Cataloging and Locating Icequakes on the Ross Ice Shelf, Antarctica to Determine Long Term Rift Behavior

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This report provides an introduction to the ARROW project and seismic behavior on ice shelves. We cataloged icequakes using seismic analysis code (SAC) and located prominent icequakes using WAVES from a seismic dataset collected from December 2nd, 2023 and January 5th, 2024. The analysis of this dataset will be used to model similar deformation systems found in icy ocean worlds in the outer Solar System like the Tiger Stripe rifts found on Enceladus. We looked into the deformation of rift zone WR4, why and how these icequakes occur along WR4, and the rift’s interior material make up. Particular hotspots of icequake activity tell us where WR4 is expanding, the strain across WR4, the diurnal tidal cycle underneath the Ross Ice Shelf, and the number of icequakes show correlation, and the calculation of wave velocity travelling across WR4 provides insight into the material make up of the mélange. The possible relationship between strain, tidal cycle, and seismicity provides a valuable tool for modelling seismicity in similar systems in other ice shelves. These events will be relocated using hypo-DD to increase the accuracy of modelling for similar rift zones across the Antarctic and on icy ocean worlds.

INTRODUCTION

The following section is an introduction to provide background on ice shelves, ice shelf morphology, the Ross Ice Shelf, the ARROW Project, seismic events, and the process and significance of locating seismic events.

Ice Shelves

The Ross Ice Shelf and others like it continually shift and change across time. Such shelves are formed as ice flows from the Antarctic ice sheets and reforms into a large floating mass on the ocean. These massive shelves remain attached to the coastline and continue to build up as glaciers in the interior of Antarctica continue to melt. Across the entire of the continent, there are approximately 300 ice shelves, shown in Figure 1, spread along its coastline with the Southern Ocean and hold a similar amount of ice to the entire Greenland Ice Sheet.

Figure 1. Map of the 9 largest ice shelves in Antarctica. These 9 ice shelves represent over 90% of the total area. The largest, the Ross Ice Shelf, is just about the same size as Spain.

Antarctic ice shelves are a critical buffer zone that slows the melting process and prevents glacial melt from directly flowing into the ocean. However, these ice shelves lose mass due to basal melting (melting on the underside of the ice
shelf), culminating in ice shelf collapse and iceberg calving (the splitting off of an iceberg) on the seaward edges of a shelf. On average, Antarctic ice shelves lose roughly 3,000 Gigatons of mass due to calving and basal melt annually \(^2\). A majority of this loss of mass is from small- to medium-sized shelves, while larger ice shelves (shown in Figure 1) contribute roughly 50% of ice melt despite holding over 90% of the total mass of ice surrounding the continent. Not only do these shelves slow down the melting of Antarctic glaciers and interior ice sheets, they are a critical part in minimizing the contribution to global sea level rise from melting ice in Antarctica due to their unique role as a buffer between landlocked ice and the Southern Ocean.

The Ross Ice Shelf

The Ross Ice Shelf (shown in red in Figure 1 and again in Figure 2) is the largest ice shelf in Antarctica with an area of about 478,000 km\(^2\). It is located in the Ross Sea, roughly 3,500 km south of New Zealand. First discovered by Sir James Clark Ross during his expedition to find the Southern Magnetic Pole in 1841, it became a starting point for future expeditions, including Roald Amundsen’s successful route to the pole in 1911. At its thickest, the Ross Ice Shelf is 750 m thick and 150 m at its thinnest along the Ross Sea. In our models, we assumed a thickness of 300 m (0.3 km) due to the location WR4 within the Ross. It is also well known for being the origin of the largest recorded iceberg, iceberg B-15; iceberg B-15 had an area of 11,000 km\(^2\), roughly the same size as Jamaica.

Figure 2. Most of the Ross Ice Shelf is claimed by New Zealand as part of the Ross Dependency. It takes up a large portion of the Ross Sea and completely covers Roosevelt Island. Despite standing almost 50 meters above the water, over 90% of the ice contained within the Ross Ice Shelf is found under the surface. It is also only 320 kilometers from the South Pole.

Ice Shelf Morphology

Antarctic ice shelves are constantly shifting and changing and will grow and shrink simultaneously. Ice shelf growth is generally caused by snow fall, refreezing of glacial melt, and the freezing of water from underneath the ice shelf,
although a shelf growing in this manner is uncommon. The shrinking of an ice shelf mainly stems from basal melting and iceberg calving, with an insignificant amount from surface; most surface melting is replaced by snow accumulation so the amount of melt from the surface is rather negligible. Basal melting is an issue that causes the thinning of these ice shelves and increases the flow rate of ground ice from continental Antarctica. Much of this melting occurs because of temperature fluctuations in the local ocean environment and the thermodynamic interaction between the ice shelf and the water bordering it. Water freezing to or melting off of an ice shelf is dependent on heat flux from through the ice shelf and the heat flux from the sea. An overview of the morphological makeup of an ice shelf is shown in Figure 3.

![Diagram of the morphology of a typical ice shelf and its interaction with the most common sources of melting and ice shelf degradation](image)

Within ice shelves themselves, large cracks in the surface, referred to as rifts, penetrate from the surface of the shelf to ocean below. Often seen as precursors to iceberg calving events, these rifts expand, both widening and growing laterally, over large timescales with no discernible pattern; expansions are often random and rapid periods of growth followed by minimal activity. The interior of these rifts, called the mélangé, is a treacherous region with unknown material make up; think of the mélangé as the Colorado River if the rift was the Grand Canyon. Because of how dangerous this region is to study, finding P- and S-wave travel times across the mélangé can give an idea to what material makes it up through comparison with known travel times.

### The ARROW Project

The Antarctic Rift Research for Ocean Worlds (ARROW) project is a research project focused on gathering data from Western Rift 4 (WR4) in the Ross Ice Shelf. 16 seismometers and 12 GPS stations were placed along a 7 km stretch near the westernmost opening of the rift, shown in Figure 4. The seismometers continuously collected seismic data for ~35 days, from December 4th, 2022 to January 8th, 2023, and the GPS stations collected data for ~40 days. The goal was to create a seismic catalog of events that occurred along the edge of rift zone WR4 and analyze the catalog to determine short- and long-term rift behavior and the possible modality of icequakes.

Discovering why and how icequake occur, icequake modality, and how these icequakes affect the propagation of these rift zones through ice shelves will also allow for future modelling of other rift zones in ice shelves on Earth and on icy ocean worlds in the outer Solar System. One such example system to be modelled are the Tiger Stripes of Enceladus, an icy ocean moon with an orbiting Saturn, shown in Figure 5. WR4 is analogous to each of the Tiger Stripes in size and composition, so the long-term behavior and modality of seismic events can help model how the Tiger Stripes and other rifting sites form.
Figure 4. 8 stations were placed on the north side of rift WR4 and 8 stations were placed on the south side. 14 of the stations were placed 1 km away from the edge and 2 stations, one on the north and one on the south, were 2 km from the edge and 1 km from the center station on either side. The green dots represent the GPS station locations and the red squares represent the seismic stations; 11B, 13B, 14B, 218B, 21B, 22B, and 32B have a seismometer and a GPS station.

Figure 5. One of the most prominent features on the surface of Enceladus, the Tiger Stripes are 4 prominent rifts found on its southern hemisphere. Each rift is roughly 130 km long, 2 km wide, and 0.5 km deep. From left to right, Camphor Sulcus, Alexandria Sulcus, Cairo Sulcus, Baghdad Sulcus, and Damascus Sulcus.

Icequakes

For our catalog of events, we marked every sizable waveform that emerged from outside the noise as an icequake. More generally, an icequake is any form of seismic activity that originates within an ice shelf. Very few studies have been run of seismic activity on ice shelves; studies on rifts similar to WR4 have found that these rifts propagate in episodic bursts of activity (roughly 4 hours) at approximately 2 week intervals. There is also evidence of tides increasing the frequency of icequake events. While we assumed that most events in our catalog stemmed from rift
propagation, other possible sources include snow-bridge collapse (snow falling into the central region of the rift, the mélange), low flying planes, high winds, and other similar surface disturbances. An example event is shown in Figure 6.

Figure 6. An example icequake from our catalog with a high signal-to-noise ratio (SNR), a comparison between the peak amplitude of a seismic wave and background noise. A higher SNR makes for a "cleaner" event to do further analysis on. The P-wave arrival is marked with a vertical black line, while the S-wave arrival surface wave arrival time can be seen at shifts in the amplitude of the arriving signal.

Like other seismic events, icequakes have multiple different wave components that make up the total energy propagating through a medium: the P-wave, the S-wave, and the surface wave. The P-wave (pressure wave) is the fastest travelling seismic wave that often serves as a precursor to a seismic event. Such waves can travel through all 3 states of matter with a velocity following Birch’s Law:

\[ v_p = a(\bar{M}) + b\rho \]  \hspace{1cm} (1)

where \( a(\bar{M}) \) is an empirical formula calculated from experiment with the mean atomic mass \( \bar{M} \), \( b \) is a constant, and \( \rho \) is the density of the matter. An S-wave (shear wave) is the second fastest travelling seismic wave. Like P-waves, S-waves can also travel through matter, unlike surface waves, but they are transverse waves; S-waves can only propagate in solids and liquids with a high viscosity. Its velocity can be calculated via:

\[ v_s = \sqrt{\frac{\mu}{\rho}} \]  \hspace{1cm} (2)
where $\mu$ is the average rigidity of the material and $\rho$ is the density of the material. The last wave to arrive during a seismic event is the surface wave and travel at $\sim 90\%$ of the velocity of an S-wave. Surface waves in seismology are generally a combination of two waveforms, Rayleigh waves, an acoustic wave that travels along the surface of a solid, and Love waves, horizontally polarized waves; each waveform is shown in Figure 7.

![Figure 7](image)

Figure 7. These are four main components of a seismic wave. The body waves are made up of the P-wave (top left) and S-wave (top right) and the surface waves are made up of Raleigh wave (bottom left) and Love wave (bottom right). P-waves are compression waves so they do not really show a typical waveform while the rest all appear with a recognizable waveform.

Cryoseismic events occur at faults just like traditional earthquakes. In seismology, there are three types of faults: normal (dip-slip), reverse (thrust), and strike-slip. A normal or dip-slip fault, shown in Figure 8, is a fault where the block above the fault moves downward with respect to the block below the fault. These faults often occur due to extension between the two blocks. A reverse fault, also shown in Figure 8, is a type of dip-slip fault where the upper block moves over the lower block at an area of compression. Strike-slip faults, shown in Figure 9, occur when two of these blocks slide past one another.

![Figure 8](image)

Figure 8. Shown in the visual on the left, the upper block slides down the lower block in a normal fault, causing the release of energy; generally, such faults cause magnitude 4.0 or lower earthquakes. On the right, the upper block slides up the lower block along a reverse fault. Reverse faults often release much more energy and are associated with earthquakes of magnitudes above 8.0.

![Figure 9](image)

Figure 9. Strike-slip faults are defined by significant lateral motion with very little vertical motion. The difference between sinistral and dextral strike-slip faults is sinistral faults have lateral motion to the left while dextral faults travel to the right. They generate earthquakes with a magnitude 4.0 and above generally.

There are numerous ways to calculate the magnitude of a seismic event. The Richter Scale, defined by Charles Richter in 1935, was the first attempt to create a numeric scale for magnitude:

$$M_L = \log_{10} \left( \frac{A}{A_0} \right)$$

where $M_L$ describes the local magnitude. This equation requires the use of a Wood-Anderson seismograph and is not accurate for earthquakes with a magnitude of above 7.0 ($A$ is the excursion of a Wood-Anderson seismograph). Today, the Richter scale is used for small, localized events or on large, well-defined earthquakes. Instead, the moment
magnitude, $M_w$, is calculated using:

$$M_w = \frac{2}{3} \log_{10} M_0 - 9.1$$

(4)

where $M_0$ is

$$M_0 = DA\mu$$

(5)

a function of the rigidity of the material, area of the fault, and distance the fault shifted \[10\]. These magnitudes can then be related to the number of occurrences in a region above a certain magnitude using Gutenberg-Richter relationship:

$$\log_{10} N = a - bM_w$$

(6)

where $N$ is the frequency, $a$ is the number of earthquakes at a certain magnitude, and $b$ is the scaling relationship \[11\]. The typical $b$-value of earthquakes is $\sim 1$, but previous studies have found that $b$-values on ice shelves to be $\sim 1.2 - 1.5$ \[12\]. This $b$-value is similar to that of volcanic regions and slow slip events, an earthquake that releases its energy discontinuously over a longer time period (a few hours to a few months).

**Locating Seismic Events: Triangulation**

Triangulation can be used to locate the epicenter of seismic event; an epicenter is the point directly above the hypocenter of an earthquake. In order to perform triangulation, at least 3 seismometers will need to register energy from the event. Then, P-wave and S-wave arrival times at each seismometer are picked, shown in Figure 10, and the difference is taken:

$$\Delta t = t_S - t_P$$

(7)

$$d = \frac{\Delta t}{v_p - \frac{1}{v_s}}$$

(8)

Measuring the difference between these two arrival times allows for the distance from the station to an event to be calculated. Using this distance as the radius to draw a circle, the event can be located at the point of intersection of every station’s circle, shown in Figure 11.

Figure 10. An example of P- and S-wave arrival picks. The P-wave arrival time is picked at the first arrival of any energy from the seismic event, marked by a growth in amplitude from the background noise. The S-wave arrival time is the next shift up in amplitude after the P-wave’s arrival. S-waves generally carry more energy so the amplitude of the S-wave is larger.

Figure 11. Once every P- and S-wave arrival time is picked, the difference in arrival times is taken (using Equation 6) to approximate the distance each station was from determined to create a circle of that radius. Each circle was then generated onto a map with its center at the seismometer. Once each circle was drawn, the intersection point of every circle is the approximate epicenter of the event.

This is the most common technique for calculating an event’s epicenter and is the method of choice for WAVES,
a widely used seismic location software. An epicenter location has the latitude and longitude coordinates of the event but lacks the depth component. Since the P- and S-arrivals are manually selected, the locations are accepted as accurate reflections of the origin of seismic activity. They cannot find the exact hypocenter of the event which includes a depth component.

The location of a seismic event can tell us what fault the event occurred on and where the damage would be most severe. By locating the icequakes occurring along WR4, we can learn where the rifting is most likely to continue to propagate and deform, along with exact positions where parts of the ice shelf may have collapsed into the mélange. Icequake locations serve as strong indicators as to where the rifting process is active and rift zones like WR4 are continuing to deform, providing an integral part for modelling of extraterrestrial rift zones found in ice sheets on icy ocean worlds in the outer Solar System.

**METHODS**

**Data Collection**

Our seismic data used to create the catalog of events along rift zone WR4 was collected between December 4th, 2022 to January 8th, 2023 by 16 Fairfield ZLand 3-C nodal seismometers; their locations along WR4 are shown in Figure 12. Each seismometer recorded ∼35 days seismic data at a 500 Hz sampling rate continuously. However, all 16 seismometers were not actively collecting data until December 9th, and the earliest installed seismometers began ending their data collection on January 3rd. Alongside the seismometers, 12 CGPS stations were deployed and recorded 40 days of data, sampling at 0.033 Hz. 8 GPS stations were collocated with 8 of the seismometers. 8 seismometers and 6 GPS stations were placed on the northern and southern sides of the mélange at the eastern-most lateral edge of WR4; the outer edges of rift zones are generally more active than the interior regions of a deformation in the ice shelf.

An active source seismic survey was also run while the team was onsite in Antarctica. This survey is used as a test to determine the propagation speeds of the different waveforms through different media. Because the location of these surveys is known, it can also be a good indicator to the accuracy of the locating software. Our survey used a sledgehammer to create seismic waves that propagate through our target zone. This can provide valuable insight into both the material make up of the mélange from how fast P- and S-waves travel through the mélange as well. A member of the team can be seen making the hammer strike for the survey in Figure 13.

**Catalog Creation**

The data collected by the 16 seismometers was uploaded to IRIS, the NSF’s geoscience database. Before beginning to analyze and catalog events, all ∼35 days worth of data had to be downloaded before pre-processing of our data could begin. We wrote a script that downloaded each day’s dataset in ∼5 hours. A second script would merge the data and remove the mean and trending within the data; this removes the instrument response from the data. Once
Figure 13. A member of the team using the sledgehammer to run the active source seismic survey

A day’s worth of data is run downloaded and merged, the raw data is ready to be analyzed for events.

To create the catalog of events, myself and another intern Emily sorted each day’s data into hour long segments shown on every seismometer collecting data using Seismic Analysis Code (SAC), a general purpose waveform analysis and processing application. Across the hour long segments, an event would appear as a large spike in amplitude (see Figure 13). In order to register an event to the catalog, we would zoom in around an event to see the full waveform; an example of this is shown in Figure 6. A locator tag was placed before the first P-wave arrival time, denoted as $t_0$, and rough P-wave arrival picks were also marked by hand, labelled $p$. This process was repeated for all spikes in amplitude across all 24 hours and 35 days of recorded seismic data.

Figure 14. This is how the seismic waves would show up on the hour long segments. All seismic events we recorded to our catalog had arrival time longer than 15s at every station that recorded seismicity which is why they appear as these spikes. Figure 6 shows a zoomed in look at these events.

Figure 15. The entire catalog of events organized into a histogram showing the number of events every hour across the ~35 days

Across the entire ~35 day window of recorded data, Emily and I recorded and added to the catalog over 6,136 unique seismic events, with most events having a magnitude less than 0.0, shown in Figure 15.

Before beginning to locate every event, we then organized the entire catalog of events by signal-to-noise ratio (SNR), from highest to lowest. SNR is the measurement of the level of an measured signal compared to the background noise; therefore, higher SNR makes for identifiable P- and S-wave arrival times. In order to find the SNR of an event, a script was written to isolate each event from the entire dataset, using the $t_0$ identifiers, into 20 second long segments, and calculates the individual event’s SNR by comparing the highest amplitude and lowest amplitude found in the 20s window. The entire catalog is then reorganized by SNR from highest to lowest, allowing for the best events to be
Located first.

**Locating Icequakes**

Using the reorganized catalog, Emily and I uploaded events with the highest SNR into WAVES individually; WAVES is a seismic analysis software that uses triangulation to find the icequakes origin. When an icequake is uploaded to WAVES, the 20 second waveform is shown alongside a seismogram of the event for each seismometer; any seismometers that did not show clear arrival times were removed from the triangulation process. A model of the material make up of the Ross Ice Shelf was used to simulate accurate P- and S-wave propagation velocities within the shelf, shown in Table I; the velocities are the established propagation speeds for P- and S-waves within each material and the depths are approximations made based off of observations of the Ross Ice Shelf in this region.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Depth (km)</th>
<th>P-Wave Velocity (km/s)</th>
<th>S-Wave Velocity (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Ice)</td>
<td>0.3</td>
<td>3.7</td>
<td>1.85</td>
</tr>
<tr>
<td>2 (Water)</td>
<td>0.8</td>
<td>1.5</td>
<td>0</td>
</tr>
<tr>
<td>3 (Crust)</td>
<td>30</td>
<td>6</td>
<td>3.4</td>
</tr>
<tr>
<td>4 (Upper Mantle)</td>
<td>120</td>
<td>8.05</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Table I. The table outlines the P- and S-wave velocities within the different layers of the Ross Ice Shelf and the the assumed depth of each material within the shelf used in the model of the Ross in WAVES.

We manually selected he P- and S-wave arrival times at each seismometer; P-wave arrival at the first arrival of any energy in the seismogram and S-wave. WAVES then triangulates the event using the difference in arrival times and the P- and S-wave velocities outlined in our Ross model.

![Figure 16](image1.png)

Figure 16. An example of P- and S- wave arrival picks in WAVES, showing the waveform above the seismogram of the seismic wave arriving at the station (A zoomed in view of the arrival time selections can be found in Figure 25 in the appendix). The P-wave arrival time is picked at the first arrival of any energy from the seismic event, marked by a growth in amplitude from the background noise. The S-wave arrival time is the next shift up in amplitude after the P-wave’s arrival. S-waves generally carry more energy so the amplitude of the S-wave is larger. Dark blue represents low magnitude signals bright red represents high magnitude signals. This scale changes from event to event in WAVES. The black lines are the manually selected P- and S-wave arrivals and the light gray are WAVES’s approximate P- and S-wave arrival picks.

![Figure 17](image2.png)

Figure 17. Once every P- and S-wave arrival time is picked for an event in our catalog, the difference in arrival times is taken (using Equation 6) to approximate the distance each station was from determined to create a circle of that radius. Each circle was then generated onto a map with its center at the seismometer. Once each circle was drawn, the intersection point of every circle is the approximate epicenter of the event.
ANALYSIS

Of the 6,136 events in the catalog, 465 events were located along WR4 through WAVES’s triangulation method. Every located event and the hot spots of seismic activity are shown in Figure 18.

![Figure 18](image)

Figure 18. Each dot represents an individually located event. Most events are located very close to WR4 with very few outliers, especially concentrated along the northern side near WR4’s easternmost edge.

The largest event originated along the northern face of WR4 on December 20th. It is shown in Figure 23 in the appendix. The event highlighted was found to be the largest magnitude event to occur over our 35 day data collection window.

The active source seismic survey is shown in Figure 24 and demonstrates how much longer it takes a wave to propagate through the mélange and how useful seismograms are to making accurate P- and S-wave arrival picks. While the waveform becomes noisy at seismometers across the mélange (103) or far away from the origin (114), the seismogram shows the magnitude of certain frequencies, allowing for an approximate P-wave arrival time to be selected. From the arrival times, the velocity of P-waves within the mélange can be calculated.

The GPS data collected alongside the seismic data was used to find strain rates across WR4. There are two components to the strain, the normal strain and the shear strain. Normal strain occur at deformations perpendicular to the cross section while shear strain occurs parallel to the cross section. Because the ice shelf is on floats above the Ross Sea, its diurnal tide will stress and strain the shelf, especially in regions of previous deformation; a diurnal tidal cycle is a tidal cycle with one high tide and one low tide every lunar day. These strain rates were found using the changes in location of each GPS station across the entire 35 day data collection period. The strains across WR4 are shown in Figure 19.

DISCUSSION

Looking at a heat map of event location in Figure 20, there are two clear sections of high seismicity along the northern side of WR4. This would indicating high seismicity in regions near a rift’s outermost edge and provides evidence of icequakes being indicators of rift deformation.

When comparing the strain across the rift to the histogram of events, higher strain appears to correspond with a higher number of seismic events, suggesting that periods of high strain. Comparing the strain to the diurnal tidal cycle over the ~35 day time period, the sinusoidal form of the strain and the diurnal tidal cycle line up temporally. The modality of the icequakes may correspond with the diurnal tidal cycle beneath the Ross Ice Shelf.

When looking at the arrival times at every seismometers in the active source seismic survey, the energy from the seismic wave arrives latest at seismometer 10 which is across WR4 but only ~3 kilometers away from 104; the P-wave arrival times and distances are shown in Table 2.
Figure 19. The normal strain and shear strain across WR4 and within the ice were calculated. While the neither strain found within the ice has a discernible pattern, the normal strain appears to have sinusoidal pattern.

Figure 20. Heat map of events occurring along WR4

<table>
<thead>
<tr>
<th>Station</th>
<th>P-Wave Arrival (s)</th>
<th>Distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>103</td>
<td>1.4</td>
<td>3</td>
</tr>
<tr>
<td>104</td>
<td>0.1</td>
<td>0.01</td>
</tr>
<tr>
<td>106</td>
<td>0.4</td>
<td>1</td>
</tr>
<tr>
<td>108</td>
<td>0.6</td>
<td>2</td>
</tr>
<tr>
<td>110</td>
<td>0.7</td>
<td>2.25</td>
</tr>
<tr>
<td>112</td>
<td>0.8</td>
<td>3</td>
</tr>
<tr>
<td>114</td>
<td>1.1</td>
<td>4</td>
</tr>
</tbody>
</table>

Table II. Table showing the different P-wave arrival times and distances to the seismometers. 103’s P-wave arrival time is much later than 112’s arrival time (1.4s vs 0.8s) demonstrating the difference in P-wave velocity through the mélange.

From this, we were able to calculate an approximate P-wave velocity within the mélange:

\[ t_{arrival} = \frac{d_{north}}{v_p^{ice}} + \frac{d_{mlange}}{v_p^{mlange}} + \frac{d_{south}}{v_p^{ice}} \]  

(9)
Rises in the strain rates between December 20th and December 30th correspond with a rise in the number of seismic events. This is also evident with a large spike in events on December 31st and a dramatic increase in strain across WR4; over 50 events were isolated on a day where the strain rate reached its highest magnitude.

The tidal maximum occurred between December 20th and 30th and follows a sinusoidal pattern. The normal strain across WR4 has a similar sinusoidal form with a maximum amplitude falling between December 20th and 30th, implying correlation between strain and tidal cycle. Note: the temporal scale on both plots do not line up exactly.

A velocity of $v_{\text{mlange}} \approx 1.16 \text{ km/s}$ is significantly slower than the typical P-wave velocity in ice $(3.4 \text{ km/s} - 3.8 \text{ km/s})$ and in water $(1.45 \text{ km/s} - 1.5 \text{ km/s})$.

Studying icequakes along rift zone WR4 have given us many valuable insights into the morphology of ice shelves due to cryoseismic activity around these rifts. There is strong evidence of correlation between the diurnal tidal cycle underneath the Ross Ice Shelf, the normal strain across WR4, and the number of icequake occurrences. A rise in the number events between December 25th and 26th occurs at a tidal maximum and has the highest strain rates across WR4. If icequakes are tidally modulated, this lends credible evidence toward for the modality of rift zone deformation to be tidally modulated, a valuable insight towards the modality of other rift zone systems in Antarctica and icy ocean worlds in the outer Solar System. Learning P-wave velocities from the active source seismic survey gave valuable insight into the interior make up of the mélange due to how slow the P-wave travels through the mélange’s interior $(1.16 \text{ km/s})$. Currently to dangerous to learn any other way, P-wave velocity data is a valuable source of information on mélange interiors and their material make up.

**FUTURE WORK**

For future locating of icequakes within this dataset, the software hypo-DD, developed by Felix Waldhauser, is a double-difference hypocenter earthquake locating software that takes the difference of Geiger’s equation for locating earthquakes:

$$ t_i = T_i + t_0 $$

where $t_i$ is the arrival time of the P-wave, $t_0$ is the origin time of the event, and $T_i$ is found by:

$$ T_i = \sqrt{\frac{(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2}{v_{\text{wave}}}} $$

Hypo-DD finds the hypocenter with latitude-longitude-depth coordinates where as WAVES finds the epicenter of the seismic event which only contains a latitude-longitude coordinates. Hypo-DD relocates events using the double-difference method, it takes the difference between two neighboring events’ difference in P- and S-wave arrival times.
These residuals are then reiterated and relocated until the least-squares solution is minimized between hypocentral pairs [3].

Using the manually selected P- and S-wave arrival times by us in WAVES, we can relocate our events using hypo-DD all at once; hypo-DD can relocate up to 10,000 events at the same time. We may also run hypo-DD on our entire event catalog due to how many events hypo-DD can handle all at once. This is especially useful because a neighboring event in hypo-DD is considered to be any event within 10 kilometers of another event; all events we located using WAVES were within 5 kilometers of each other.

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Figure 23. Even the largest event in our catalog had clear P- and S-wave arrival times appear in 12 of the 16 seismometers. The main reason is due to the make up of the mélange due its high energy absorption and waves struggling to propagate across WR4. The waveform of this event is longer in seismometers that are found to be farther away from the origin of the event, demonstrating the difference in P- and S-wave arrival times from seismometer to seismometer. The smiley face indicates the location of the icequake; the triangulation indicated on the map is for a separate event.
Figure 24. The initial hammer shot for the active source seismic survey was taken 10 meters from seismometer 104 and registered on 6 other seismometers, including seismometer 103 on the southern side of the WR4. The seismogram was especially useful for detecting the P- and S-wave arrival times across WR4 because of how noisy the waveform became when crossing through the mélange.
Figure 25. A zoom-in on the selected P- and S-wave arrival times. The P-wave is selected on first change in amplitude from the background noise, and the S-wave is selected when the amplitude shifts again.