ETH zürich

Repeated ground-penetrating radar measurements to detect seasonal and annual variations of an englacial conduit network

Gregory Church[1,2], Andreas Bauder[1], Melchior Grab[1,2], Cédric Schmelzbach[2], Hansruedi Maurer[2]

[1] Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zürich, Zürich, Switzerland

[2] Institute of Geophysics ETH Zürich, Zürich, Switzerland

Work submitted to the Cryosphere and currently in review: Church, G., Grab, M., Schmelzbach, C., Bauder, A., and Maurer, H.: Monitoring the seasonal changes of an englacial conduit network using repeated ground penetrating radar measurements, The Cryosphere Discuss., https://doi.org/10.5194/tc-2020-94, in review, 2020.

What are englacial conduits? And why study them?

- Surface meltwater is routed through the glacier's interior by englacial drainage systems, before it can reach the subglacial drainage system.

- Subglacial drainage systems play an important role on the dynamics of glaciers (Iken et al., 1996; Bingham et al., 2008). For example, high subglacial water pressure can lubricate the ice-bed interface, which may result in a faster sliding velocity (Iken and Bindschadler, 1986; Zwally et al., 2002).

From Gulley et al (2009)

- The subglacial water pressure can dramatically increase, when the drainage system does not adapt quickly enough, while surface meltwater is routed rapidly through the englacial drainage system. There is often a short time lag between the surface meltwater being present and the increase in glacier velocity (Bingham et al., 2005).

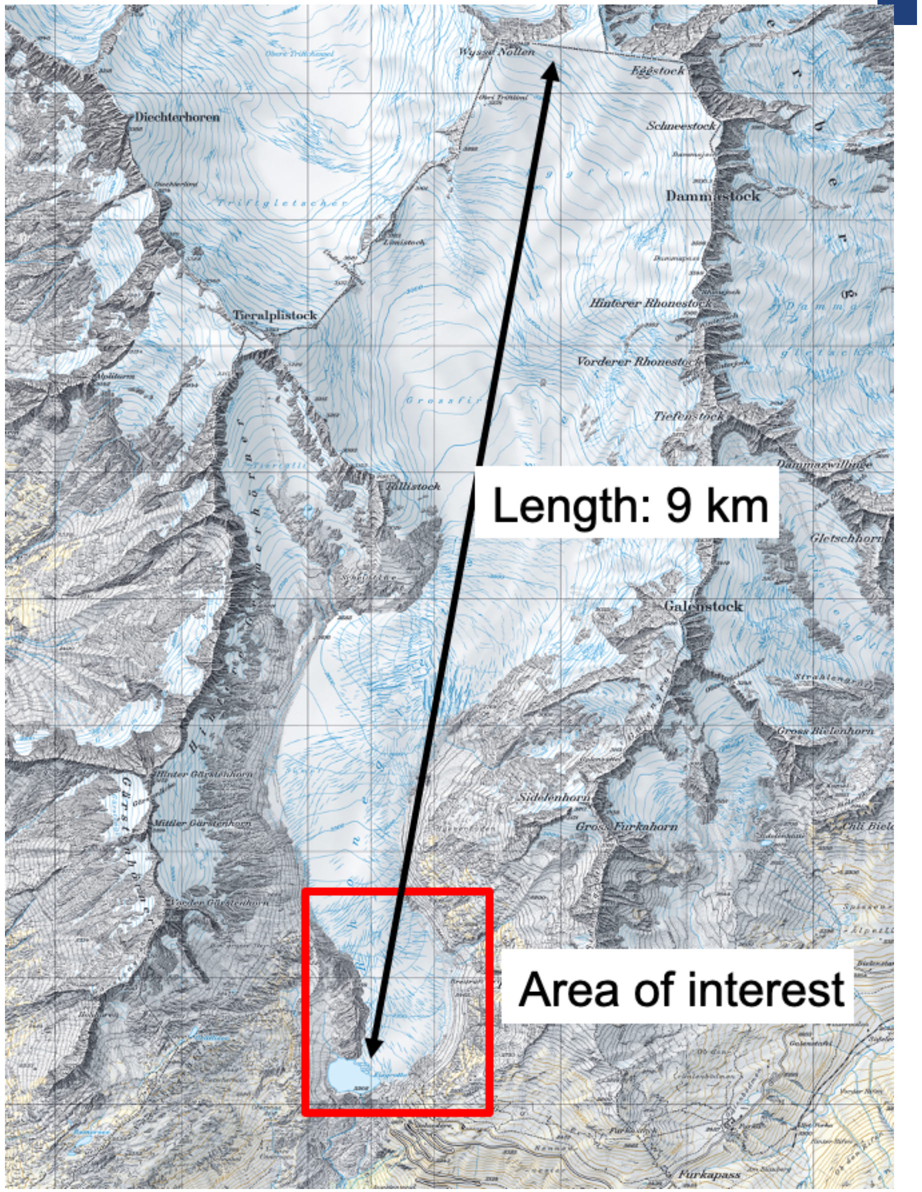
- Therefore, studying the seasonal evolution of an englacial drainage system throughout the melt season is key to understanding how and when they transport water to the subglacial drainage systems.

Study Site – Rhone Glacier

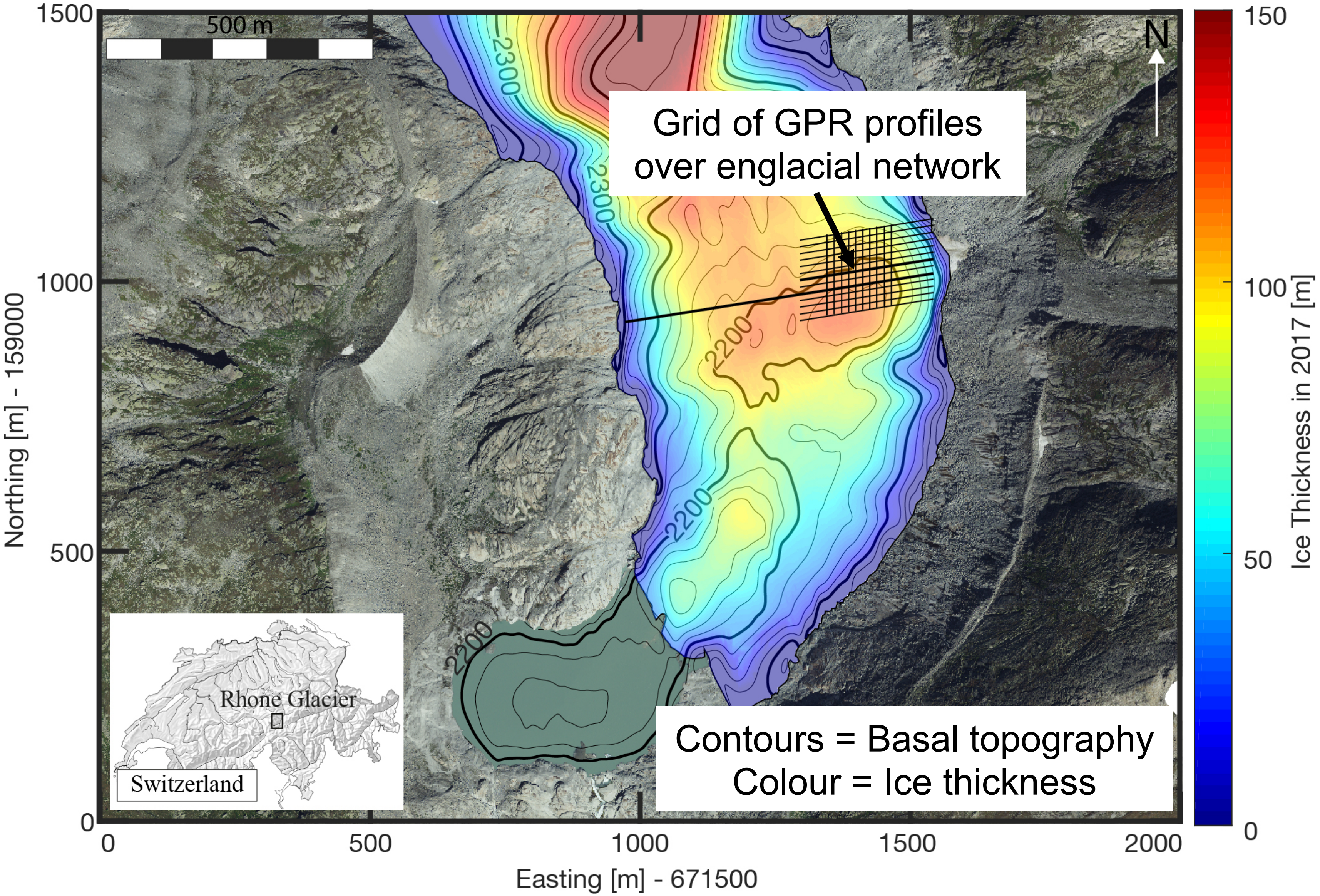
- The englacial conduit monitoring experiment was conducted on the Rhonegletscher, which is a 9 km long temperate alpine glacier located in Switzerland.

- The glacier is retreating and a proglacial lake formed in 2005 at its terminus.

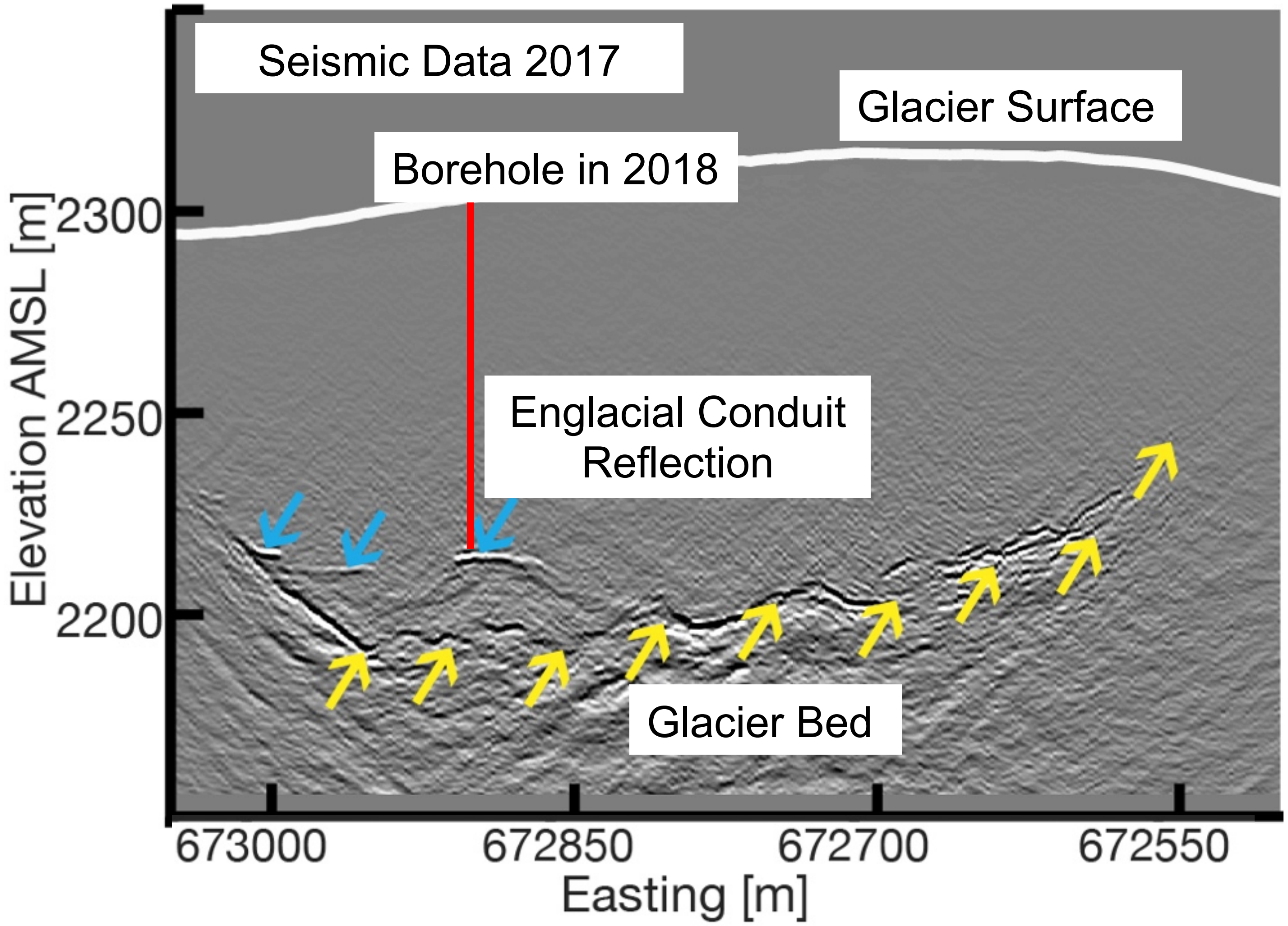
- The repeated ground-penetrating-radar (GPR) measurements were performed within the ablation zone, where the ice thickness was approximately 100 m.

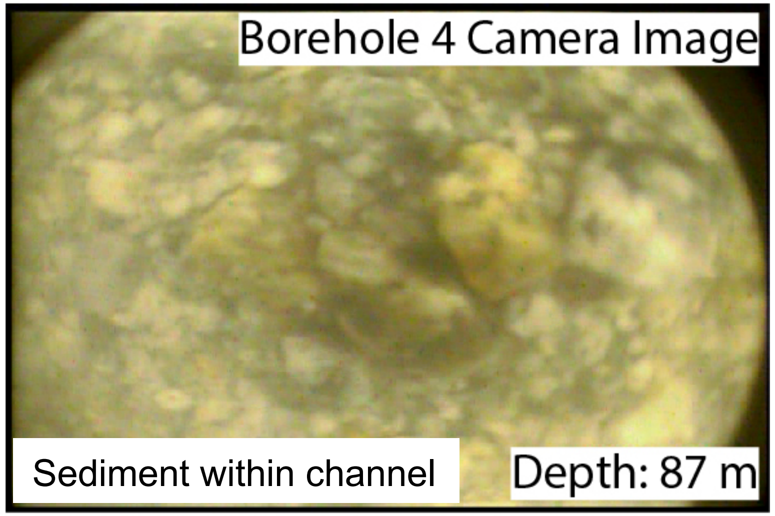


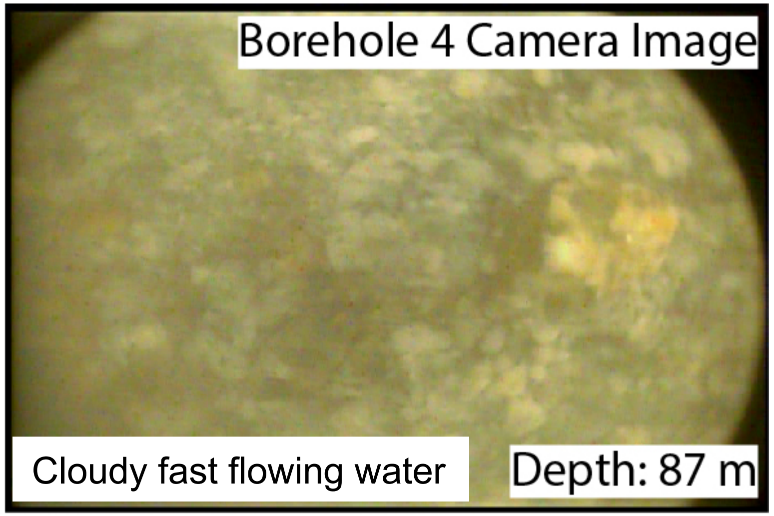
- The englacial conduit monitoring experiment was conducted on the Rhonegletscher, which is a 9 km long alpine temperate glacier located in Switzerland.
- The glacier is retreating and a proglacial lake formed in 2005 at its terminus.
- The repeated ground-penetrating-radar (GPR) measurements were performed within the ablation zone, where the ice thickness was approximately 100 m.



- Prior to undertaking repeated GPR measurements, we detected an englacial conduit network in 2017 using seismic reflection surveying. The conduit presence was confirmed in 2018 using a borehole camera. (Church et al. 2019)







Borehole camera video: https://doi.org/10.3929/ethz-b-000406689

Ground Penetrating Radar Acquisition

- The GPR acquisition was performed using a PulseEkko 25 MHz GPR system and the grid of profiles were acquired over ***several years*** in both ***winter (snow covered)*** **&** ***summer (snow free)***.

- A single GPR profile was acquired:

  Summer (September) 2012
  Winter (April 2016) 2015/2016
  Summer (September) 2017

- Englacial conduit GPR monitoring grid was acquired:

  7 x 2018: March, April, May, July, September, October, December

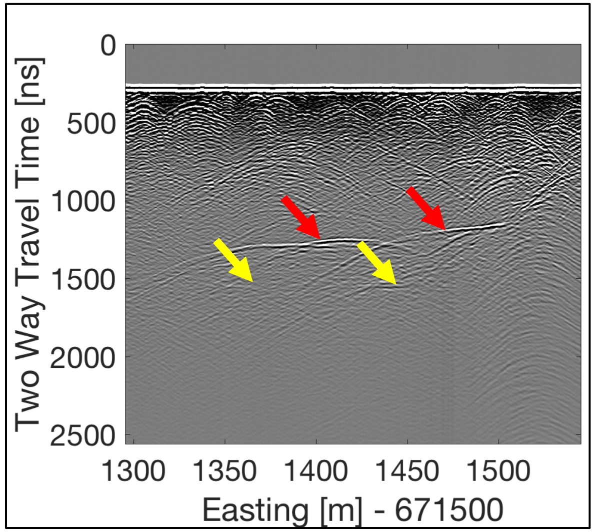
  2 x 2019: February, August

Ground Penetrating Radar Processing

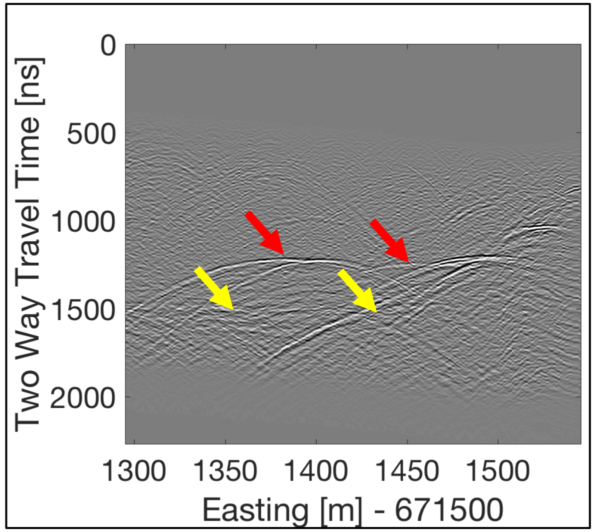
ETH zürich

- The GPR processing was performed using a combination of an in-house MATLAB based toolbox and Seismic Unix. The processing aim was to recover the GPR reflection coefficients from the englacial conduit reflection by means of an impedance inversion scheme. This workflow was based upon the processing described in Schmelzbach et al. (2012)

1. Raw GPR Data

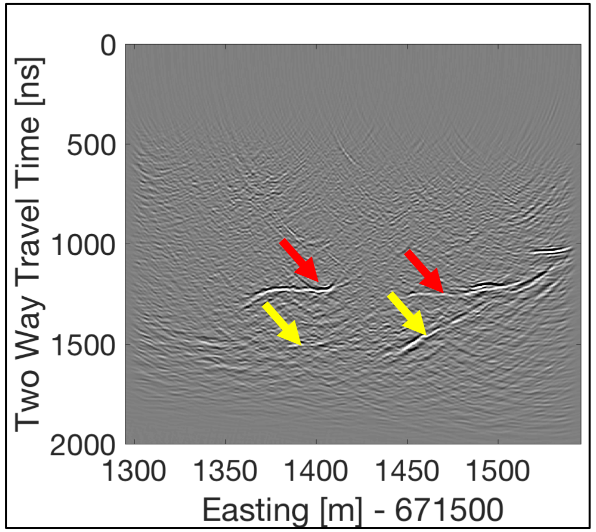


2. Pre-Processing

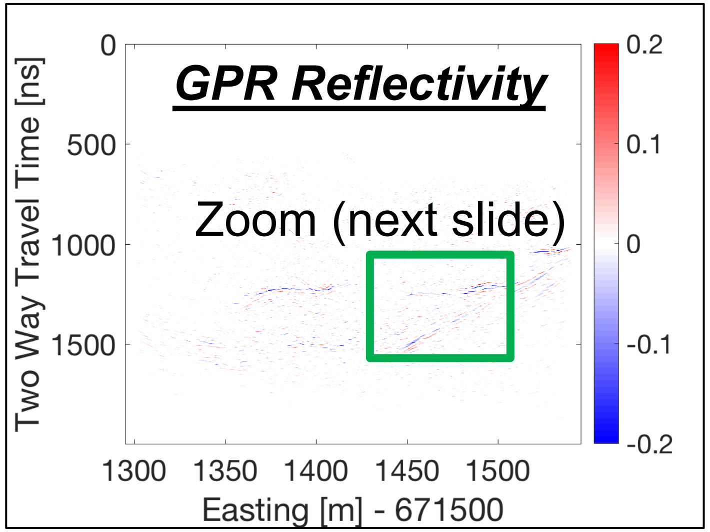


Assign spatial information
Set time zero & record length
Interpolate clipped data
Butterworth bandpass filter
Binning to 1 m trace spacing
Deterministic Amplitude Correction
GPR Deconvolution*
Elevation Static Correction

3. Phase Shift Migration



4. Post-Migration Processing



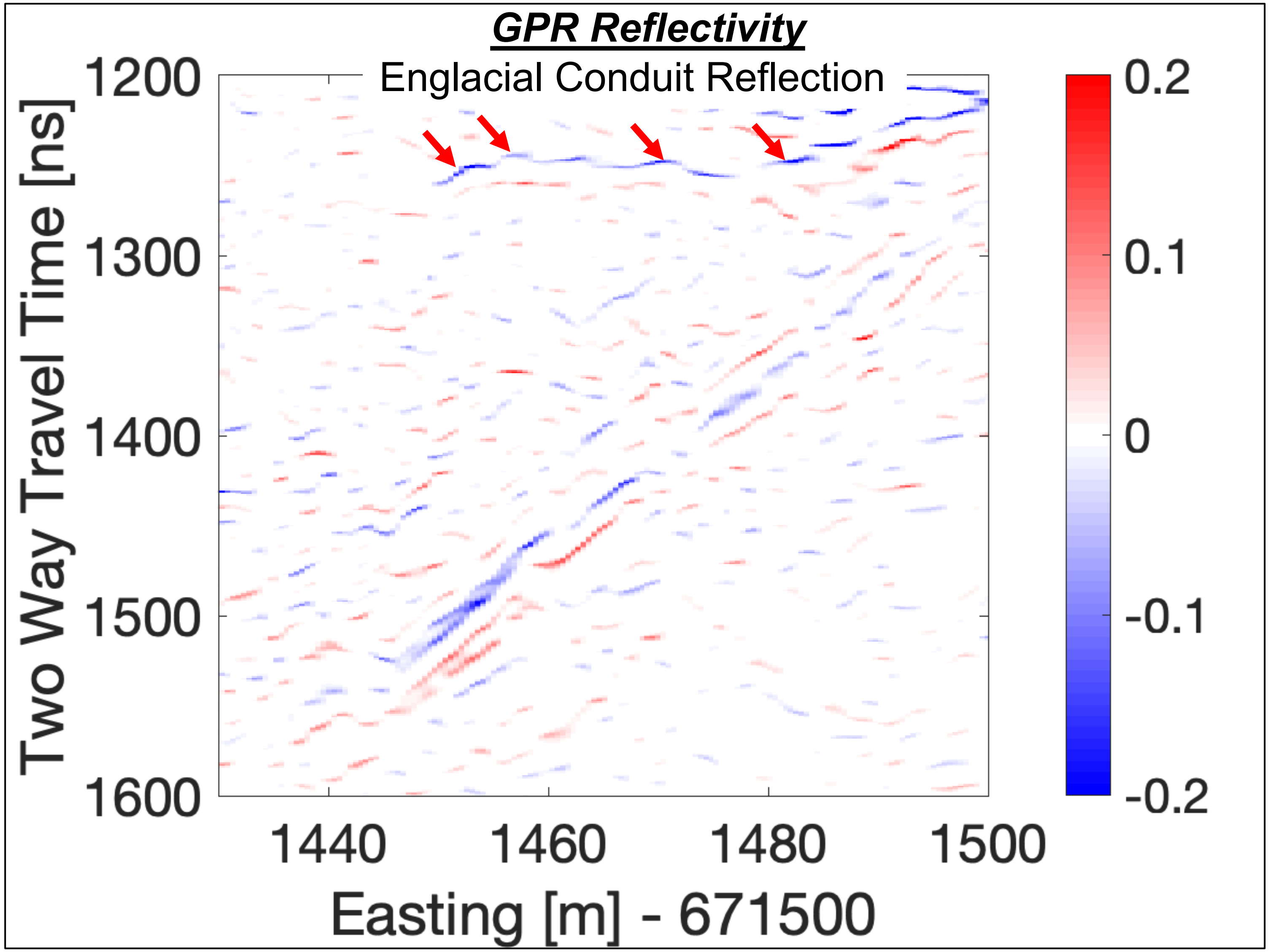
Sparse deconvolution to extract reflectivity**
Reflectivity Calibration using borehole observations

Englacial reflection
Bed reflection

* Schmelzbach et al. 2015
** Sacchi 1997

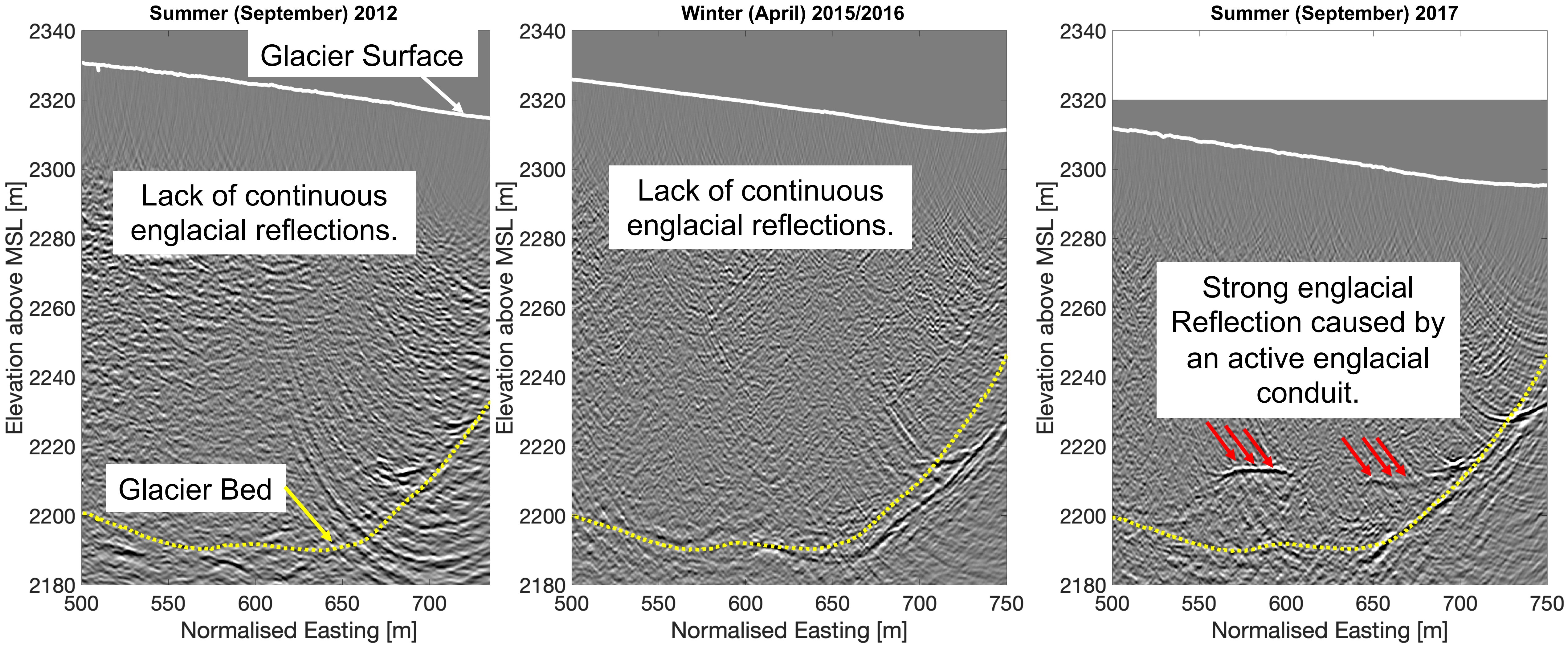
- GPR reflectivity is a material property and is caused by a contrast in GPR impedance.
- The reflection coefficient explains the proportions of energy that are reflected from a given interface. Its values range between -1 and 1. Their magnitudes and polarities are indicative for the electrical material properties adjacent to an interface.
- Typical glaciological GPR reflection coefficients:

Media	Reflectivity
Ice / Water	- 0.6
Ice / Air	+ 0.3
Ice / Bedrock	- 0.1
Water / Ice	+ 0.6

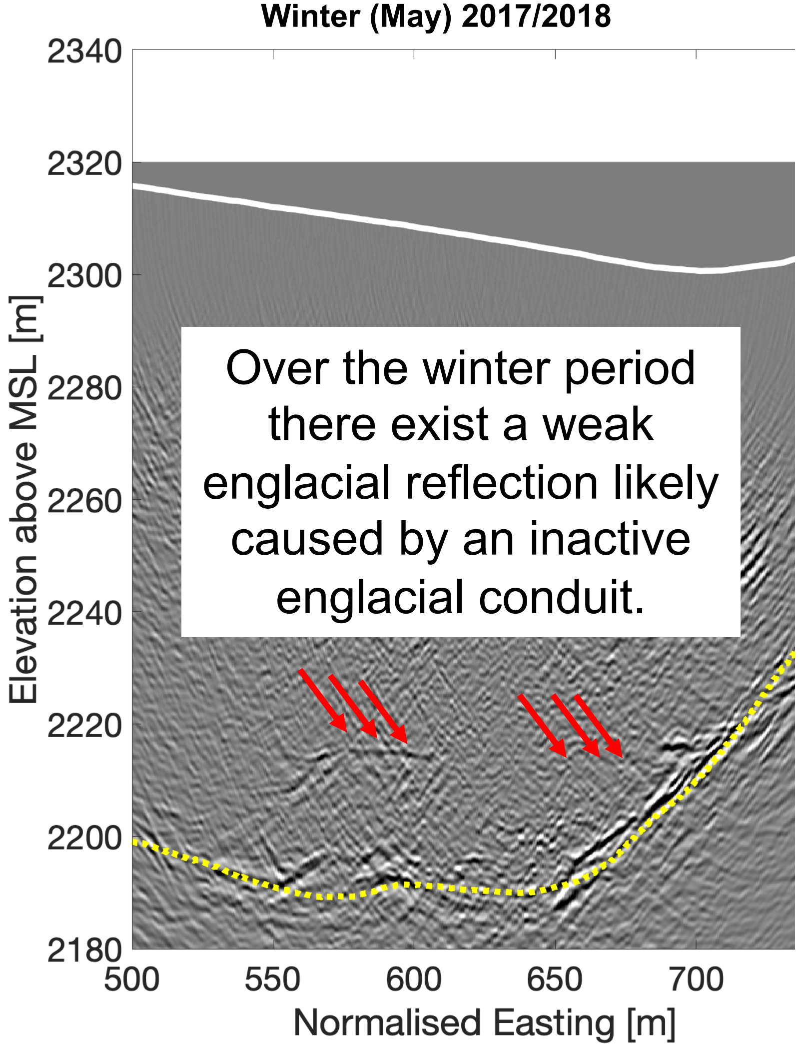


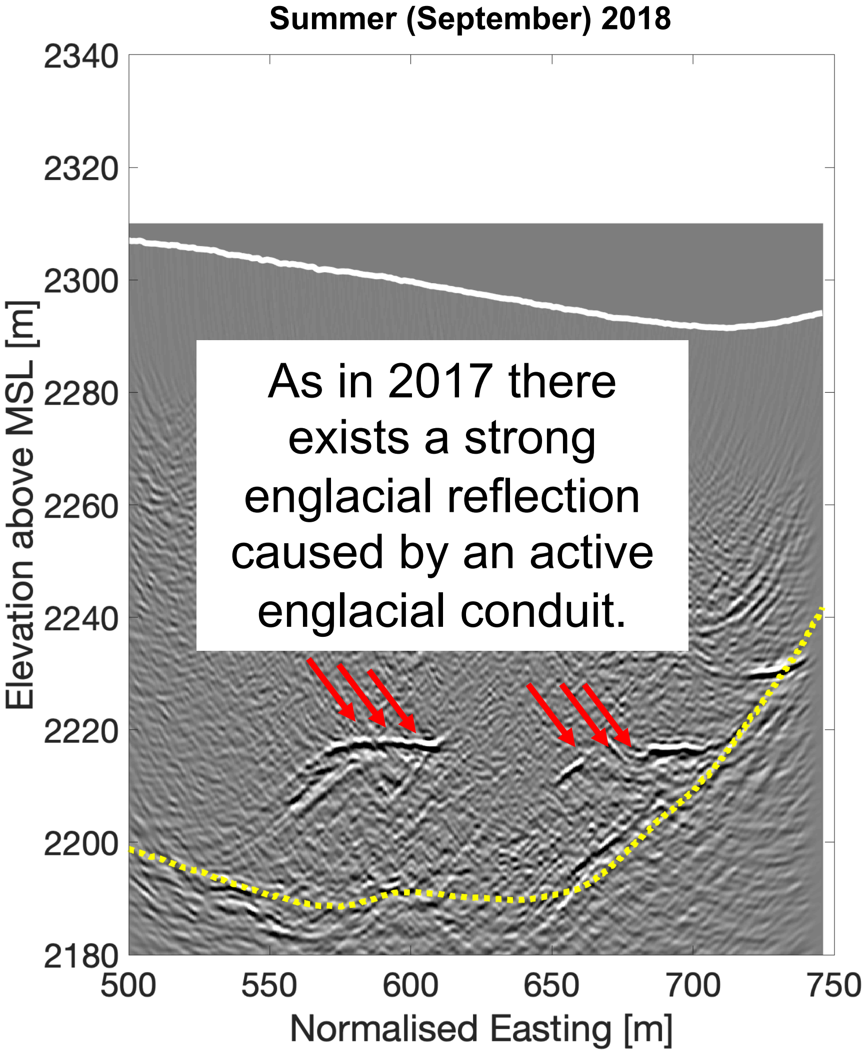
Annual GPR Imaging Results 2012-2017

- Here we present the annual GPR imaging results between 2012 and 2017…



- Here we present the annual GPR imaging results between in 2018…





Observations

The englacial drainage system '***appeared***' in ***summer 2017***. It was not visible during the summer 2012 campaign, nor the 2016 winter measurements.

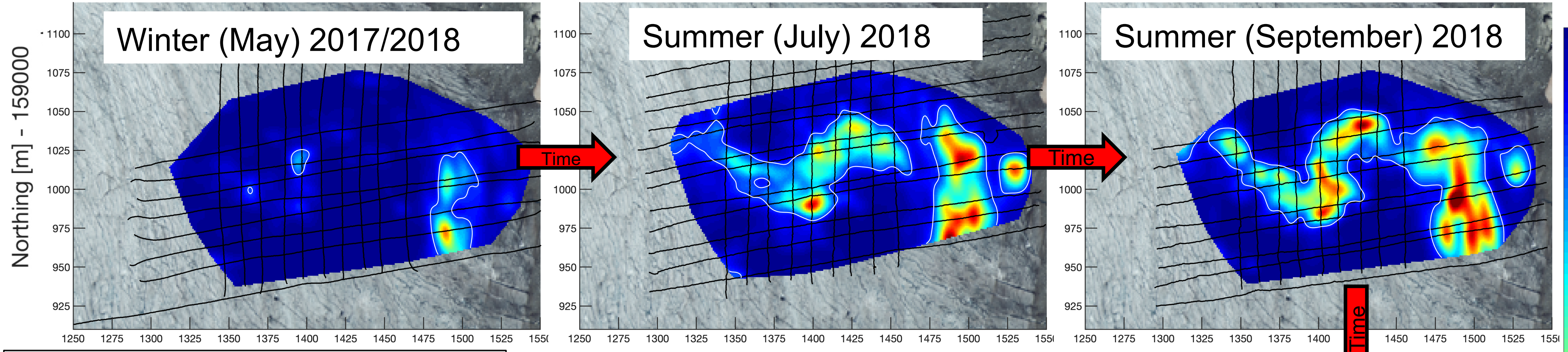
During ***winter 2017/2018*** there exists a very weak englacial reflection, this is likely a result of the drainage system become ***inactive***.

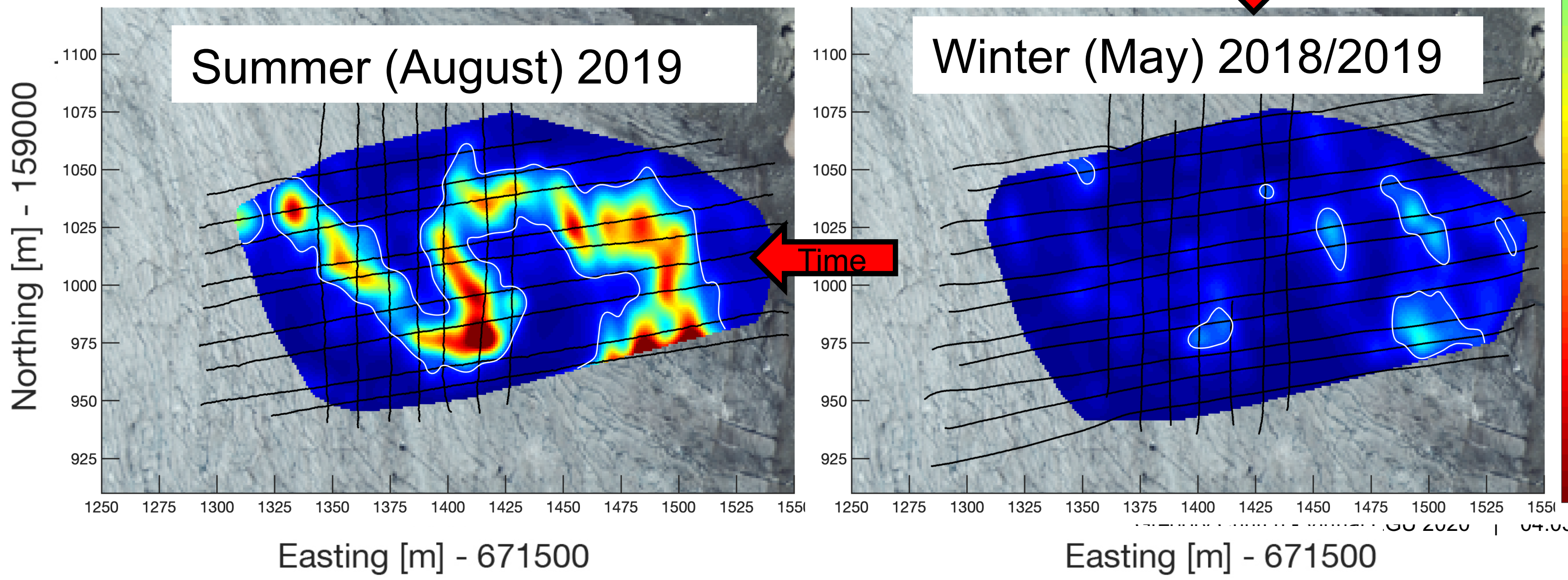
The englacial conduit was present within the GPR section in an identical position after the winter shut down in **summer 2018.**

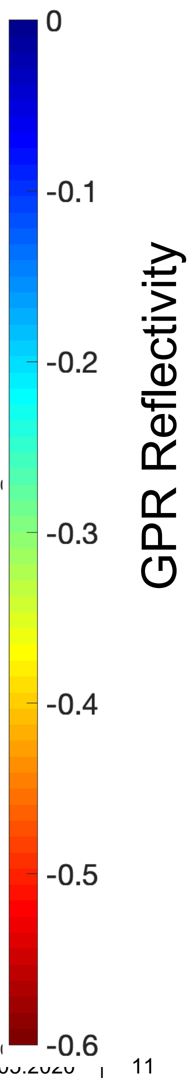
Reflectivity Extracted Along Englacial Conduit Reflection Results

Media	Reflectivity
Ice / Water	- 0.6
Ice / Air	+ 0.3
Ice / Bedrock	- 0.1
Water / Ice	+ 0.6

- The GPR reflectivity was then extracted along the englacial conduit reflection, interpolated, smoothed and plotted in plan view (black lines represent the GPR lines).







Observations

Successfully ***spatially mapped*** a ***meandering*** englacial conduit.

Summer has high absolute reflectivity values (<-0.2), indicating the **presence of a wet glaciological environment** (water).

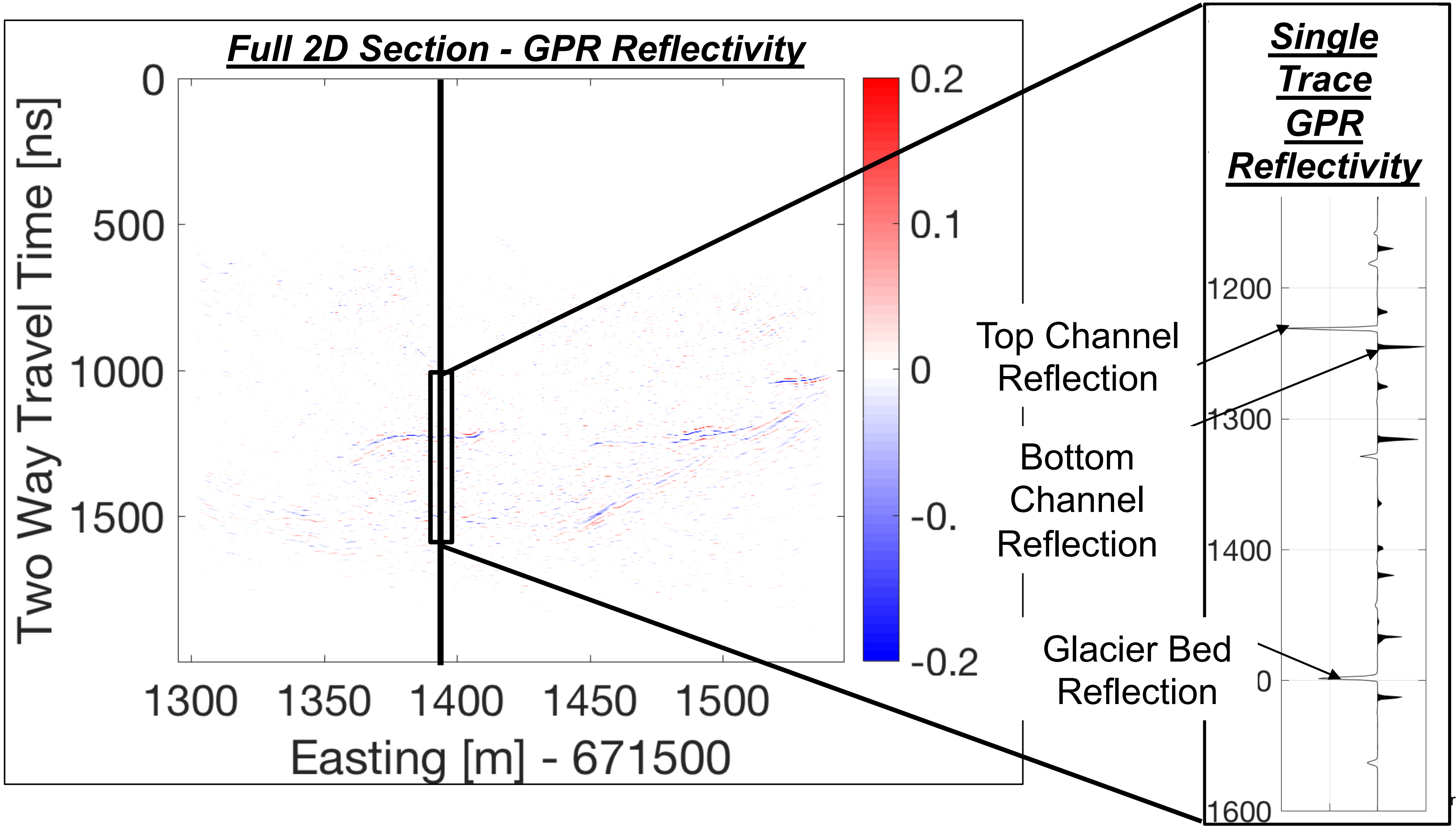
July 2018 shows a **disconnected englacial conduit network**, whereas **later in the summer** (September) the network is **completely connected**.

The **network reopens after a winter shut down** and appears in an **identical location**.

Winter ***reflectivity*** is around ***0***, therefore ***no water*** or ***air*** in ***englacial conduit – conduit physically closes.***

GPR Modelling – Channel Thickness Methodology

- We have successfully mapped the meandering extent of the englacial conduit using GPR measurements and we have observed a shut down of the englacial conduit during the winter period. Furthermore, we subsequently investigated the thickness of the englacial conduit using the GPR reflectivity.



Channel top and bottom **time difference = 28 ns**

Channel **Thickness:**
~0.47 m (28/2 * 0.0333)

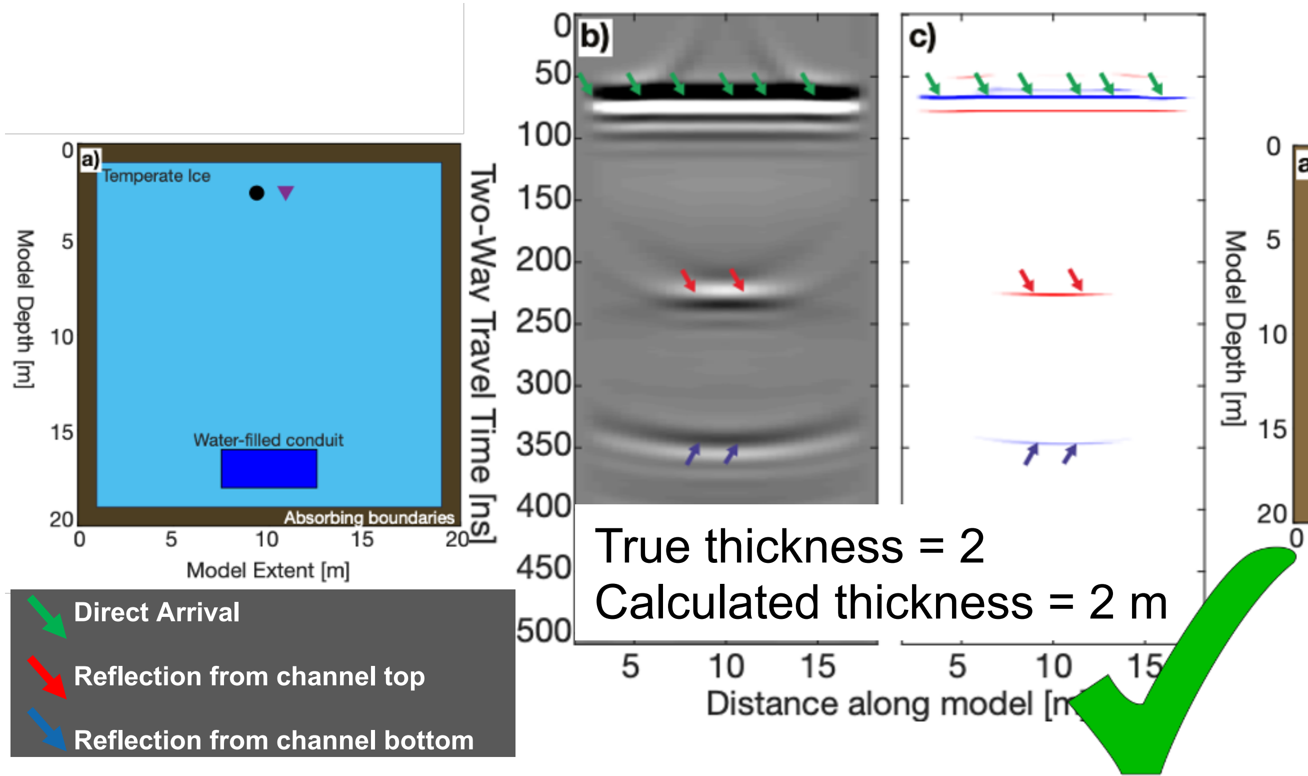
25 MHz GPR Wavelength in water = 1.333 m

Question: Are we able to detect thin layers? Forward modelling experiment to investigate.

- The thickness observed from a single reflectivity trace (previous slide) was 0.47 m. In order to determine if this thickness is able to be imaged using a 25 MHz GPR system, we performed forward modelling using thin water filled conduit models (FD EM wave equation solver: gprMAX (Warren et al., 2016)). Several model runs were computed where the water-filled conduit thickness was varied between 0.1 and 2 m. The synthetic GPR data was processed using the impedance inversion processing route and subsequently, the reflectivity was extracted. Examples of 2 m and 0.3 m conduit thickness is shown:

2 m thick conduit model

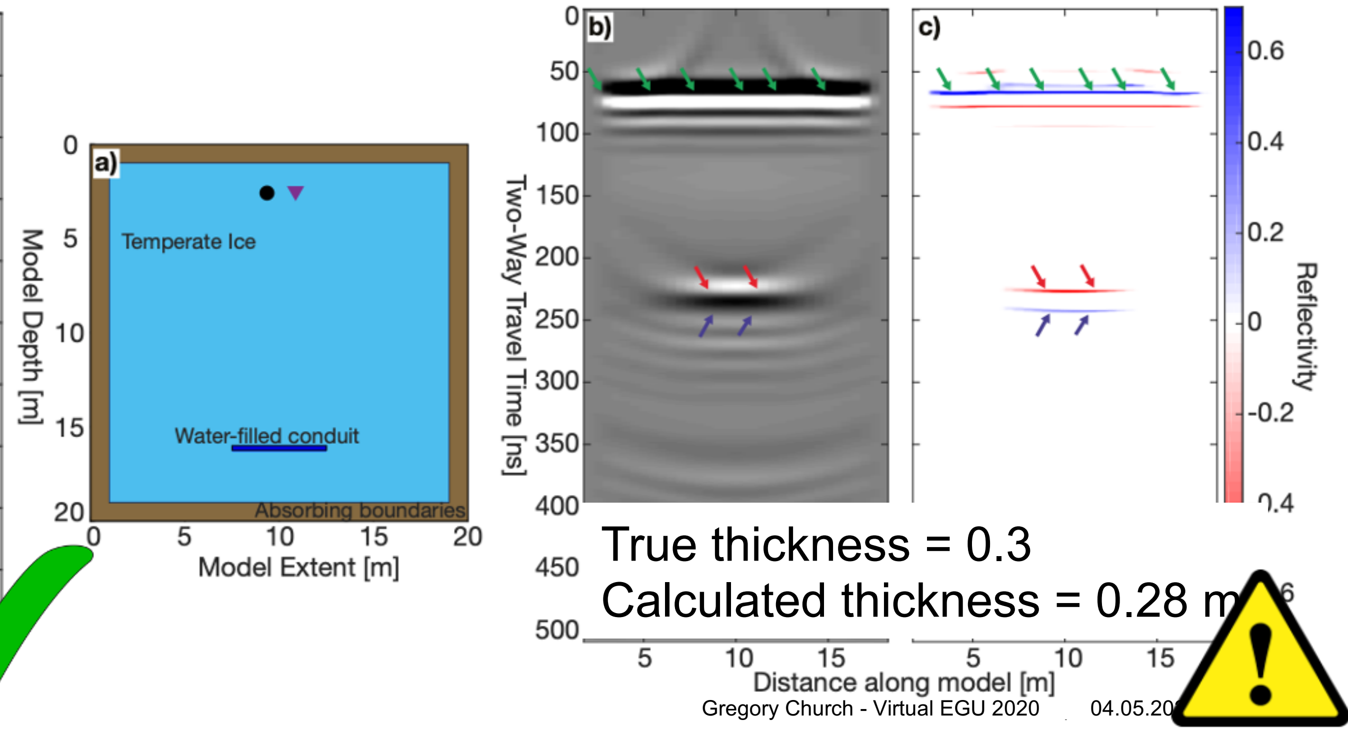
Model | GPR Data | Reflectivity



True thickness = 2
Calculated thickness = 2 m

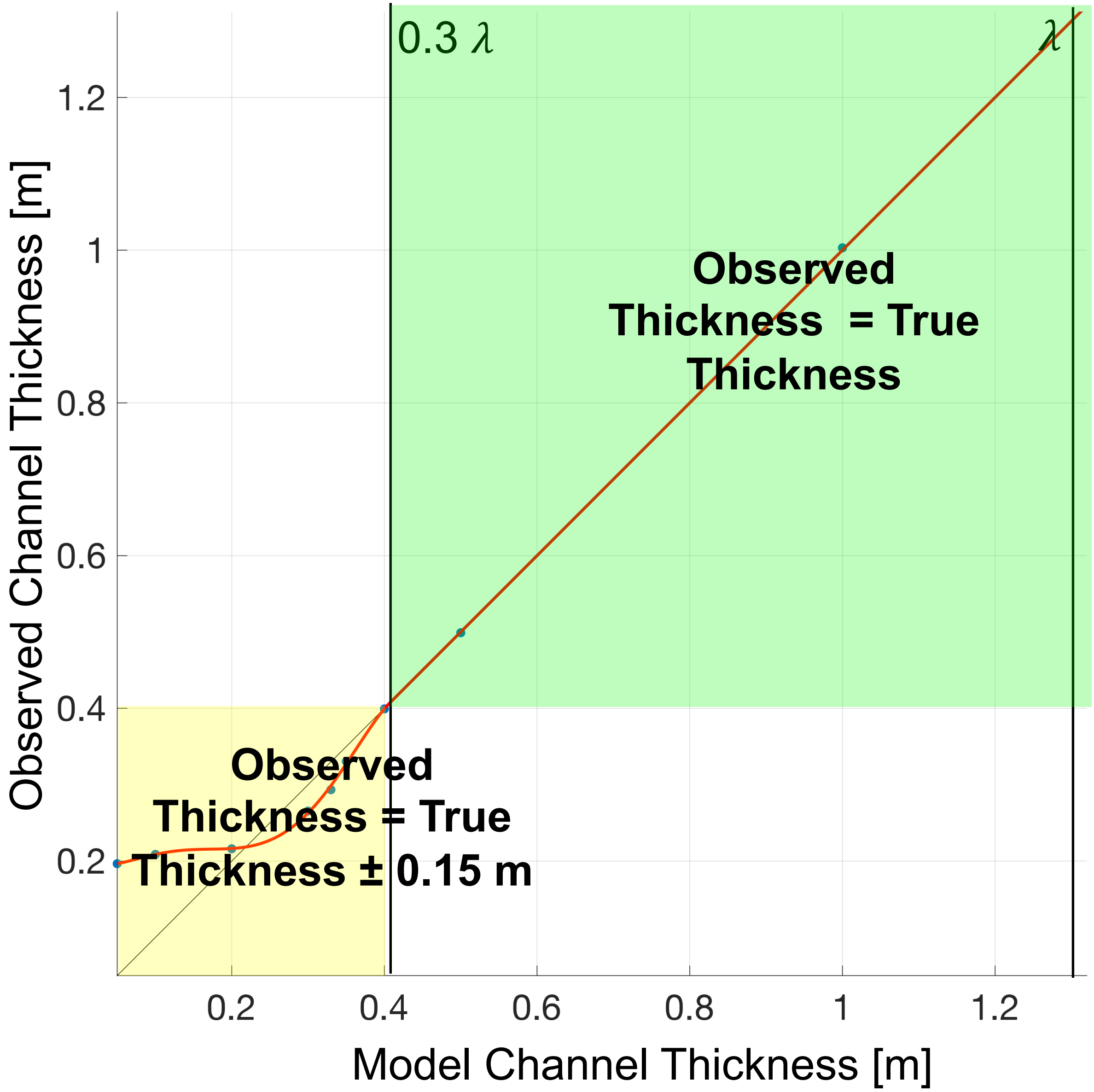
0.3 m thick conduit model

Model | GPR Data | Reflectivity



True thickness = 0.3
Calculated thickness = 0.28 m

- The model with a 2 m channel thickness yielded the correct thickness.
- Whereas, the model with a 0.3 m channel thickness yielded a difference of 0.02 m between observed in the GPR data and the true model.
- For all other conduit thickness models we are able to state that models greater than 0.4 m (30% of wavelength) yield correct thicknesses. On the contrary, model thicknesses below 0.4 m the GPR data provided a thickness within 0.15 m of the actual true model.
- Using this information, we related this to the observed conduit thickness for the August 2019 survey.

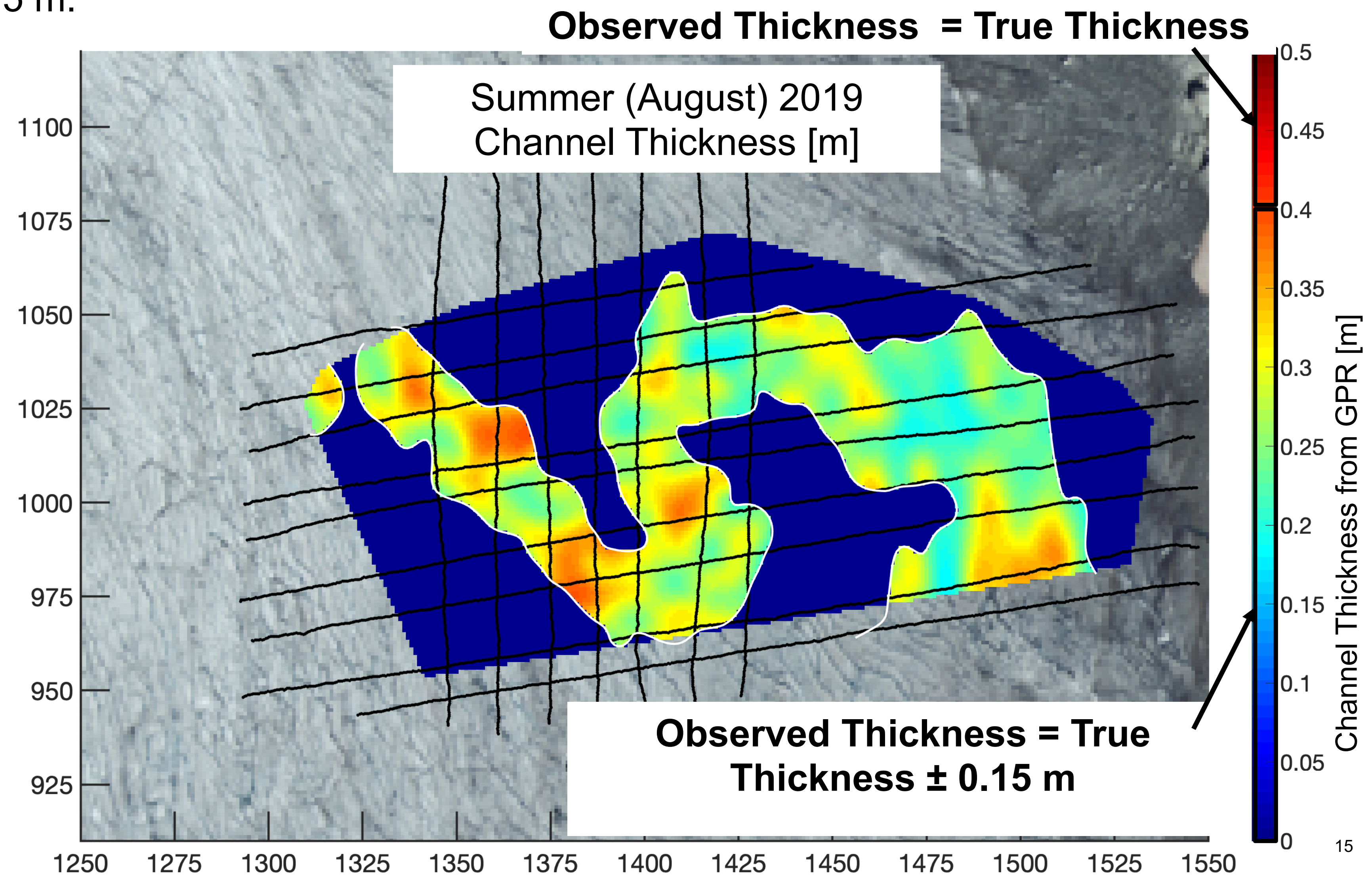


Englacial Conduit Conduit Thickness Results

- The englacial conduit thickness for August 2019 is between 0.25 and 0.5 m. Therefore, we are able to state with confidence that areas above 0.4 m represent the true conduit thickness whereas values below are subject to an error of 0.15 m.

- The majority of englacial conduit has **thicknesses below 0.4 m.**

- Therefore, the ***englacial conduit is a thin layer***.



- *Conduit extension*

The conduit extended around 250 m in length and between 20-45 m in width. The conduit thickness in summer was found to be between 0.2 and 0.4 m with little variation within all other summer months (results not shown).

- *Conduit inclination*

Across the entire conduit there exhibits a ten metre elevation difference, thereby indicating that the conduit has a low inclination (approximately 2 degrees).

- *Conduit shape*

The shape of the conduit shows a sinusoidal outline that runs perpendicular to the ice flow direction. To the best of our knowledge this is the first example of a temperate glacier to have an active englacial system survey using geophysical techniques and showing a sinusoidal shape.

- *Conduit formation*

Comparing the conduit's profile and cross section to those described by Gulley et al. (2009) the likely formation is extensional hydrofracturing. Hydrofracturing on extensionally stressed glacial ice provides a horizontal profile (shallow dip) and an englacial conduit cross-section that is thin and wide. Such extensional stresses may result from the turning of the Rhonegletscher at the survey site towards the proglacial lake. Additionally, the hydrofracturing can be supported by the fact that periods of high water pressure were observed as a result of the borehole expelling water 3-4 m above the glacier surface in August 2018.

Summary & Conclusion

ETH zürich

- By using repeated GPR measurements and processing the data with an impedance inversion to extract the reflectivity, we have successfully imaged and mapped the changing spatial extent and thickness of an active and dynamic englacial conduit network on a temperate glacier.

- In summer the englacial conduit was active, leading to large negative reflectivity values (<-0.2). The Rhonegletscher's englacial network followed a sinusoidal shape throughout the melt season. The conduit is 15-20 m wide and between 0.2 and 0.4 m thick. Such a conduit cross section (wide and thin) can occur as a result of hydraulic fracturing with extensional stresses acting on the ice, based upon the englacial conduit shape review by Gulley et al. (2009).

- The englacial conduit was found to be inactive during the winter period, with reflectivity values between -0.05 and -0.15. Therefore, we speculate that during the winter the conduit network either physically closes or becomes very thin (<0.1 m). The englacial conduit became active in an identical location after a winter shut down.

- Difficulties arise when interpreting a series of reflectors that are separated by the vertical resolution. The forward modelling has shown that two horizons are perfectly distinguishable when they are separated by more than 0.3 x wavelength.

Work submitted to the Cryosphere and currently in review: Church, G., Grab, M., Schmelzbach, C., Bauder, A., and Maurer, H.: Monitoring the seasonal changes of an englacial conduit network using repeated ground penetrating radar measurements, The Cryosphere Discuss., https://doi.org/10.5194/tc-2020-94, in review, 2020.

Gregory Church
church@vaw.baug.ethz.ch

Thank-you for reading!

References:

Bingham, R. G., Nienow, P.W., Sharp, M. J., and Boon, S.: Subglacial drainage processes at a High Arctic polythermal valley glacier, Journal of Glaciology, 51, 15–24.

Bingham, R. G., Hubbard, A. L., Nienow, P. W., and Sharp, M. J.: An investigation into the mechanisms controlling seasonal speedup events at a High Arctic glacier, Journal of Geophysical Research: Earth Surface, 113, 1–13,

Church, G. *et al.* (2019) 'Detecting and characterising an englacial conduit network within a temperate Swiss glacier using active seismic, ground penetrating radar and borehole analysis', *Annals of Glaciology*, 60(79), pp. 193–205.

Gulley, J. D. *et al.* (2009) 'Mechanisms of englacial conduit formation and their implications for subglacial recharge', *Quaternary Science Reviews*. Elsevier Ltd, 28(19–20), pp. 1984–1999.

Iken, A. and Bindschadler, R. A.: Combined measurements of Subglacial Water Pressure and Surface Velocity of Findelengletscher, Switzerland: Conclusions about Drainage System and Sliding Mechanism, Journal of Glaciology, 32, 101–119.

Iken, A., Fabri, K., and Funk, M.:Water storage and subglacial drainage conditions inferred from borehole measurements on Gornergletscher, Valais, Switzerland, Journal of Glaciology, 42, 233–245, 1996.

Sacchi, M. D. (1997) 'Reweighting strategies in seismic deconvolution', *Geophysical Journal International*, 129(3), pp. 651–656. doi: 10.1111/j.1365-246X.1997.tb04500.x.

Schmelzbach, C., Tronicke, J. and Dietrich, P. (2012) 'High-resolution water content estimation from surface-based ground-penetrating radar reflection data by impedance inversion', *Water Resources Research*, 48(8), pp. 1–16. doi: 10.1029/2012WR011955.

Schmelzbach, C. and Huber, E. (2015) 'Efficient deconvolution of ground-penetrating radar data', *IEEE Transactions on Geoscience and Remote Sensing*. IEEE, 53(9), pp. 5209–5217. doi: 10.1109/TGRS.2015.2419235.

Warren, C., Giannopoulos, A., and Giannakis, I.: gprMax: Open source software to simulate electromagnetic wave propagation for Ground Penetrating Radar, Computer Physics Communications, 209, 163–170

Zwally, H. J., Abdalati, W., Herring, T., Larson, K., Saba, J., and Steffen, K.: Surface melt-induced acceleration of Greenland ice-sheet flow, Science, 297, 218–222,