Impact of Stress Field on the Stability of Supraglacial Channels in Western Greenland

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Abstract

The viability of supraglacial channels has important implications for melt water transport and runoff across the ablation zone of western Greenland in the future. This study determines whether supraglacial channels will be able to continue transporting water given the current stress acting on the supraglacial channels by the surround ice. Surface velocities derived from the RADAR-SAT Interferometric Synthetic Aperture Radar are used to calculate the strain rate, which is converted into the mean effective tensile stress acting on each channel. The "Maximum Potential Depth" is estimated based on the balance between the ice overburden pressure and the longitudinal strain rate. Examining the relationship between the length and slope of supraglacial channels shows that shorter channels have higher slopes while longer channels have lower slopes. From this result, we conclude that the ice sheet imparts higher stresses, which act to keep the channel open, on those channels with steeper slopes than supraglacial channels with shallower slopes. Supraglacial channels are more susceptible to closure when the "Estimated Channel Depth" of a given channel has not yet propagated to the "Maximum Potential Depth" where the ice overburden pressure surrounding the channel is greater than the longitudinal strain and thus the tensile stress trying to keep the channel open. The majority of the supraglacial channels in our study do not remain viable as a means of transporting water with a small portion being viable under the current tensile stress conditions. Awareness of supraglacial channel viability allows for further understanding of the meltwater variability and of the importance of supraglacial channels in draining lakes.

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β	channel slope
ε	strain rate tensor
ε_{xx}	longitudinal strain rate
μ	effective viscosity
ρ_i	ice density
Ψ	viability parameter
σ'	Cauchy deviatoric stress tensor
σ_e	effective stress
σ_{xx}	longitudinal stress
σ_{yy}	transverse stress
σ_v	effective tensile stress
τ_{xy}	shear stress
υ	velocity
A	flow law parameter
B	ice stiffness parameter
d	channel depth
d_E	estimated channel depth
d_N	maximum potential depth of a channel
g	gravitational acceleration
n	Glen’s flow law coefficient
n_c	Gaukler-Manning coefficient
P	wetted perimeter of a channel

Q	water discharge through a channel
R_h	cross-sectional area of a channel
V	average velocity of water flow through a channel

Chapter 1: Introduction

The Greenland Ice Sheet (GIS) has recently experienced thinning and accelerated flow speed that contributes to global sea level rise primarily through a few large ice streams (Luckman and Murray, 2005; Rignot and Kanagaratnam, 2006; Howat et al., 2007; Pritchard et al, 2009; Zwally et al., 2011). In addition to a regional increase in mass flux, there has been an increase in surface melt, resulting in a 30% increase in runoff with 15% of this runoff contributing to global sea level rise (Zwally et al., 2002; Box et al., 2006). Surface melt water infiltration is an important factor in influencing the local ice flow through episodic drainage (Zwally et al., 2002; Boon and Sharp, 2003; Fountain et al., 2005; Das et al., 2008). The supraglacial hydrologic system is complex and processes that are responsible for surface melt water transport, melt water infiltration, and the storage of melt water are not well understood. Supraglacial lakes are an important component of the supraglacial hydrologic environment and are responsible for seasonal storage and infiltration through the hydro-fracture process (Walder, 1982; Alley et al., 2005; Lüthje et al., 2006, Box and Ski, 2007; McMillan et al., 2007; Sneed and Hamilton, 2007; van der Veen, 2007; Das et al., 2008; Krawczynski et al., 2009; Sundal et al., 2009; Tsai and Rice, 2010; Lampkin, 2011; Selmes et al. 2013). It has been noted that moulins and crevasses are important for transporting surface melt water deeper into the ice sheet (Colgan et al., 2011). Increasingly, there have been efforts to understand the role that supraglacial channels play in regulating in situ lake drainage and how supraglacial channels facilitate melt water infiltration (Lampkin and Vanderberg, 2013; Yang and Smith, 2013). This work seeks to improve our understanding of supraglacial channels and their impact on potential melt water infiltration and larger ice sheet dynamics.

Chapter 2. Background

Supraglacial channels largely emerge as a result of surface melt runoff channelized by crevasses (Fountain and Walder, 1998) or as the consequence of surface lake drainage dynamics (Raymond and Nolan, 2000). Early investigations on supraglacial channels have established controls on their morphological characteristics and evolution (Zeller, 1967; Knighton, 1972; Ferguson, 1973; Parker, 1975; Dozier, 1976; Knighton, 1985; Marston, 1983). Smith (1976) observed that supraglacial channels containing water are capable of propagating deeper into the ice sheet than those channels not transporting melt water. Supraglacial channels have a higher rate of change of velocity when they flow over regions with steep slopes and low resistance from the channel bed (Knighton, 1981). Sinuosity of channels can be enhanced in these regions resulting in shortening of channels under compressive stress regimes (Knighton, 1985).

The evolution of a supraglacial channel is governed by the following three factors: (1) ice dynamics, (2) turbulent flow of melt water through channel, and (3) heat flux between melt water channel boundaries (Isenko et al., 2005; Jarosch and Gudmundsson, 2012). These factors interact to either maintain the channel, such that it can continue to transport melt water, or to close the channel, such that it is no longer hydrologically viable. Hydraulic incision driven by heat loss from the water to the ice, melt water discharge, and channel slope enhances the channel hydraulic cross-section (Knighton, 1981; Jarosch and Gudmundsson, 2012). Isenko et al. (2005) determined that the temperature of melt water within a channel approaches an equilibrium temperature ($\sim < 0.1\ °C$), which affects the rate of ablation along channel walls and hence the incision rate. The water temperature exponentially approaches the equilibrium temperature and the distance at which they are the same depends on the channel length (Isenko et al., 2005).

Recent studies have focused on characterizing supraglacial channels across the GIS. Lampkin and Vanderberg (2013) conducted the first regional-scale assessment of supraglacial channel networks from high-resolution imagery over west-central Greenland and determined that the ablation zone has two hydrologic modes: (1) crevasse and moulin terminating channels that dominate at elevations < 800 m and (2) higher-order channel networks prevalent at elevations > 800 m. Channel networks linking channels to another channel or linking channels to lakes are predominately found at elevations between 800 and 1200m and are correlated with fewer lake occurrences, lower surface velocities (~50 m a^{-1}), and the ice flow is dominated by internal deformation over basal sliding (Lampkin and Vanderberg, 2013). Due to small size of supraglacial channels, the moderate or course resolution of most satellite images is not high enough. In addition, it is difficult to differentiate between slush and water because they have similar spectral signatures in the visible and near-infrared bands. Yang and Smith (2013) developed an automated “spectral shape” procedure that uses high-resolution satellite images containing spectral and shape information to define supraglacial streams over the ablation zone. Developing this “spectral shape” method for high-resolution data yields a much higher value of accurately detecting supraglacial streams over other methods (Yang and Smith, 2013).

This study builds on the work by Lampkin and VanderBerg (2013) and seeks to understand the current capacity for channels to transport melt water through an assessment of the degree of channel closure due to the local stress field. The magnitude of the surface stress field is obtained from satellite-derived velocity fields. Lastly, we calculate the maximum depth at which channels theoretically would propagate without the influence of hydraulic incision.

The next section of this paper describes the data used in this study. Section 4 explains the analysis methods and calculations used in the study. This is followed by Section 5, which discusses the results of this study, and Section 6, which contextualizes the results. The final section of this paper summarizes our findings.

Chapter 3. Data

Three main pieces of data were used in this study. Supraglacial channels used in this study were previously delineated in a study by Lampkin and Vanderberg (2013) using Landsat panchromatic imagery. Calculations of the tensile stress and determination of viability were completed using the RADARSAT-1 fine beam Interferometric Synthetic Aperture Radar surface velocity and the Advanced Spaceborne Thermal Emission and Reflection Radiometer digital elevation model. All of the data sets used in this analysis encompass the 2007 melt season across the Jakobshavn Isbrae region of west-central Greenland.

3.1 Supraglacial channel data

Supraglacial melt channels delineated from cloud-free, Landsat panchromatic imagery at 12.5 m^2 spatial resolution during the 2007 melt season were used in this analysis. Melt channels were manually delineated and classified based on topological relationships (Lampkin and Vanderberg, 2013). The spatio-temporal evolution of hydrologic networks was assessed over the Landsat path (009)/row (011) scene covering the Jakobshavn Isbræ drainage basin. Additional details of channel characteristics are provided in Table 1.

Classification	Description	Mean Length	Mean Elevation	Mean Width	Mean Slope
Tributary	Flow into lake/other melt channel	1904.57 m	1040.53 m	55.15 m	0.0114 degrees; $1.944*10^{-4}$ radians
Connector	Flow from one supraglacial lake to another lake	2368.33 m	1087.97 m	53.35 m	0.00958 degrees; $1.672*10^{-4}$ radians
Terminal	Flow into non-lake features (i.e. crevasse or moulin)	2028.20 m	829.20 m	53,49 m	0.0108 degrees; $1.885*10^{-4}$ radians

Table 1: Summary of supraglacial channel characteristics describing the role each channel classification has in transporting water, as well as the mean length, elevation, width and slope (in units of degrees and radians). All table content borrowed from Lampkin and VanderBerg (2013).

3.2 Surface velocity and elevation data

Surface velocity values were derived using data from the RADARSAT-1 fine beam Interferometric Synthetic Aperture Radar (SAR). The data was collected and averaged over an approximately a 96-day period (Joughin et al., 2010). The surface velocity is gridded at a resolution of 500 meters (Joughin et al., 2010).

Surface elevation of the supraglacial channels was used over our study area. The digital elevation model (DEM) utilized for surface elevation takes elevation data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). ASTER is released in 1° x 1° tiles with a 30 m horizontal resolution (Howat et al, 2014).

Chapter 4. Methods

Prior to assessing the impact of stress on the ability of supraglacial channels to continue transporting melt water across the ice sheet, we examined the relationship between channel hydro-geomorphic properties. This includes a comparison of channel length and channel slope. Following this analysis, the effective stress acting on each supraglacial channel was found and then the channel maximum potential depth was calculated. Finally, the viability of supraglacial channels was estimated using the ratio and definition described in Section 4.3.

4.1 Derivation of stress field

Measured surface velocity components were used to derive the surface strain rates, which are converted to stresses using Glen's Flow Law (Glen, 1955):

$$\sigma' = 2\mu\dot{\varepsilon} \tag{1}$$

where σ' is the Cauchy deviatoric stress tensor, $\dot{\varepsilon}$ is the strain rate tensor and μ is the non-linear effective viscosity:

$$\mu = B\sigma_e^{\frac{1-n}{n}} \tag{2}$$

where B is the ice stiffness parameter, σ_e is the effective stress and n is Glen's flow law coefficient (Cuffey and Paterson, 2010). In our study, we set the Glen's flow law coefficient to 3.

An inversion method is performed to obtain a spatial estimate for B since it is used as a proxy for the ice viscosity. The inversion for the ice stiffness parameter, B, involves two versions of the Stokes equations using Ice Sheet System Model (ISSM). In ISSM, ice is considered to be isotropic and viscous with the ice flow described using the full Stokes formulation, which includes momentum balance and the effects of incompressibility. The incompressible form of the equations for conservation of mass assuming negligible acceleration and neglecting the effect of the Coriolis force are:

$$\nabla \cdot \upsilon = 0 \tag{3}$$

$$\nabla \cdot \sigma + \rho g = 0 \tag{4}$$

where υ is velocity, ρ is ice density, g is the acceleration due to gravity, and $\nabla \cdot \sigma$ is the divergence of the stress tensor, σ. In addition to equations 3 and 4, Glenn's Flow Law (Equation 1) is also employed.

Ice stiffness is dependent on temperature. This term is initialized using ice temperature data. To obtain the boundary conditions, the basal friction law is applied. Assuming that the driving stress is only balanced by basal friction and nothing else, the basal friction coefficient can be imposed. For lower boundary, which lies at the ice-bedrock interface, a Coulomb-style basal friction law is used (Cuffey and Paterson, 2010). The upper boundary of the model in ISSM is assumed to be stress-free as this is the interface between the ice surface and the air.

Using the converted strain rates, we are able to calculate the minimum and maximum principle stress σ_1 and σ_2 as:

$$\sigma_1 = \frac{1}{2}\left(\sigma_{xx} + \sigma_{yy}\right) + \sqrt{(\frac{1}{2}\left(\sigma_{xx} + \sigma_{yy}\right)^2 + \tau_{xy}^2} \tag{5}$$

$$\sigma_2 = \frac{1}{2}\left(\sigma_{xx} + \sigma_{yy}\right) - \sqrt{(\frac{1}{2}\left(\sigma_{xx} + \sigma_{yy}\right)^2 + \tau_{xy}^2} \tag{6}$$

where σ_{xx}, σ_{yy}, and τ_{xy} are the longitudinal, transverse and shear stresses, respectively. The effective tensile stress (σ_v) can then be estimated using:

$$\sigma_v^2 = \sigma_1^2 + \sigma_2^2 - (\sigma_1\sigma_2) \tag{7}$$

as described in Vaughan (1993).

To obtain the mean effective tensile stress along each of the mapped supraglacial channels, the supraglacial channel map and the effective tensile stress are overlaid.

4.2 Estimating Channel Depth

Using the channel width measured from the archive of mapped supraglacial channels and the finding by Knighton (1981) that the ratio of a channel's width to its depth is between 3.4 and 12 provides an estimate of the minimum and maximum depth to which a supraglacial channel can propagate. The maximum depth found from this estimation will be referred to as the "Estimated Channel Depth" for the remainder of this paper.

4.3 Calculation of Channel Maximum Potential Depth

In a similar manner to how the mean effective tensile stress along each supraglacial channel was found, we obtained the mean longitudinal strain rate along each supraglacial channel. The mean longitudinal strain along each supraglacial channel was found by overlaying the longitudinal strain and channel map and used to calculate the depth of supraglacial channels. The maximum depth of a supraglacial channel occurs at the depth where the stress imparted by the ice sheet on the channel changes from tensile to compressive.

The depth of supraglacial channels can be calculated based on the balance between the creep-closure rate due to the ice overburden pressure and the longitudinal strain rate as outlined in Nye (1957):

$$d_N = \frac{2}{g\rho_i}\left(\frac{\dot{\varepsilon}_{xx}}{A}\right)^{\frac{1}{n}} \tag{8}$$

where d_N is the channel depth, ρ_i is the ice density, g is the gravitational acceleration, ε_{xx} is the longitudinal strain rate, and A and n represent flow-law parameters. Values used for the ice density, and the two flow-law parameters are the same as those outlined in Mottram and Benn (2009). This calculation of the channel depth is effectively known as the Nye Depth, but will be referred to as the "Maximum Potential Depth" for the remainder of this paper. In this calculation of channel depth, we have assumed a constant ice density throughout the GIS similarly to Mottram and Benn (2009); however, channels and ice thickness affect the density by reducing the effect of the hydrostatic pressure.

In calculating the depth of supraglacial channels, it is assumed that the supraglacial channels are not filled with water. Supraglacial channels are not water-filled throughout the entire year, but during the melt season, they are partially filled with water, enhancing to the amount of discharge from the channel and allowing the channel to propagate deeper into the ice sheet. Smith (1976) continued the work of Weertman (1973) by investigating how water-filled crevasses are able to penetrate deeper into the ice sheet with an increasing depth of water. Both Weertman (1973) and Smith (1976) are in agreement that when a crevasse is filled to a level equal to or greater than 94.6% of its depth, then the crevasse depth can penetrate to the bottom of the glacier.

4.4 Definition of Viability

To define viability, this study determines whether the current depth of any given supraglacial channel is close to its maximum depth. In doing this, we make use of the ratio between the “Estimated Channel Depth” and the “Maximum Potential Depth” such that

$$\Psi = \frac{d_E}{d_N} \begin{cases} < 1: & Viable \\ > 1: & Not\ Viable \end{cases} \tag{9}$$

where Ψ is the viability parameter, d_E is the “Estimated Channel Depth”, and d_N is the “Maximum Potential Depth”. The viability parameter can be interpreted to mean that when the “Maximum Potential Depth” of a channel is much larger than the “Estimated Channel Depth”, then the supraglacial channel has not yet propagated deep enough into the ice sheet such that the stress will not cause the channel to close up. The converse is also true. If the “Maximum Potential Depth” is close to or less than the “Estimated Channel Depth”, then the supraglacial channel has already propagated close to or below the maximum depth at which the ice overburden pressure will allow and thus the channel is at risk of closing up and no longer transporting melt water.

4.5 Calculation of Potential Discharge

Calculating the potential discharge of each supraglacial channel utilizes channel geometry. In the study by Lampkin and VanderBerg (2013), the width of each channel was previously measured. The width is then used to estimate the depth of supraglacial channels as explained in Section 4.2. Assuming the flow of water in an open channel, we apply the Gauckler-Manning equation (Gauckler, 1867; Manning, 1891) to relate the water discharge (Q) to the average velocity (V) of a channel, its slope (β), and hydraulic radius (R_h):

$$Q = VA_c \tag{9}$$

with V being defined as:

$$V = \frac{1}{n_c} R_h^{\frac{2}{3}} \beta^{\frac{1}{2}} \tag{10}$$

where n_c is the Gauckler-Manning coefficient, R_h written as $R_h = A_c/P$, with A_c being the cross-sectional area of the channel and P the wetted perimeter of the channel.

Chapter 5. Results

As previously mentioned in Section 4, the channel hydro-geomorphic properties and the effective tensile stress acting on supraglacial channels were evaluated prior to analyzing and determining supraglacial channel viability. The following subsections will describe our findings for each of these pieces we explored in this study.

5.1 Hydro-geomorphic Properties of Supraglacial Channels

Using the channel archive created by Lampkin and VanderBerg (2013), the distribution of supraglacial channel lengths and the relationship between the length of supraglacial channels and the slope of each channel were examined. The distribution of supraglacial channel lengths shows that the majority of channels are less than five kilometers long, with the largest amount of channels being between one and two kilometers in length (Figure 1).

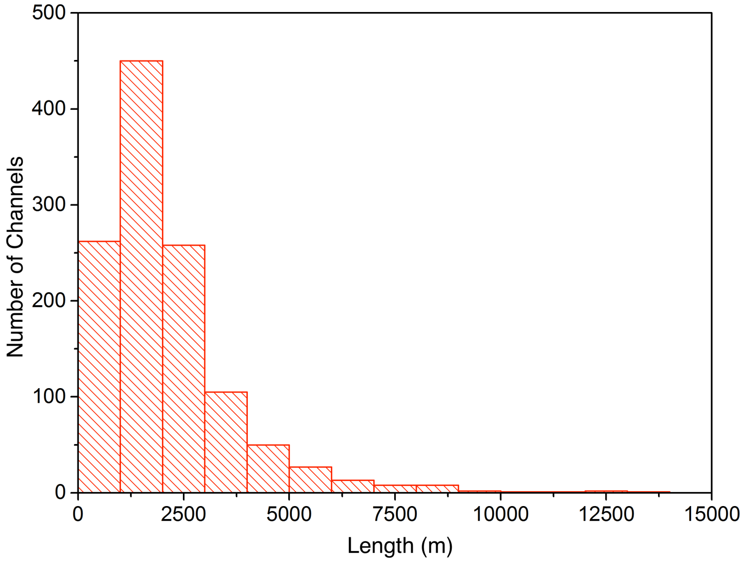

Figure 1: Histogram of supraglacial channel lengths showing that the majority of channels are less than 5 kilometers and very few supraglacial channels are longer than 10 kilometers.

The slope of each supraglacial was calculated by using the difference between the elevation at the endpoints of each channel and the length of the channels. Shorter supraglacial channels have higher slope while longer supraglacial channels have lower slope. However, some short supraglacial channels have higher slopes (Figure 2).

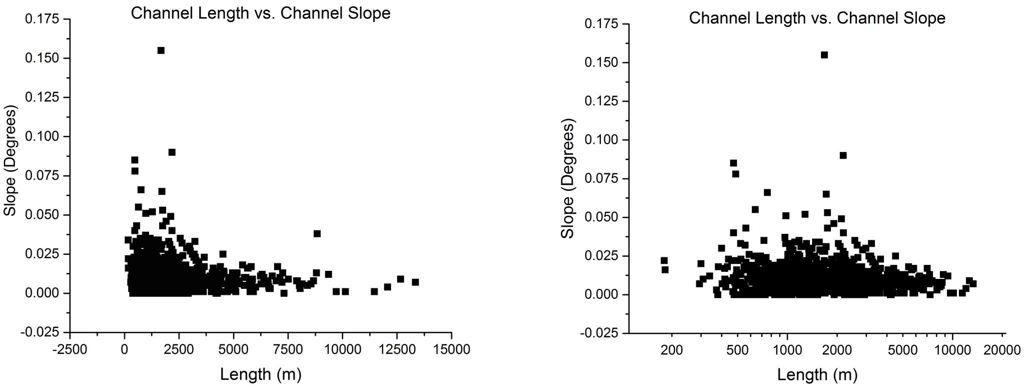

Figure 2: Distribution of channel length (x-axis) plotted against the channel slope (y-axis) for all three classifications of supraglacial channels, indicating that shorter channels have higher slopes and longer channels have lower slopes. The plot on the left shows the distribution in terms of a linear scale of channel length and on the right, in terms of the logarithm of channel length.

The plots shown in Figure 2 reveal that a non-linear relationship exists between a supraglacial channel's length and its slope. The majority of supraglacial channels surveyed have small slopes (~< 0.005 degrees) but the length of these channels with small slopes varies. A similar statement can be made about short supraglacial channels: there is a range of slope values for the shorter supraglacial channels (~< 2 km). The length and slope of supraglacial channels are connected to the tensile stress acting on these channels. It is generally thought that the stresses acting on longer channels compress the channel. Channels with steeper slopes experience higher stresses from the ice, which will act to keep the channel open and able to transport water. Conversely, the stress on short channels is thought to be extensive, allowing the channel to continue transporting water and those channels with smaller slopes typically have smaller stress imparted by the ice acting on them.

5.2 Effective Tensile Stress

The mean effective tensile stress acting on each supraglacial channel (Figure 3) is broken down into the three classifications as outlined in Lampkin and VanderBerg (2013).

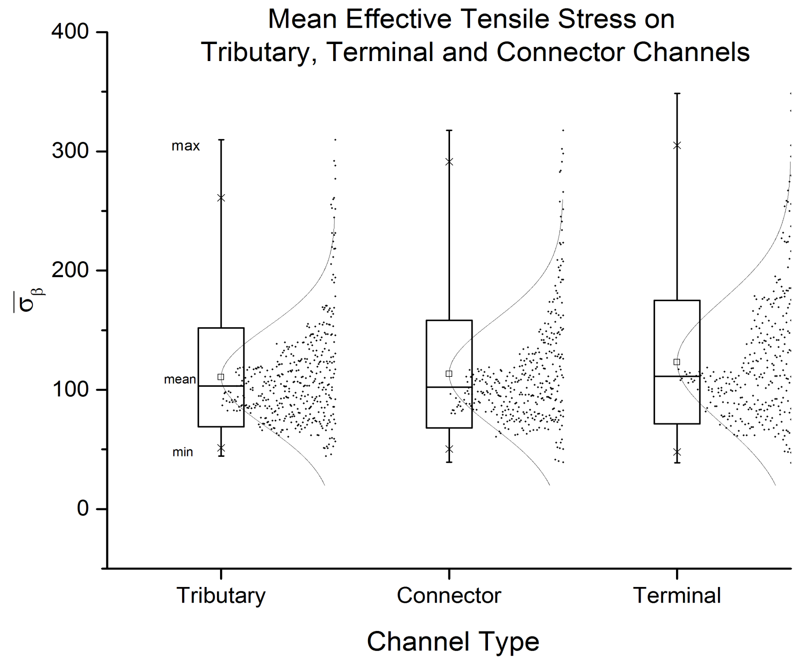

Figure 3: The mean tensile stress ($\overline{\overline{\sigma_\beta}}$) acting along each channel is plotted as a box-and-whisker plot and is broken down by channel type: Tributary, Connector, and Terminal. The top and bottom of the box show the 25th and 75th percentiles with the whiskers indicating the outliers. A similar magnitude of mean effective tensile stress acts on each type of supraglacial channel.

These three classifications of supraglacial channels are Tributary, Connector, and Terminal, with description of their relationship to the larger supraglacial environment provided in Table 1. The mean value of the mean effective tensile stress acting on each of the three classifications of supraglacial channels is similar for all three classifications of channels. The Terminal class of supraglacial channels has a larger spread of mean effective tensile stress values, although its mean value is still of comparable magnitude to the mean value of the Tributary and Connector classes of supraglacial channels. Due to the end behavior of the Terminal class of supraglacial channels being that these channels transport water off the GIS, we believe that this class of supraglacial channels is the most important to understanding the viability of channels and has implications for melt water transport.

5.3 Potential Discharge of Supraglacial Channels

The ratio of the "Estimated Channel Depth" to the "Maximum Potential Depth" when related to channel discharge helps to explain whether channel incision can overcome the ice overburden pressure to keep the channel viable. Computing the amount of discharge from each channel and plotting it against the ratio of the "Estimated Channel Depth" to the "Maximum Potential Depth" as in Figure 4 shows that channels with low discharge have a low ratio of the "Estimated Channel Depth" to "Maximum Potential Depth" are more viable.

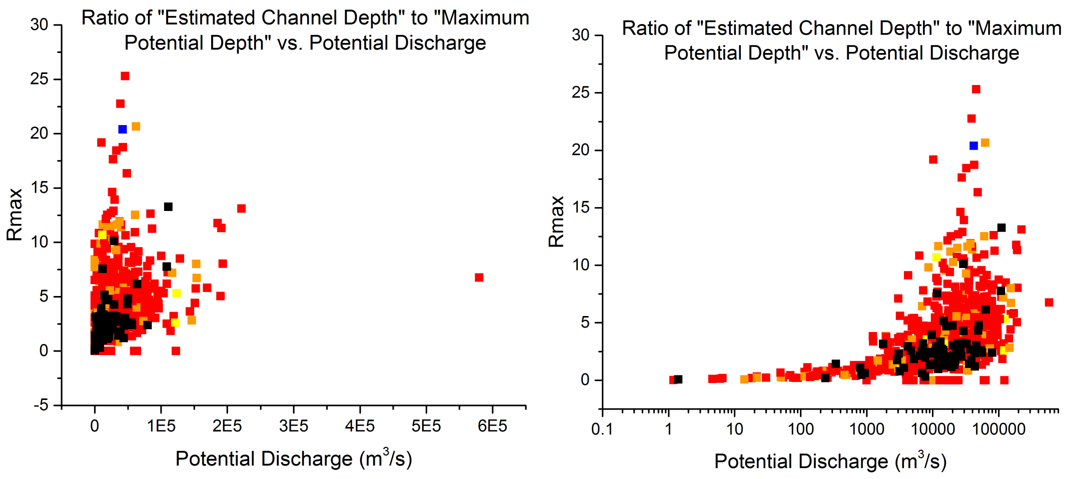

Figure 4: The potential discharge of each supraglacial channel (x-axis) plotted against the ratio of the maximum estimated depth to the Nye Depth (y-axis), shown with a linear scale of potential discharge at the top and in terms of the logarithm of potential discharge in the plot at the bottom. Each channel is represented by one point color-coded based its slope, where a low slope is red and high slope is blue. Black points represent channels with a slope of 0.

However, some supraglacial channels have low discharge and a high viability parameter, indicating that some supraglacial channels with low discharge have the potential to close up and to no longer be a mechanism for transporting melt water across the GIS. Since there is not a clear pattern of supraglacial channel slope in Figure 4, this shows that the orientation of a channel relative to the direction of maximum extension is more important for channel viability.

5.4 Channel Viability

In this paper, we use channel viability as a measure of whether or not a given supraglacial channel will be able to continue transporting melt water across the ablation zone of the GIS. Supraglacial channel depth is related to the ice overburden pressure in the calculation of "Maximum Potential Depth". The ratio of the "Estimated Channel

Depth” to the “Maximum Potential Depth”, when related to channel discharge, helps to explain whether channel incision and/or melt water flowing through a channel can overcome the ice overburden pressure to keep the channel viable. Using this ratio as a viability parameter, the viability of each supraglacial channel is plotted at the center point of each channel (Figure 5 a-c).

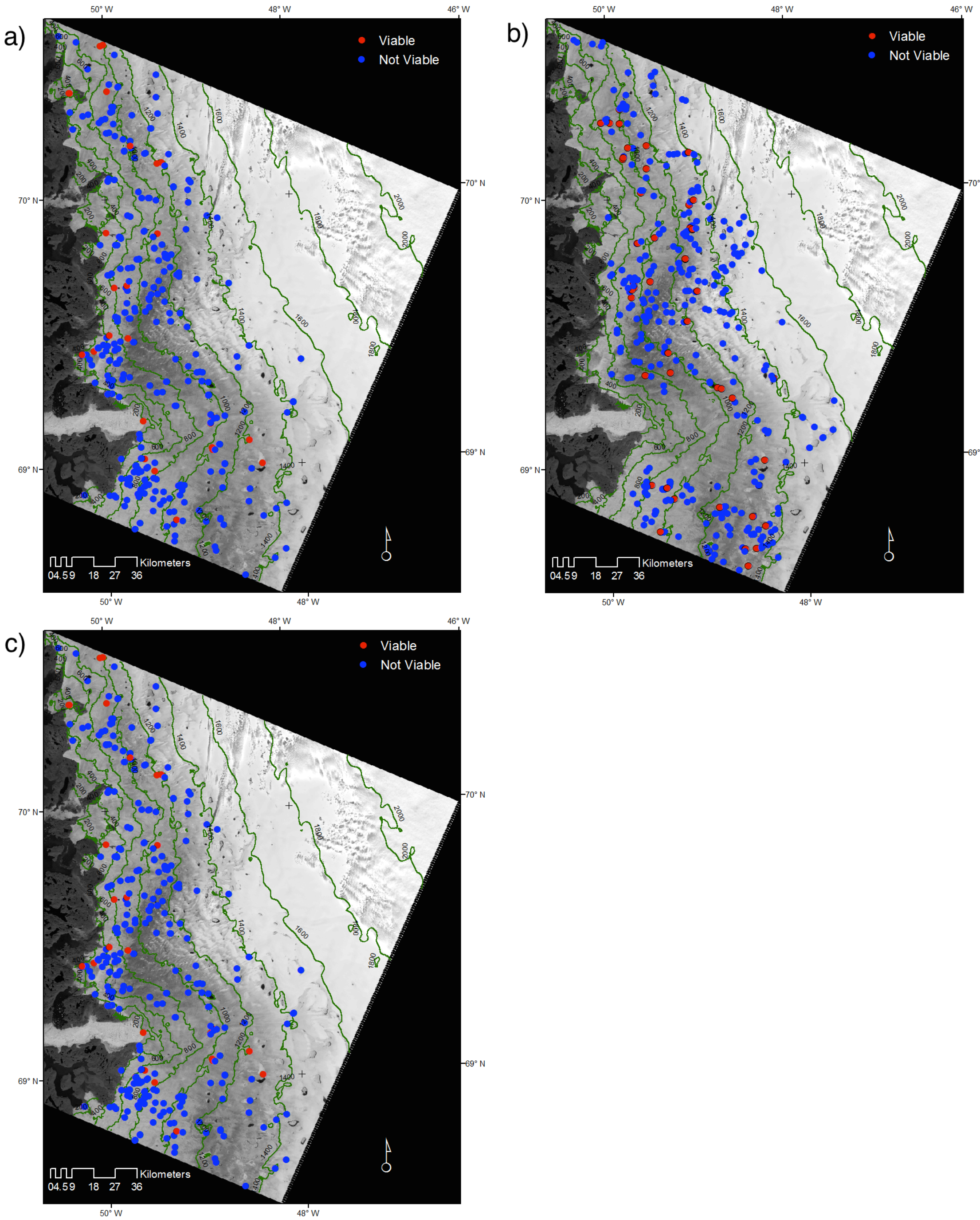

Figure 5: Study area maps showing the ratio of estimated maximum depth to the Nye depth is shown for each channel plotted as red (ratio < 1, or viable) and blue (ratio > 1, or not viable) markers. Elevation contours at an interval of 200 m are superimposed in green contours over Landsat Enhanced Mapper Plus imagery. The three maps (clockwise from top left) show this ratio for each of the three types of channels: a) Tributary Class of channels; b) Connector Class; c) Terminal Class. The majority of channels will close up and not be able to transport water, while a much smaller proportion (<10%) of channels will remain viable as a means of transporting water.

As seen by Figure 5, the majority of supraglacial channels will not be a viable means of transporting melt water across the supraglacial environment of the GIS under the viability parameter. There is not a well-pronounced spatial pattern of supraglacial channel viability with respect to where viable versus non-viable channels are located in this region of west-central Greenland. However, the majority of viable channels are located at slightly lower elevations (~<1.2 km), with only a few viable supraglacial being located above this elevation.

Additionally, the quantity of viable and non-viable channels and the proportion of viable supraglacial channels are presented in Table 2.

Class	Total Number of Channels	Viable Channels (Rmax <1)	Non-Viable Channels (Rmax > 1)	Proportion of Viable Channels
Tributary	454	34	420	7.48%
Connector	397	44	353	11.08%
Terminal	337	25	312	7.42%
Total	1188	103	1085	8.67%

Table 2: Amount and proportion of viable channels based on the ratio of "Estimated Channel Depth" to "Maximum Potential Depth" broken down by channel class. Approximately 90% or more of channels do not remain viable as a mechanism for transporting water over the ice sheet, while less than 10% of supraglacial channels will continue to be viable as a means of transporting melt water across the supraglacial environment of the GIS.

Of the almost 1200 supraglacial channels used in this study, it is expected that less than 10% of the channels remain viable. In comparing the proportion of viable versus non-viable channels between each class of supraglacial channels, it is necessary to keep in mind the total number of supraglacial channels contained in each class. Supraglacial channels in the Tributary Class have the largest amount of channels, numbering almost half of the total channels used in this study, while the Terminal class contains the fewest amount of supraglacial channels. The Terminal Class of supraglacial channels contains the smallest proportion of viable channels with only 7.42% of the supraglacial channels being viable. In contrast, the Connector Class of supraglacial channels has the largest proportion of viable channels at slightly above 11%. With the Terminal Class of supraglacial channels having important hydrologic implications, we will discuss further what the potential impacts are of having a class of supraglacial channels with such a small proportion of them being viable.

Chapter 6. Discussion

Previously conducted studies have examined the acceleration of the GIS flow and the spatial distribution of supraglacial channels (Lampkin and VanderBerg, 2013). There have also been many theoretical studies conducted on melt channel evolution (Jarosch and Gudmundsson, 2012) and crevasse or fracture propagation (Van der Veen, 2007; Mottram and Benn, 2009). This study is the first study to our knowledge that investigates how the stresses applied by the GIS on supraglacial channels will affect the channel's ability to remain viable and to continue to transport water over the ablation zone of the GIS. Because the GIS is slow to react to changes in the climate (Zwally, 2002), stresses acting on supraglacial channels are also slow to change over time. Despite slow changes of the ice sheet, the depth of supraglacial channels adjusts rapidly to changes in stress as the stress varies from tensile to more compressive, or less extensive (Mottram and Benn, 2009).

Throughout our study, a few assumptions were made in the calculations that possibly are potential sources of error. The archive of mapped supraglacial channels contains very few long channels (Figure 1), which is why we are unable to make any statements with confidence about the viability of channels longer than 5 km. As the mean effective tensile stress acting on each supraglacial channel was evaluated, the azimuth and orientation of the stress in relation to the direction of channel flow was not accounted for. By excluding the orientation of stress acting on the channel, the effective tensile stress acting on supraglacial channels could be smaller or larger than what is presented in this study. However, channels may not be oriented in the direction of glacial flow, which is generally easterly across our study area. Those supraglacial channels that are oriented in a north-south direction are incised deeper into the ice sheet with a larger “Maximum Potential Depth” and as a result, these channels are thought to have a lower value of melt water discharge flowing through them.

In calculating the “Maximum Potential Depth” of supraglacial channels, it was assumed that channels were not filled with water. However, there is a temporal variation of melt water in the supraglacial channels. When channels are filled even partially with water, the channels are able to propagate deeper into the ice sheet (Smith, 1976; VanderVeen, 1998). The amount of time the channels are filled with water during a given year and depth of water in the channels in our study is unknown. Therefore, the calculated channel depth represents the minimum “Maximum Potential Depth” any particular channel can have since we do not include channel incision by water as a factor that can act to increase channel depth.

Despite being a means of calculating the depth of crevasses, we have applied what is effectively known as the Nye depth formulation to calculate the “Maximum Potential Depth” of supraglacial channels. In their modeling of supraglacial channels, Jarosch and Gudmundsson (2012) treat the channel evolution as evolving from surface crevasses (Fountain and Walder, 1998) or from the drainage of supraglacial lakes (Raymond and Nolan, 2000). We interpret this as being able to apply similar methods of estimating properties of a channel as those used to measure properties of a crevasse. As described in Nye (1951), the behavior of ice flow and deformation is assumed to be quasi-viscous so that there is minimal deformation below a critical value of the yield stress and the deformation does not increase much above this critical value. Channels that are more closely spaced experience stress not only from the surrounding ice sheet but also from the nearby channels. The close spacing of channels reduces the bulk density of the ice, which in turn reduces the effects of hydrostatic pressure. This means that closely spaced crevasses cannot penetrate as deep into the ice sheet and thus are shallower than crevasses that have more space between them (Mottram and Benn, 2009). The majority of channels in this study are not closely spaced, with the exception of a few channels that are close to other channels or are in the Tributary class of channels. Thus, the reduction in hydrostatic pressure does not play a large role in affecting the "Maximum Potential Depth" of channels in this study, although it does, to some extent that is not explored in this study, affect channels in the Tributary class. Closely spaced channels experience a lower net stress intensity factor, leading to deeper channels and higher values of tensile stress (VanderVeen, 1998). Additionally, ablation at the walls of crevasses can enhance the effects of hydrostatic pressure in regions of highly spaced crevasses since it can act as one of the main mechanism for keeping a crevasse that is in a region of compressive stress open (Mottram and Benn, 2009).

Since the channels used in this study have small slopes (Table 1), the following assumptions must be checked for their truthfulness: the ice is thick, the curvature of the bed is small, and that the rate of snowfall and ablation is slowly varying in a spatial sense (Nye, 1951). From satellite measurements, it known that the ice over Jakobshavn is considerably thick and since our study area covers only a portion of the ice sheet, it can be reasonably assumed that the rate of snowfall and ablation slowly varies. Nye (1951) points out that applying the Nye depth formula to Greenland has further complications in that the flow must be entirely East-West, which is true for Jakobshavn since it generally has an easterly flow, and small-scale irregularities in the flow must be ignored, which is true in our study as we have obtained mean values along each supraglacial channel. According to Nye (1951), the ice can only be incised in regions of active flow and on uniform slopes, which was also assumed in the study by Lampkin and Vanderberg (2013) because this is where the tensile layer of the ice sheet occurs.

6.1 Viability Based on Tensile Stress and Channel Class

Evaluating and drawing conclusions about channel viability from the mean effective tensile stress acting on supraglacial channels is not sufficient. Although Figure 3 suggests that supraglacial channels in each of the three channel classes experience a similar magnitude of stress, some of the supraglacial channels are still more viable than others. Because all three types of channels experience comparable magnitudes of tensile stress, we can conclude that there are similar processes acting on all the channels. Similarly, the longitudinal strain rate is less than the ice overburden pressure acting on most of the channels, which means that the weight of the ice above the channel is larger than the longitudinal strain from the ice surrounding the channel, potentially causing the channel to close up.

As we have previously mentioned, channel orientation relative to the direction of flow and tensile stress as well as the channel slope have implications for the viability of supraglacial channels. Supraglacial channels with higher slopes are found were the values of longitudinal extension and therefore tensile stress, is larger. In terms of channel orientation, the orientation of the supraglacial channel relative to the direction of maximum extension has a larger impact on channel viability than the slope of a supraglacial channel. When supraglacial channels are oriented in a north-south direction in an easterly flow field, as is the case for our study area, the channels are capable of propagating deeper into the ice and incising closer to their “Maximum Potential Depth”. Channels oriented in this same manner typically have a lower discharge, or volume of meltwater flowing through the channel.

Terminal channels deposit surface melt water into moulins or crevasses, as described in Table 1. The end behavior of this type of channel makes this class of supraglacial channels the most important of the three classifications of supraglacial channels because these channels transport water into larger glacial features that are a significant part of the mass balance of the GIS. This classification of supraglacial channels contains the largest proportion of non-viable channels and smallest proportion of viable channels (Table 2), which has implications for water transport into larger features of the GIS. The smallest proportion of non-viable channels is in the Connector classification of channels (Table 2). These supraglacial channels will most likely not be viable as a means of transporting water from one lake to another over time unless the rate of melt water discharge through the channel is large enough to overcome the creep-closure rate.

6.2 Viability Based on Ratio of “Estimated Channel Depth” to “Maximum Potential Depth”

While the value of mean effective tensile stress acting on supraglacial channels is insufficient for determining channel viability, the viability parameter we employ allows for determination of channel viability. As previously explained in Section 4.5, the viability parameter is based on the ratio of the “Estimated Channel Depth” to “Maximum Potential Depth”. Those channels with an “Estimated Channel Depth” closer to the

“Maximum Potential Depth” have lower volumes of melt water flowing through them. Furthermore, channels with an “Estimated Channel Depth” that is not yet close the “Maximum Potential Depth” are in a potentially more extensive, or less tensile, environment with the orientation of the channel acting to pull the channel walls apart and allowing the channel to remain a viable means of transporting melt water across the ablation zone.

As is seen in Figure 5, there are some supraglacial channels with a large viability parameter representing the ratio of “Estimated Channel Depth” to “Maximum Potential Depth”. When the viability parameter is very large, it means that the “Estimated Channel Depth” is much greater than the “Maximum Potential Depth”. This can occur for combination of a few reasons. First, the volume of melt water flowing through the channel is very large, so the supraglacial channel has a high rate of incision into the ice sheet. Secondly, these channels whose “Estimated Channel Depth” exceeds the “Maximum Potential Depth” are potentially wider channels. Wider channels have the capacity to transport larger amounts of melt water across the ablation zone of the GIS. Finally, these channels are possibly oriented closer to the direction of maximum longitudinal strain. For these supraglacial channels, the stress of the ice sheet acting on the supraglacial channel helps to keep the channel open as a melt water transport mechanism since the maximum longitudinal strain represents a more extensive stress. However, in this study, the direction of longitudinal strain, and therefore tensile stress, relative to the supraglacial channels was not considered.

6.3 Possible Impacts of Channel Closure on Viability of Lakes

Connector channels have some implications for the variability and viability of supraglacial lakes. If a channel connecting two lakes is no longer viable, it is possible the lake that the channel previously drained into will dry up unless that lake has other sources of melt water feeding into it. It is well known that supraglacial lakes fill during the winter when there is the most accumulation and drain during the warmer summer melt season. The viability of lakes that are more dependent on water drainage into them due to channelized flow will be most impacted by the viability of supraglacial channels and the potential for channel closure.

Chapter 7. Conclusions

Our study assesses the viability of supraglacial channels based on which channels are most likely to close up over time assuming that the stresses applied from the surrounding ice and all other factors remain the same in the future. Due to similar mean tensile stress values acting on each of the three classes of supraglacial channels, mean effective tensile stress is not a good indicator of channel closure. However, channel depth is more meaningful, showing that channels in the Terminal class are least viable and channels in the Connector class are most viable. While our calculation of the "Maximum Potential Depth" represents the minimum depth of a supraglacial channel, the channel could propagate deeper into the ice sheet due to the incision by the flow of water and melting of the channel walls. Channelized flow allows water to penetrate to the glacier bed and the temporal variability of melt water flowing into the channels can lead to short-term ice velocity changes of the Jakobshavn Isbrae region of west-central Greenland. Understanding the viability of supraglacial channels allows for a greater comprehension of the temporal variability of surface meltwater flowing over the ice sheet and of the importance of channels to aid in draining supraglacial lakes and transporting water off the GIS.

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