{[(\frac{H}{D_{84}})^{5/3} + 6.76]^{1/2}}$$

(2) Q = discharge = UWH

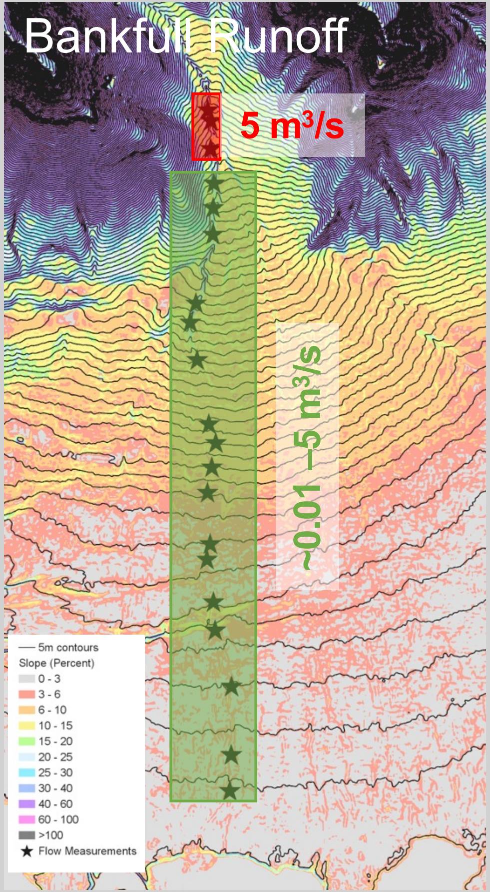
Variable power flow resistance equation (VPE) (Ferguson, 2007 and 2012)

- H = flow depth (field)
- D_{84} = grain size (field, 84^{th} percentile)
- S = slope (field, DEM)
- U = average flow velocity

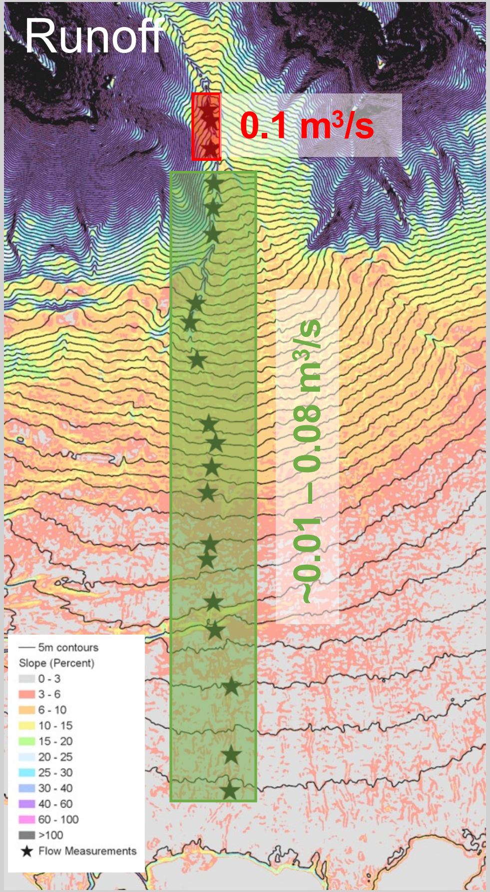
Results: Storm discharge

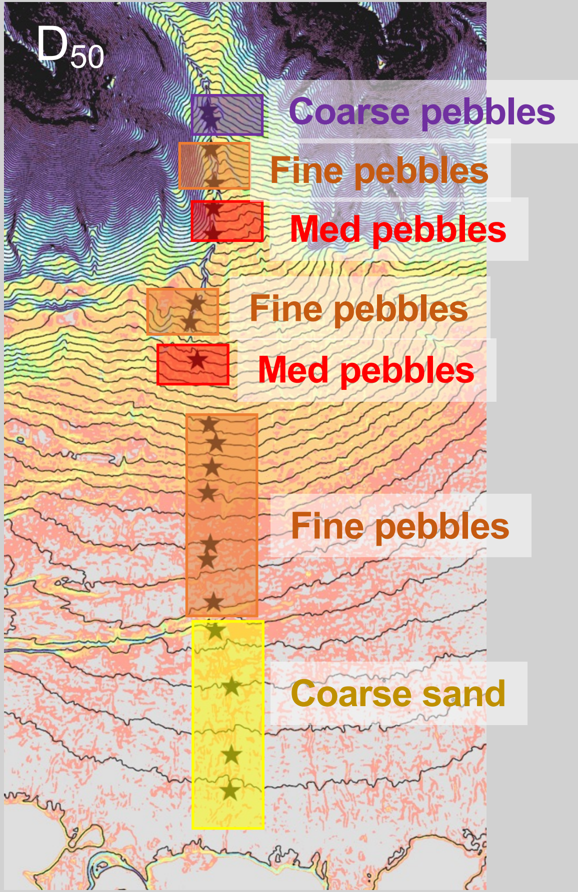


Results: Bankfull discharge

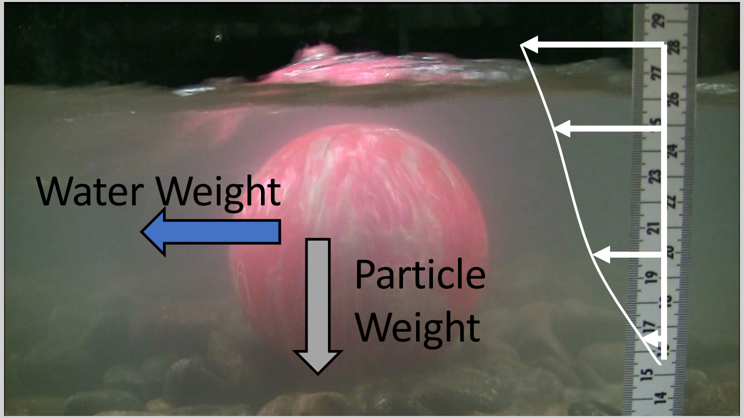


Results: Grain size





Results: Fluvial sediment flux



Force of flow / Particle weight →

$$\tau_* = \frac{\rho g h S}{(\rho_s - \rho) g D}$$

Sediment flux α τ* / τ*$_c$, where τ*$_c$ is the threshold over which sediment starts to move (τ* / τ*$_c$ > 1 means sediment moving)

$$\tau_c^* = 0.15S^{0.25}$$

Lamb et al. (2008)

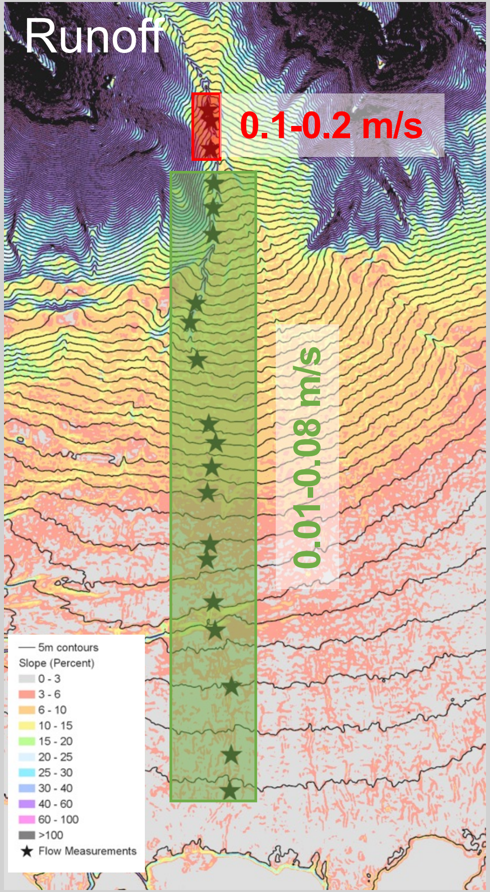
$$\tau_c^* = 0.021 + 0.015exp[-20F_S]$$

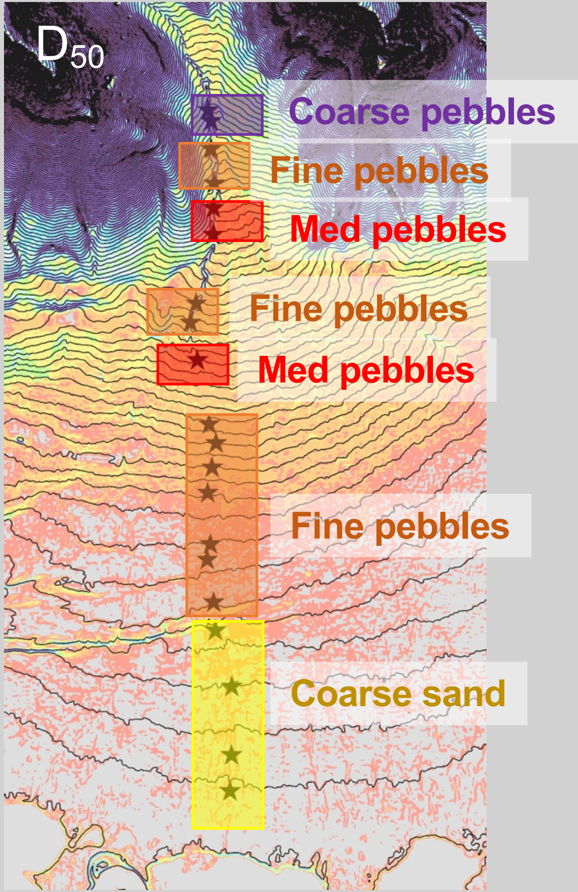
Wilcock and Crowe (2003)

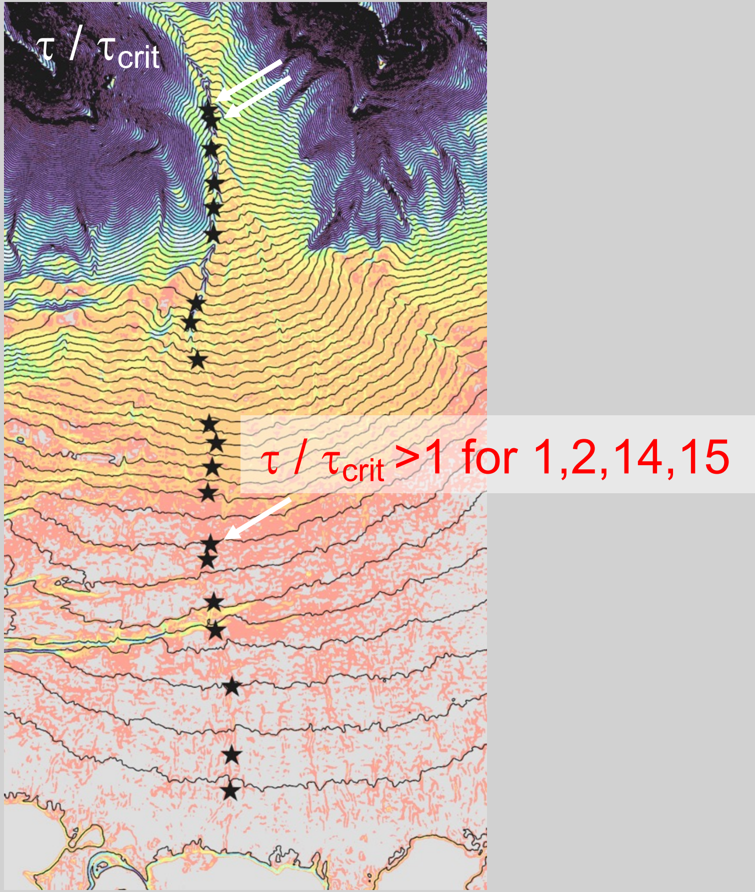
$$\tau^*_c = 0.56S^{0.5}$$

Schneider et al. (2015)

Results: Fluvial sediment flux







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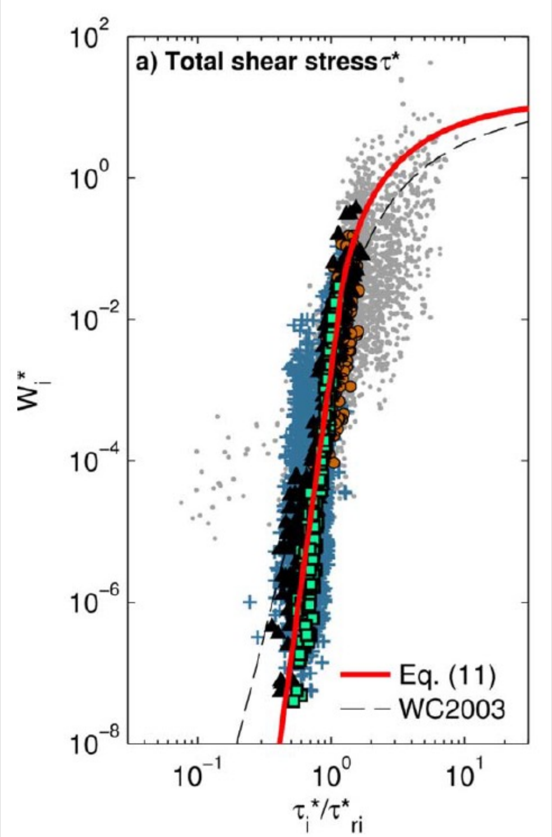
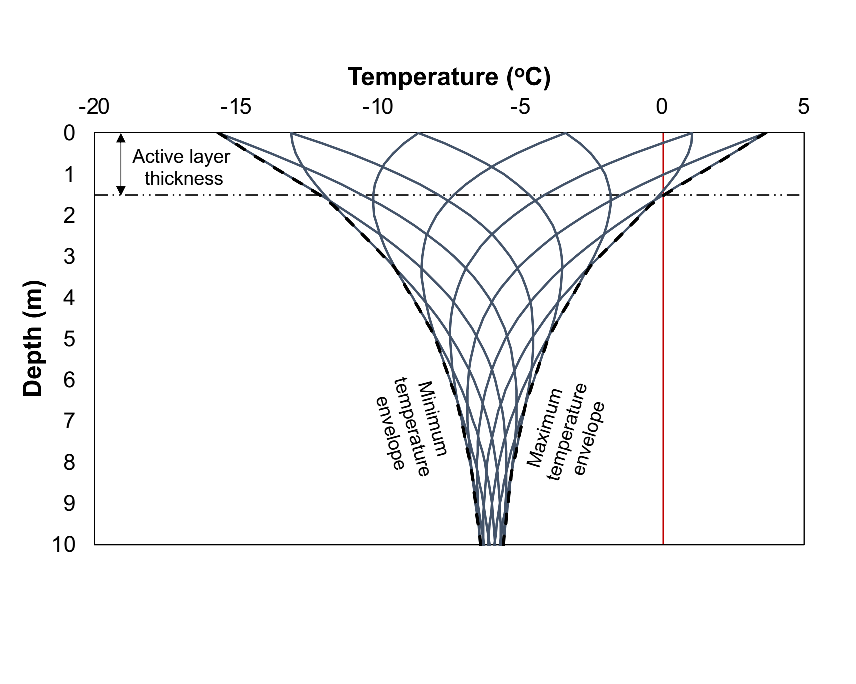


Schneider et al. (2015)

- $W* = \frac{q_s}{D_{50}\sqrt{RgD_{50}}}$ = Einstein number
- For range of $\tau* / \tau*_c$ estimated, dimensionless sediment flux per unit width (W) ranges from 0 to 0.4 (for storm) and 10^{-6} to 5 (for bankfull)
- Converted to dimensional flux, we estimate fluxes of 0 to 0.04 m^3/hr during storm and 0.3 to 440 m^3/hr (**70 m^3/hr average)** during bankfull

Results: Debris flow sediment flux

$$T(z,t) = \bar{T} + \Delta T e^{-z/z_*} \sin\left[\frac{2\pi t}{P} - \frac{z}{z^*}\right]$$



Anderson et al. (2013)

- Using simple diffusion model with periodic BC, estimate active layer depth is ~ 1.5 m
- Most debris flow deposits were 1 – 2 m thick
- Possible that size of mass failures controlled by melting and failure along permafrost table – but intermittency unknown…

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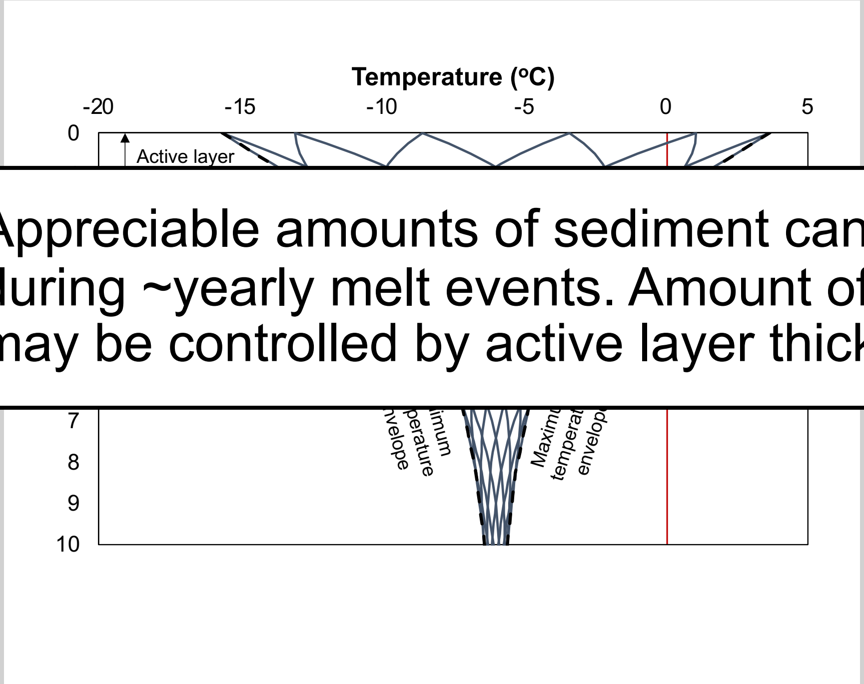

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Appreciable amounts of sediment can be moved by fluvial processes during ~yearly melt events. Amount of sediment delivered by debris flows may be controlled by active layer thickness on hillslope/talus.

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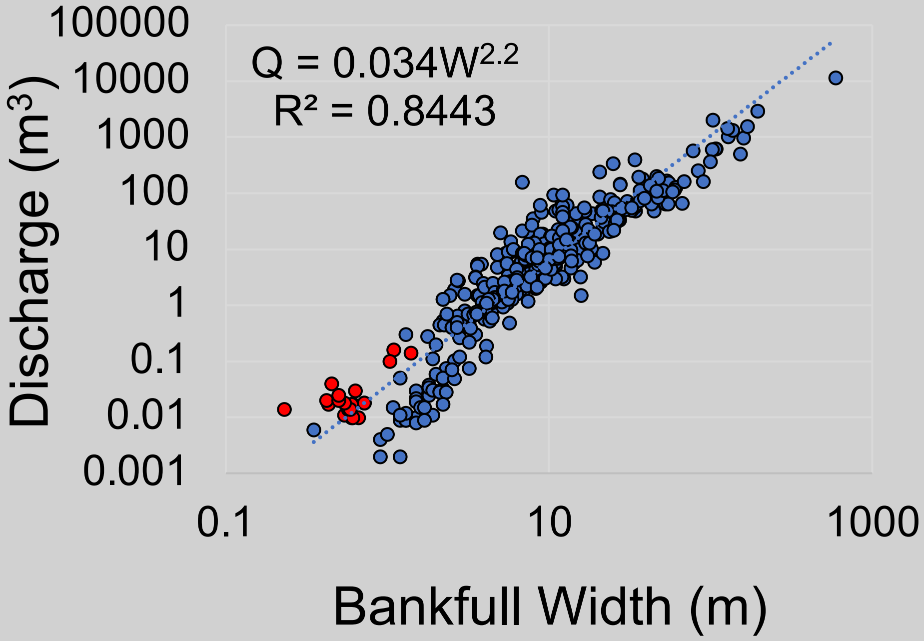
Results: Arctic fan compared to terrestrial alluvial rivers



Terrestrial data from Palucis and Lamb (2017)

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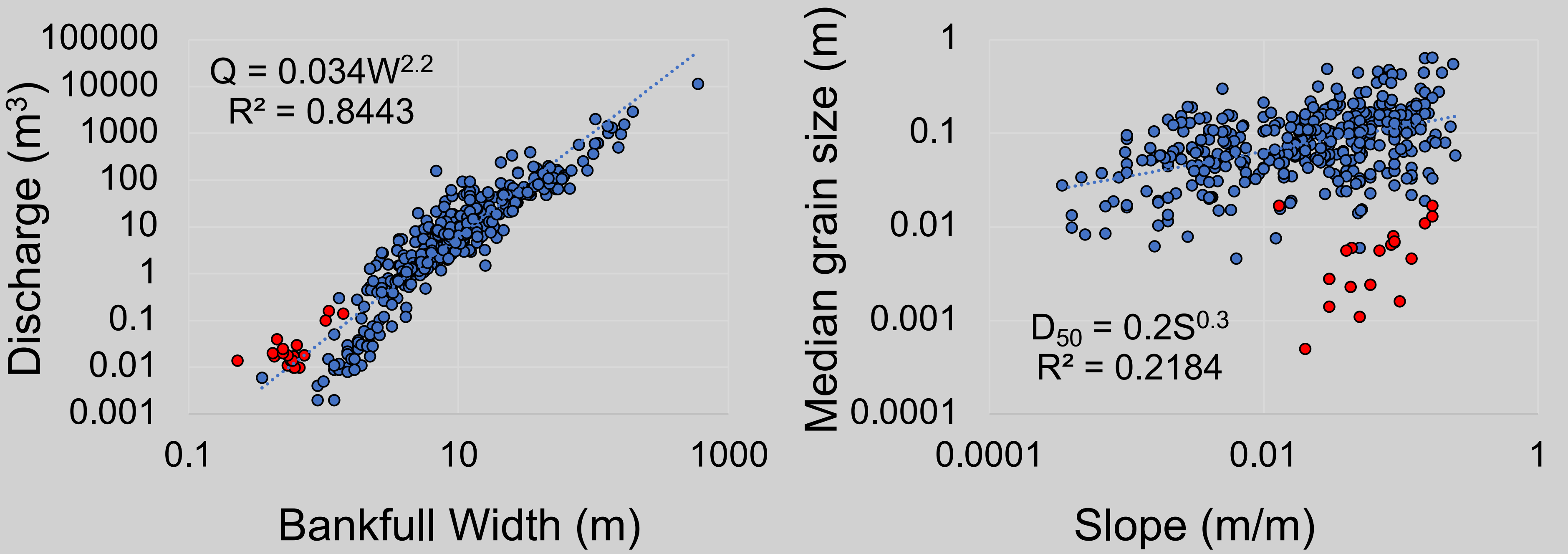
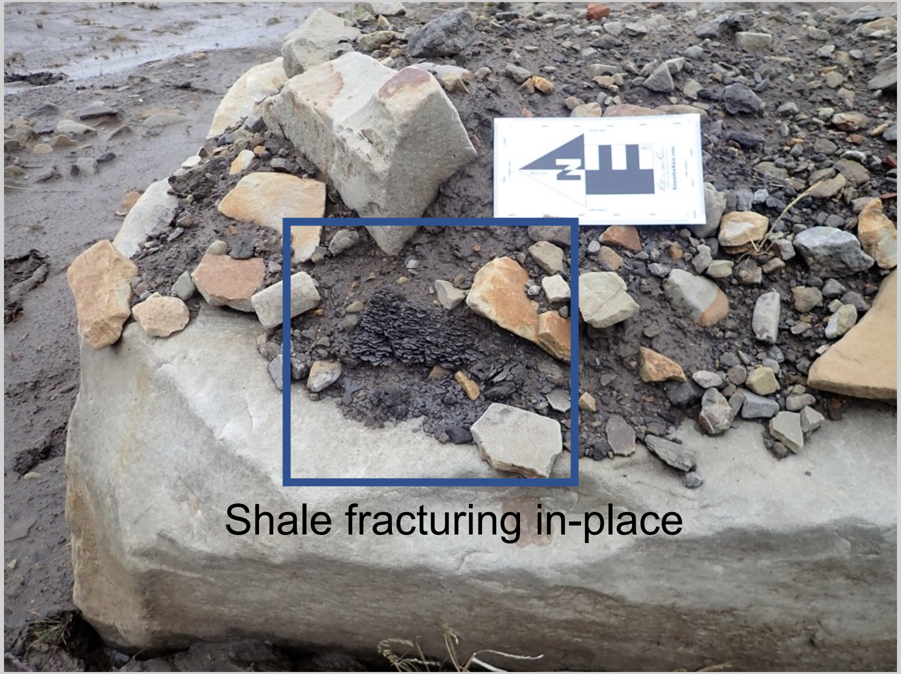


Terrestrial data from Palucis and Lamb (2017)

Results: Shale fracturing



Results: Shale fracturing

Shale fracturing in-place

Discharge-width relation still holds for this arctic fan channel, but grain sizes within channels are finer relative to other (more temperate) steep streams

Conclusions

- Compared to earlier work and other periglacial fans, surface processes and sedimentology suggest that much of the fan is build by fluvial processes, not debris flows

- Appreciable amounts of sediment can be moved by fluvial processes during ~yearly melt events. Amount of sediment delivered by debris flows may be controlled by active layer thickness on hillslope/talus

- Icy processes seem to be an important control on sediment amounts and grain size entering the fan system, as well as sorting along fan → fine-grained sediment in steep channels might promote mass flow events / in-channel debris flows

Thanks!

- NASA SSW grant 80NSSC19K0539
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