2002 Geophysical Depth Measurements Using Seismic Reflections on the Llewellyn Glacier Juneau Icefield, Alaska-Canada

Ryan S. Cross
Advisers: Dr. Maynard Miller & Guy Adema
Juneau Icefield Research Program

Abstract

During the 2002 summer field season of the Juneau Icefield Research Program (JIRP), a reflection seismic survey was conducted to determine depths of the sub-glacial bedrock interface in the F10 sector of the Llewellyn Glacier, Juneau Icefield, Alaska-Canada. The seismic profile was at 1550m elevation, some 3km up-glacier form the 2002 ELA. Kinepak charge explosives were detonated at eight locations on this glacier profile, and reflections were recorded by 24 high frequency geophones. The geophones were connected to a Bison signal stacking 8000-model seismograph, located near the center of the glacier. Data were processed and used to interpret a depth profile of the Llewellyn Glacier at this location. This profile, in conjunction with a velocity profile, is used to calculate the "mass flux" of the Llewellyn Glacier near its mean neve line (5 year ELA). Using the known surface velocity, ice depth, ice temperature, slope, and glacial cross sectional shape a theoretical surface velocity. Comparing the calculated theoretical surface velocity to the measured surface velocity reveals the velocity of the basal slippage. These same parameters can also be used to calculate the theoretical velocity of a column of ice.

Analysis indicates a maximum glacier depth of 900 meters, 3.3 km from the west margin of the glacier, at F10 (see map). On this profile the average surface velocity calculated from differential GPS over a four day time period was 24 cm/day, with a maximum velocity calculated at 30 cm/day. From the depth in this sector of the

northward flowing Llewellyn Glacier, and its velocity, a sub-rectilinear flow mode is indicated, with notable basal slippage. A mass flux is estimated to be $1.8x10^5 m^3 yr^{-1}$.

Assisting in this team field study were Robert Hahn, Matt Smith, and Nathan Zimmerman. This seismic team also successfully surveyed a comparable ice depth profile across the upper Mendenhall Glacier at the 1700m surface elevation in the Alaskan sector of the icefield. These surveys expand the JIRP geophysical network, comprising some two dozen key glacier profiles obtained since 1992.

Introduction

The Juneau Icefield Research Program has been operating every summer on the Juneau Icefield in Southeast Alaska and British Columbia sense 1946 under the direction of Dr. M.M. Miller. One of the many ongoing projects on the icefield has been to conduct seismic depth profiles in order to understand the glaciers in a more three dimensional volumetric way. The seismic study presented in this article is an extenuation of this ongoing seismic research on the Juneau Icefield. One of the key principals of studying glaciers is understanding how they flow, how much they flow (mass flux of ice) and how this affects the stability of the glacier. By multiplying the cross-sectional area of a profile with the mean yearly glacier velocity the flux through such a profile can be calculated. This has been done for profiles on the near by Taku glacier and it was found that the largest ice flux was near the neve line. By calculated the mass flux at the neve line on the Llewelyn glacier I believe that we can reveal the largest ice flux that could be found on that glacier.

Methodology

The first step to conducting the seismic depth profile was to locate and survey the area where we would be working. A profile location on the Llewelyn location was chosen near F-10 peak and was surveyed in using a Trimble GPS system. Markers were set every 500 meters and labeled West to East 0 to 8 respectively. To increase the efficiency of the work a snowmachine was used to transport people and equipment across the glacier and to the various blast locations. The seismograph was centered at survey stake 3 with twelve geophones spreading 345 meters in each direction. Geophone #1 was furthest to the west and # 24 was furthest to the east with a total spread of 690 meters. The Geophones were firmly placed in the snow approximately .5 meters below the surface and then reburied to reduce any wind noisy and other possible disturbances. The seismograph used was a Bison Series 9000 Digital Instantaneous Floating Point Signal Stacking Seismograph and was set to record at .2 milliseconds and take 10,000 samples, with a high cut of 60 and a low cut of 16. Kinepak an Ammonium Nitrate based explosive was used to create a blast large enough so that a reflection off of the bedrock could be detected. Chart 1 lists the shot location and the number of sticks of Kinepak used. Because we did not have a shot phone a count down over a FM radio had to be used to coordinate the blast and the recording. Eight blasts were detonated and usable results were recorded for each.

By knowing the distance between the blast and the nearest geophone and by knowing that the primary wave traveled at a speed of approximately 3600m/s we were able to calculate the zero time for each of the seismic records. The zero times, the location of the shot, the elevation of the shot and the geophones, and the relative times of the reflection waves that were hand picked off of the record could then be entered into a excel program specifically designed for calculating a depth profile.

Calculations

-theoretical velocities and basal slippage

The following is a brief derivation of how to calculate the theoretical surface velocity and the theoretical column velocity. These calculations can then be compared to actual measurements and the velocity of basal sliding can be estimated.

Glens flow law states that $\epsilon = A\,\tau^n$

Where ϵ is the shear strain rate, A depend on ice temperature crystal orientation, impurity content and perhaps other factors, τ is the shear stress, and n is a constant.

$\tau = \rho g(H\text{-}z)\sin\acute{\alpha}$

Where ρ is density of ice, g is gravity, H is the surface elevation, z is some elevation at depth, and ά is the slope of the glacier.

u designates velocity, du/dz is velocity with respect to depth, u(z) is velocity at depth z and u_b is the velocity at the base of the glacier.

$\epsilon = ½(du/dz)$

$du/dz = 2A(\rho g\sin\acute{\alpha})^n(H\text{-}z)^n$

$\int$ from 0(bed) to z du $= (2A(\rho g\sin\acute{\alpha})^n\,{}_0^z\int(H\text{-}z)^n\,dz$

$u(z)\text{-}u_b = (2A/n+1)(2A(\rho g\sin\acute{\alpha})^n[H^{n+1} - (H\text{-}z)^{n+1}]$

If $u_b = 0$ (no slip) than the theoretical surface velocity is

$u_{surface} = u(H) = (2A/n+1)(\rho g\sin\acute{\alpha})^n[H^{n+1}]$ (1)

To find the theoretical velocity of a column we integrate again from the base (0) to H.

Theoretical velicity of a column $= \langle u\rangle_{column} = \int$(from 0 to H) udz =

$(2A/n+2(\rho g\sin\acute{\alpha})^n[H^{n+1}]$ (2)

This is an interesting result because we can see that by substituting τ back in to the equations 1 and 2 we get.

$U_s = (2A/n+1)(\tau)^nH^{n+1}$

$\langle U\rangle_{column} = (2A/n+2)(\tau)^nH^{n+1}$

From this we can see that

$\langle U\rangle_{column} = U_s(n+1/n+2) \approx 4/5\ u_s$

In other words the velocity of the column is approximately 4/5 the surface velocity.

These equations are derived assuming many factors one of which is that we are working with and infinitely wide sheet of ice. To correct for this we add into the equation a constant called a shape factor that is based on the general shape of the glacial valley (i.e. parabola, semi-ellipse, or rectangle) and of the relation ship between the width that the depth. Approximate values can be found in Patersons's physics of glaciers. Another value that we do not have yet is the flow parameter A. These values are also listed in Paterson and have the units ($s^{-1}(kPa)^{-3}$). The value of n is another number that can be found in Paterson the standard being found to be n=3.

For our specific calculation the following values were used.
$A= 3.4x10^{-24}(s^{-1}(Pa)^{-3})$
n=3
Shape factor = f =.65
ρ=918kg/m^3
g= 9.81m/s^2
ά = 1.8 degrees
H = 850 meters

$u(H) = (3.4x10^{-24})(4^{-1})((918)(.5)(9.18)(\sin 1.4))^3[850^4] = 2.74x10^{-6}m/s$

3600seconds in an hour and 24 hours in a day gives us

$2.35x10^{-6}$ x 3600 x 24 = <u>.24m/day</u>

mean velocity of a column =
$\langle u\rangle = (3.4x10^{-24})(5^{-1})((918)(.5)(9.18)(\sin 1.4))^3[850^4] = 2.2x10^{-6}m/s$ = <u>.19 m/day</u>

With a measured center surface velocity of .295m/day we can find the theoretical basal slippage.

Surface velocity = theoretical surface velocity do to deformation + basal slippage. Rearranging this we see that surface velocity minus theoretical surface velocity equals basal slippage.

$U(H)_{measured} - U(H)_{theoretical}$ = basal slippage
.295 - .24 = <u>.06m/day</u>

-Mass flux
The mass flux of ice through a cross section of a glacier is simply the cross sectional area multiplied by the average cross sectional velocity. For the Llewellyn glacier the cross sectional area was found by using a gird method on a profile 9(see graph) created using the seismic data collected. This method revealed a cross sectional area of 2064m^2.

According to Paterson's The Physics of Glaciers "the mean velocity over a cross-section (mean over both thickness and width) is within a few percent of the mean surface velocity (mean over width only)." This tells us that we can find the average of the values listed in the survey chart and this will be the mean velocity over the cross-section. The mean surface velocity calculates out to be .2398m/day.

Mass flux = (cross sectional area) x (mean surface velocity)

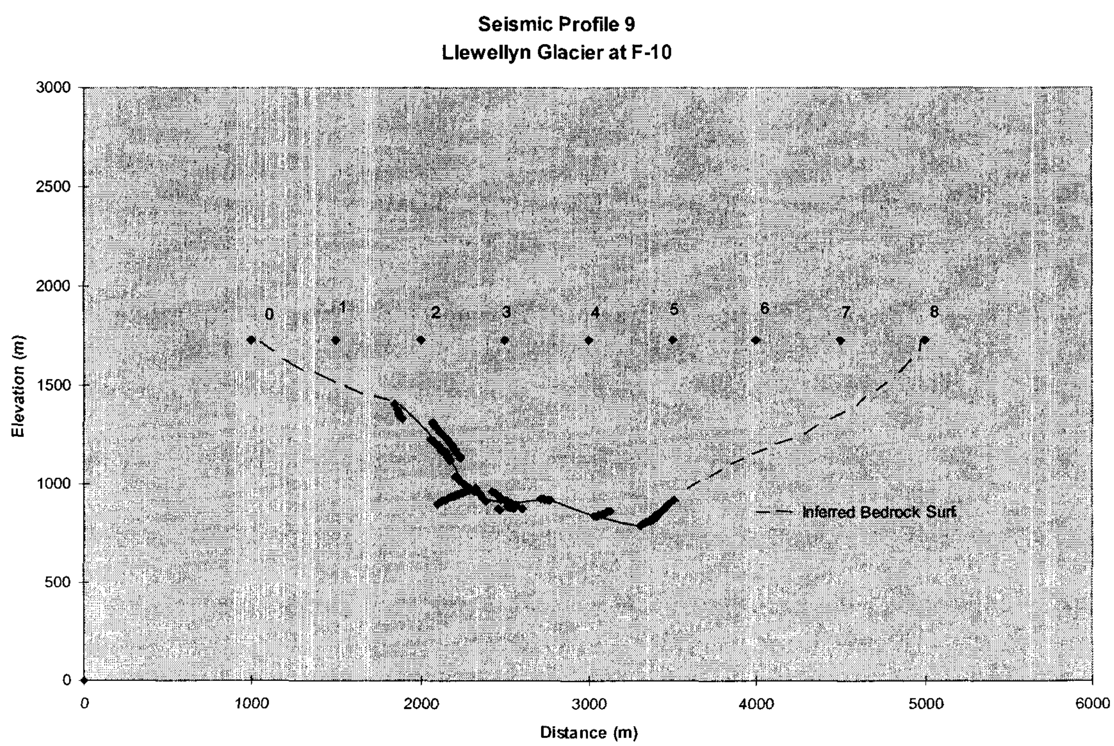
Mass flux = (2064m^2)(.2398m/day) = 495m^3/day

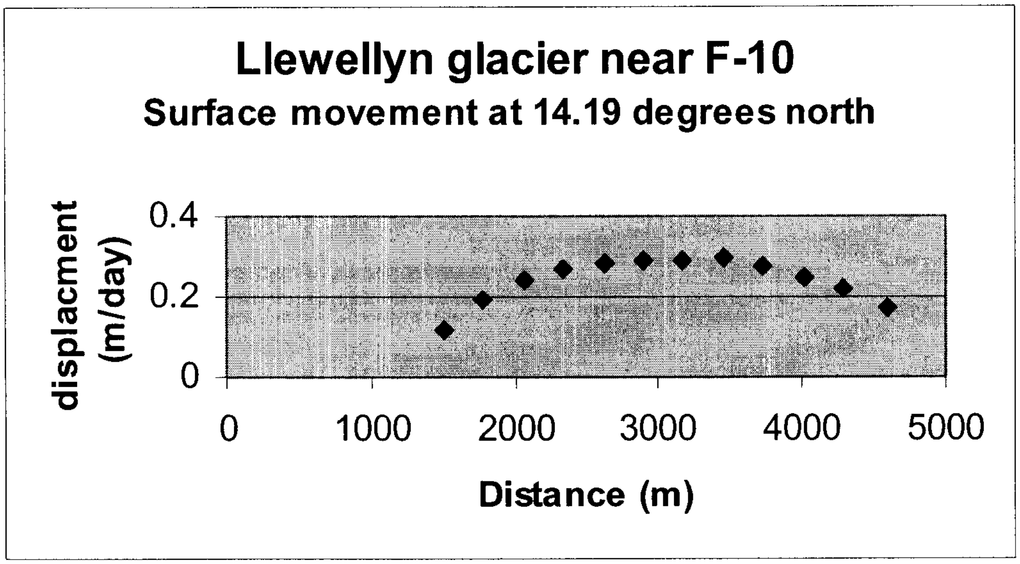
Times 365 days in a year = 1.8 x10^{5}m^3/year

Conclusion:

Chart 1

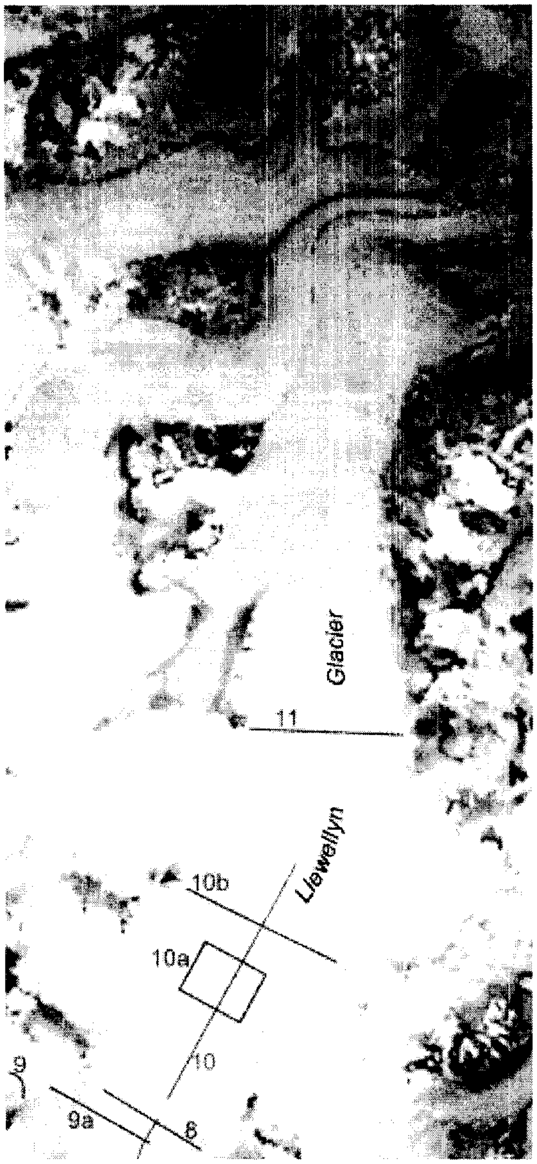
Record #	Flag #	distance from west margin (m)	distance to nearest geophone (m)	# of sticks	zero time (ms)
9	2	2000	155	15	161
11	1	1500	655	20	-100
12	0	500	1155	20	46
13	4	3000	155	15	-1
14	5	3500	655	20	10
15	6	4000	1155	25	-63
16	7	4500	1655	25	54
18	3	2500	0	25	144





Survey profile 11 data

Distance from flag 1 (m)	Displacement (m/day)
1500	0.114751
1780	0.190108
2058	0.238552
2341	0.265614
2617	0.282804
2892	0.286964
3171	0.289989
3452	0.295516
3732	0.275242
4020	0.24831
4294	0.220318
4588	0.169919



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