Exploring the Mechanisms and Causes of High Elevation Crevasses in the Interior of the Greenland Ice Sheet

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Introduction

Greenland is home to the world's second largest ice sheet, with enough ice to raise current sea levels by over seven meters if it were to melt completely. It is therefore of global importance to study changes in ice sheet dynamics with rising temperatures. During Greenland's record-breaking melt season of 2012, enough snow melted at high elevations to expose dozens of cracks at elevations of up to 1900 m above sea level (asl) in southwest Greenland (Figure 1). Previous studies had indicated that strain rates at elevations above 1600 m asl were too low for stress fractures to form (Poinar et al., 2015). Our research aims to answer how high-elevation crevasses form in Greenland's interior. We studied the behavior of a set of cracks at the KAN-U field station in southwest Greenland and investigated possible interactions of these cracks with local topography.

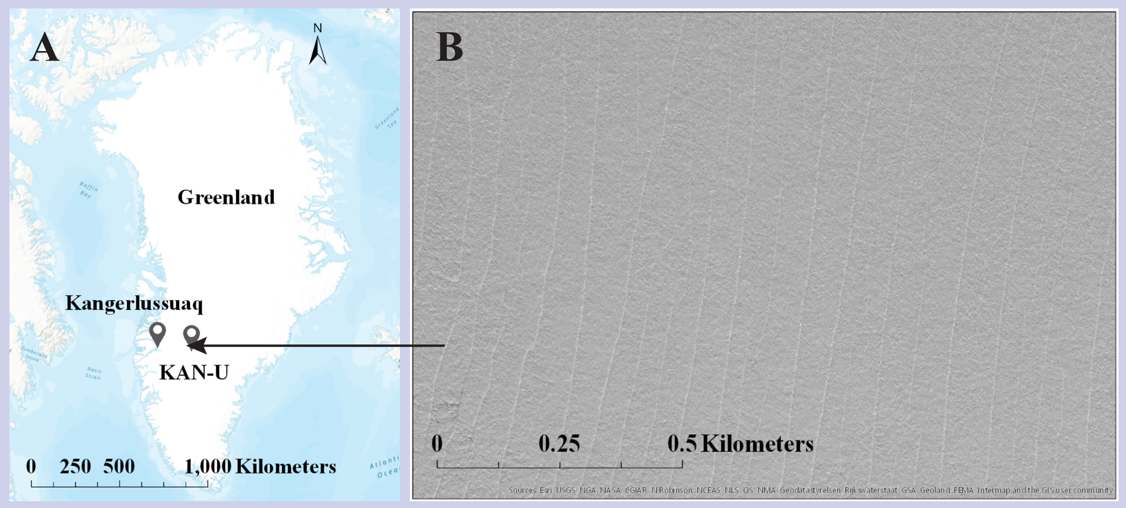


Figure 1A: Map of Greenland showing locations of Kangerlussuaq and KAN-U field site in southwest Greenland. **Figure 1B**: Worldview-1 satellite image showing an area west of KAN-U containing many crevasses. Source: WorldView-1 (Imagery (c) 2012 Digital Globe).

Methods

In April 2017, our team installed five Trimble NetR9 differential GPS stations among high-elevation crevasses located about 2 km northwest of the KAN-U field station in southwest Greenland. These stations, referred to by the names MCF1 - MCF5, recorded latitude, longitude, and elevation data every 15 seconds from April 30, 2017 until May 1, 2018 (Figure 2).

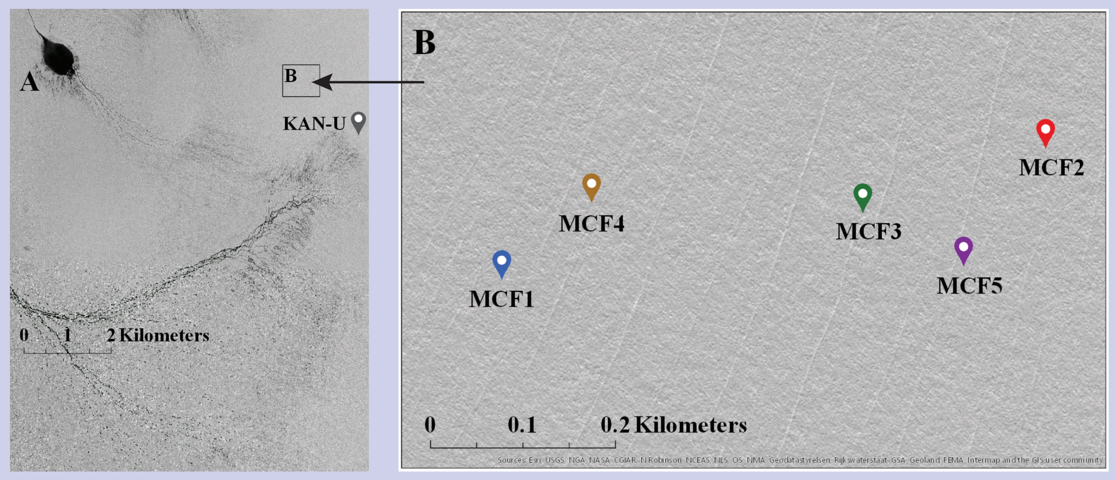


Figure 2A: WorldView satellite image of sluch fields and surface lakes near KAN-U field station. **Figure 2B:** Close-up WorldView image of study site with approximate locations of Trimble Net R9 GPS stations. Source: WorldView-1 (Imagery (c) 2012 Digital Globe).

Data processing workflow:

1. Send .o files to OPUS website for known error correction
2. Import .T02 files for each station into Trimble Business Center
3. Use OPUS result to correct MCF5 locations. Relative movements tied to single MCF5 location for 5/1/2017
4. Maximize resolution and process baselines
5. Export .csv files for point locations
6. Use Python with Osgeo and Matplotlib modules to sort, convert, and plot data
7. Import shapefiles from Python plots into ArcGIS
8. Add Arctic DEM mosaic and WorldView-1 satellite image "WV01_20120812150521".
9. Export .png images
10. Interpret resulting plots and maps

Results

- The GPS stations traveled west-northwest 55.72 m at an average of 14.96 cm/day with a 0.99 m total loss in elevation (Figures 4, 6, and 7).
- The stations appear to have sped up during the summer by 1 - 2 mm and slowed comparably during the winter (Figure 7).
- MCF1 and MCF4 were placed farther downslope than the other three stations (Figure 8). They also moved about 2 mm per day faster (Figure 7) and moved away from MCF5 about 0.2 mm/day faster (Figure 9).
- Stations MCF1 - MCF4 moved away relative to MCF5 at a rate of 0.5 to 2.0 mm/day as the area spread out (Figure 9).
- Rates of spreading appeared to increase in winter and remain higher than starting rates for the duration of the study (Figure 9).
- The crevasses are oriented roughly perpendicular to the direction of flow (Figure 4).
- The crevasses appear to be bending as the ice flows over local topography through a region heavily affected by lakes and slush fields (Figures 3 and 5).
- MCF3 was disconnected from the antenna in October and stopped recording. Data for all GPS stations were corrupted or lost for 14 days mainly in winter.

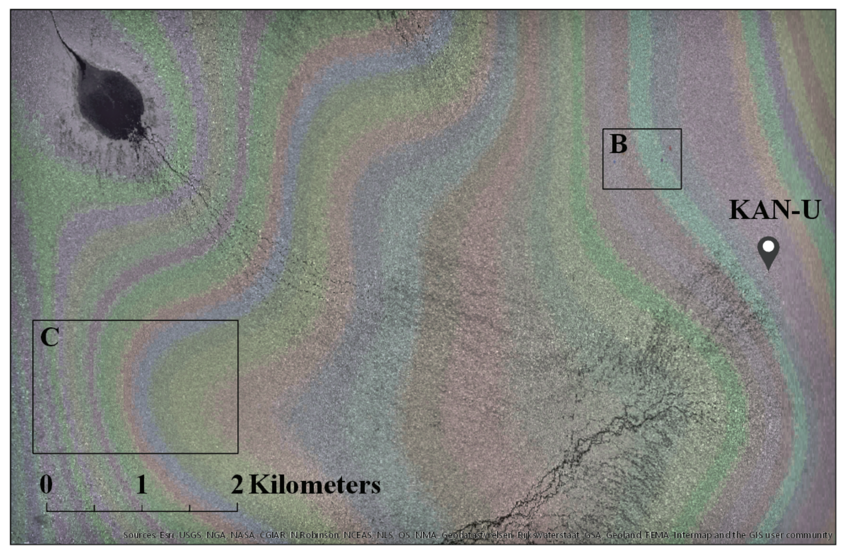


Figure 3: Arc GIS map overlay of the area near KAN-U field station. Area B is expanded in figure 4 and area C is expanded in figure 5. Colored bands represent 2 m elevation contours. Sources: WorldView-1 imagery and Arctic DEM release 6.0 (Imagery (c) 2012 Digital Globe).

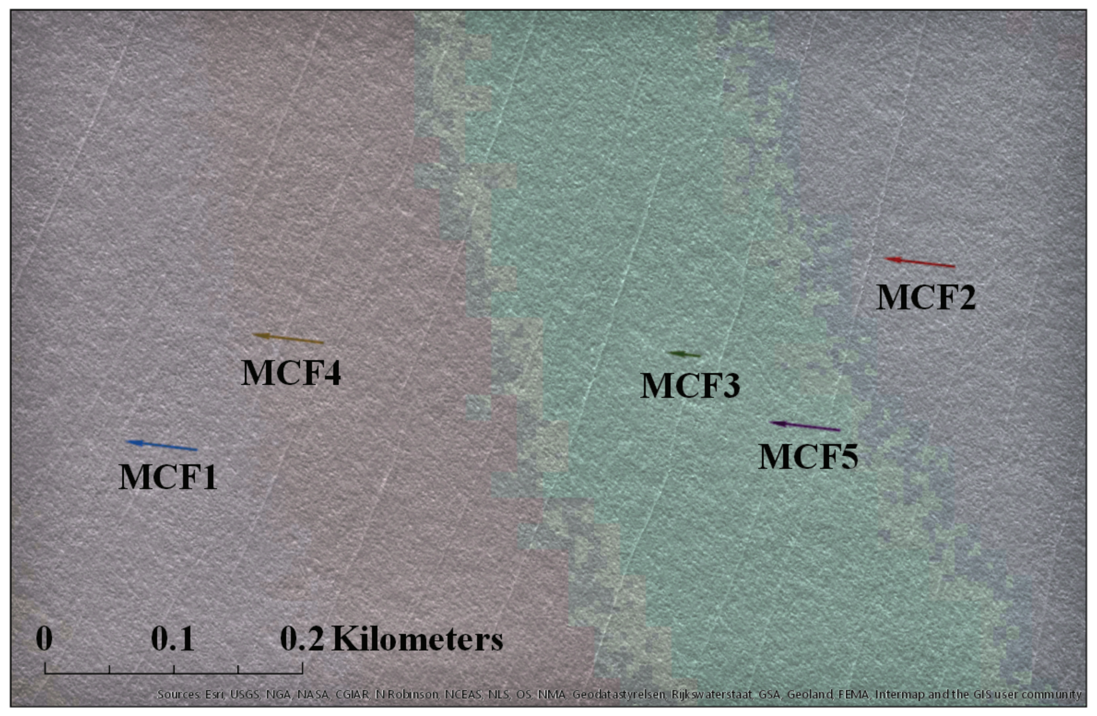


Figure 4: View of the 2017-2018 study site location corresponding with area B in figure 3. Orientation of the crevasses is roughly perpendicular to the direction of movement of the GPS stations. Colored bands represent 2 m elevation contours. Sources: WorldView-1 and Arctic DEM release 6.0 (Imagery (c) 2012 Digital Globe).

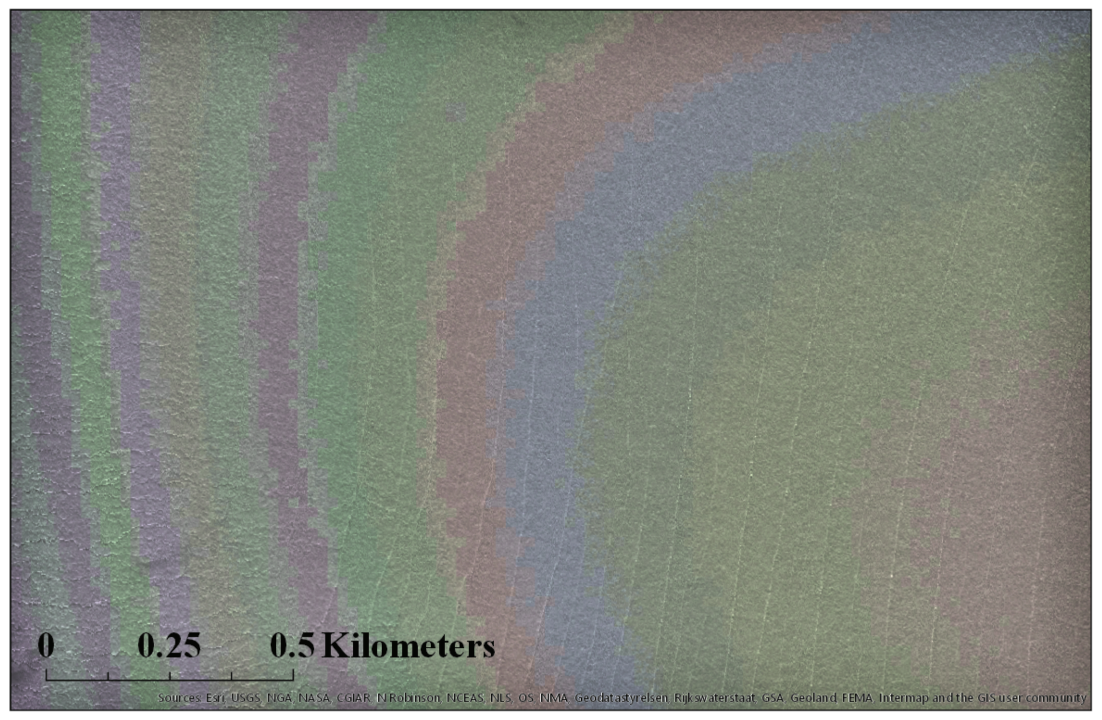


Figure 5: View of an area of crevasses 8 - 10 km downslope from KAN-U field station corresponding to area C in figure 3. Orientation of the crevasses shows strong correlation to local topography. Colored bands represent 2 m elevation contours. Sources: WorldView-1 and Arctic DEM release 6.0 (Imagery (c) 2012 Digital Globe).

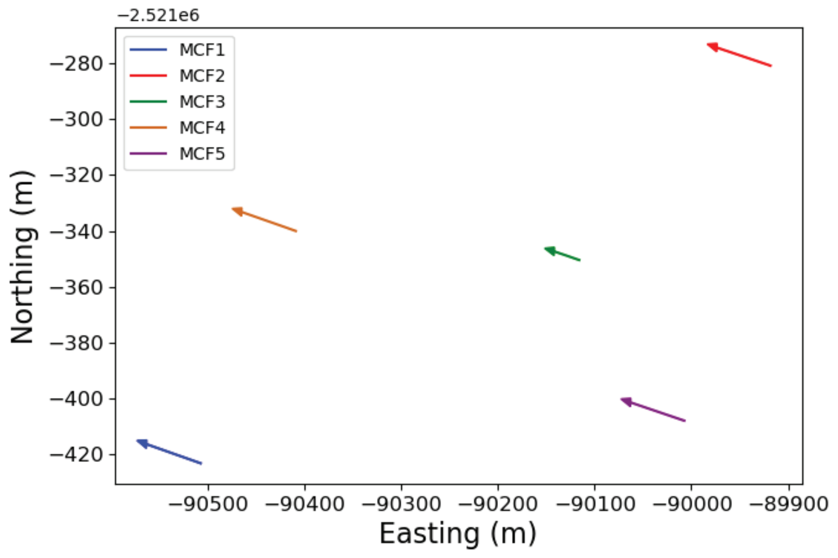


Figure 6: Absolute movements of GPS stations in easings and northings. Movement is west-northwest.

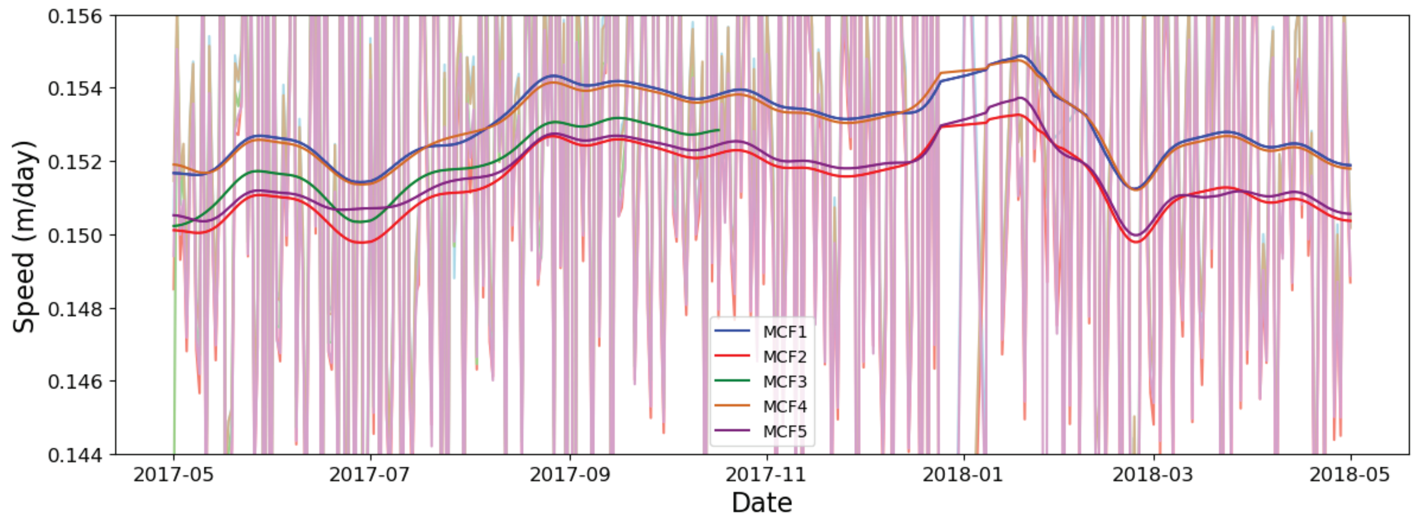


Figure 7: Speeds of absolute GPS station movement. Noisy raw data are shown in lighter shades. A Gaussian filter with a standard deviation of seven days was used to smooth the data and find a trend. Smoothed curves are shown in darker shades.

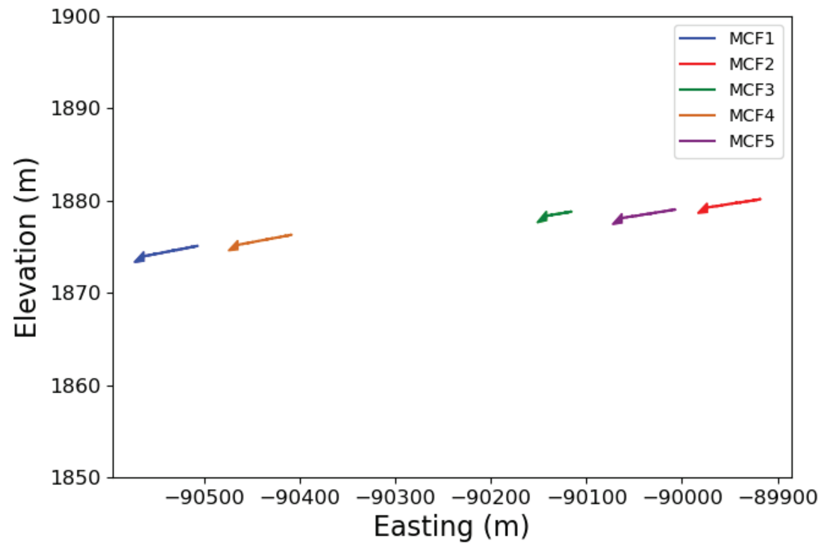


Figure 8: Absolute movements of GPS stations in eastings and elevations, showing downhill movement as the stations move toward the west.

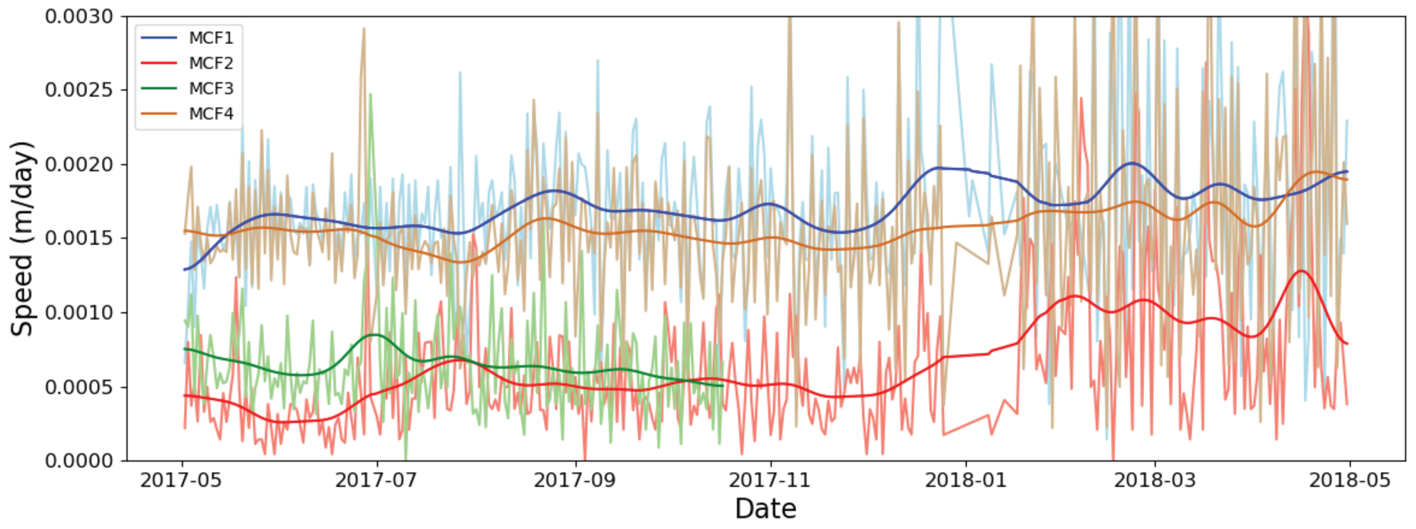
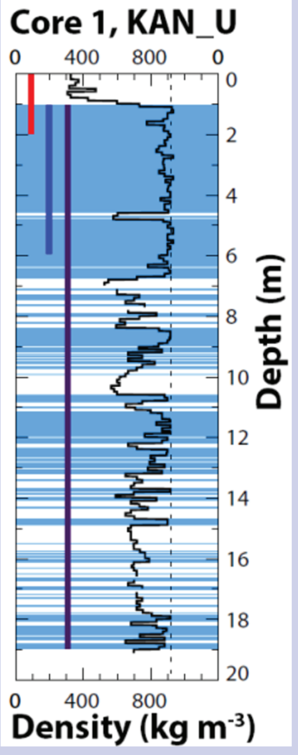


Figure 9: Speeds of GPS stations MCF1 - MCF4 relative to MCF5. Noisy raw data are shown in lighter shades. A Gaussian filter with a standard deviation of seven days was used to smooth the data and find a trend. Smoothed curves are shown in darker shades.

Discussion

- Strong correlation between orientation of crevasses, local topography, and direction of flow indicate strain plays a part
- Data confirm 2009 - 2013 study on ice flow acceleration at KAN-U (Doyle et al., 2014). We found a 7.5% increase over 2009.
- Strain rates likely increased but still far lower than the estimated 0.5% critical strain rate (Poinar et al., 2015)
- Increasing strain rates not likely to be acting alone
- Top layers of subsurface consist of firn, porous snow in process of being compressed to ice
- Ice cores show ice slabs meters thick from refrozen meltwater (Figure 10) (Macghuth et al., 2016)
- Ice slabs may be more brittle than firn alone, requiring much lower strain rates than firn alone (Figure 11)



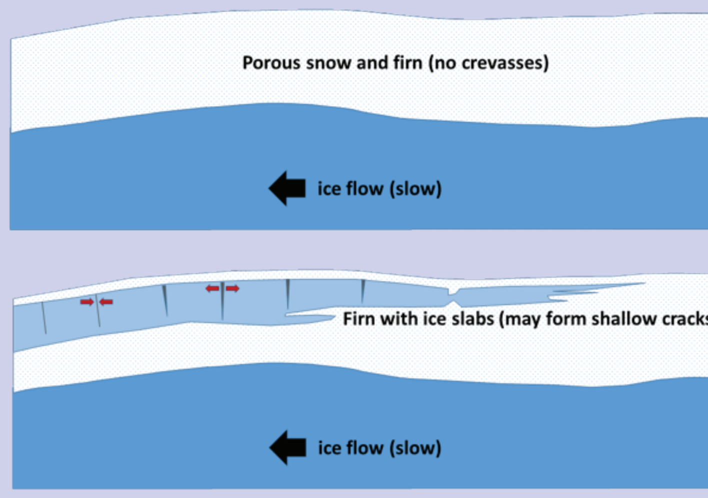


Figure 10: (Left) 2012 ice core taken from KAN-U showing ice lenses in blue and firn in white.
Figure 11: (Above) Porous materials tend to be more ductile and can generally deform with stress. More dense materials lack of pore space, reduces their ability to deform and making them more likely to fracture.

- Another potential contributor could be expansion and contraction as meltwater warms subsurface firn (Charlampadis, 2016)
- Cracks formed by thermal contraction are generally hexagonal while the crevasses in our study are linear
- No evidence of sudden sustained location jumps which may indicate opening of cracks from spontaneous surface lake drainage downslope
- Possibility remains that crevasses were already present before 2012 when they were exposed

Conclusion

We conclude that the most likely mechanism for the formation of high elevation crevasses in southwest Greenland is brittle surface ice with accelerated flow over local topography. We cannot, however, completely rule out a combination of factors, which may include increased strain rates and thermal expansion and contraction of surface ice. More study will be needed to investigate further.

As the climate warms, the resulting changes in the dynamics of ice sheets will have consequenses for the entire globe. Increasing volumes of meltwater are added to the oceans each year. This massive input of fresh water raises sea levels and may disrupt climate regulation in coastal regions worldwide. It is therefore important to better understand how crevasses are forming at high elevations and what effects they may have on future ice mass loss.

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