Signal Attenuation of Tectonic Tremor-like Signals due to Sediment in the Cascadia and Izu-Bonin-Mariana Subduction Zones

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Abstract

Defined limitations of the locked state in subduction zones are necessary to understand the frictional characteristics of the subduction interface as well as the hazard associated with earthquakes and tsunamis. Slow slip events provide insight into which areas are locked by revealing the segments that can accommodate movement between large earthquakes and segments that cannot. Tectonic tremor, a seismic signal, is an indicator of these events and can be seen on seismometers. Cascadia and Izu-Bonin-Mariana are contrasting subduction zones and from their differences in seabed roughness and sediment thickness, we can better understand how tectonic tremors propagate. Both subduction zones have offshore plate boundaries where seismic stations are limited, which makes observation of tectonic signals difficult. Therefore, we search stations for tectonic tremor one at a time instead of triangulating the signal. Resulting signals are analyzed for any overlaps between stations to further validate the signal. Generalized seafloor transects are studied to see how seabed roughness and sediment thickness influence the number of overlapping signals. Regions with high sediment thickness tend to have fewer subsurface signals and overlapping signals. Regions with a smooth seabed tend to generate more water column signals from bottom currents, short duration events, and ship-noise. Cascadia, an area with a smooth seabed and high sediment thickness, has over 60 times the overall signals that Izu-Bonin-Mariana has. However, 99.89% are considered water column noise and 0.11% are overlapping tremor-like signals. Izu-Bonin-Mariana, an area with a rough seabed and thin sediment thickness, has fewer signals but less noise and more overlapping signals. With a deeper understanding of the influences on offshore signal propagation, we are able to have a fuller picture of the locked state. Limitations of the locked state enables accurate predictions of earthquakes and mitigation of the risk associated.

Plain Language Summary

The Cascadia subduction zone stretches from northern Vancouver Island in Canada to northern California in the United States. This continental margin is capable of producing megathrust earthquakes, which are the most powerful earthquakes on Earth, with magnitudes of 9.0 or greater and often followed by a tsunami. Knowing whether the plate boundary is slipping or locked can provide insight into when and where the next megathrust earthquake might occur. During a slow slip event, tectonic plates slide past each other over long time periods, slow enough that the movement is not felt by humans. Some areas can accommodate this movement, and some cannot. Areas that cannot, are locked and may generate large earthquakes. Tectonic tremor, a rumbling signal observed on seismometers, is an indicator for slow slip events and therefore informs that a region is not locked. We look for this signal offshore, where the Cascadia margin lies, on ocean bottom seismometers. These instruments sit on the seafloor and measure ground movement. We are investigating how seabed roughness and sediment thickness impacts signals captured on ocean bottom seismometers. Roughness is a measure of how bumpy or smooth the seafloor is and thickness is a measure of how much sediment there is between bedrock and the seafloor, both factors that can deflect or absorb signals. To see the influence of these factors, we consider the Izu-Bonin-Mariana subduction zone, another subduction zone with strong contrasts to Cascadia. Izu-Bonin-Mariana has an old ocean crust that is dense and subducts easily which results in a deep trench. Izu-Bonin-Mariana also has low sedimentation rates because it is surrounded by the Pacific Ocean without much land to supply sediment. On the other end of the spectrum, Cascadia has no trench, due to the subduction of young, low-density ocean crust that resists subduction, in an area of high sedimentation. Knowing how

sedimentation impacts signals found on ocean bottom seismometers will allow us to sift through signals more efficiently and provide a clearer picture of the potential for megathrust earthquakes.

Introduction

1.1 Subduction Zone Processes

In subduction zones, megathrust earthquakes are produced. These earthquakes are the largest on Earth because the plate interface is locked, preventing tectonic plates from sliding past one another. These regions of the subduction zone interface are seismogenic, locked in place until stress builds enough to cause an earthquake rupture (Mazzotti and Adams, 2004). However, the locked state often varies spatially throughout the outer wedge of the subduction zone. Areas that are not locked can accommodate motion and experience a slow slip event, an aseismic activity that releases tension over an extended period. During a slow slip event shear stress can be reduced, specifically in regions where the fault is experiencing slow creeping movement (Bürgmann, 2018). Slow slip events are seen onshore in geodetic data, at the same time as these events, a rumbling signal called tremor is seen on seismometers (Rogers & Dragert, 2003). Therefore, we know that tremors are an indicator of slow slip events. These events can inform the extent of the locked state. Understanding the spatial extent of the locked seismogenic zone is vital for understanding how much and where slip can be expected in a large earthquake.

1.2 Observation limitations

Observing tremor signals in offshore subduction zones is difficult. There are limited ocean bottom seismometer stations that are often optimized for wide spatial coverage instead of being clustered, which allows for triangulation of signals, the standard practice for locating the source of a signal. As a result, many data sets have not been examined for tectonic tremors. The single-station method developed by Krauss et al. (2024) processes a station’s signals independently of others, allowing for the analysis of many stations without the requirement of clustered stations. Using this method, tectonic tremor-like signals were found on cabled ocean bottom seismometers (OBSs) offshore Oregon (Krauss et al., 2024). These OBS were part of the Ocean Observatories Initiative Regional Cabled Array (OOI-RCA). However, these signals are not confirmed cases of tremor because they were not found on multiple stations and they could not be connected to a tectonic event.

1.3 Structural and sedimentation influences

We investigate how Cascadia and Izu-Bonin-Mariana’s sediment structure could attenuate signals found on ocean bottom seismometers. Signal attenuation is a process where surfaces and mediums may absorb mechanical waves, reducing the strength of the signal. This process is seen in subduction zones when OBS stations exhibit signals of different power depending on the station's proximity to the source of the signal. The Izu-Bonin-Mariana and Cascadia are two subduction zones that exhibit contrasting structural characteristics. The Izu-Bonin-Mariana has an old and high-density ocean crust, the Western Pacific plate, subducting under a younger ocean crust, the Philippine Sea plate. The Pacific plate easily subducts which results in a deep trench and high tectonic activity in the region (Oakley, 2009). On the other hand, the Cascadia Margin involves young and low-density ocean crust subducting under a continental plate. This crust resists subduction (Clague, 1997) which results in a minimal trench and a stuck plate interface. Consequently, Cascadia is less active and has a megathrust earthquake approximately every 500 years (Witter, 2003). Adding to the subduction zones’ differences, Cascadia is off the west coast of the United States which supplies ample sediment. On the other hand, the Izu-Bonin-Mariana subduction zone is surrounded by the Pacific Ocean without much land nearby, resulting in low sediment supply. From the subduction zone's structural and site differences, the seabed roughness and sediment thickness should largely vary. By integrating OBS data alongside bathymetric data, we are applying structural and site knowledge to our interpretation of seismic signals.

Examining the influence of seabed roughness and sediment thickness can inform how signals are impacted by their environment, and in turn, provide insight to signal source whether tectonic or otherwise. We hypothesize there are more overlapping signals of tectonic tremor in the Izu-Bonin-Mariana subduction zone than the Cascadia subduction zone due to less sedimentation and a rougher seabed.

Methods

2.1 Ocean Bottom Seismometer Signal Processing

We use the method defined in Krauss et al. (2024) and expand signal-station processing to other ocean bottom seismometer stations in Cascadia and Izu-Bonin-Mariana subduction zones utilizing the SAGE Earthscope database (EarthScope Data Services, 2024). The single-station approach is specifically designed for OBSs to isolate tectonic tremor-like signals from other tectonic and environmental noise using waveform and spectral characteristics. We then look for signals that overlap with signals on other stations and examine the distance and timing of these occurrences. We analyze 33 and 82 stations from the Izu-Bonin-Mariana and Cascadia subduction zones, respectively (Figure 1). 5 stations from Cascadia have a longer time series and were cabled and buried unlike the other stations so, these stations were analyzed without the same trigger and temporal restraints as the remaining stations. These 5 stations are not included in Figure 1.

Table 1: Evolution of tremor-like signals counts through validation criteria at the Cascadia subduction zone and the Izu-Bonin-Mariana subduction zone. All Stations were deployed for ~9 months at a time. Canada NEPTUNE stations are not included in the table because of their extended deployment but go through the same process that accounts for their deployment length.

	Total detections of tremor-like signals	Signals overlapping within 120 min of each other (percent of total)	Filter out bottom currents (percent of total)	Require that signals are within 300 km of each other (percent of total)
Cascadia	49224	68.7%	0.11%	0.11%
Izu-Bonin-Mariana	782	40.8%	40.8%	38.4%

Detecting tremor-like signals with a single station begins with identifying timestamps that represent potential tremor observations. Here, emergent signals are selected and impulsive signals, such as earthquake body wave arrivals, are discarded. We identify tremor-consistent emergent signals by calculating the short-term average long-term average (STA/LTA) for each station's data channel as described by Krauss et al. (2024). In addition to passing the STA/LTA triggering, the detection must be longer than 30 seconds. Next, the triggers are processed to determine the signal's classification. The number of waveform peaks are counted after applying a Gaussian filter to smooth the waveform; we require more than one peak for the signal to be kept as a tremor candidate. This approach is designed to identify T-phases, which typically have one peak in the smoothed waveform, while tremor typically has multiple peaks. The detections are then scanned for ship noise using Welch's method (Welch, 1967); signals with clear spectral peaks, which are indicative of the monochromatic bands associated with ship noise, are discarded. Finally, tectonic tremor has a decrease in spectral power when the signal reaches above 10 Hz, so a ratio between the low and high frequencies is calculated (F_{LH}). This is a ratio between the median of power at 5-10 Hz and the median of power at 10-15 Hz. Tectonic tremor signals should have a higher F_{LH} than non-tectonic signals. The F_{LH} is determined separately at each subduction zone by visually analyzing waveform and spectrograms at different frequency ratios, investigating which ratio clears noise without removing tremor-like signals. A F_{LH} of 100 was chosen for Cascadia and an F_{LH} of 10 was chosen for Izu-Bonin-Mariana. Following this automatic processing, which significantly reduces the number of candidate signals, remaining T-phases, ship noise, and other marine acoustic signals are identified and discarded via visual inspection of waveform and spectrograms. Following analysis of each individual station, we search for overlapping signals by identifying when a signal's timestamp is within 120 minutes of another signal and the stations' coordinates are within 300 km of each other. Finding a signal on multiple stations further validates the signal, increasing the likelihood that the source is tectonic rather than noise. Bottom currents are filtered out by removing stations with over 200 signal triggers. This number was determined both by examining the signals on stations with more than 200 triggers and plotting station trigger counts to see where there is a jump in signal triggers per station. In Cascadia, limiting to 200 triggers or less removed 15 stations and in Izu-Bonin-Mariana this did not remove any stations. Cascadia stations offshore Washington, FN01C and FN05C, were further investigated to determine if their signals were in connection with strong weather. This data was obtained from the ERA5 global weather and climate database.

2.2 Sediment Characterization

To investigate seabed roughness and sediment thickness, I used multi-beam sonar with the NCEI (National Centers for Environmental Information) GlobSed database (NOAA National Geophysical Data Center, 2013). Mapping occurred on the R/V Thompson from March 21st, 2026, to March 31st, 2026, using the hull-installed Kongsberg EM124 Multibeam system. The ship was not cleared to go over sites where the ocean bottom seismometer stations were located. Instead, a 6 km multibeam transect with bathymetric features that were generalized to represent that region was chosen (Figure 1). These data were cleaned in QPS Qimera, then gridded to 30 m, and exported to QGIS. In QGIS, I created a profile of this transect so that the depth, slope, and roughness of the seabed could be quantified. I made a line of best fit to determine the slope, and a standard deviation calculation was performed to determine the roughness. Higher standard deviation values indicate a rough seabed texture. The GlobSed database was used for sediment thickness.A distribution of sediment thickness at all ocean bottom seismometer stations in Izu-Bonin-Mariana and Cascadia was created to observe sediment thickness differences in each subduction zone.

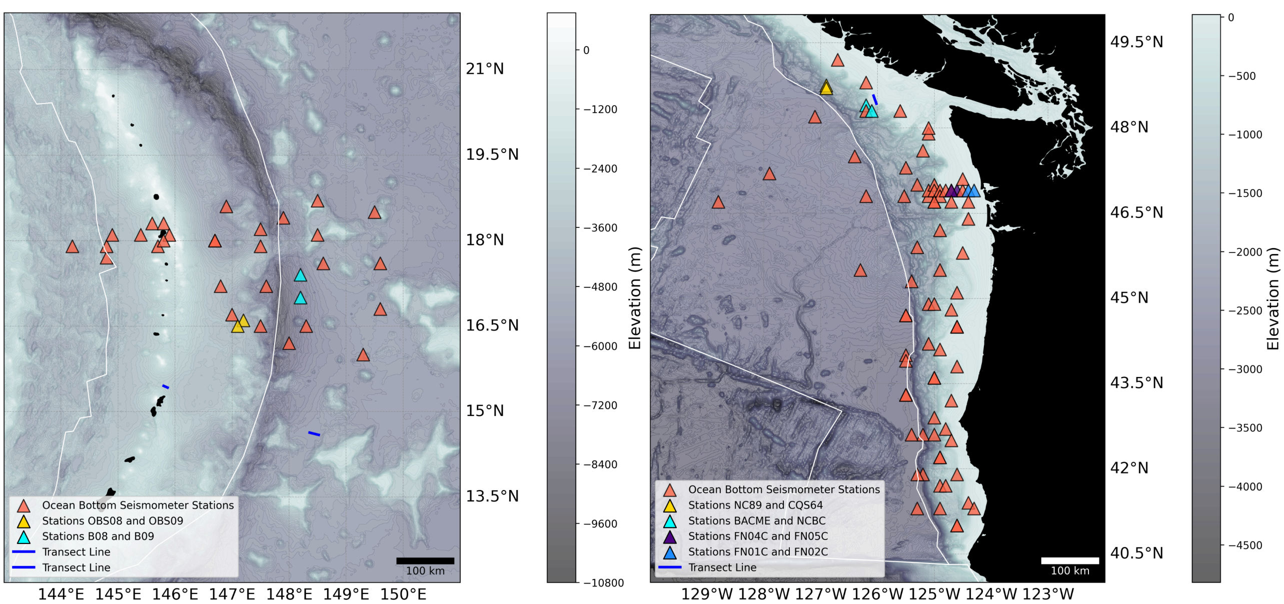

Figure 1. Map of the Izu-Bonin-Mariana (left) and Cascadia (right) subduction zones with Ocean Bottom Seismometer stations labeled as a triangle. Non-orange triangles highlight station pairs whose signals are used as case studies. Blue lines indicate the location of transect lines that were used for seabed roughness calculations.

Results

3.1 Sediment Structure and Characteristics

The distribution of sediment thickness at each ocean bottom seismometers on both margins were found to differ significantly (p-value << 0.01 after the one-sided t-test) (Figure 2). Cascadia's mean sediment thickness is 605 m while Izu-Bonin-Mariana's is 183 m. The standard deviation at Cascadia is 447 m and Izu-Bonin-Mariana is 80.8 m (Figure 2). Transects at Cascadia and Izu-Bonin-Mariana of approximately the same distance, 15 km, were selected to calculate seabed roughness (Figure 1). In Cascadia, a transect near stations highlighted in Figure 1 was drawn. In Izu-Bonin-Mariana, the boat was not approved to go to the OBS stations in the area. Instead, a transect with similar bathymetry to the area of interest was selected. To compare across transects at different depths, the means of each transect was removed. After removing the mean seabed elevation, we use the standard deviation from the slope as a measure of seabed roughness. The Cascadia standard deviation along the transect is 51.6 m. The standard deviation in Izu-Bonin-Mariana is 138.3 m east of the Mariana Trench and 100.0 m west of the Mariana Trench (Figure 3). The Izu-Bonin-Mariana standard deviation is nearly 2 times that of the standard deviation in Cascadia.

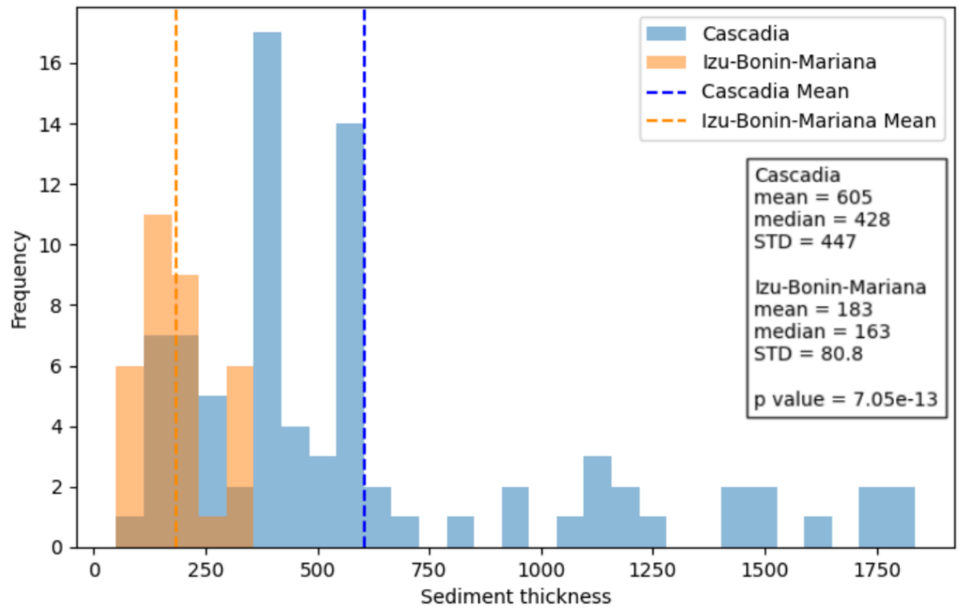

Figure 2. The distribution of sediment thickness at all ocean bottom seismometers analyzed. Cascadia stations are shown in blue with a blue dashed line marking the mean. Izu-Bonin-Mariana stations are shown in orange with a dashed orange line marking the mean. The Cascadia sediment thickness distribution is statistically greater than Izu-Bonin-Mariana with a p value < 0.01.

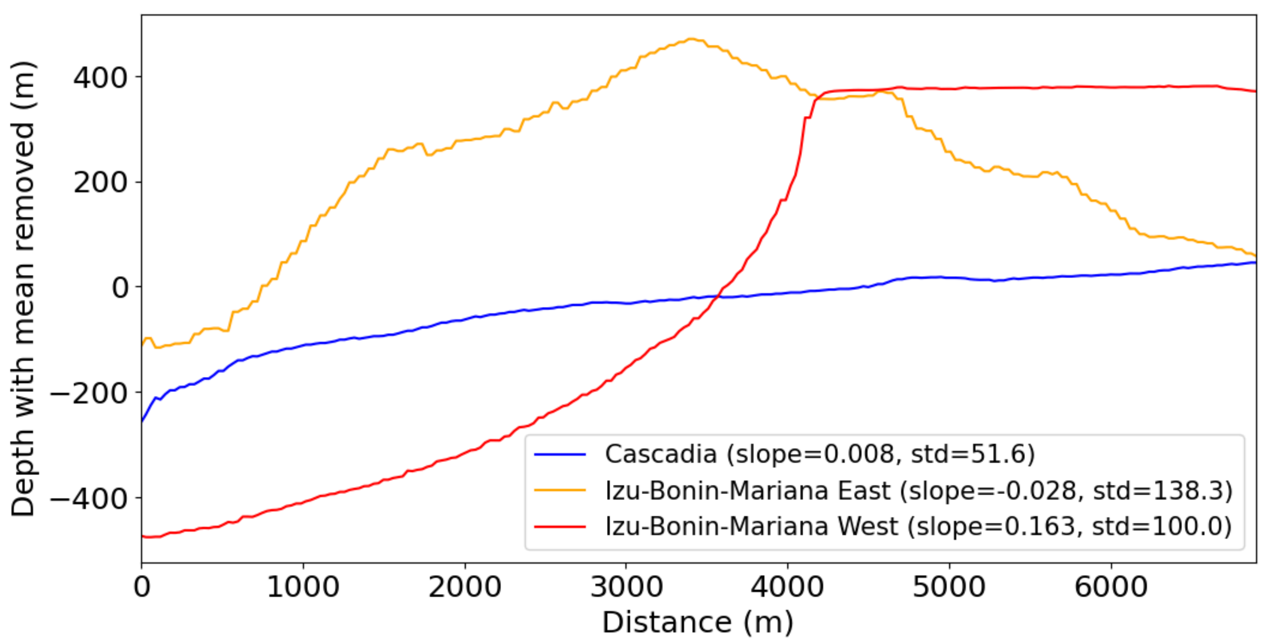

Figure 3. The seafloor roughness and slope in the Cascadia and Izu-Bonin-Mariana subduction zones. Distance along the transect is on the x axis and depth with the mean removed is on the y axis. Cascadia is colored blue, Izu-Bonin-Mariana East is colored yellow, and Izu-Bonin-Mariana West is red.

3.2 Signal Overlaps in Izu-Bonin-Mariana and Cascadia Subduction Zones

The Cascadia subduction zone has 49,224 tremor-like signals after running a triggering and classification code on the 77 stations that have around 9 months of data. Izu-Bonin-Mariana has 782 signals after running the same triggering and classification code on 33 stations that also have about 9 months of data. Then, signals are checked for overlaps. The first overlap restriction limits signal start times to being within 120 minutes of each other; the potential Cascadia tremor signals are reduced to 66.7% of the original. Izu-Bonin-Mariana signals are reduced to 40.8% of the original signals. Following this, the bottom currents are filtered out leaving Cascadia with 0.1% of the original signals and Izu-Bonin-Mariana with 40.8% of the original signals. We then require that the recording stations are within 300 km of each other, a distance determined by the known velocity of tremor (Obara, 2002) and the time limitation previously given. This leaves Cascadia with 0.1% of the original signals, 53 signals, and Izu-Bonin-Mariana with 38.4 % of the original signals, 300 signals (Table 1).

3.3 Examples of Overlapping Waveform and Spectral Characteristics Consistent with Tremor

Two areas in Cascadia and Izu-Bonin-Mariana (Figure 1) exhibit signals with waveform and spectral characteristics consistent with tremor. The resulting waveform and spectrogram from these areas is compared to neighboring stations. Neighboring stations are stations in the area, less than 50 km away, that can help validate the signal by providing evidence that the signal is not the result of instrument noise or highly localized. In Izu-Bonin-Mariana, Station OBS09 and OBS08 were situated to the west of the deformation front and lay on the overriding plate. OBS09 exhibits waveform characteristics consistent with tremor. Its neighboring station OBS08 is 15 km away and records a similar signal. Stations B09 and B08, sitting 45 km apart, are east of the deformation front and are on the subducting plate. Here, B09 exhibits waveform and spectral characteristics consistent with tremor and there is a signal on B08 as well (Figure 4).

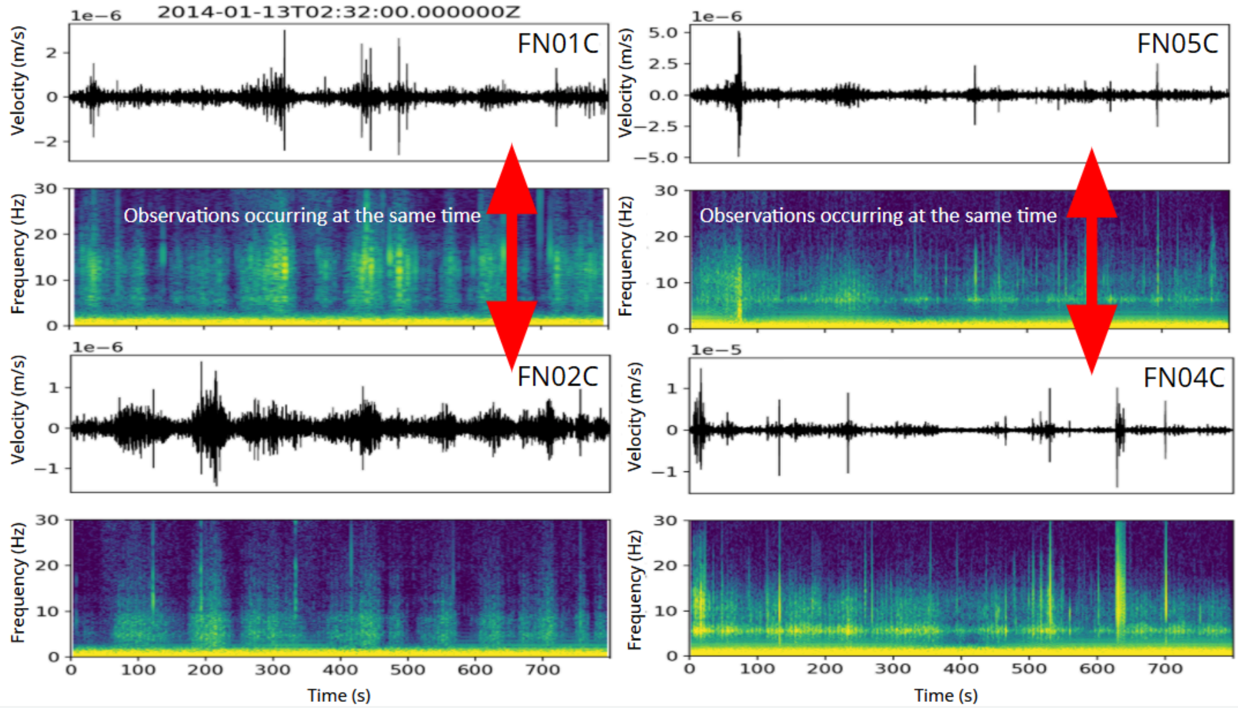

Figure 4. Waveform and spectral at two stations in Izu-Bonin-Mariana (thin sediment): OBS09 and B09 (top row) illustrating characteristics consistent with tremor. Their neighboring stations OBS08 and B08 (bottom row), 15 km and 45 km away respectively, see a similar signal at the same time.

In Cascadia, stations NC89 and BACME have signals consistent with tremor (Figure 5). These two stations also have neighboring stations. All four stations are part of the Canada NEPTUNE array and are cabled, buried, and have a longer timeseries. For those reasons, these stations were studied separately from the 9 month stations and are not included in the calculations of Table 1. They are processed the same way but have different trigger and temporal limitations to account for the difference in temporal scale. Stations NC89 and CQS64 are both on the overriding plate with 4 km between them. NC89 exhibits a signal with waveform and spectral characteristics consistent with tremor. At the same time, CQS64 does not have a signal. Stations BACME and NCBC are also situated on the overriding plate, there is 15 km between them.

BACME also has waveform and spectral characteristics consistent with tremor, but the same signal is not contemporaneously recorded at station NCBC (Figure 5).

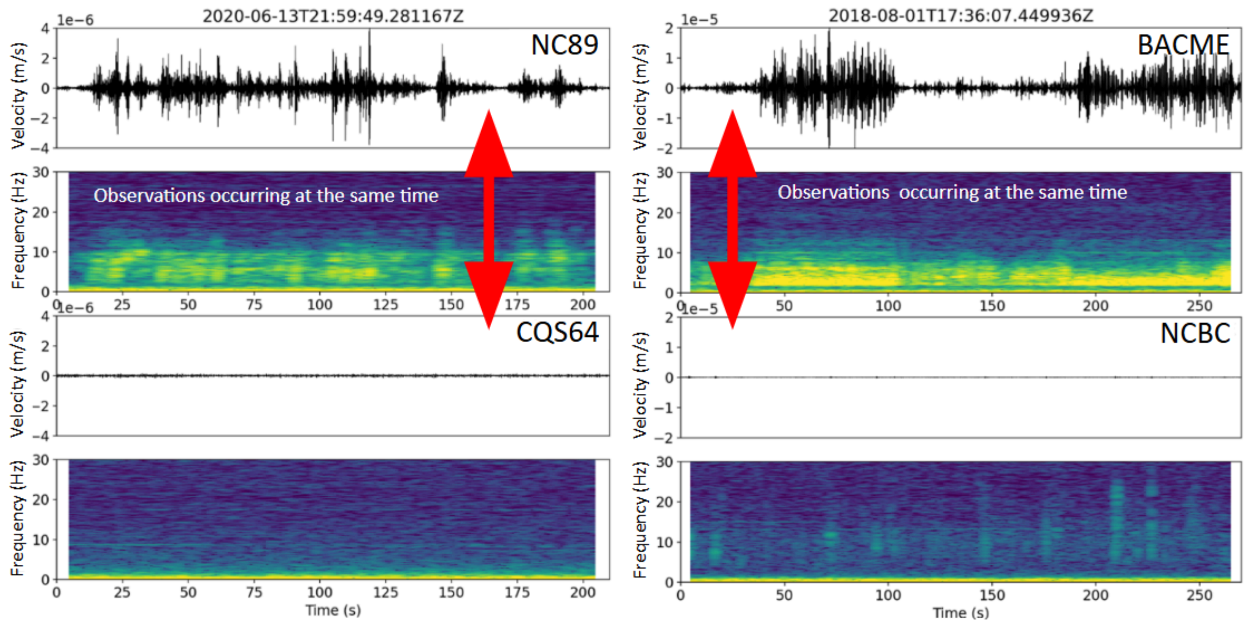

Figure 5. Waveform and spectral at two stations in Cascadia (thick sediment): NC89 and BACME (top row) illustrating characteristics consistent with tremor. Their neighboring stations CQS64 and NCBC (bottom row), 4 km and 15 km away respectively, do not see any signal at that time.

Offshore Washington, stations FN01C and FN05C also exhibit tremor-like signals. Similar signals are seen at their neighboring stations, FN02C and FN04C, 10 and 8 km away. In the waveform, there are multiple peaks and emergent signals. In the spectragram, there is power below 20 hz. All characteristics that are visually inspected and consistent with tremor. The waveform and spectragram also shows spikes, a feature that is not seen in tremor. When evaluating FN02C's relationship between wind speed and seismic velocity the R value is 0.22. At a station without tremor-like characteristics, the R value was less than 0 (Figure 7).

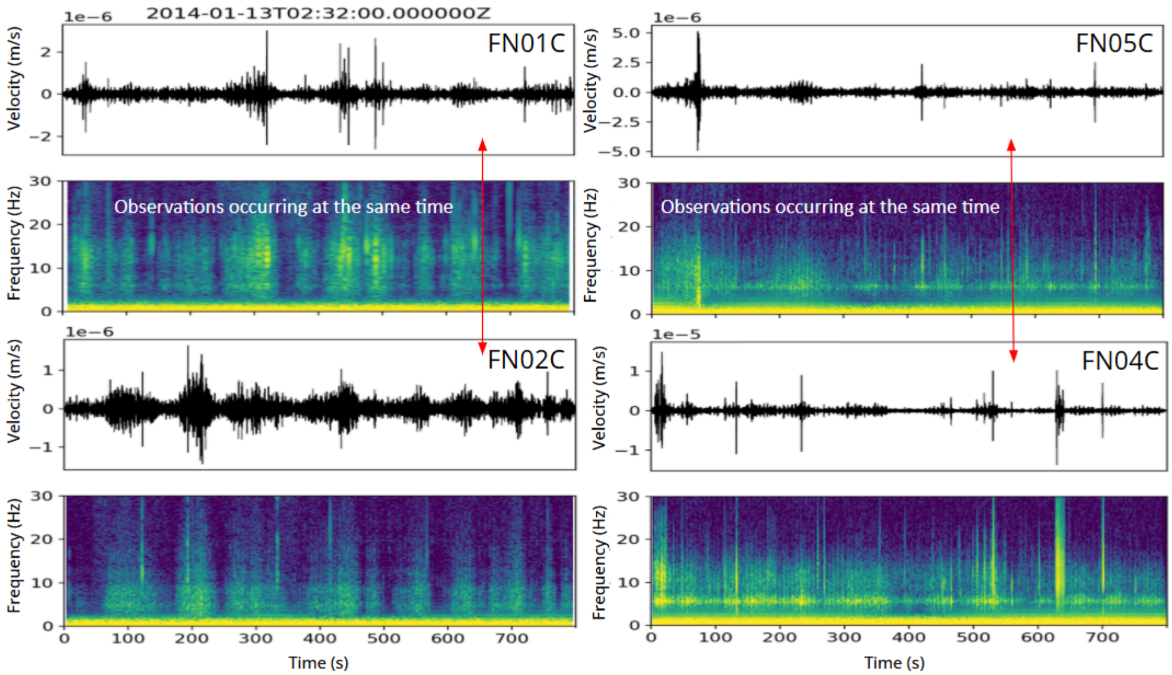

Figure 6. Waveform and spectral at two stations in Cascadia (thick sediment): FN01C and FN05C (top row) illustrating characteristics consistent with tremor as well as spike-y features. Their neighboring stations FN02C and FN04C (bottom row), 10 km and 8 km away respectively, saw a similar signal at that time.

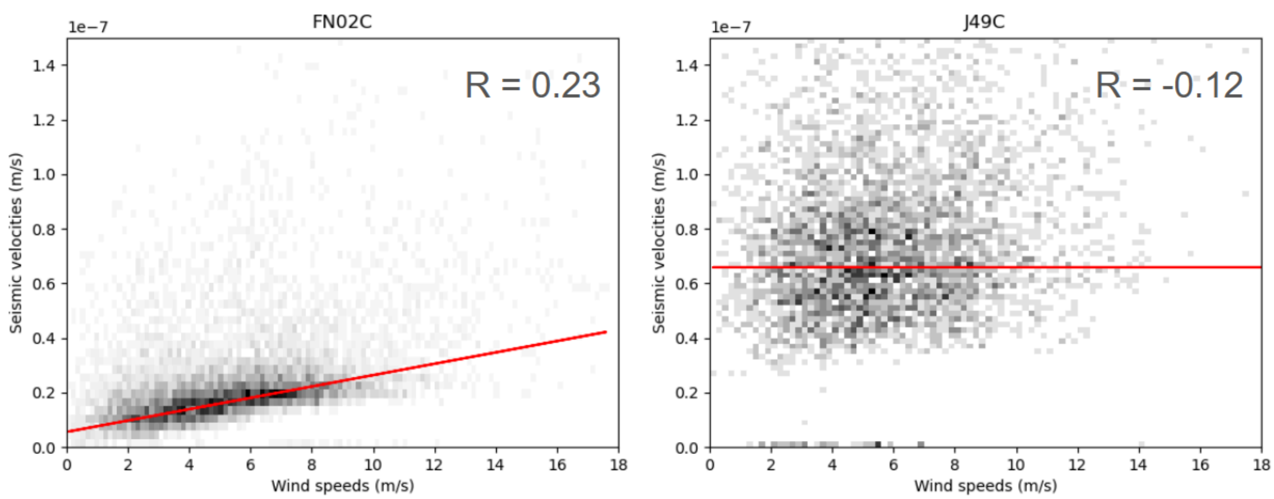

Figure 7. Density Distribution of Wind Speeds versus Seismic Velocities at FN02C and J49C, two Cascadia ocean bottom seismometer stations. FN02C is a station with tremor-like signals while J49C does not exhibit these features.

Discussion

4.1 Seabed Roughness and Sediment Thickness in the Izu-Bonin-Mariana and Cascadia Subduction Zones

The seabed is rougher in the Izu-Bonin-Mariana subduction zone than the Cascadia subduction zone. The standard deviation from the slope of the seabed in Izu-Bonin-Mariana is nearly 2 times the standard deviation of the Cascadia seabed (Figure 3). The mean of each seabed is taken out of the equation to eliminate differences in the incline of the seabed. This is simply comparing the deviation from the bed, and therefore the roughness of the bed. In a 2002 study, seismic signals were utilized to determine sea floor characteristics (Davis et al., 2002). They observed a relationship between sea floor roughness and scattering of acoustic signals. A rough bed suggests that signals originating from the water column will be attenuated since there are more surfaces to interfere with signals. Note there were limitations in the areas that the R/V Thomas G. Thompson was able to travel in the Izu-Bonin-Mariana region.

The distributions of sediment thickness in Cascadia and Izu-Bonin-Mariana show that Cascadia has significantly more sediment on top of the subducting crust. The mean of the Cascadia distribution is more than 3 times greater than the mean of the Izu-Bonin-Mariana distribution. The p-value is $\ll 0.01$, making the Cascadia distribution of sediment thickness at the ocean bottom seismometer sites greater than Izu-Bonin-Mariana with high confidence (Figure 4). This agrees with previous knowledge of the sediment sources in each subduction area. Cascadia is near a large land mass which supplies sediment. Izu-Bonin-Mariana does not have a large sediment source since it is surrounded by the Pacific Ocean. Additionally, once the Western Pacific plate reaches the Izu-Bonin-Mariana subduction zone, the plate is old and dense. Therefore, this plate subducts easily and there is no time for sediment to accumulate.
Izu-Bonin-Mariana has 6 times the amount of signals that are consistent with tremor even with

Cascadia having 60 times the total signals. The difference in sedimentation distribution and subsurface signals aligns with previous work that used sediment thickness values to estimate signal attenuation (Schock et al., 1989). These findings also agree with the argument that higher sedimentation rates block subsurface signals and prevent them from being seen on multiple neighboring stations.

4.2 Cascadia Subduction Zone and Izu-Bonin-Mariana Ocean Bottom Seismometer Signals

The process of both computational and individual visual verification can filter the majority of ship noise, t-phases, short duration events, and bottom currents. But there is a range of processes that could create these types of signals such as biological disruptions, instrument noise, high wave energy, and other events not yet identified. In the Cascadia subduction zone there are large counts of total tremor-like signal detections. But the fraction of these signals that make it through the verification process is only 0.1% of the total. Cascadia has a smooth seabed and a thick layer of sediment which I predict would increase the water column signals and decrease the overlapping signals. Of the 49,224 total signals found in Cascadia, 99.89% were determined to be water column noise instead of tectonic activity. Additionally, there is a lower total number of overlapping signals in Cascadia, despite Cascadia having double the stations. On the other hand, in the Izu-Bonin-Mariana subduction zone there are fewer triggers of tremor-like signals. Of these signals, 61.6% were determined to be water column noise. There is a higher percentage of signals in Izu-Bonin-Mariana that make it through the verification process. The seabed in Izu-Bonin-Mariana has a rough texture that could be limiting the water column signals. It is important to note that these signals are still not confirmed as tremor, but the verification process establishes them as unlikely to be noise. Previously, seabed roughness and sediment thickness were not considered when examining these signals. Incorporating sediment structure provides additional context and improves interpretation of the data.

Izu-Bonin-Mariana has a rough seabed and a thin layer of sediment which would mean fewer water column signals and more overlapping signals. Izu-Bonin-Mariana has fewer original signal triggers but more than a third make it through the validation process and there are 6 times more overlaps found in Izu-Bonin-Mariana than in Cascadia. In the stations in the offshore Washington region of Cascadia, signals look similar to tremor but there are features that do not align. There is a stronger relationship between wind speeds and the seismic velocities detected at FN02C, with tremor-like signals, compared to J49C, no tremor-like signals. These signals and the detection of higher seismic velocities are likely due to weather rather than tectonic activity. In the Canada region of Cascadia, there can be a strong tremor-like signal on one station, but we don't see it on the neighboring station. If the signal is in fact tremor, there must be something in between those stations that blocks the signal from reaching the neighboring station. This would imply that the signals are highly localized and the slow slip events responsible for the tremor signals occur in close proximity to the stations that these signals are seen on. In Izu-Bonin-Mariana, we can see a tremor-like signal on one station and a similar signal on neighboring stations. This aligns with our findings that Izu-Bonin-Mariana lacks the blocking mechanism that Cascadia has. We argue this mechanism is the seabed roughness and sediment thickness.

Conclusions

This study aims to see if seabed roughness and sediment thickness has an impact on the attenuation of tectonic tremor signals in the Cascadia and Izu-Bonin-Mariana subduction zones. The Izu-Bonin-Mariana subduction zone was found to have a thinner layer of sediment than the Cascadia subduction zone. Izu-Bonin-Mariana also has a rough seabed compared to Cascadia's smooth seabed. High sedimentation rates are thought to attenuate subsurface signals and rough seabed is thought to attenuate water column signals. Cascadia has 60 times more the total tremor-like signal triggers than Izu-Bonin-Mariana, which fits the seabed roughness hypothesis. In Cascadia, strong tremor-like signals are present at one station but not its neighbor and similar signals in Izu-Bonin-Mariana are seen both on the station and the neighbor. This observation supports the sediment thickness hypothesis. From these observations, we interpret that Cascadia has an environment that is conducive to tectonic signal interference due to water column noise and attenuation subsurface signals quickly. Izu-Bonin-Mariana has an environment that doesn't see much noise from the water column and subsurface signals are able to travel further. These findings contribute to knowledge of subduction zone behavior and characteristics of tectonic tremor-like signals with the intent to further understand the locked state of subduction zones. This study found a consistent relationship between sediment structure and tectonic signals but only two subduction zones were explored. There were also limitations in the areas that the R/V Thomas G. Thompson was able to travel in the Izu-Bonin-Mariana region. Lastly, there is limited spatial and temporal data from ocean bottom seismometers. To validate these observations, more subduction zones should be studied for tectonic tremor and more ocean bottom seismometers should be deployed.

Acknowledgements

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Artificial Intelligence Usage Acknowledgement

AI was used as coding support in this project.

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