Determination of the Modifying Effects of the Firn Aquifer in Helheim Glacier Using Reflection Seismology and Radar Surveys

Benton Williams

Nicholas Schmerr

Geol 394

Abstract:

The Greenland ice sheet is a continental glacier on the island of Greenland that covers most of the island's surface. The Helheim glacier is an outlet glacier on this ice sheet on the southeastern section of the island that contains a firn aquifer. The Firn Aquifer is an aquifer of liquid water that resides a couple meters beneath the surface of the glacier. Previous studies of this glacier noted an unusual velocity profile of seismic waves at the base of the liquid firn aquifer and a few meters below it. A goal of this study is to determine if the aquifer is modifying the glacier as it flows through the glacier causing the observed increased velocities or if Some other process is causing the increased velocities. Another goal of the study is to understand if it is necessary to modify current used calculations in determining Firn aquifer porosity in order to take the increasing velocity profile into account when using reflection seismology. In this study, seismograms produced during studies of the firn aquifer within Helheim glacier and radar surveys were used to calculate if the increasing seismic velocities observed in the base of the aquifer are present throughout the entirety of the glacier to determine if the aquifer causing this velocity change.

Introduction:

Helheim ice sheet is an ice sheet in Greenland on the southeastern side of the island. The glaciers importance comes from the fact that it is being heavily Effected by the climate change that has been occurring during the Holocene (Andresen et al., 2011) and also its reactions to climate increases on a timescale of 3-10 years. Over the two decades, Helheim glacier and Greenland's other low elevation outlets glaciers have been thinning at rates of almost 10m/yr (Abdalati, 2001).

In the past 20 years an aquifer has been growing underneath the higher snow-fall areas of the ice sheet, also known as a firn aquifer. The Firn aquifer has been spreading over recent years and its total area has reached over 21,900 square km (Miège et al., 2016). The Firn aquifers form in areas of large surface melt and high snow and ice accumulation (Munneke, 2014). Water from the firn aquifer can also contribute to sea level rise.

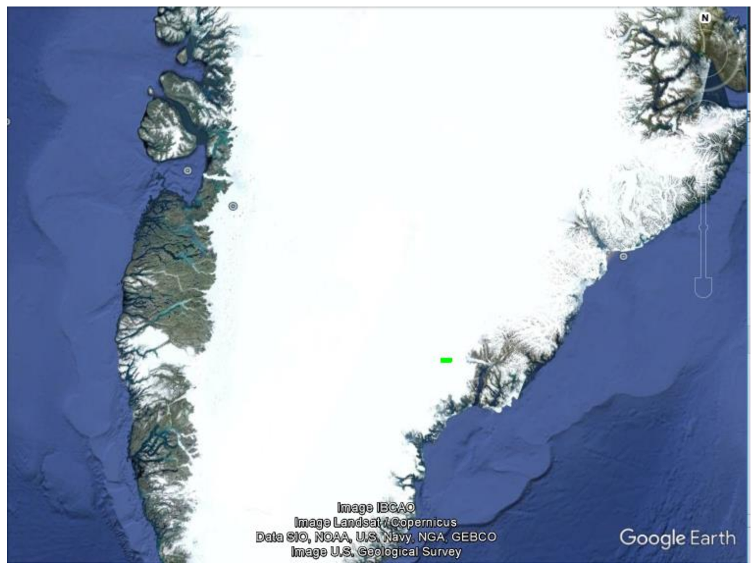

Figure 1: Green marks the line of test sites used to collect data

The firn aquifer in Helheim glacier has an average depth of 27.7m (Montgomery, 2017) with an average thickness is 11.5 m. Given that the area of the aquifer is over 21,900 square km, there are almost 251 km^3 of freshwater stored in the ice. This added volume of water makes the Helheim ice sheet important as global temperatures rise and more melt accrues within it.

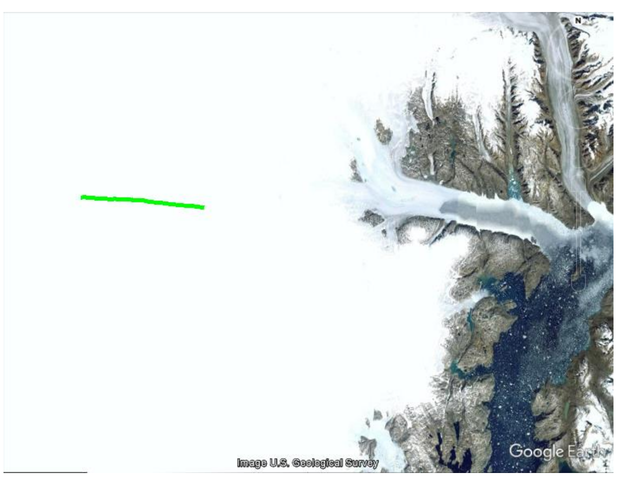

Figure 2: Close up image to show relationship on the test sites in comparison to the terminus of the ice sheet

The area of my study is limited to the outflow region of the Helheim ice sheet on the southeastern section of the ice sheet as shown in figure 1. These test sites were chosen for my data because they fall along the ice flow line of the ice sheet. Figure 2 shows the trace of the ice flow line (in green) that my test site locations were on top off. I am limited to data that was originally gathered for the purposes of studying the underlying firn aquifer that was collected in 2016 (Montgomery, 2017) and radar sounding data completed in the same area in 1993 (CReSIS, 2016). Radar data are not used in this study from any successive years because the firn aquifer growth reduced the effectiveness of radar penetrating to the bedrock of the glacier and instead reflected off of the surface of the firn aquifer itself.

Along the line of my test sites, it was found that the ice directly beneath the firn aquifer seemed to have increasing seismic wave velocities (Montgomery, 2017). It was also found from multiple ice cores that reveal an increase in 0.2-0.5 m layers of clear ice directly beneath the firn aquifer (Koeing et al., 2014).

Problem:

The increasing seismic velocities (figure 3) as the glacier travels down gradient to the east may be due to modifying effects of the firn aquifer freezing at its base causing a an increased amount of clear ice at areas with higher degrees of freezing. Clear ice has a faster seismic velocity than the velocity through firn and would show the increased velocity observed at the base of the aquifer by in Montgomery et al. (2017). However, this modifying effect of the firn aquifer would not affect any more than just the base of the aquifer and a few meters below it, and would have negligible effect on the velocity of seismic waves throughout the entirety of the glacier.

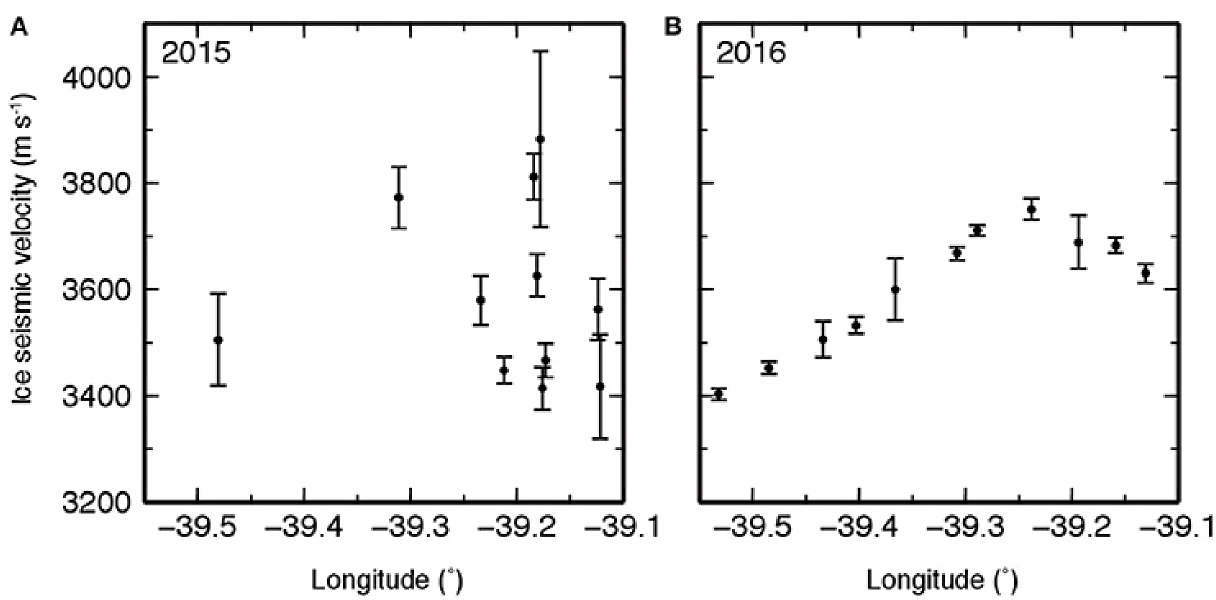

Figure 3: Graph produced by Montgomery et al. 2017 showing the seismic velocities directly beneath the firn aquifer at various longitudes along the test line

My hypothesis is that the basal freezing of the aquifer and buildup of clear ice are the reasons for the increased velocities observed in the study by Montgomery et al. (2017).

In order to test my hypothesis, I need to measure the velocity of seismic waves through the entirety of the glacier at the same locations that the original base velocities were calculated and compare them to see if any correlation between the two exists. If no correlation exists between the velocities of the base of the aquifer and those of the whole glacier, then the only thing that could be affecting the seismic velocities at the base of the aquifer would be the aquifer itself. However, if it is found that there is a correlation between the seismic velocities, then there must be another process that is affecting the glacier as a whole because the aquifer only should affect the area directly beneath where the clear ice is building up. This would also conclude that the increased presence of lens' clear ice at the base of the aquifer is not the reason for the increased velocities observed.

I will use reflection seismology to determine the travel time of seismic waves to the bedrock and back and then use radar surveys from before the existence of the firn aquifer to calculate depth to the bedrock.

However, radar does not work efficiently in the Helheim ice sheet in recent years because the firn aquifer inside of the ice sheet reflects the radar back before the radar wave has reached the bedrock (Miège et al, 2016). Although use of radar to determine bedrock topography and glacial thickness is very useful and accurate, it is limited to only those ice sheets that are solid ice, or contain very limited liquid water in them.

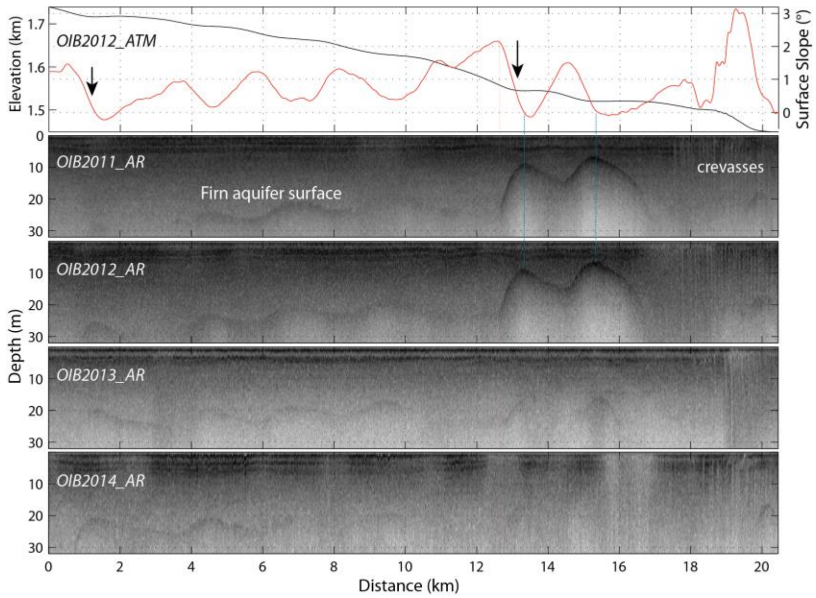

Figure 4: radar data showing increased viewing of firn aquifer surface instead of bedrock sirface throughout a series of years

I will be using reflection seismology to determine two way travel time of seismic waves, and from that the velocity of the seismic waves throughout the entirety of the glacier can be determined. Reflection seismology has most notably been used to determine the locations of economically useful materials inside of the earth, such as oil and natural gas (Waters, 1987). Reflection seismology uses artificially produced seismic waves to determine points beneath the surface of the earth by recording the time that a reflected seismic wave takes to hit a series of recording units. The amount of time that the wave took to return to the series of recording units would then be used to determine the depth that the reflected wave came from, allowing for salt domes and other geological structures to be determined. In my study I will be using a series of seismograms recorded by lines of geophones that were gathered in the field in 2016. These sets of seismograms will not have the reflection issue that radar has because our tests use seismic waves instead of radar. Seismic waves, specifically the P-wave, can travel through and across water.

Procedure:

Initial seismograms were collected in the field over a period of two years. Both series of tests had multiple test sites that ran over the entirety of the length of the test area shown in figure 2. Each year the test sites started on the western-most section of the testing area and moved east, with one test site every 1 or 2 km as determined and marked in Montgomery et al. (2017).

At every test site, a line of 24 geophones were aligned down the ice-flow line and separated by 5m each. Then a source metal plate is placed down the line from the geophones that becomes the source of the seismic wave. The farthest point of the geophone seismic source placement is 270m away from the first geophone, and then the plate is moved closer to the geophone line by 30m and struck again. This process continues until the metal plate has fully passed the geophone line and is 270 meters away from the last geophone in the line. This allows for plenty of potential reflections from the bedrock at different times giving plenty of opportunities to get two way travel times.

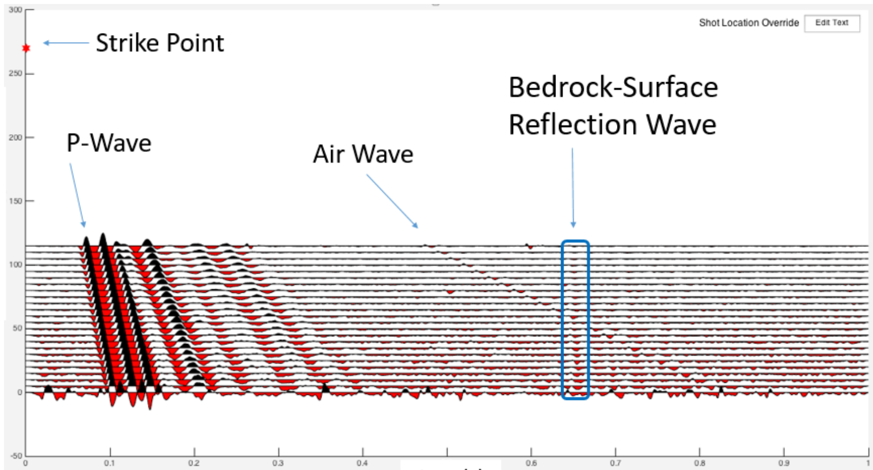

Figure 5: seismogram produced by a geophone test with a strike point 270m away from the first geophone. X-axis is time, Y-axis is meters

The metal plate that is placed as the seismic source is then struck by a hard object, such as a shovel or a sledge hammer, that sends seismic waves out from the impact zone, that are then recorded at the separate geophones. These geophones record the wave's relative amplitudes. The plate is struck multiples times in succession in order to amplify the reading of the wave by stacking them on top of each other. This allows for a lot of potential noise from wind and footsteps that may drown out the seismic wave to be drowned out instead, and have the wave be recorded clearly.

The geophones then record the data provided for that specific hit time and produce a seismogram like the one reproduced in figure 5. These seismograms produced are normally still full of lots of noise that originally can mask the bedrock reflection wave, so I limit the wavelengths it shows me to anything higher than 120 hertz. The purpose of this limitation is the remove any very small wave lengths that are typically produced by wind and the noise made by melting ice. In Figure 5 you can see the multiple different seismic and sound waves that the geophones capture, starting on the left with the direct P and S waves, followed by an in air sound wave that then interescts our desired wave, the bedrock reflection. Figure 6 shows a magnified version of the reflection wave.

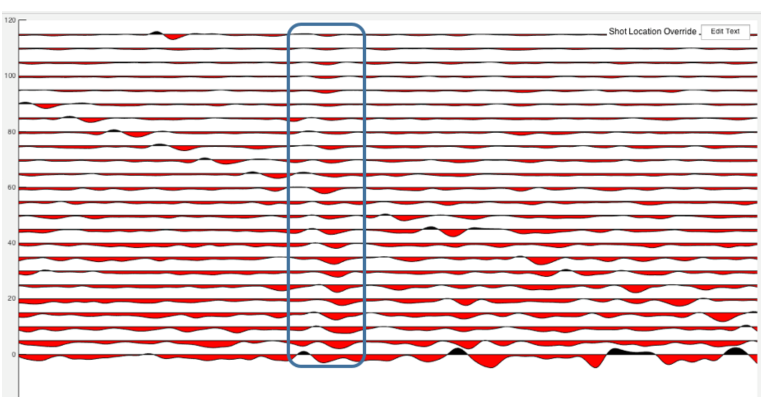

Figure 6: zoomed in image of figure 5 to show the bedrock reflection wave, and the intersecting air sound wave.

As shown in figure 6, the reflected wave is still muddled by noise, and that is why the repeated strikes are so important so that the bedrock reflection wave can be differentiated from the backround. The bedrock reflection wave also has another issue with it in that the air sound wave passes through it in the middle of the geophone line, distorting both waves at that point. That specific datum where that interference occurs will not be used in the production of depth measurment as it is clearly affected by the air wave passing through it.

I then pick the times that the bedrock reflection wave is received at the geophones and place those points on a meter squared by time squared plot, as shown in figure 7. A line is then fit to the points on the graph in figure 7 that is defined by the equation in figure 8.

$$t^2=\left(\frac{1}{V^2}\right)X^2+t_o^2$$

Figure 8: equation defining the fit line found in figure 8

This equation can be used to calulate both two way travel time as the y-intercept, as well as the seismic velocity as the slope. This slope is not usuable to determine the true seismic velocity because there is a very large uncertainty in these meaurments that make the slope have anywhere from a 20 to 70% uncertainty. However, this uncertainty does not continue on for the y intercept due the the accuracy of the recording devices. This leads to a highly accurate two way travel time that needs to be converted into velocity using radar calculated depths.

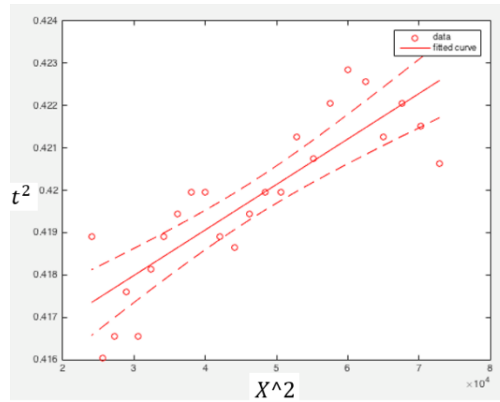

Figure 7: Data plotted from the initial response times as a function of depth of the bed reflection wave. Error bars are dashed. X-axis is time in seconds^2 and Y axis is meters^2.

I calculate the depth of the bedrock to a much more accurate degree using radar surveys (CReSIS, 2016) of Helheim glacier that follow along a similar path as the series of test sites that were taken in Montgomery et al. (2017) as shown in figure 9. The plane flies over the surface of the glacier at a known altitude and sends down a radar wave. The radar wave then travels down through the ice sheet until it hits the bedrock, where it is then reflected and comes back up and is captured by a receiver on the plane. This occurs thousands of times during the flight and produces the image shown in Figure 10.

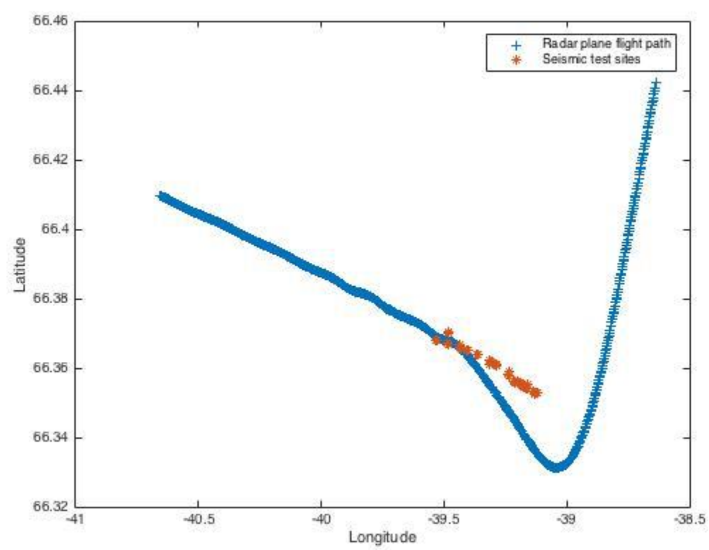

Figure 9: Flight path of the radar survey plane (CResis, 2016) and sites of seismic testing (Montgomery et al., 2017)

Each pixel on figure 10 has a specific longitude and latitude on the x-axis, and travel time on the y-axis that is provided by the radar survey program. I picked each pixel coordinate on the bedrock reflection signal in figure 10 and converted them into a travel time and a longitude for that pixel. I then used the known velocity of radar through ice

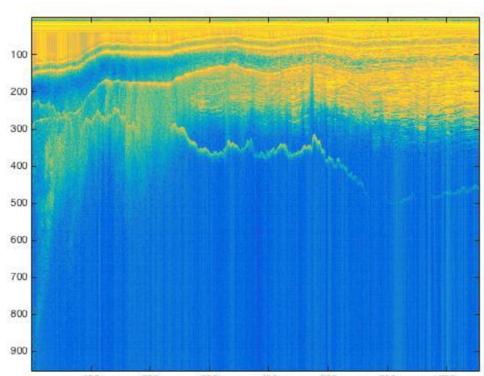

Figure 10: Radar survey data from 1993 in a pixel by pixel format showing surface reflections, reverberations and bedrock reflection

that was provided by the survey data again to calculate the depth to the bedrock at all the longitudes that the seismic test sites where stationed at using the equation shown in figure 11. The reason that depth is multiplied by two is because the travel time produced in the radar data set is the amount of time for the radar to travel from the plane to the bedrock and back, or a two way travel time, that requires that the time value be divided by two or the depth be multiplied by two.

$$V = 2D/t$$

Figure 11: equation to determine depth using two way travel time and velocity

I then use my calculated two way travel time from the seismograms produced in Montgomery et al. and the calculated depths from my radar survey data and put them through the same equation in figure 11 to produce a seismic velocity at each of the test site locations. These seismic velocities for the whole glacier are then compared to the seismic velocities of the base of the aquifer (Montgomery et al., 2017) to see if there is any correlation between the two sets.

If there is a correlation then the seismic velocties that are increasing at the base of the aquifer are doing so not because of modification of the glacier by the aquifer but instead because of some larger process that is affecting the glacier as a whole along its flow path. If no correlation is found then it must be the aquifer that is modifying the seismic velocities at the base of the aquifer.

Results and Analysis:

Line	Lat	Long	Elev (m)	TWT seis (s)	Uncert Seis	TWT Radar (s)	Uncert Radar	Depth Ice (m)	Uncertainty Depth	Vp (m/s)	Uncert Vp	V ice at base (m/s)
14/15	66.3608	-39.28916696	1595	0.645	0.004	0.00001590	4E-08	1343	3	4164	3	3711
16/17	66.36182698	-39.30867199	1611	0.644	0.002	0.0000165	3E-07	1394	27	4325	27	3668
18/19	66.35796603	-39.23812796	1559	0.555	0.003	0.00001360	4E-08	1149	3	4143	3	3751
20/21	66.363958	-39.36604997	1636	0.708	0.002	0.00001720	7E-08	1453	6	4106	6	3600
22/23	66.36509903	-39.40386903	1651	0.724	0.004	0.00001720	4E-08	1453	3	4014	3	3532
24/25	66.36572197	-39.43440104	1658	0.681	0.003	0.0000163	3E-07	1377	23	4046	23	3506
26/27	66.36694598	-39.485491	1698	0.686	0.003	0.0000158	1E-07	1334	10	3892	10	3452
28/29	66.36779398	-39.532072	1703	0.663	0.004	0.0000156	4E-07	1322	38	3989	38	3403

Table 1: data collected showing location of the test sites, two way travel times of both the seismic wave and the radar waves, depth and final velocities of the seismic waves at each site, with compared to given seismic velocity at the base of the aquifer from Montgomery et al. on the far right.

Table 1 contains the calculated values of the two-way travel times and depths produced form both the seismograms in Montgomery et al. (2017) as well as the radar survey data provided by CReSIS (2016). The latitude and longitude represent the location of each seismic line produced by Montgomery et al. (2017). Elev represents the elevation above sea level of each location. TWT seis and Uncert seis are the two way travel times produced with the seismograms along with the uncertainties calculated in seconds. TWT radar and Uncert Radar are the two way travel times in seconds and the uncertainties of radar survey data in the same location as the test site. Depth Ice and Uncertainty depth are the calculated depths and uncertainties of Helheim glacier using the radar two way travel times. And finally Vp and Uncert Vp are the calculated seismic velocities through the entire depth of the glacier (Figure 11). The final column is the recorded seismic velocities produced in Montgomery et al. (2017) at the base of the aquifer. The final velocity measurements are far more accurate than they would have been if we had only used the seismograms and the equation in figure 8, showing the necessary use of the radar survey data to calculate depths. It should be noted that the calculated seismic velocities for the whole glacier are around 400-500 m/s faster than the seismic velocities at the base of the firn aquifer.

In figure 11 you can see the correlation of the two-way travel times of the seismogram data and the two-way travel times of the radar data at each test site location. Although the values of these two-way travel times may have been quite different they do correlate with each other quite well.

In figure 12 and 13 we see the corresponding seismic velocities of the whole glacier and the base of the aquifer. The faster seismic velocities for the whole glacier are most likely due to the longer travel time through solid ice as well as going through colder ice, that cause increased seismic velocities. The correlation continues in figure 13 where the calculated seismic velocities for the base of the aquifer and the glacier as a whole are plotted against each other and show an r^2 value of 0.6 that shows that there is a pattern of increased seismic velocities further down slope on the glacier. This can also be shown by the very similar slopes in figure 12 between the base of the aquifer and the whole glacier itself.

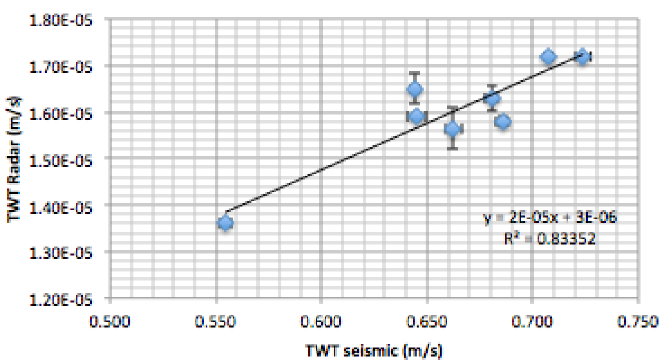

Figure 11: two way travel time of the seismic waves at each test site vs. the two way travel times of the radar

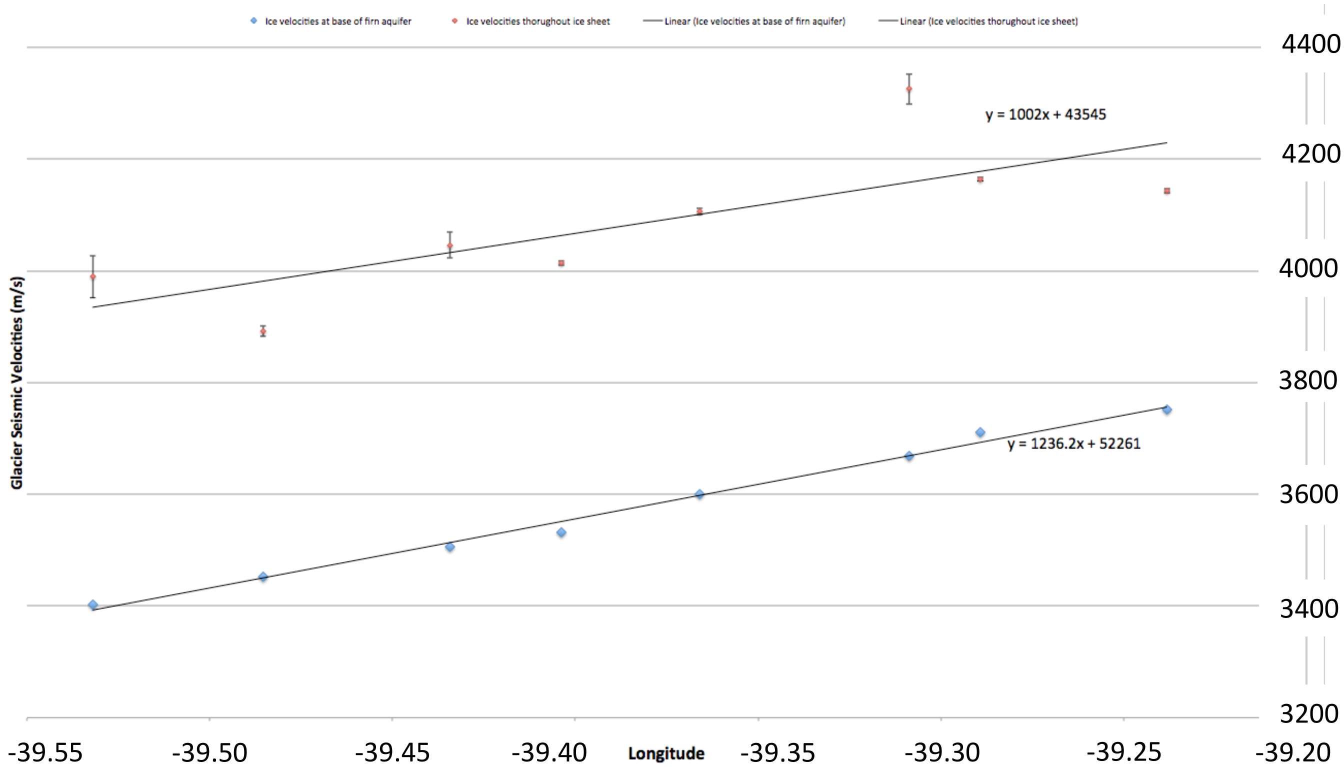

Figure 12: Seismic velocities of the whole aquifer and the base of the aquifer vs. the longitude of the test sites

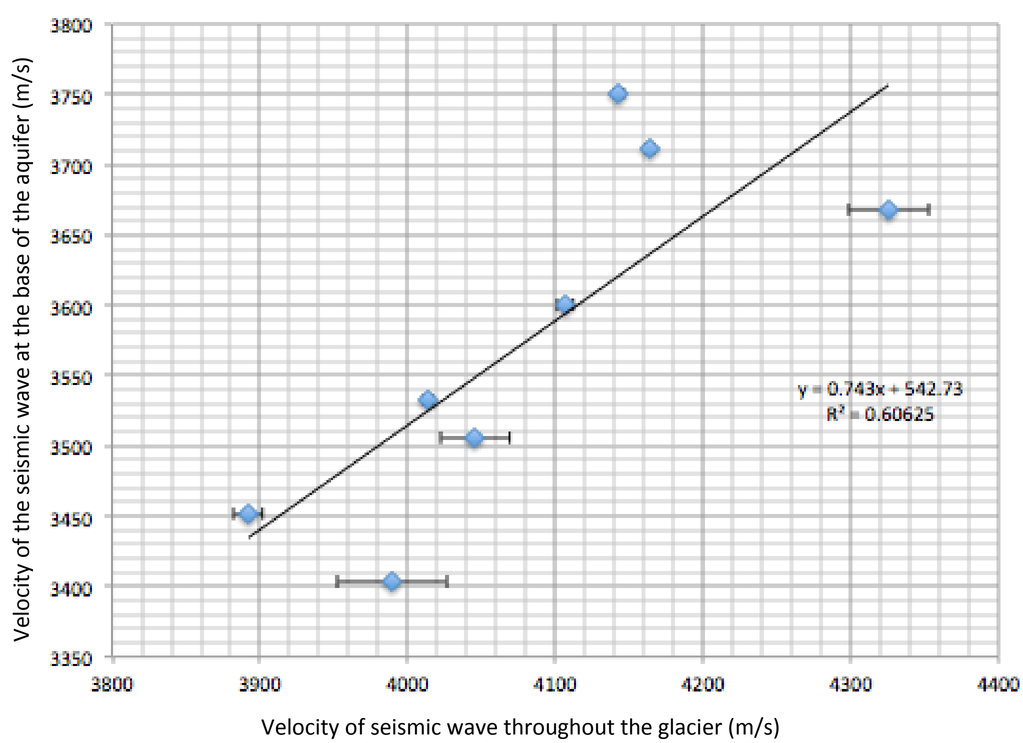

Figure 13: Seismic velocities through the glacier vs. Seismic velocities at the base of the aquifer at each site

This correlation between the seismic velocities of the base of the aquifer found in Montgomery et al. (2017) and the seismic velocities I have produced for the entirety of the glacier, demonstrate that there is a pattern of increasing seismic velocities along both the base of the aquifer as well as through the depth of the glacier. This correlation supports that theory that a process is occurring within the glacier as a whole that is producing a noticeable increase in seismic velocities as the glacier and firn aquifer travel down the ice flow line towards the moraine of the glacier. Further study will need to be taken to find out what process is occurring within the glacier causing this increased velocity to occur.

Appendix

Honor Code:

I pledge on my honor that I have nor given or received any unauthorized assistance on this assignment/examination.

Benton Williams

11/21/2017

Bibliography

1. Abdalati, W., et al. (2001), Outlet glacier and margin elevation changes: Near-coastal thinning of the Greenland ice sheet, Journal of Geophysical Research: Atmospheres, 106, 33,729–33,741.
2. Anderson, D. L. (1961). Elastic wave propagation in layered anisotropic media. Journal of Geophysical Research,66(9), 2953-2963. doi:10.1029/jz066i009p02953
3. Bentley, C. R. (1972). Seismic-wave velocities in anisotropic ice: A comparison of measured and calculated values in and around the deep drill hole at Byrd Station, Antarctica. Journal of Geophysical Research,77(23), 4406-4420. doi:10.1029/jb077i023p04406
4. CReSIS. 2016. data1993_rdshelheim Data, Lawrence, Kansas, USA. Digital Media. http://data.cresis.ku.edu/.
5. Evans, S. (1963). Radio techniques for the measurement of ice thickness. Polar Record,11(75), 795. doi:10.1017/s0032247400056187
6. Mathews, W. H. (1974). Surface profiles of the laurentide ice sheet in its marginal areas. Journal of Glaciology,13(67), 37-43. doi:10.1017/s0022143000023352
7. Miège, C., Forster, R. R., Brucker, L., Koenig, L. S., Solomon, D. K., Paden, J. D., Box, J. E., Burgess, E. W., Miller, J. Z., Mcnerney, L., Brautigam, N., Fausto, R. S., Gogineni, S. (2016). Spatial extent and temporal variability of Greenland firn aquifers detected by ground and airborne radars. *Journal of Geophysical Research: Earth Surface,121*(12), 2381-2398. doi:10.1002/2016jf003869
8. Montgomery, L. N., Schmerr, N., Burdick, S., Forster, R. R., Koenig, L., Legchenko, A., Ligtenberg, S., Miège, C., Miller, O. L., Solomon, D. K. (2017). Investigation of Firn Aquifer Structure in Southeastern Greenland Using Active Source Seismology. Frontiers in Earth Science,5. doi:10.3389/feart.2017.00010
9. Munneke, P. K., Ligtenberg, S. R., Broeke, M. R., Angelen, J. H., & Forster, R. R. (2014). Explaining the presence of perennial liquid water bodies in the firn of the Greenland Ice Sheet. Geophysical Research Letters, 41(2), 476-483. doi:10.1002/2013gl058389
10. Petrenko, V. F., & Whitworth, R. W. (2006). *Physics of ice*. Oxford: Oxford University Press.
11. Waters, K.H. (1987). Reflection seismology: A tool for energy resource exploration. Third edition. United States: John Wiley and Sons Inc., New York, NY.