The University Of Sheffield.

Christopher T Lloyd, Christopher D Clark, Darrel A Swift

Department of Geography, University of Sheffield, UK

Controls on the location and geometry of glacial overdeepening

What is an overdeepening, and why is the phenomenon interesting?

1. The process of a glacier eroding below the fluvial graded profile is known as overdeepening
2. The landform generated by this process is also termed an overdeepening
3. Overdeepenings are common features of glaciated / formerly glaciated landscapes, typically found in cirques and glacial troughs

What is an overdeepening, and why is the phenomenon interesting?

4. Suggested that overdeepenings develop by glacial erosive processes (quarrying, abrasion and glacial meltwater erosion)

(see Hooke, 1991; Alley et al., 2003)

5. Pre-existing valley topography and geology are also thought to be significant controls

(see Glasser, 1995; Kessler et al., 2008; Krabbendam & Glasser, 2011)

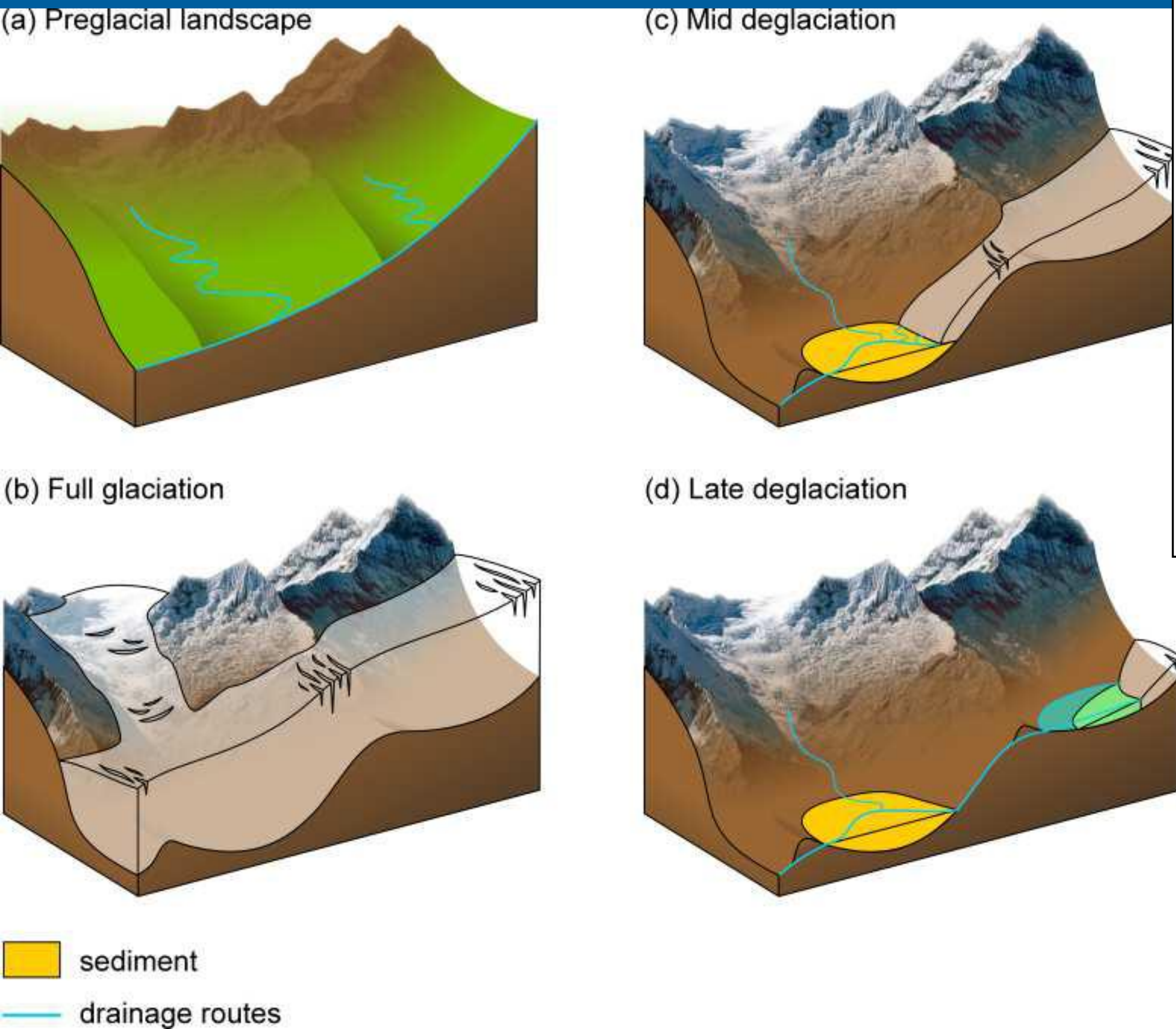
6. Of interest because overdeepening process is thought to be major control on glacial landscape development, and has potential to influence response of ice masses to climatic changes

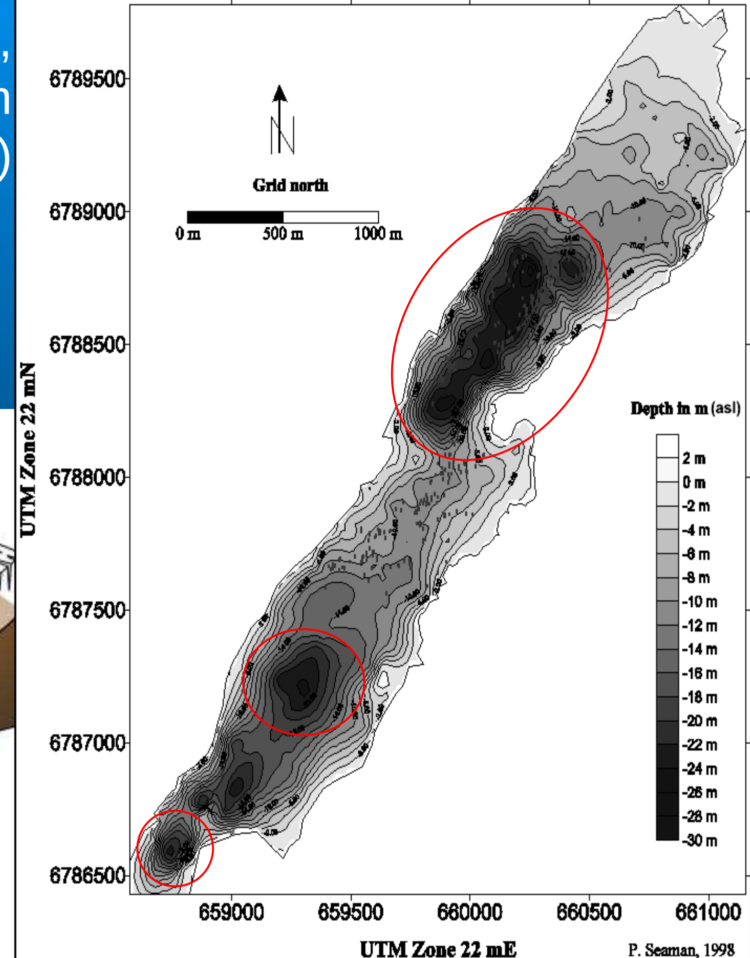
- Glacial overdeepenings have never been systematically studied

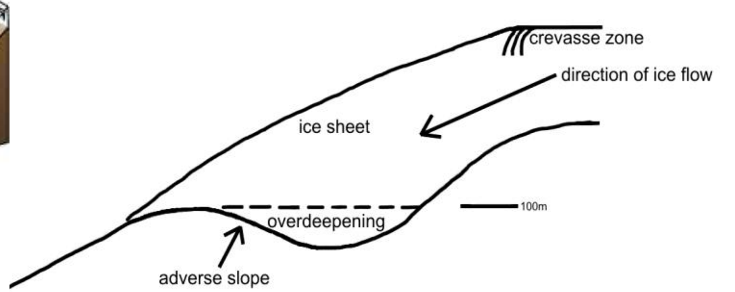
- Investigation analyses several hundred overdeepenings, examining controls on overdeepening location and geometry, focusing on influence of glacial confluence and geology, in and around Labrador province of Canada

Bathymetry of the Ikka Fjord, SW Greenland (modified from Seaman, 1998)

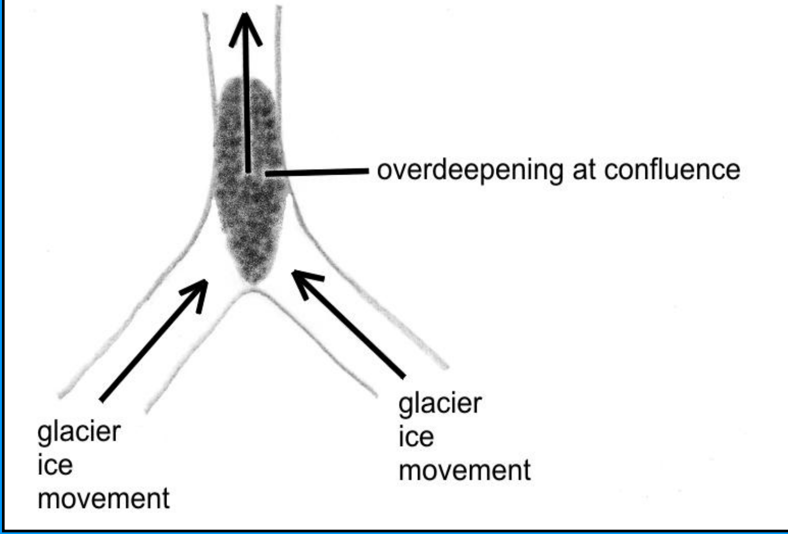
Schematics illustrating typical glacial and post-glacial context of overdeepened basins under temperate valley glaciation (Cook, S.J., Swift, D.A., submitted)







Hypotheses



• *Overdeepening initiation is driven by change in glacial valley cross-sectional area, via influencing basal ice velocities (i.e. a focus of localised ice acceleration, or 'speed up')*

• *Proximity to major geological fault-zones will, subsequently, drive change in overdeepening geometry (specifically, overdeepening depth), via influencing supply of basal ice debris*

The University Of Sheffield.

Method

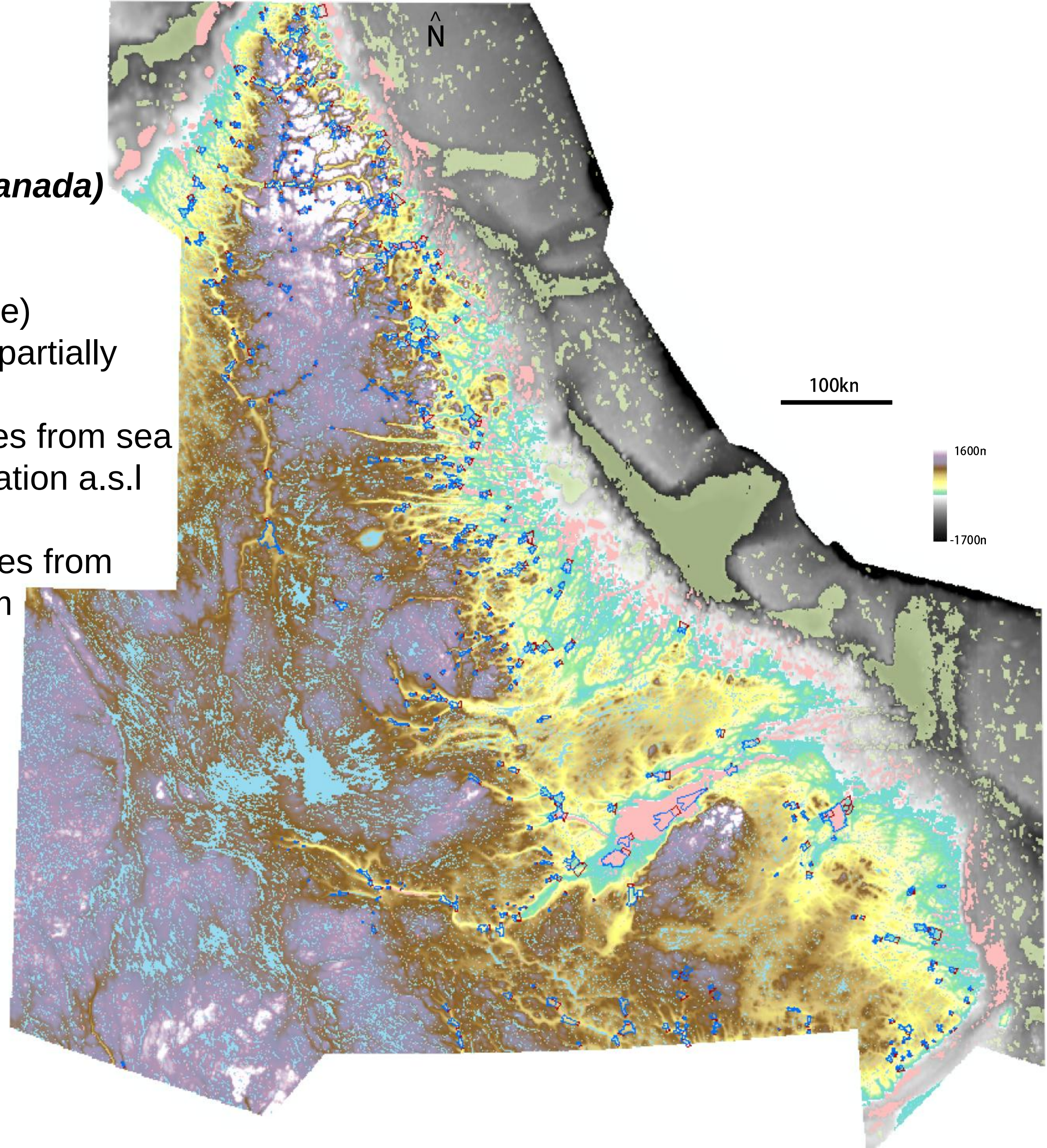
• Analysis tools: GIS software (ESRI ArcGIS) and spreadsheet software (Excel)
• Datasets examined: NASA SRTM3 and GEBCO (08) digital elevation models (DEMs) of the study region

1. *Identifying overdeepenings using sink fill algorithm + filtering*
2. *Identifying confluences by manual methods (i.e. visually, and by slope and contour)*
3. *Identifying confluence, overdeepening associations (GIS tool)*
4. *Calculating and analysing confluence cross-sectional area (CSA) ratio values (i.e. take transverse profiles of tributary and trunk valleys; change in CSA through confluence expressed as ratio)*

The University Of Sheffield.

The study region (Labrador, Canada)

Key:
- Glacial confluences (blue outline)
- Overdeepenings (rose, empty/ partially sediment filled; light blue, lakes)
- SRTM3 topography scale ranges from sea level (turquoise) to ~1600m elevation a.s.l (white)
- GEBCO bathymetry scale ranges from sea level (white/grey) to ~-1700m depth (black)



Method

5. *Analysis of confluence (tributary:trunk) ratio relationship with overdeepening metrics*

The metrics considered:

- Overdeepening area
- Maximum overdeepening depth
- Distance between confluence centre (the theoretical position of peak ice velocity) and proximal edge of overdeepening
- Distance between confluence centre and location of maximum overdeepening depth

The University Of Sheffield.

Method

6. *Analysis of confluence (tributary:trunk) ratio relationship with overdeepening metrics, for geological zones of the study region*

    - Geological subsets are: igneous, metamorphic, sedimentary and structural shear/ fault zones

- Utilised GIS shapefile datasets of geology of Labrador; 1:1,000,000 scale & geology of Switzerland; 1:500,000 scale

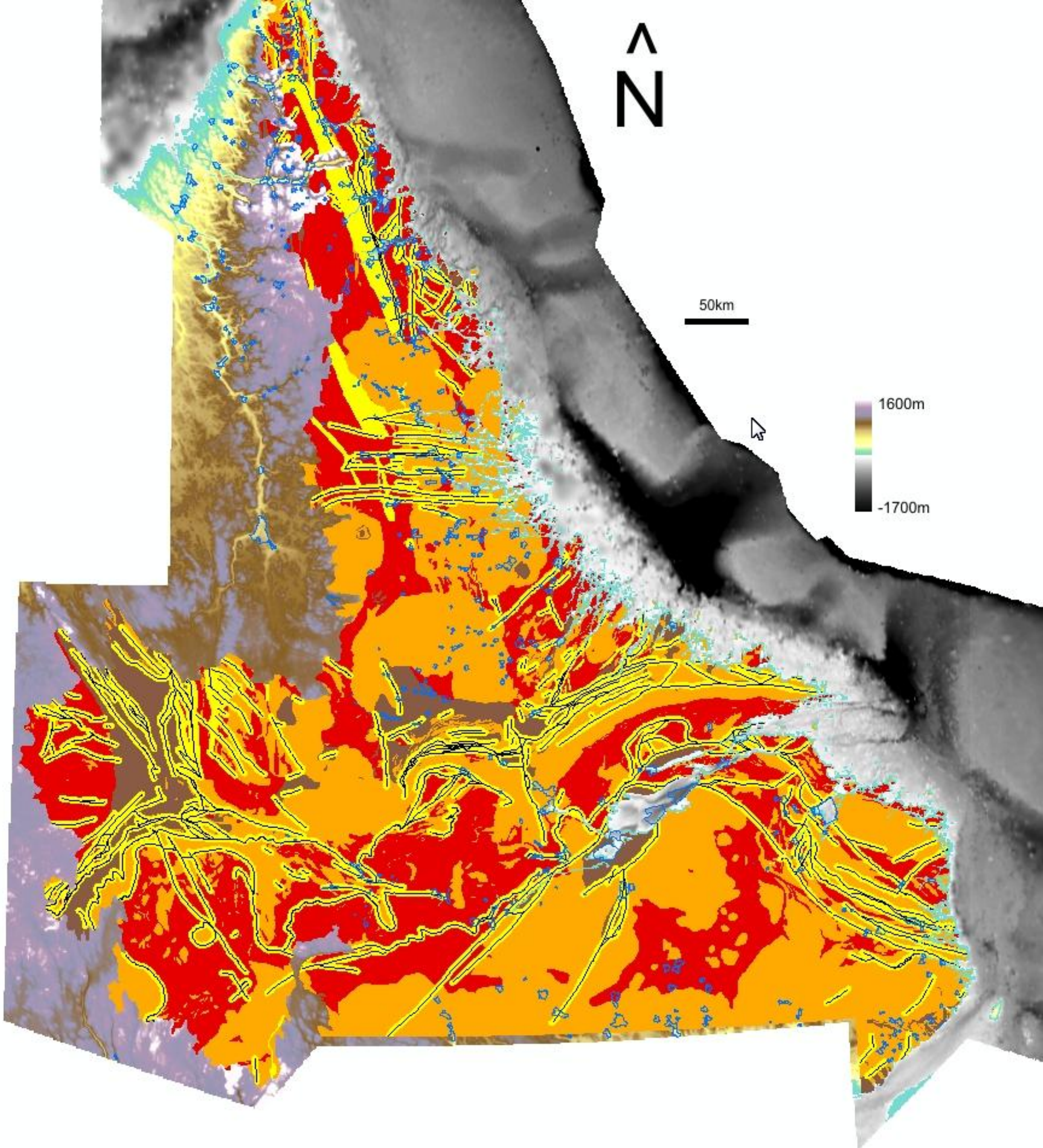
(Wardle, et al., 1997; Swiss Federal Office of Topography (SwissTopo), 2010)

The Geological zones:

Key:
• Igneous (orange)
• Metamorphic (red)
• Sedimentary (brown)
• Structural shear/ fault (yellow, fault lines black)

•Glacial confluences (blue outline)

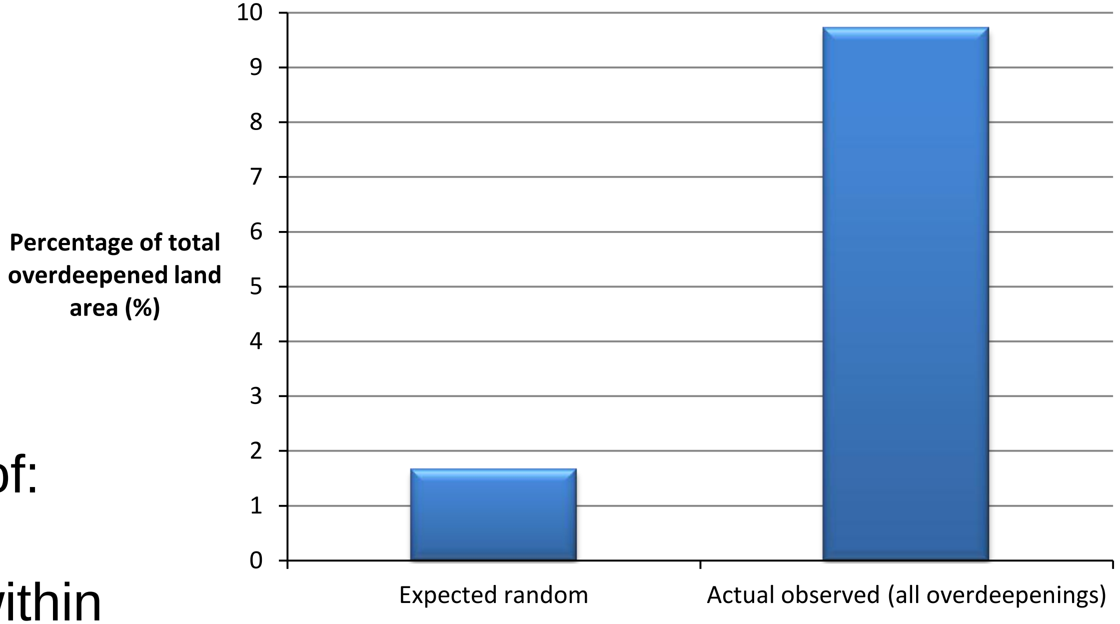
• SRTM3 topography scale ranges from sea level (turquoise) to ~1600m elevation a.s.l (white)
• GEBCO bathymetry scale ranges from sea level (white/grey) to ~-1700m depth (black)



The University Of Sheffield.

Results

‘Speed-up’ Hypothesis Warm-up!



Following simple area analysis of:

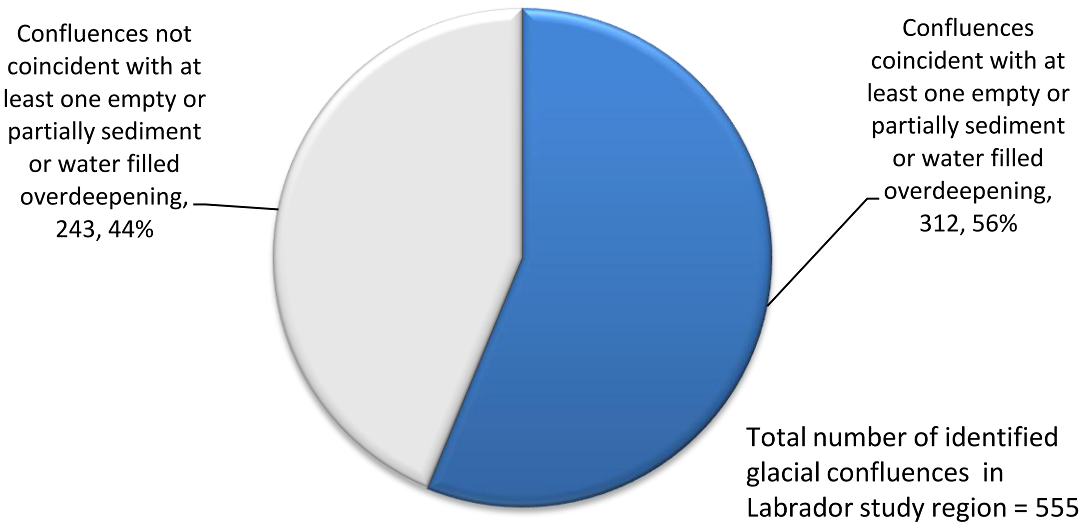
1. The study region
2. Overdeepenings contained within
3. Confluences contained within

Estimated random coincidence of glacial confluence and overdeepenings: *1.66%* of total overdeepened area of study region

Actual observed coincidence of glacial confluence and overdeepenings: *9.71%* of total overdeepened area of study region

Actual observed coincidence is 586.5% higher than should be the case if coincidence occurs by chance

‘Speed-up’ Hypothesis Warm-up!



- A high percentage (56%) of confluences are coincident with overdeepenings within the study region

The University Of Sheffield.

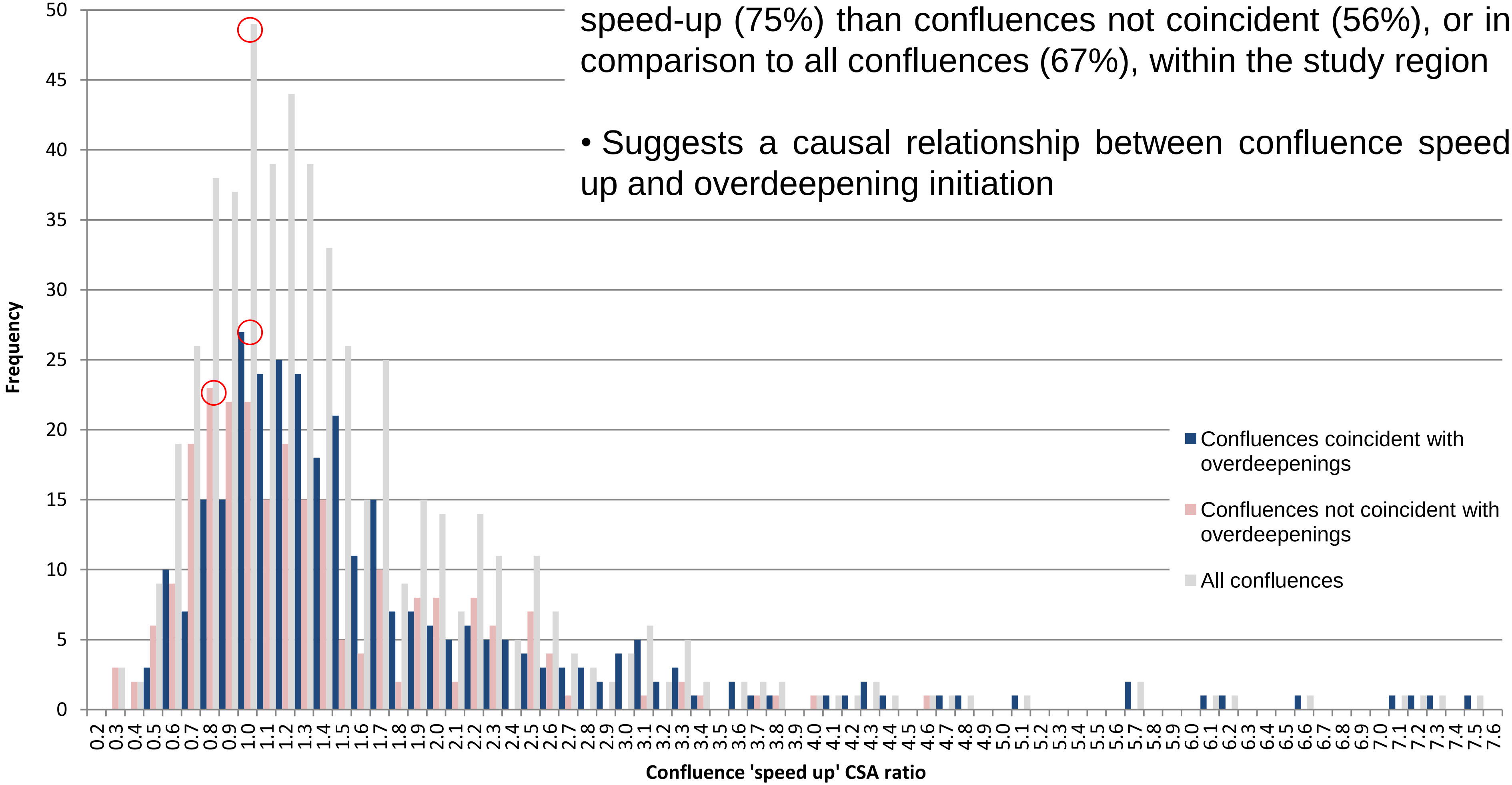
‘Speed-up’ Hypothesis

Analysis of confluence (tributary:trunk) ratio within study region

- Values greater than 1.0 indicate an effective ‘speed up’ of ice within the confluence

- Confluences coincident with overdeepenings have more speed-up (75%) than confluences not coincident (56%), or in comparison to all confluences (67%), within the study region

- Suggests a causal relationship between confluence speed up and overdeepening initiation



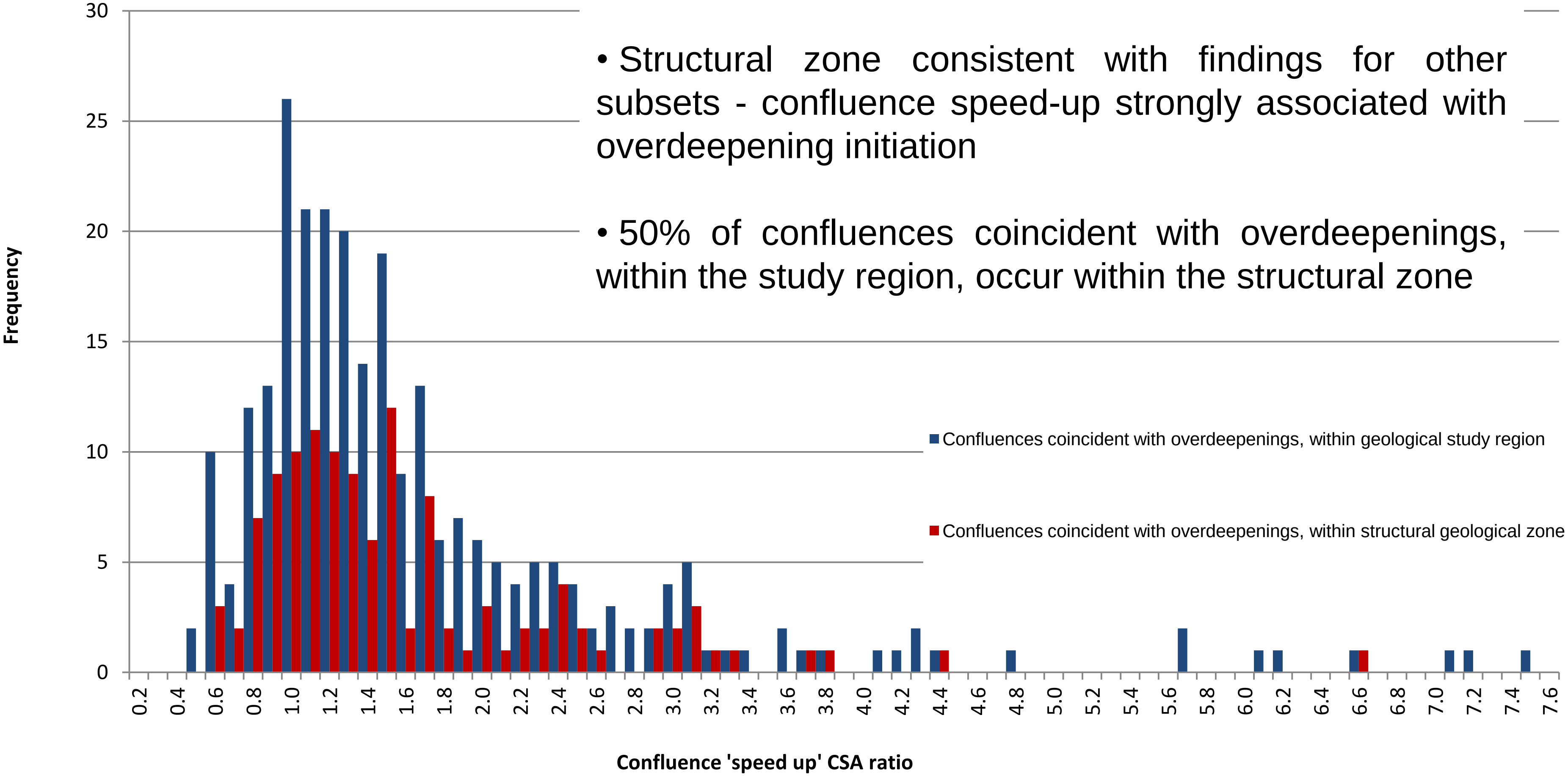
'Speed-up' Hypothesis

Analysis of confluence (tributary:trunk) ratio within structural zone

• Number of confluences coincident with overdeepenings within the structural zone, which demonstrate speed-up (74%), very similar to that encountered for confluences coincident with overdeepenings within the wider study area (75%)

• Structural zone consistent with findings for other subsets - confluence speed-up strongly associated with overdeepening initiation

• 50% of confluences coincident with overdeepenings, within the study region, occur within the structural zone



The University Of Sheffield.

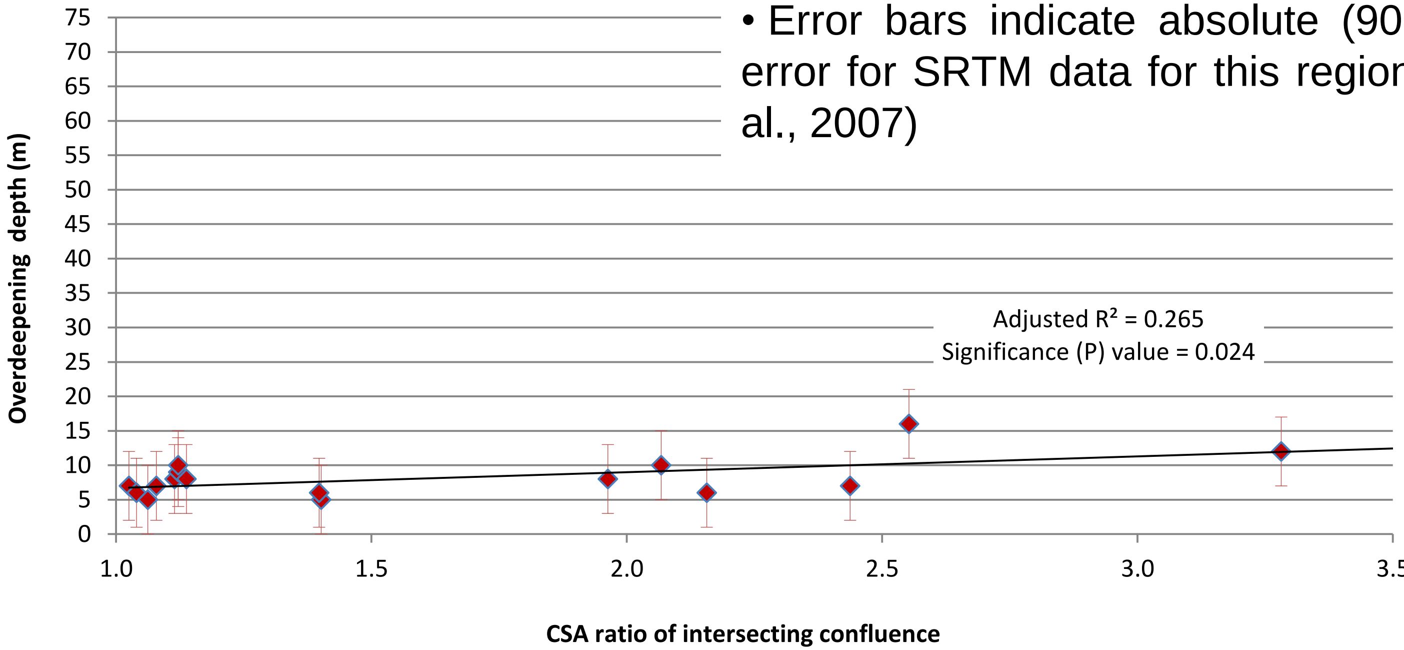
'Basal ice debris' Hypothesis

Analysis of confluence ratio relationship with overdeepening metrics: Labrador

• Statistically valid relationship between confluence cross sectional area ratio (speed-up) and maximum overdeepening depth (using filtered data), **only within the structural zone**

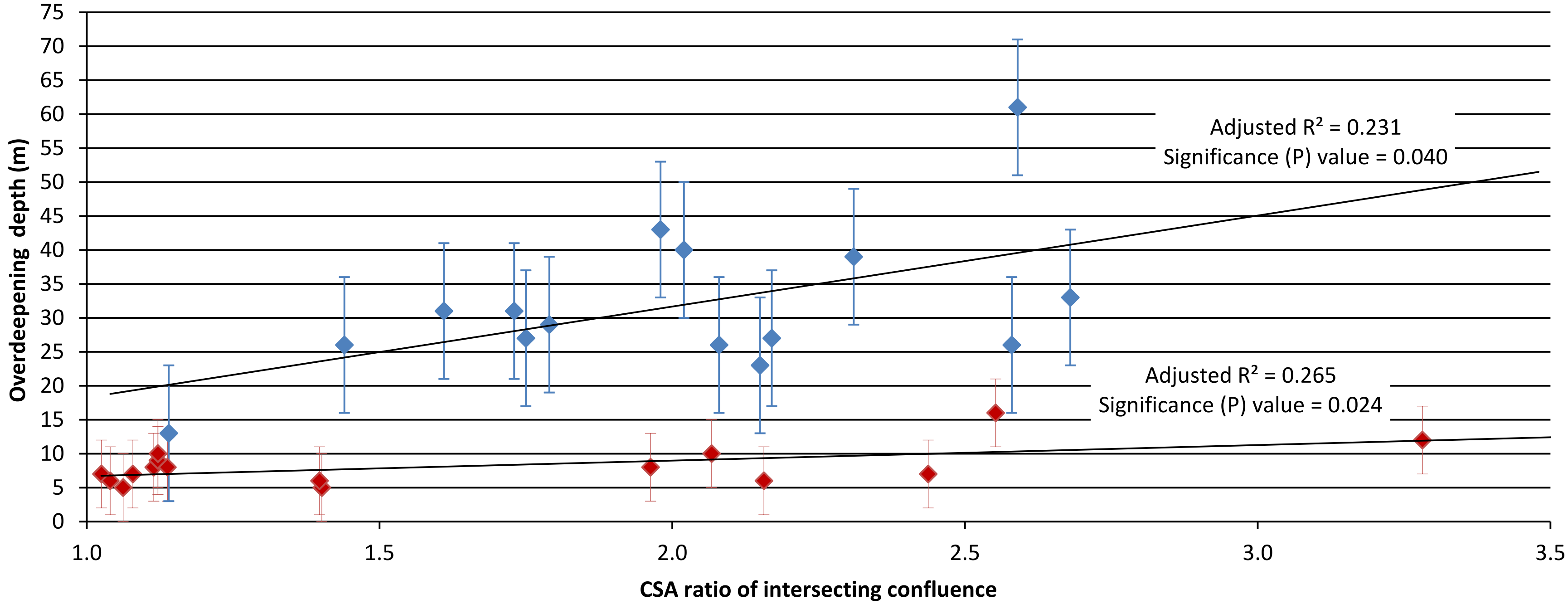
• Suggests that structural faulting, where it occurs, is a secondary control upon overdeepening development within confluences

• Error bars indicate absolute (90%) vertical linear error for SRTM data for this region (<=5m) (Farr, et al., 2007)



Analysis of confluence ratio relationship with overdeepening metrics: Labrador & Switzerland

‘Basal ice debris’ Hypothesis



- Relationship between confluence ratio and maximum overdeepening depth (using filtered data) within the structural zone, for Swiss study region (blue), also statistically significant
- Confirms that Labrador result (red) is repeatable
- Findings similarly suggest that structural faulting is a secondary control upon overdeepening development within confluences
- Error bars indicate absolute (90%) vertical linear error for SRTM data used in these tests (Labrador <=5m , Switzerland <=10m) (Farr, et al., 2007)

- No evidence for relationships between confluence ratio and any overdeepening metric within study region
- So no evidence for influence of confluence, as control on overdeepening *development*, subsequent to overdeepening *initiation* by confluence speed-up

- But significant relationship(s) may be masked in data by other controls operating at local and/or regional scale?

- Even when data divided into geological zones, very little evidence for relationship between ratio and metrics
- So no evidence for influence of geology, as control on overdeepening development, other than in structural zone

The University Of Sheffield.

Conclusions

- Examined several hundred glacial overdeepenings in the Labrador Province of Canada, to investigate controls on overdeepening location and geometry

- Analyses show that overdeepening correlates strongly with glacial confluence, and correlation is strongest where confluence geometry indicates ice-flow speed-up

- Further, magnitude of ice-flow speed-up correlates with overdeepening depth only for confluences situated in or near major geological fault-zones

Conclusions

- Findings therefore support the hypothesis that overdeepening can be initiated by an increase in ice velocity

- Further, we conclude that overdeepening development is most effective where fractured bedrock enables efficient quarrying

References:

- Alley, R. B. et al., 2003. Stabilizing feedbacks in glacier-bed erosion. *Nature,* Volume 424, pp. 758-760.
- Cook, S.J., Swift, D.A. submitted. Subglacier basins: their origin and importance in glacial systems and landscapes. Earth Science Reviews.
- Farr, T. G. et al., 2007. *The Shuttle Radar Topography Mission.* [Online] Available at: http://www2.jpl.nasa.gov/srtm/SRTM_paper.pdf [Accessed February 2012].
- Glasser, N. F., 1995. Modelling the effect of topography on ice sheet erosion, Scotland. *Geografiska Annaler. Series A,* 77(1-2), pp. 67-82.
- Hooke, R. L., 1991. Positive feedbacks associated with erosion of glacial cirques and overdeepenings. *Geological Society of America Bulletin,* 103(8), pp. 1104-1108.
- Kessler, M. A., Anderson, R. S. & Briner, J. P., 2008. Fjord insertion into continental margins driven by topographic steering of ice. *Nature Geoscience,* Volume 1, pp. 365-369.
- Krabbendam, M., Glasser, N.F., 2011. Glacial erosion and bedrock properties in NW Scotland: Abrasion and plucking, hardness and joint spacing. Geomorphology. Volume 130, pp. 374-383.
- Seaman, P. G., 1998. *Ikaite formation in a fjord environment with special reference to Ikka fjord (unpublished phd thesis).* [Online] Available at: http://www.reocities.com/RainForest/Vines/1486/ikkap.htm [Accessed February 2012].

Acknowledgments:

The University of Sheffield, Department of Geography, Learned Society Fund

The British Society for Geomorphology, Postgraduate Grant