CLUSTER ANALYSIS OF THERMAL ICEQUAKES USING THE SEISMOMETER TO INVESTIGATE ICE AND OCEAN STRUCTURE (SIIOS): IMPLICATIONS FOR OCEAN WORLD SEISMOLOGY

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Introduction: Ocean Worlds are of high interest to the planetary community (*1*, *2*) due to the potential habitability of their subsurface oceans (*3*–*5*). Over the next few decades several missions will be sent to ocean worlds including the Europa Clipper (*6*), Dragonfly (*7*), and possibly a Europa lander (*8*). The Dragonfly and Europa lander missions will carry seismic payloads tasked with detecting and locating seismic sources. The Seismometer to Investigate Ice and Ocean Structure (SIIOS) is a NASA PSTAR funded project that investigates ocean world seismology using terrestrial analogs. The goals of the SIIOS experiment include quantitatively comparing flight-candidate seismometers to traditional instruments, comparing single-station approaches to a small-aperture array, and characterizing the local seismic environment of our field sites. Here we present an analysis of detected local events at our field sites at Gulkana Glacier in Alaska and in Northwest Greenland approximately 80 km North of Qaanaaq, Greenland (Fig. 1a).

Both field sites passively recorded data for about two weeks. We deployed our experiment on Gulkana Glacier in September 2017 (Fig. 1b) and in Greenland in June 2018 (Fig. 1c). At Gulkana there was a nearby USGS weather station (*9*) which recorded wind data. Temperature data was collected using the MERRA satellite (*10*). In Greenland we deployed our own weather station to collect temperature and wind data. Gulkana represents a noisier and more active environment. Temperatures fluctuated around 0°C, allowing for surface runoff to occur during the day. The glacier had several moulins, and during deployment we heard several rockfalls from nearby mountains. In addition to the local environment, Gulkana is located close to an active plate boundary (relative to Greenland). This meant that there were more regional events recorded over two weeks, than in Greenland. Greenland's local environment was also quieter, and less active. Temperatures remained below freezing. The Greenland ice was much thicker than Gulkana (~850 m (*11*) versus ~100 m (*12*, *13*)) and our stations were above a subglacial lake. Both conditions can reduce event detections from basal motion. Lastly, we encased our Greenland array in an aluminum vault and buried it beneath the surface unlike our array in Gulkana where the instruments were at the surface and covered with plastic bins. The vault further insulated the array from thermal and atmospheric events.

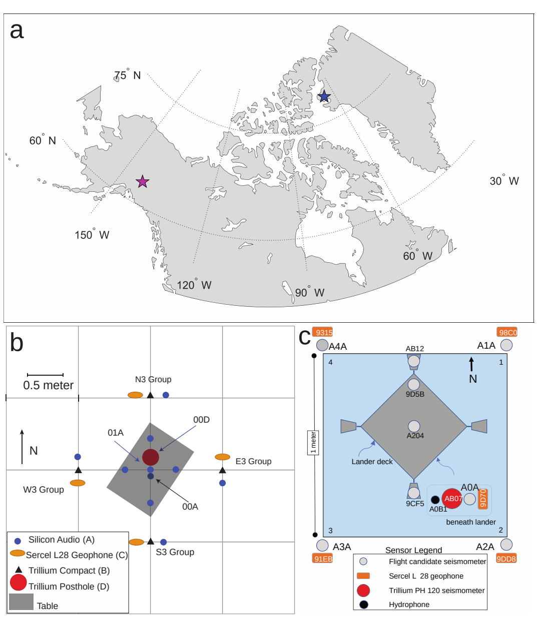

Figure 1. a) Map of the SIIOS Array in Alaska (purple) and Greenland (blue). Schematic of Small Array in b) Gulkana and c) Greenland

Event Detection and Clustering: To detect local events we filtered the data between 5-20 Hz. Using the Obspy module in python (*14*), we performed a short-term average/long-term average (STA/LTA) approach to determine where amplitudes spiked. For short term we used 1.5 seconds and 40 seconds and a ratio of 20 to detect events (*15*). Through this approach we detected 104 events at our Greenland site and 2252 events at our Gulkana site. The Gulkana site showed a strong correlation with both temperature and changes in temperature, while Greenland did not show this relationship (*16*). Once we had a catalog of events, we performed a hierarchal cluster analysis to cluster events based on the Hilbert transform of their waveforms.

Gulkana: For Gulkana, there were 5 distinct categories (Fig. 2a). The first category was about 1-1.5 seconds in duration with peak energy early in the waveform. 631 events fell into this cluster. The dominant frequency tended to occur between 300-400 Hz. The events were most likely to occur before 5 am local time, or after 3 pm local time. The second cluster contained

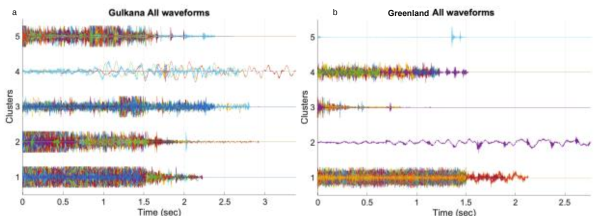

Fig. 2. Events are normalized by their maximum amplitude. a) Cluster results for Gulkana. Cluster #4 was not used in analysis due to the limited number of events. b) Cluster analysis for Greenland. Clusters 2 and 5 were not used in further analysis.

816 events which were slightly shorter and also had peak energy within the first 0.5 seconds. The dominant frequency also tended to occur between 300-400 Hz, but many events also showed the strongest power between 10-20 Hz. The third category contained 94 events and tended to be longer and had peak amplitudes between 1-1.5 seconds. The dominant frequencies were primarily around 300-400 Hz. The 4th cluster had long period energy and only contained 5 events, thus was not used for further analysis. The final cluster of 696 events showed two peaks in amplitudes about 0.5 seconds apart. Dominant frequencies occurred between 300-400 Hz, or between 50-100 Hz.

Greenland: Greenland had five major clusters (Fig. 2b). The 1st cluster had 80 events. The dominant frequencies were between 50-200 Hz. Clusters 2 and 5 only had 1 event each and were thus excluded from further analysis. Cluster 3 had 14 events. They tended to be shorter in duration than cluster 1 and have more impulsive energy. The dominant frequencies were all between 125- 325 Hz. Cluster 4 only had 8 events. They tended to have longer durations and could include multiple pulses of energy. The dominant frequencies were either between 10-70 Hz or between 250-300 Hz.

Temporal and Spatial Results: Previous analysis showed that events at Gulkana tended to occur during the day when changes in temperature peaked. We compared the clusters to see if they all followed a similar pattern or if they deviated from the general trend. Cluster 5 events retained the relationship and most events occurred between 10 am and 6 pm. Category three also tended to during daylight hours, although more events tended to occur after noon and until 6 pm. Cluster 2 events were more likely to occur before 2 pm than later in the evening. The first cluster did not show the same relationship as the other events. These events were more likely to occur before 6 am or after 3 pm.

For Greenland, the first cluster of events all occurred between 10am-7pm except for three events. The 3rd and 4th cluster showed no time preference.

Since the cluster groups showed differences in not only their waveforms but also times at which they were likely going to occur, we tested if their locations also varied. To perform this task, a polarization analysis determined from which direction the events were most likely to originate (*17–19*). At Gulkana, the events all tended to originate to the east of the array. Cluster 1 events tended to occur 30°-120°. Most Cluster 2 events also originated toward the east, but some events also occurred 20°W of North from the array. Cluster 3 events tended to occur around 50-60°, 80-100°, 190-200°, or 240-300° from North. Cluster 5 events typically occurred between 50-120°. In Greenland, the 1st and 3rd cluster mostly originated from the Northwest (330-350°). The 4th cluster originated from the Northeast (40-60)° and from the Southwest (220-230°).

The two field sites represent two potential deployment scenarios for ocean world exploration. Gulkana, the more active site, represents a landing site near an active fault system or high levels of surface activity. Greenland represent the opposite, a landing site far from active faulting. In either scenario, a seismometer would be tasked determining local seismicity. A cluster analysis can be used to distinguish between seismic sources and characterize the local seismicity.

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