C43A-0522: Capturing fracture propagation in a glacier using passive seismology

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ABSTRACT

We recorded 112 hours of continuous 3-component seismic data on 9 short period sensors at Bench Glacier, Alaska. We identify hundreds of small amplitude surface fracture events using a crosscorrelation search algorithm designed to identify events having strong Rayleigh waves—characteristic of surface fracturing. Using Rayleigh wave group arrival times, we determine event epicenters. Defining a cluster of events, we manually pick P- and S-wave arrival times to further constrain event locations. Using the improved locations, we see that events related to a single fracture migrate both in time and space. To estimate bulk ice properties, we analyze the amplitude of all surface fracture events on the glacier.

INTRODUCTION

- **Bench Glacier** - alpine glacier (approx. 1 km x 7 km and 180 m thick) located near Valdez, Alaska
- **Sensors** – Mark Products L28 3C short period sensors
- **Array** – Nine sensors in cross shape—approx. 100 m separation
- **Data** – Recorded continuously at 250 Hz from August 10 to 15, 2007

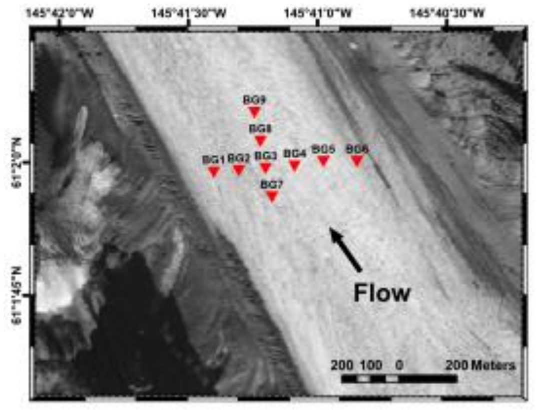
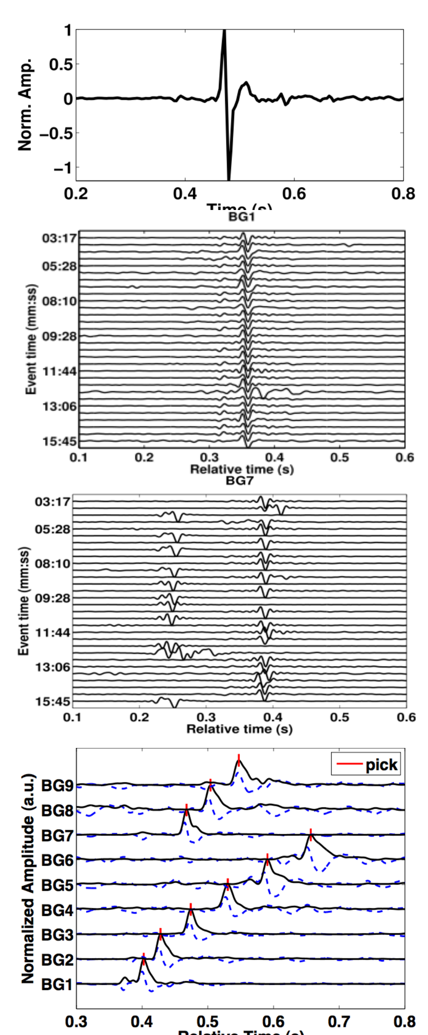


Figure 1. The 9-station array on Bench Glacier, Alaska, USA.

EVENT PROCESSING STEPS



a) Event identification: We crosscorrelate search wavelet (shown in Figure 2-top) with vertical component continuous recording at station BG3. A correlation > 0.5 over the 1 second window is considered an event trigger. Figure 2 (middle plots) show 31 events over 15 minutes recorded at BG1 and BG7.

b) Pick Rayleigh wave group arrival: We extract 1 second of data from all 9 stations. We calculate the envelope in the window and pick group arrival times. An example event is shown in Figure 2 (bottom).

c) Amplitude information: We instrument-correct the waveforms and numerically integrate, yielding amplitude in meters. We pick the maximum amplitude of the Rayleigh wave at each station and compute the signal-to-noise ratio (SNR) over the 1 second window.

d) Event location: We input the group arrival times and SNRs into an ordinary least-squares epicenter location algorithm. SNR must be > 5 or the arrival time at that station is not used. There must be at least 5 stations with arrival times or the event is not located. The least-squares algorithm updates epicenters until the forward modeled travel times fit the observed travel times within 1 standard deviation (4 ms).

Figure 2. Top: the search wavelet with a large Rayleigh wave. Middle: identified surface fracture events over one hour on stations BG1 and BG7. Bottom: Rayleigh wave group travel time picks—solid black line is envelope; dashed blue line is displacement.

RAYLEIGH WAVE EPICENTERS

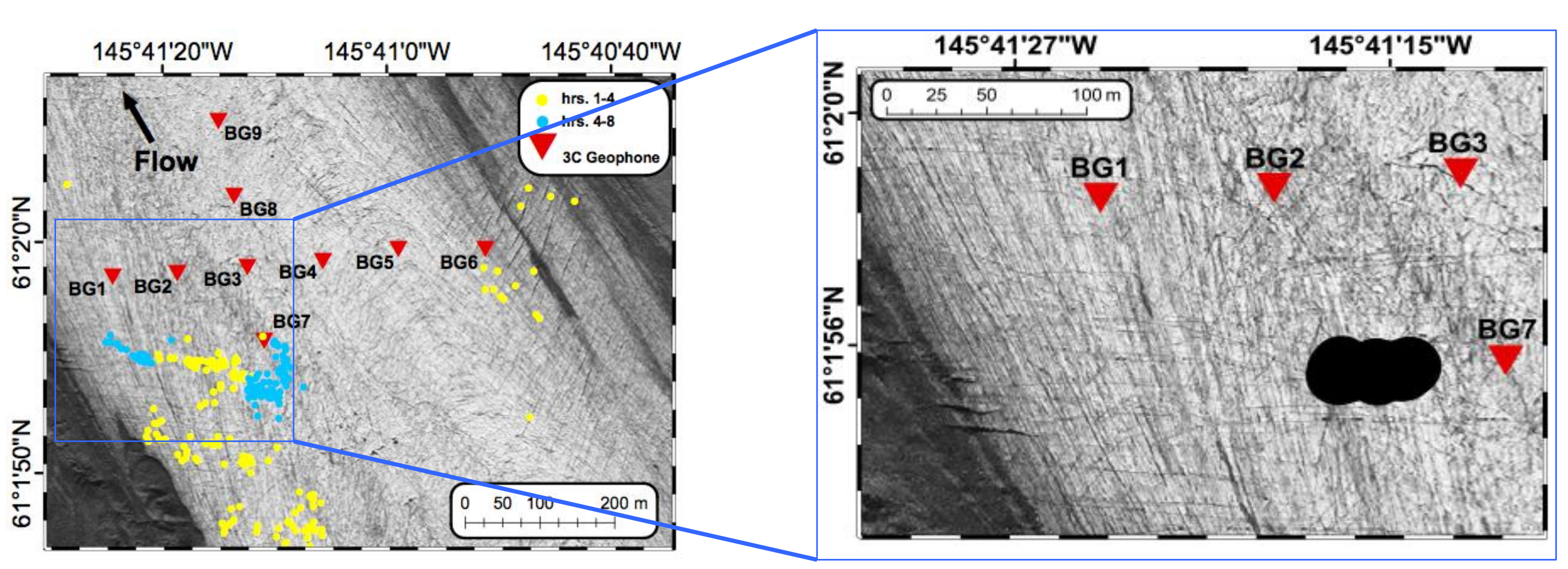


Figure 3. Left: event epicenters from travel time inversion of Rayleigh wave group arrival times over an 8 hour period. Right: zoom around a select group of events. Notice the distinct locations in the first 4 hours versus the next 4 hours of data. Circle sizes are proportional to the estimated error in epicenter location.

MONITORING FRACTURE PROPAGATION

We further investigate a group of events close in space and time. We estimated the incidence azimuth of the P-wave using an instantaneous polarization filter (Vidale, 1986) and rotated the 3C data to radial and transverse. Using the rotated data, we manually picked the P- and S-wave arrival times. Figure 4 shows the distinct arrivals on the 3 rotated components for a single event at station BG1. Figure 5 shows the estimated event locations for the cluster of events shown in the right plot of Figure 3. These locations are estimated using the arrival times of all three waves—P, S, and Rayleigh. Again, the size of the circles is proportional to the estimated location error. The error is reduced by a factor of 2 using all 3 wave types.

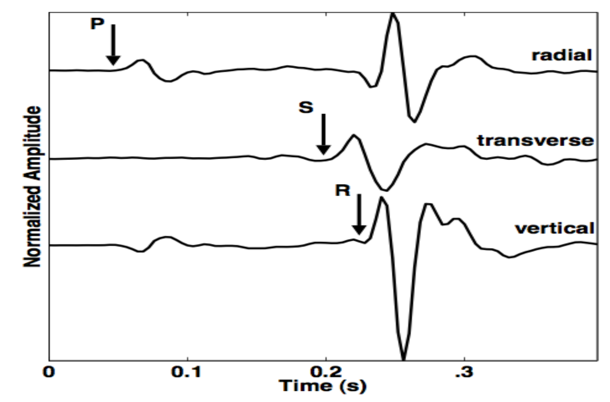


Figure 4. 3-component surface event.

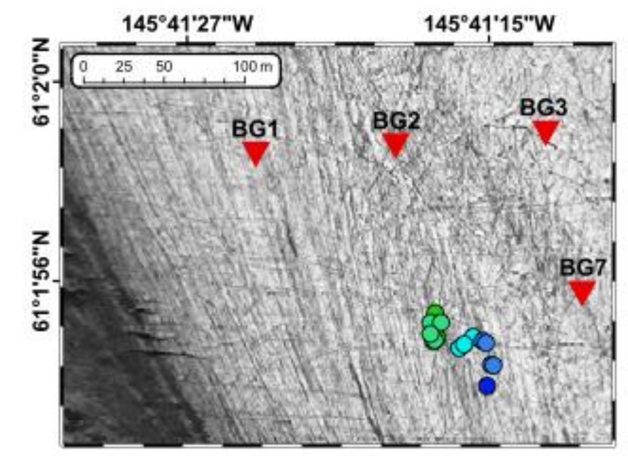


Figure 5. Locations using the joint P-, S-, and Rayleigh-wave inversion. The colors show migration of the fracture from NW to SE with time (green to blue).

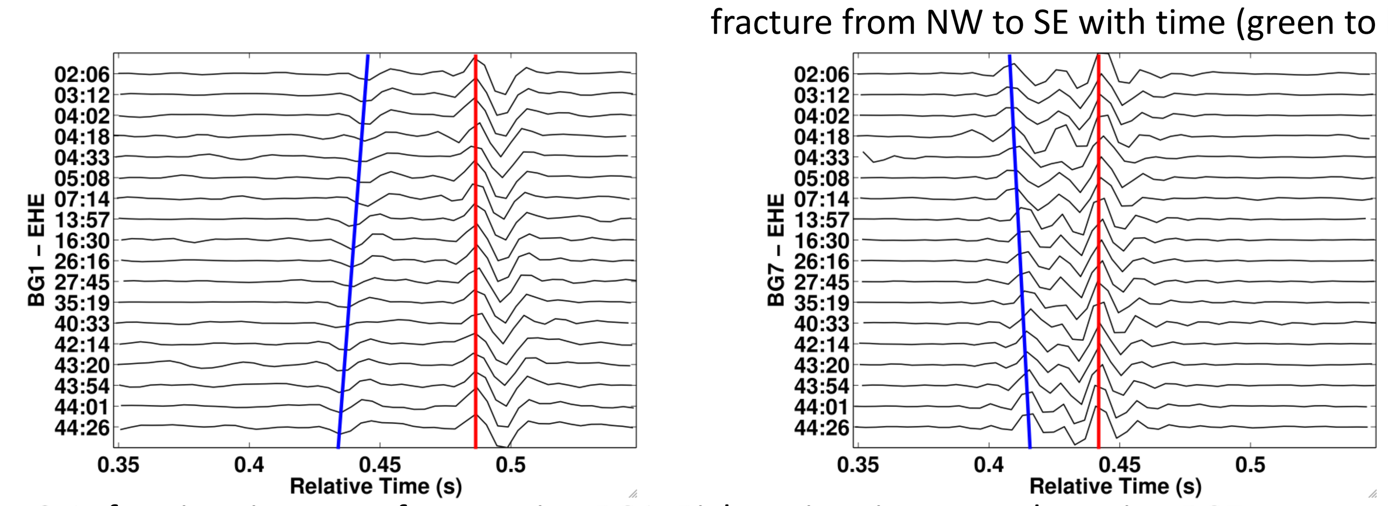


Figure 6. Left: migration away from station BG1. Right: migration towards station BG7.

Joint inversion using the three wave modes highlights the fracture moving 42 m in 45 minutes. This correlates to the migration of the P- and Rayleigh waves through time that we observe in the waveforms.

AMPLITUDE INFORMATION

We represent the Rayleigh wave amplitude as $A(R) = \frac{A_0 e^{-\alpha R}}{\sqrt{R}}$ where R is distance from the icequake epicenter to the observation, A_0 is the initial amplitude at the icequake location (R = 0), and α is an attenuation factor related to the seismic quality factor: $Q_{ice} = \frac{\omega_0}{\alpha V_0}$ where is the dominant Rayleigh-wave angular frequency and is the Rayleigh-wave phase velocity. Averaging the icequakes in the cluster, we estimate Q_{ice} at a dominant frequency of ~40 Hz to be around 97 +/- 20.

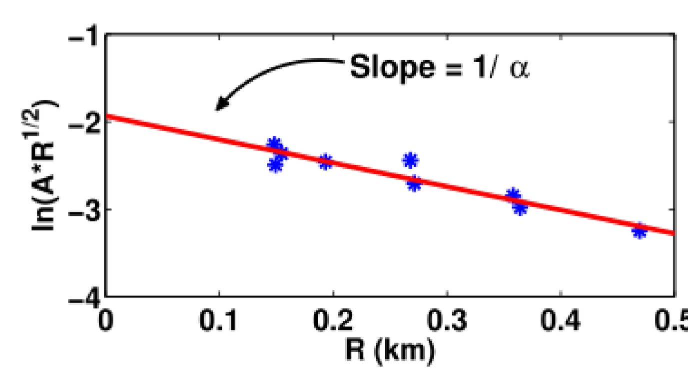


Figure 8. Natural logarithm of the maximum Rayleigh wave amplitude, corrected for geometrical spreading. The residual slope is attributed to seismic wave attenuation.

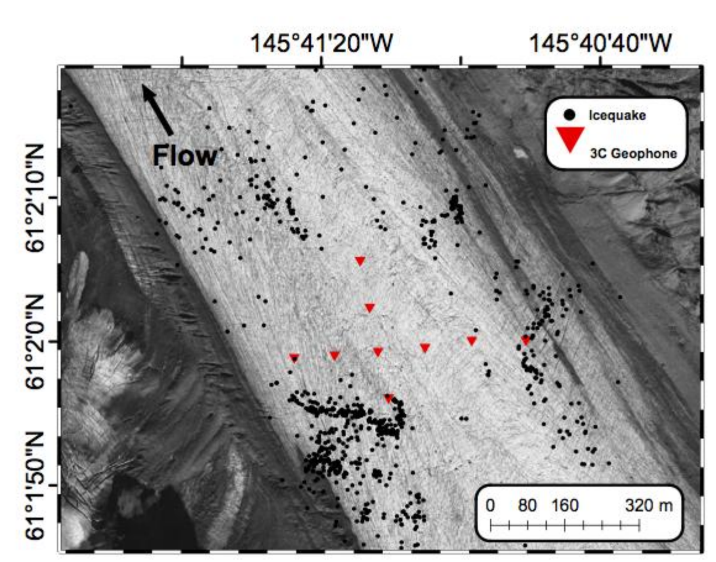


Figure 7. All surface fracture events identified at Bench Glacier.

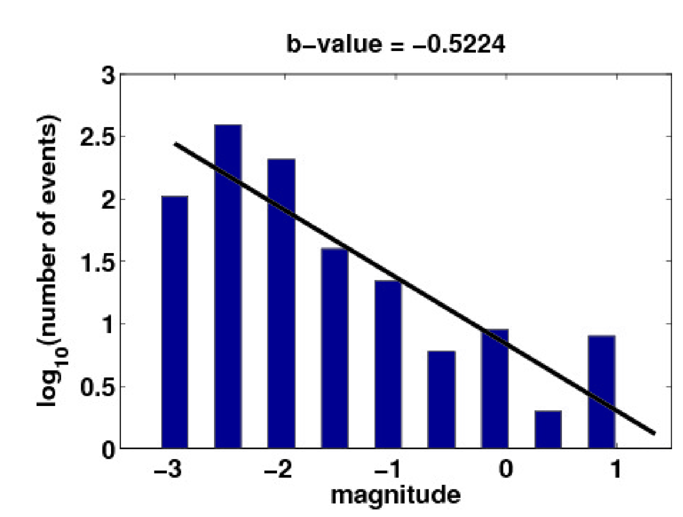


Figure 9. Number of events per relative Rayleigh wave magnitude. We estimate the b-value to be -0.5.

Our current magnitude estimates are based on the maximum amplitude of the Rayleigh wave. In order to calibrate our Rayleigh magnitudes, we are currently inverting the 3C seismic data for the moment tensor. Then we can relate our Rayleigh magnitude to the seismic moment. Preliminary results are shown below in Figure 10.

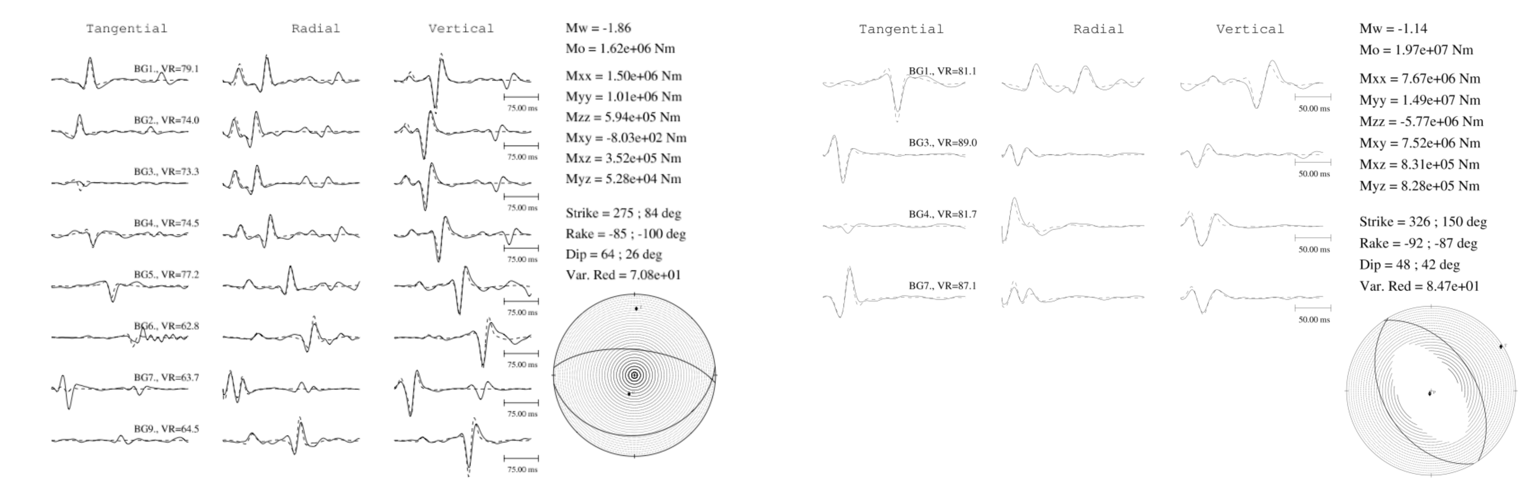


Figure 10. Left: waveform fit for surface fracture event using a full-moment tensor inversion. The event has a large isotropic component. Right: waveform for another surface fracture event. Moment tensor solution is more dip-slip for this event.

CONCLUSION

- We optimized event locations using the combined P-, S-, and Rayleigh wave travel time inversion. This method is manual at the moment and quite time consuming.
- With this resolution we can monitor individual fracture propagation.
- Majority of events are located along the edges of the glacier.

FUTURE WORK

- Double difference algorithm to improve relative event locations
- Estimate more moment tensors and develop empirical relationship between Rayleigh wave magnitude and seismic moment.
- Investigate a possible relationship between tides and number of events.

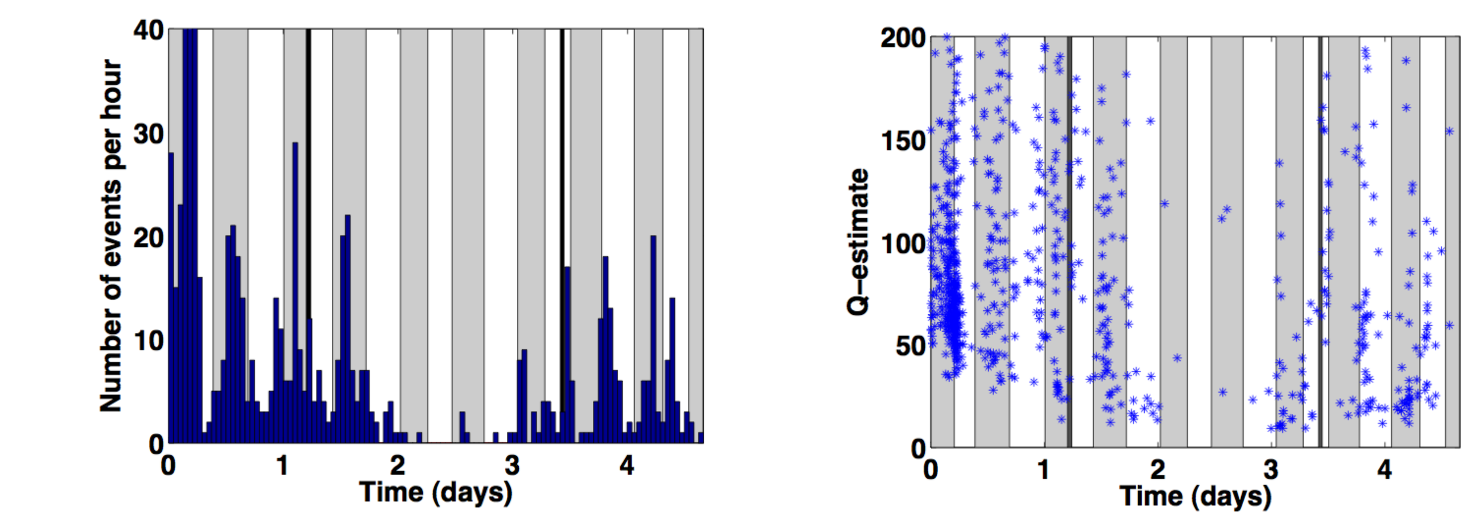


Figure 11. Left: number of events. Right: Q-estimates for each event. Tide level (high tide in grey, low tide in white) is plotted in the background. Black lines in both images indicate when the stations were reset.

The Q value that we estimate is a combination of intrinsic and scattering Q, related to the water saturation in the pore space and existing fractures within the glaciers, respectively. One possible reason why we see variation in Q is that the incidence azimuth for events changes. This leads to different travel paths in which the wave experiences different fracture systems. Another possibility for variation in our Q estimate is the radiation pattern of the Rayleigh wave based on the source mechanism, which can change as a function of azimuth. However, the Q that we estimate does fall within the range of Q values previously published (from 6 to 10 up to 300) for polycrystalline ice.

ACKNOWLEDGMENTS

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References

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