TIME LAPSE IMAGING OF THAW-BULB DEVELOPMENT BENEATH ARCTIC STREAMS USING GROUND-PENETRATING RADAR

Troy R. Brosten
Department of Geoscience
Boise State University, Boise, Idaho

John H. Bradford
Center for Geophysical Investigation of the Shallow Subsurface
Boise State University, Boise, Idaho

James P. McNamara
Department of Geosciences
Boise State University, Boise, Idaho

William Bowden
School of Natural Resources
University of Vermont, Burlington, Vermont

Michael N. Gooseff
Department of Aquatic Watershed, and Earth Resources
Utah State University, Logan, Utah

Abstract

We are investigating the responses of arctic tundra stream geomorphology, hyporheic zone hydrology, and biogeochemical cycling to climate change. Field results from summer, 2003, demonstrate that GPR is an effective tool for imaging the depth to sub-stream permafrost. The results presented here are the next step in the use of ground-penetrating radar (GPR) data for measuring sub-stream thaw over the melt season. We acquired a series of GPR profiles at nine sites from May - September, 2004, using 100, 200, and 400 MHz antennas. We selected sites with the objective of including stream reaches spanning a range of geomorphologic conditions in rivers and streams on Alaska's North Slope. Generally the streams can be placed into two categories: 1) as low-energy water flow with organic material lining the streambeds (peat streams) or 2) as high-energy water flow with cobble to gravel material lining the streambeds (alluvial streams). We acquired data using a pulsed radar system with high-power transmitter. Early in the field season we used the 400 and 200 MHz antennas to maximize resolution potential, then gradually shifted to the lower frequency 100 MHz antennas later in the season to increase depth of penetration. We placed the radar antennas in the bottom of a small rubber boat, then pulled the boat across the bank and through the stream while triggering at a constant interval via a string odometer system. Depth to permafrost was verified by pressing a metal probe through the active layer to the point of refusal. In addition, we recorded temperature data using thermocouples placed at varying substream depths along two of the seven GPR profiles. We used the temperature profiles to constrain and verify the GPR interpretation. At several sites we obtained excellent results and have produced images of thaw-bulb growth through the summer season in both alluvial and peat stream morphologies.

Table 1. Acquisition parameters at sites.

System	Sensors & Software PE100A		
Transmitter	1000 V		
Antennas	400 Mhz	200 Mhz	100 Mhz
# Stacks/Trace	8	8	8
Sampling Rate	0.2 ns	0.4 ns	0.8 ns
Recording Time	150 - 350 ns	150 - 350 ns	150 - 350 ns
Nominal Trace Spacing	5 cm	5 cm	5 cm

Field Setting and Data Acquisition

We conducted the field investigation in May - September, 2004, where we expected to measure the sub-stream thaw over the summer season. We investigated nine sites located within the Kuparuk River and Toolik Lake basins, north of the Brooks Range, Alaska (Figure 1). This presentation will focus on the preliminary results from four of those sites. The first site was located at Ox Creek ~ 20 miles north of Toolik Station along the Dalton highway. Ox Creek is a larger beaded stream with relatively fast moving water within 1 m depth channels connecting a series of small ponds with a gravel-lined streambed and organic lined stream banks. Three radar profiles were collected at the Ox Creek site. The first profile was collected across one of the connecting channels (2 m across) just upstream of a large pond. The second profile was collected across the large pond (10 m across) downstream of the first profile and the last profile was collected across the connecting channel (3 m across) downstream from the second profile.

Two sites were located along the I8 tributary series where one profile was collected upstream from a local lake (I8 Inlet) and two more profiles were collected just downstream of the outlet from the same lake (I8 Outlet a and b). Flow in the stream is characterized generally as high-energy water flow with cobble to gravel material lining the streambeds and average stream width at ~ 2 m. The I8 Inlet profile was collected along a straight reach of the stream at the same site where thermocouples were placed the previous season to monitor the temperature profile of the stream. The temperature profiles were used to constrain and verify the GPR interpretations. At the I8 Outlet site one profile was collected over a pool section of the stream and the second profile was collected just downstream over a riffle section of the tributary.

The final site we discuss was located along a meandering stretch of a small tributary of the Toolik River. This stream represents a low-energy water flow with organic material lining the streambeds. Aptly labeled as the Peat Inlet due to its morphology and location upstream from a small local lake. Stream width at the Peat Inlet site was 2 m and maximum water depth was 1.3 m. The stream channel was abrupt with nearly vertical channel walls. The GPR profile at this site was coincident with a string of thermocouples placed the previous season and again the temperature profiles were used to constrain and verify the GPR interpretations.

We used a commercial pulsed radar system with 100, 200, and 400 MHz antennas and high-powered transmitter (1000V) to maximize penetration beneath the streambed. The antennas were placed in the bottom of a small rubber boat, then pulled steadily across the stream and banks on either side. An odometer was anchored on the starting bank side with a string attached to the boat, then with the GPR unit set to record a trace every 5 cm the boat was pulled across the stream. The starting and ending position at each site was anchored with tag line to ensure the same starting and ending position for each profile. Maintaining spatial control is critical for both interpretation and application of spatial processing operators such as migration. Additional details of GPR data acquisition are listed in Table 1. In addition to acquiring the radar profiles, we measured depth to permafrost on the stream banks and shallow (< 0.5 m) margins of the streams by pressing a metal probe through the active layer to the point of refusal.

Data Processing Flow

1) Time zero correction with first break correlation to remove start of record delay and system drift.
2) DC shift and bandpass filtering with a 25-50-400-800 (for the 200 MHz) and a 12-25-200-400 Ormsby filter (for the 100 MHz) to attenuate the low frequency transient and high frequency random noise.
3) Amplitude correction varied by site.
4) F-K constant velocity migration velocity analysis to estimate thaw bulb velocity followed by conversion to interval velocities using Dix inversion.
5) Kirchhoff depth migration coupled with iterative velocity model refinement .

Ox Creek site (1)

At the Ox Creek site we recorded a strong, continuous reflection from the permafrost boundary. The data processing flow listed above was applied to the Ox Creek pond profile. After the profiles were all migrated the stream bottoms and permafrost depths were picked and then exported and graphed in a separate program to illustrate the gradual thickening of the thaw bulb throughout the summer season (Figure 1 – A). Overall we achieved excellent results from the migrated data revealing a detailed image of the permafrost boundary. Figure 2 – B displays the unmigrated GPR data recorded with the 200 MHz antenna on June 2, 2004 where the permafrost layer is obscured by scattering from cobbles on the stream bottom. The same image after migration is shown next in Figure 2 – C where the location of the permafrost layer is much clearer. Figure 2 – D illustrates how well, even in the unprocessed format, the permafrost boundary is resolved. Maximum permafrost depths determined from the GPR profiles are listed in Figure 5 in addition to depths for the remaining sites. One notable problem was the varying water depths during acquisition causing multiples to also vary with depth. Within some of the profiles the multiples obscured the permafrost boundary leading high amplitude migration artifacts during data processing.

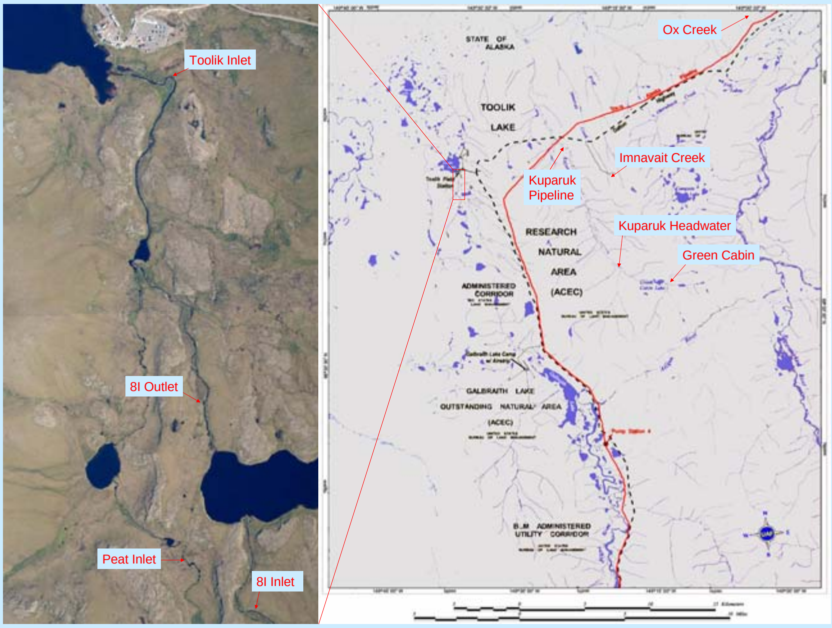


Figure 1. Location of nine study sites within the Kuparuk River and Toolik Lake basins, north of the Brooks Range.

Data acquisition at the Ox Creek site

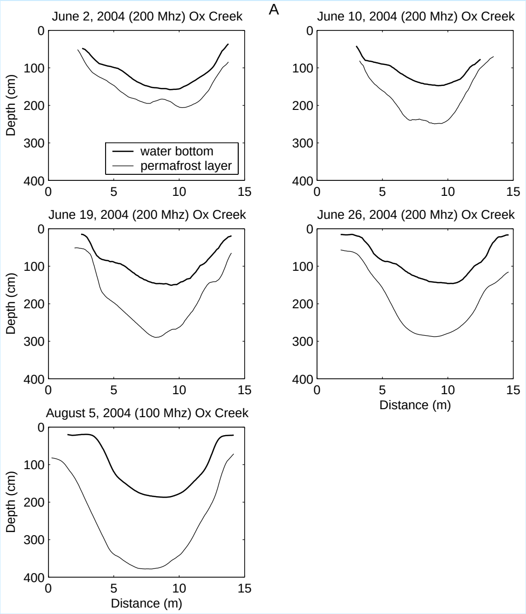
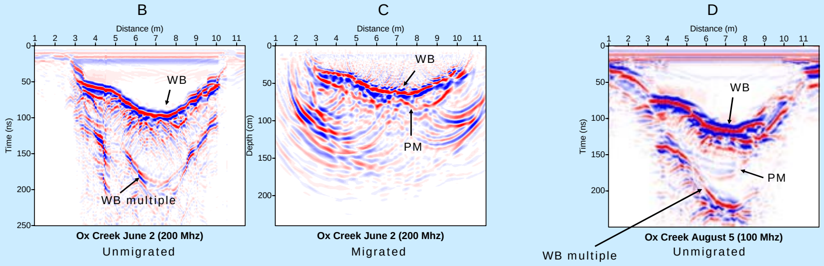


Figure 2. A) Interpreted water bottom vs. thaw bulb depths from GPR profiles recorded June to August B) pre-processed data from the Ox Creek site, C) depth migrated image, D) the 100 MHz pre-processed data from August 6th, water bottom (WB), Permafrost layer (PM).

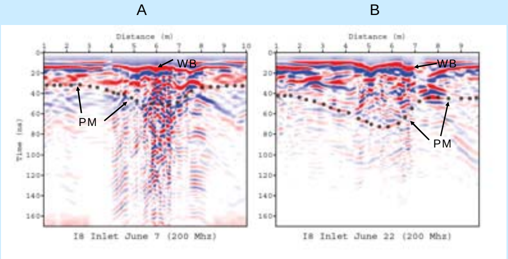


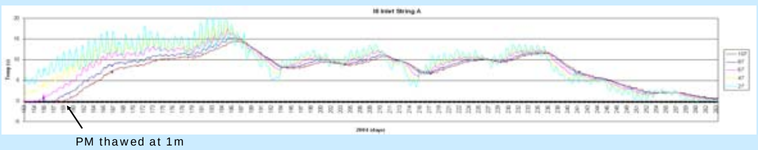
I8 Inlet site (2)

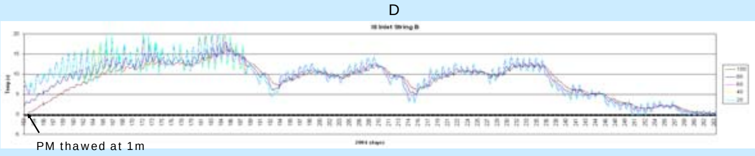
The I8 Inlet site was our most problematic site and we had some difficulty resolving the permafrost boundary. Figure 3 – A and B display unprocessed data using the 200 MHz antennas in early and late June. These profiles illustrate the permafrost thickening over the summer months. The radar data recorded numerous reflection artifacts that may be attributed to an extremely inhomogeneous streambed and substrates subsurface. While it is somewhat difficult to resolve the permafrost layer we feel confident about our picks which correlate well with the temperature profiles recorded by the thermocouples throughout the summer season. A velocity of 0.07 m/ns was attributed to the melted permafrost layer for the 8I stream sites and then multiplied by our time horizon picks to get an estimated permafrost depth in meters. Maximum permafrost depths from our calculations are listed in Figure 5. Figure 3 – C and D display two temperature profiles where the recording thermocouples were placed at varying depths (in cm) 0.15m and 1.6m from left-side stream bank respectively. It's easy to see the diurnal temperature changes in the shallow placed thermocouples whereas the overall temperature trend shows a temperature warming early June, some smaller temperature fluctuations throughout the summer months and then a gradual cooling early September. Note that the permafrost remains frozen up to June 7 for the deepest thermocouple (107 cm) closest to the stream bank while the deepest thermocouple near the middle of the stream thaws out by May 29th.

Figure 3. A) Pre-processed 200 MHz data from early-June (run section), B) pre-processed 200 MHz data from late-June (run section) C) thermocouple temperature data from the end of May through mid-September where the depth profile (in cm) is located 0.15m from left side stream bank, D) thermocouple temperature data from the end of May through mid-September where the depth profile (in cm) is located 1.6m from left side stream bank, water bottom (WB), Permafrost layer (PM).

Data acquisition site at I8 Inlet (viewing upstream)





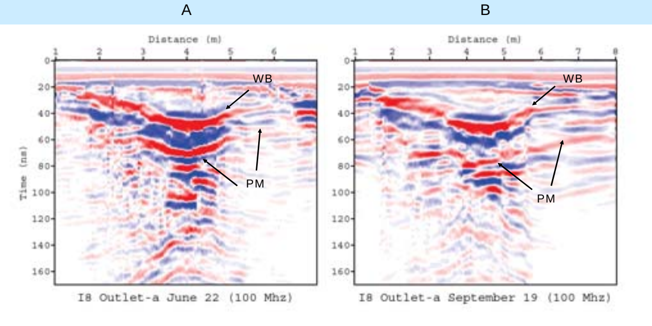


I8 Outlet site (3)

Radar profiles from the I8 Outlet site showed excellent reflections used to resolve the permafrost layer. Profiles for the riffle section (Figure 4 – C and D) illustrate the thaw bulb thickening over the summer season from 0.75m to 1.41m (Figure 5). The rapid thickening beneath the gravel bar section may be attributed to exposure of the dark colored stream bed rocks to the sun where heat is being transferred from the rock down into the subsurface materials causing a much more rapid thawing of the permafrost. In comparison to the section of profile where surface water is still flowing the thaw bulb appears to be thinner possibly due to the surface water providing some insulation to the permafrost underneath. The profiles for the small pool section (Figure 4 – A and B) show the thaw bulb slightly thicker in late June than September (Figure 5). This indicates the permafrost is starting to refreeze which matches the story told by the temperature data recorded at the 8I Inlet site.

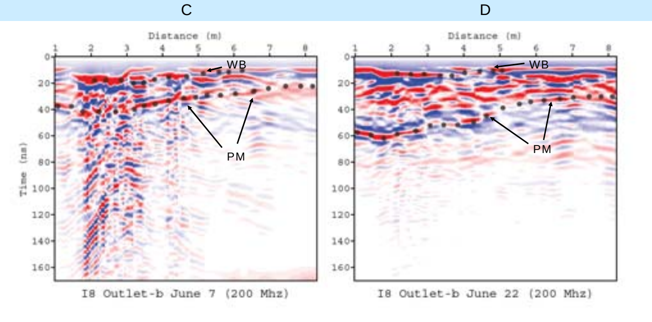
Figure 4. A) Pre-processed 200 MHz data from late-June (pool section), B) pre-processed 100 MHz data from mid-September (pool section), C) A) Pre-processed 200 MHz data from early June (riffle section), D) pre-processed 200 MHz data from late-June (riffle section), water bottom (WB), Permafrost layer (PM).

Data acquisition site at I8 Outlet-a (viewing upstream)



Data acquisition site at I8 Outlet (viewing downstream of both a and b profile sites)

Data acquisition site at I8 Outlet-b (viewing upstream)



Conclusions

Preliminary results demonstrate that GPR methods can resolve and monitor permafrost depths throughout the summer season for both gravel and peat lined stream morphologies. One distinct conclusion drawn from these results are the differences in the rate of thaw and the maximum thaw bulb thicknesses between the two stream morphologies where the maximum depth to the permafrost layer at the Peat Inlet site was 0.63m and 1 – 2m for the gravel lined stream sites. The difference in rate of thaw is illustrated by thermocouple data where the I8 Inlet temperature profiles recorded the permafrost thawed to 1m by early June and only down to 0.4m by early July at the Peat Inlet site. Some sites, Ox Creek for example, demonstrated that migration significantly improved our ability to interpret the permafrost depth. Limitations include permafrost depths that were obscured by scattering effects caused by cobbles in the subsurface. In addition, multiples sometimes obscured the permafrost layer and led to high amplitude migration artifacts. Varying water depths also caused recording times for the radar reflections to change causing some difficulties while interpreting the thaw bulb thickness between profiles.

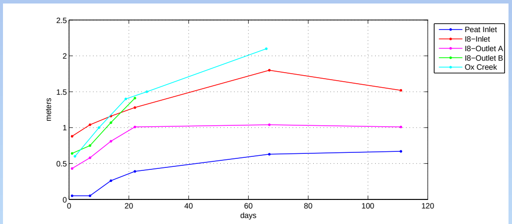


Figure 5. Maximum permafrost depths for study sites.

Acknowledgements

This work was funded under NSF Grant #0327440 and conducted at Toolik Field Station operated by the University of Alaska, Fairbanks.

Visit the hyporheic project website at:
http//:www.mines.edu/~mgooseff/arctic_proj.html

References

Bradford, J.H., McNamara, J.P., Bowden, W., Gooseff, M.N. (2005) Measuring thaw depth beneath arctic streams using ground-penetrating radar, *Hydrological Processes*, in press.

Peat Inlet site (4)

Radar profiles from the Peat Inlet site revealed a detailed image of the permafrost boundary. Bradford et al. (2005) processed GPR data profiles collected in 2003 from this same site and can provide additional information on the site and data processing techniques. A velocity of 0.05 m/ns was attributed to the melted permafrost layer for the Peat Inlet site and then multiplied by our initial picks to get an estimated permafrost depth in meters. The two profiles shown in Figure 6 illustrate the thaw bulb thickening from 0.05m in early June to 0.67m mid-September (Figure 5) which also correlates well with the temperature data recorded by the thermocouple profiles. Figure 6 – C and D display two temperature profiles where the recording thermocouples were placed at varying depths (in cm) ~0.5m and ~1.5m from left-side stream bank respectively. As in the temperature profiles shown for the 8I Inlet site it's easy to see the diurnal temperature changes for the in-stream placed thermocouples. In comparison to the I8 temperature values the seasonal temperatures recorded for the 38cm thermocouple in the Peat Inlet thawed at a much later date. This is likely attributed to the morphology of the stream where the organic lining material provide a much better insulation against seasonal temperature changes. This insulating effect cause much smaller thaw bulb thicknesses for the peat lined stream in comparison to the gravel lined streams.

Figure 6. A) Pre-processed 200 MHz data from early-June, B) pre-processed 200 MHz data from mid-September, C) thermocouple temperature data from the end of May through mid-September where the depth profile is located ~0.5m from left side stream bank, D) thermocouple temperature data from the end of May through mid-September where the depth profile is located ~1.5m from left side stream bank, water bottom (WB), Permafrost layer (PM).

Data acquisition site at Peat Inlet (viewing upstream)