Small-Array Location Capabilities using the Seismometer to Investigate Ice and Ocean Structure (SIIOS): Implications for An Ocean World Lander

A. G. Marusiak[1], N. C. Schmerr[1], S. H. Bailey[2], D.N. DellaGiustina[2], V.J. Bray[2], P. Dahl[3], E.C. Pettit[4], B. Avenson[5], R. C. Weber[6]

[1]University of Maryland College Park, College Park, MD (marusiak@umd.edu), [2]University of Arizona, Lunar and Planetary Laboratory, Tucson, AZ, [3]Applied Physics Laboratory University of Washington, Seattle, WA, [4]University of Alaska Fairbanks, Fairbanks, AK, [5]Silicon Audio, Austin, TX, [6]NASA Marshall Space Flight Center, Huntsville A

Funded by NASA PSTAR Grant # 80NSSC17K0229 and NASA NESSF Grant #80NSSC18K1260

Abstract No. 1546

Introduction

Ocean worlds have thick icy shells covering subsurface oceans [1-3]. Due to the potential habitability of the subsurface ocean, Europa has become a target for a potential lander mission [4,5]. Seismology is the preeminent method for constraining the thickness of an icy shell. The Seismometer to Investigate Ice and Ocean Structure (SIIOS) uses flight-candidate instrumentation to develop approaches for seismic studies of icy bodies. The SIIOS team deployed small aperture seismic arrays on Gulkana Glacier in 2017 and in Northwest Greenland in 2018.

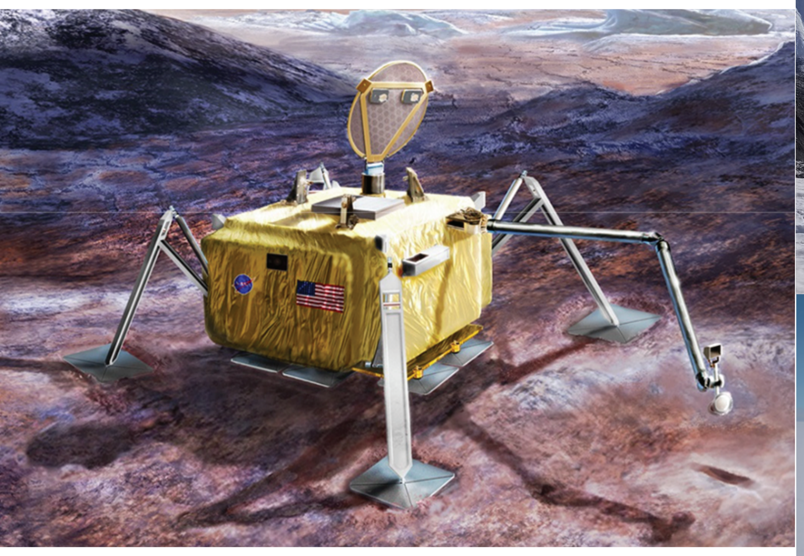
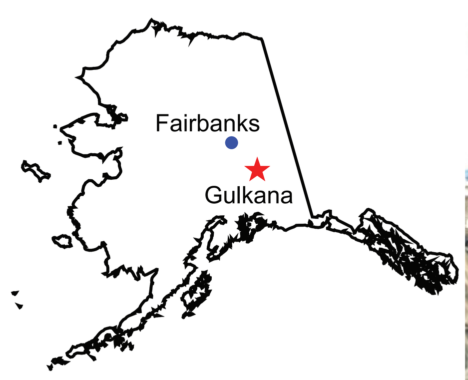
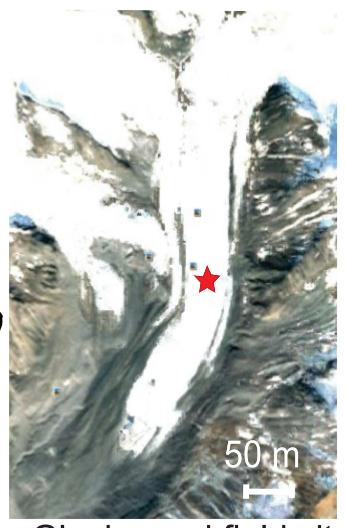
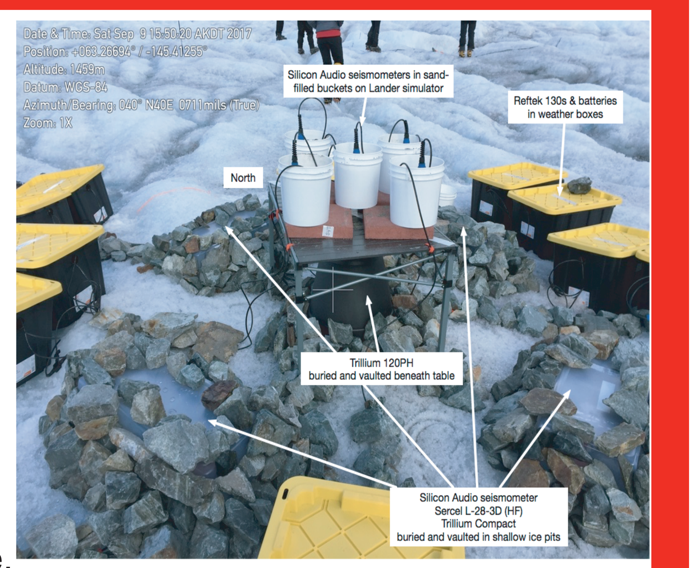


Image Credit: NASA/JPL

Field Test: Gulkana Glacier

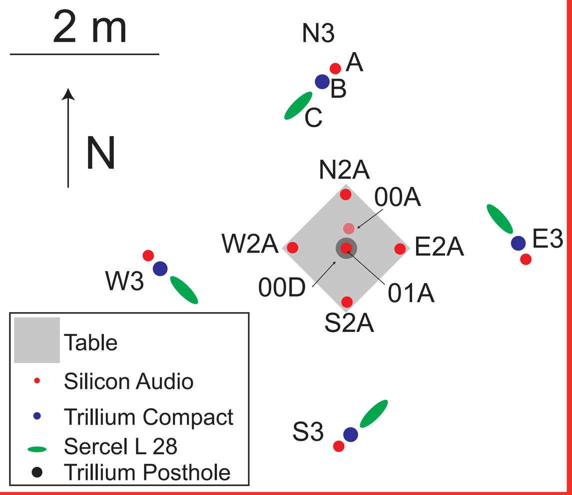




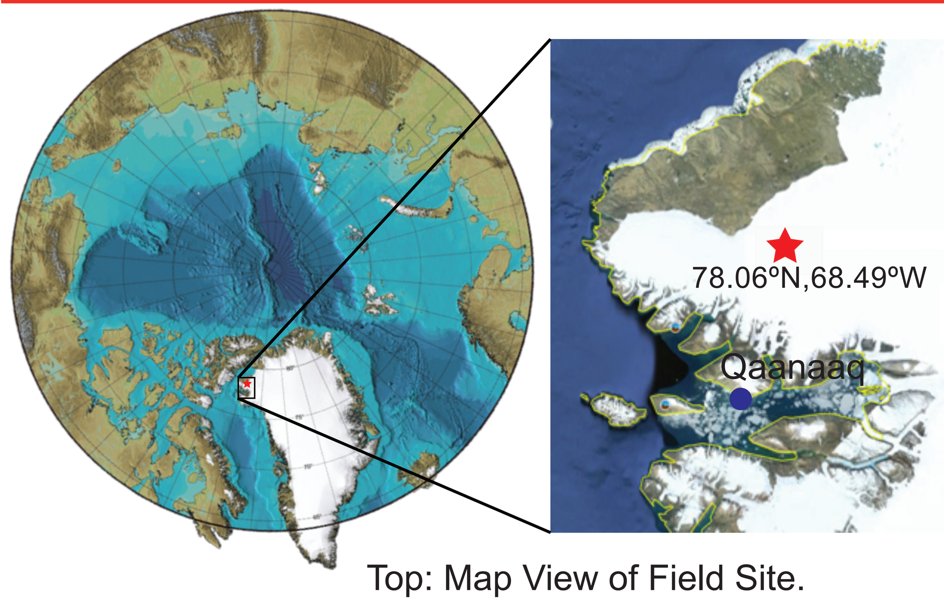


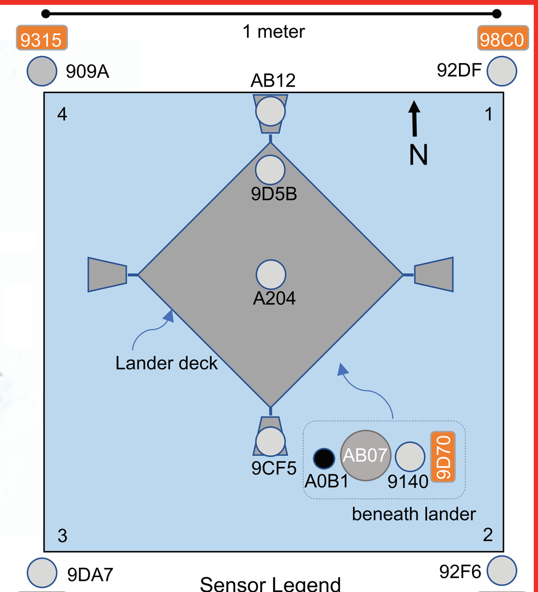
Top: Map View of Gulkana Glacier and field site. Right: Photo and Schematic of experiment

SIIOS was deployed on Gulkana Glacier in September 2017. Gulkana is classified as a "benchmark" glacier by the USGS [6] and has ice ~100 meters thick [7]. Gulkana's seismic signals include regional and teleseismic earthquakes, icequakes, rockfalls, and water drainage events from a nearby moulin. It experiences diurnal changes in seismicity.



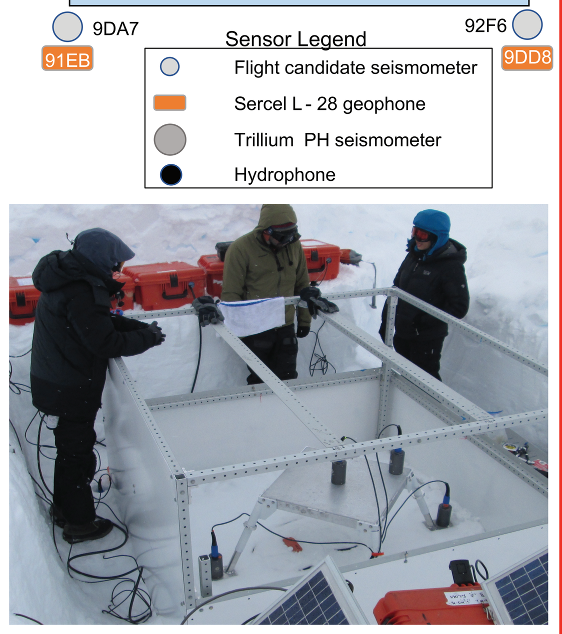
Field Test: Northwest Greenland





Top: Map View of Field Site. Right: Photo and Schematic of experiment

SIIOS was deployed at our Greenland site during the summer of 2018. The ice is ~850 m thick and sits above a subglacial lake [8]. This lake formed between the ice sheet and underlying bedrock and served as an analog for trapped water in Europa's icy shell. Greenland was a quieter site compared to Gulkana because it was farther from plate boundaries, and the mock-lander was encased in an aluminum box prior to burial.

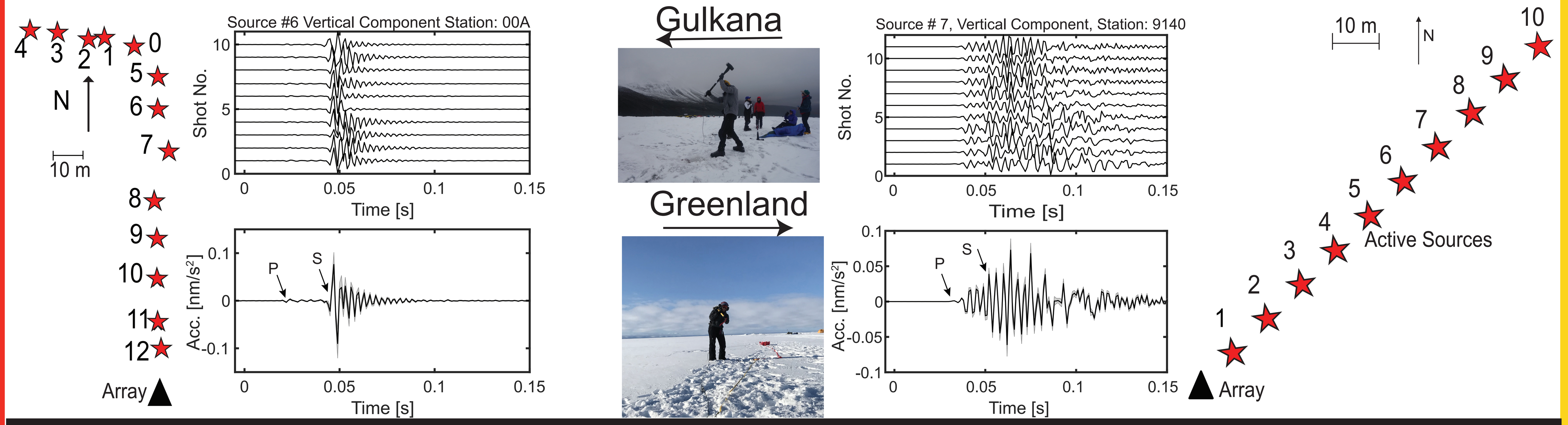


Active Source Experiment

Active source experiments were conducted at both field sites. The active source tests can be used to recover internal structure [9] but can also be used as a test for a location algorithm.

At both field sites the active source was a sledgehammer striking an aluminum plate. At each location, about ten shots were recorded in order to stack and improve the signal-to-noise ratio. At Gulkana, thirteen locations were used. The locations were about ten meters from each other but varied in azimuth. At the Greenland field site, all ten locations were in the northeast direction from the array.

Once the shots were stacked, we visually selected compressive (P) and shear (S) waves.



Constraining Distance

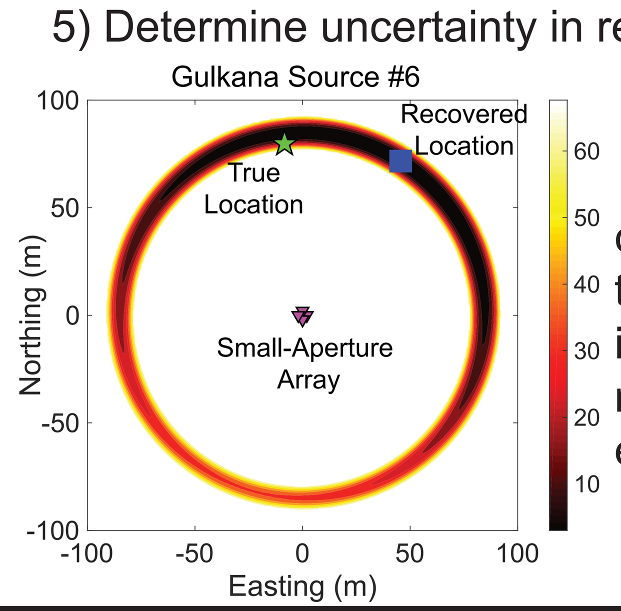
The location of the active sources were constrained using the following steps [10]:

1) Create plausible interior structure models using existing literature [11,12]
2) Build a 200 x 200 m grid to predict arrival times for each point in the grid.
3) Calculate residual between predicted and observed arrival time using sum of least squares:

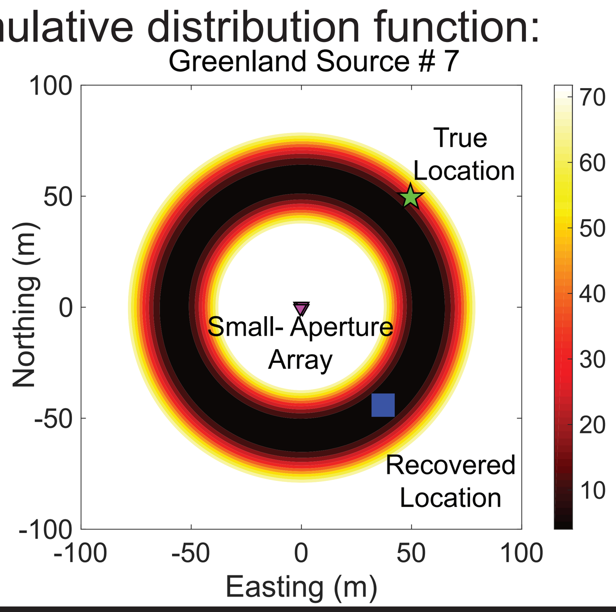
$$\text{residual}=\sum(T_{pred}-T_{obs})^2 \qquad T=T_S-T_P$$

4) Determine location of minimum residual (blue square).
5) Determine uncertainty in recovered location using Chi-Squared Probability cumulative distribution function:

$$X^2=\frac{\sum[T-T_p]^2}{\sigma^2}$$

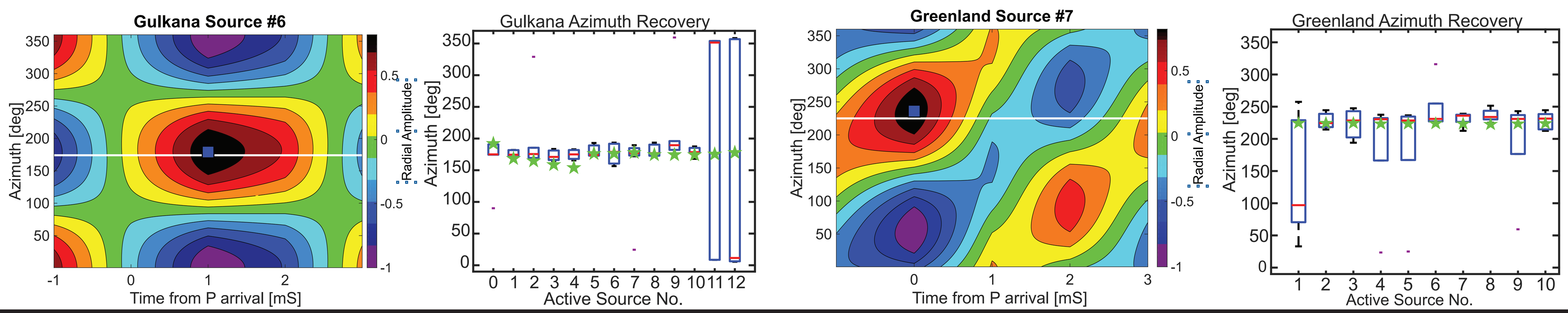


The figures demonstrate that distance is constrained well, but not azimuth. Due to the size of the small aperture arrays, the arrival times are identical or within arrival time uncertainties. This means traditional triangulation of stations was less effective. In order to recover the correct azimuth, we needed to utilize an additional method.



Constraining Azimuth

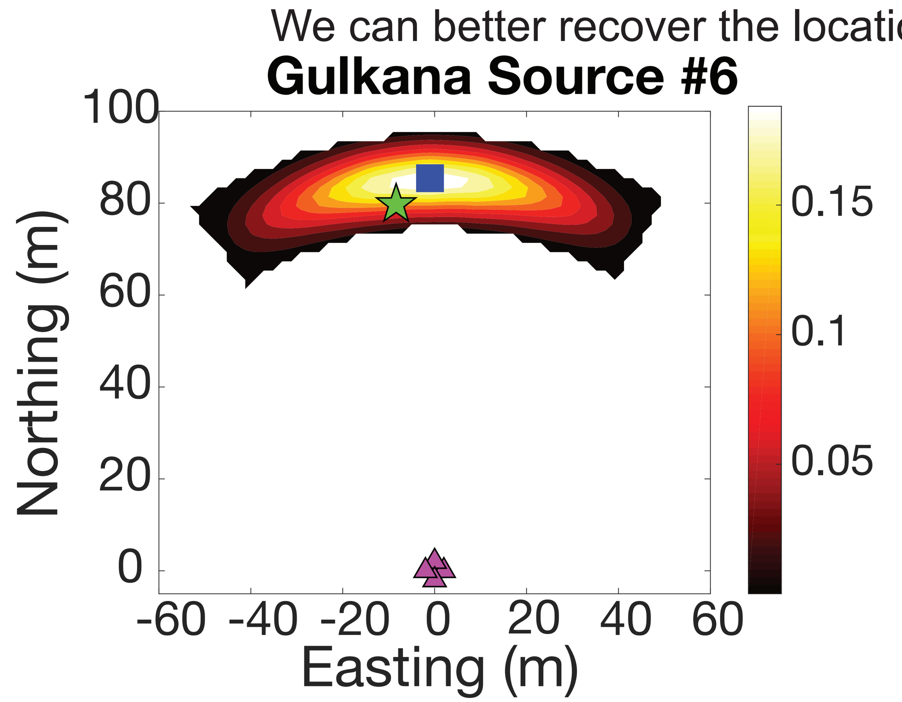
To better constrain azimuth we utilized the polarization of the P wave. When aligned along the correct azimuth, the P wave is maximized in the radial component [10]. To recover azimuth we created a range of azimuths and rotated the horizontals accordingly. The recovered azimuth occurs where the radial component is maximized (blue square in top plots).We can repeat this process for each station to determine the median (red line), 25th and 75th percentiles (blue box), and identify outliers for each location (purple dashes).



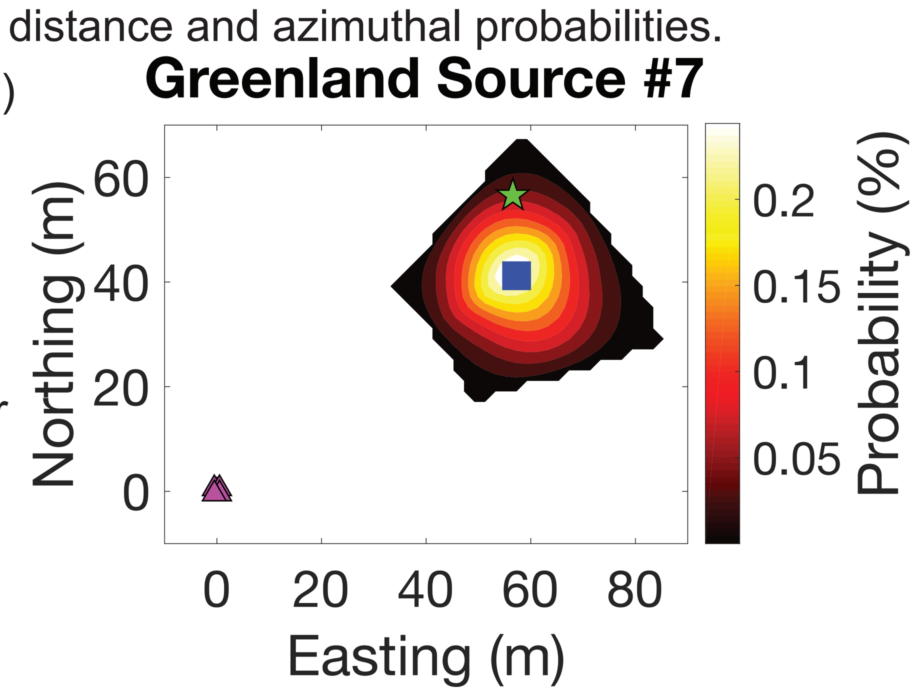
Location Recovery

We can better recover the locations by combining the distance and azimuthal probabilities.

$$P = P(dis) * P(az)$$



This approach led to a more accurate recovery of the true locations for both field sites.



Future Work

To further constrain azimuth we will test additional methods including the polarization of surface waves [13-15] and beamforming techniques [20]. The techniques will be integrated with the location grid search algorithm. We will eventually apply these techniques to regional passive events.

The passive events will further be used to create a catalog of local seismicity. The purpose of the catalog is to identify and locate sources from earthquakes, rock falls, ice-quakes and moulins. The catalog can be used to quantitatively describe advantages of a small-aperture array over a single-station.

Conclusions

Key take-away points:

- Gulkana Glacier and Northwest Greenland served as analogs for ocean worlds
- Active source experiments can provide known locations to test location abilities
- Using only arrival times and relative positions of seismic stations, we can recover distance to the event
- Event azimuth can be constrained using P wave polarization
- We can combine distance and azimuthal probabilities to recover the true locations

References

[1] Kargel et al., (2000) Icarus, 148, 226-265. [2] Reynolds et al., (1983) Icarus, 56, 245-254. [3] Marion et al. (2003) Astrobiology, 3, 785-811. [4] Hand et al. (2017) Report of the Europa Science Definition Team. [5] Pappalardo et al., (2013) Astrobiology, 13. [6] Josberger et al., (2007), Annals of Glaciology, 46, 291-296. [7] O'Neel et al., (2014) Climatic Change, 123 ,329-341. [8] Palmer et al., (2013) GRL, 40, 6154-6159. [9] Beyreuther et al., (2010) Seismological Research Letters, 81, 530-533. [10] Shearer (2019). Introduction to Seismology. (Cambridge University Press). [11]Shean et al., (2007). Antarctic Science, 19(4). [12] Montgomery et al., (2017) Frontiers in Earth Science, 5. [13] Panning et al., (2015) Icarus 248, 230–242. [14] Bose et al. (2017) Phys. Earth Planet. Inter. 262, 48–65 . [15] Khan et al., (2016) Phys. Earth Planet. Inter. 258, 28–42. [16] Edelmann & Gaumond (2011) Acoust. Soc. Am. 130, EL232-EL237.