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Publications in this series have not been edited; they are released as submitted by the author.

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ABSTRACT

In this study, we utilize US Geological Survey citizen science earthquake felt intensity data to investigate whether deep, intraslab earthquakes in the Chilean Subduction Zone show similar, "felt intensity" distributions to events of the same magnitude and depths within the Cascadia Subduction Zone (Quitoriano & Wald, 2020; USGS Earthquake Hazards Program, 2020). In a companion article (Rutherford & Cassidy, 2022) we examine crustal earthquake intensity patterns for the Chile and Cascadia subduction zones. One goal of this comparison is to determine whether felt intensity information from several recent large (M8-8.8) subduction earthquakes in Chile can be applied to Cascadia (where no subduction earthquakes have been felt since 1700). This will provide a better understanding of shaking intensity patterns for future subduction earthquakes in Cascadia – critical information for scientists, engineers, and emergency management organizations.

For this research, we utilized 20 years of catalogued "Did You Feel It?" (DYFI) citizen science data from the US Geological Survey's (USGS) earthquake online catalogue, the *ANSS Comprehensive Earthquake Catalog (ComCat) Documentation* (USGS Earthquake Hazards Program, 2021). In total, we compared intensity patterns from five earthquakes in Cascadia (M4.8, M5.0. M6.7 & M6.8) to the intensity patterns from 157 earthquakes in Chile, with the same magnitudes as the Cascadia events (M4.8-M6.8).

Our analysis involved plotting and fitting the Chile and Cascadia earthquakes' DYFI responses in order to compare the intensity patterns for the two subduction zones. Overall, we find good agreement between felt patterns in Chile and Cascadia. For example, all plots show the expected downward trend for intensity with distance; and there is generally a similar intensity clustering of responses around 50 to 300 km hypo-central distance. These results provide confidence that we can use Chilean intensity data for megathrust earthquakes in Cascadia.

INTRODUCTION

The world's largest earthquakes occur along subduction interfaces. This is where denser oceanic plates are pushed (subducted) beneath lighter continental plates. Not only do subduction zones produce large (M~9) earthquakes, but they also produce large tsunamis (Di Menna & Flick, 2005; Staisch, Walton, & Witter, 2019). Figure 1 shows the three types of earthquakes that occur in subduction zones: 1) shallow earthquakes in the continental (overriding) plate; 2) deep, intraslab earthquakes within the subducting oceanic plate; and 3) plate interface (or subduction) earthquakes that result from movement along the subduction fault.

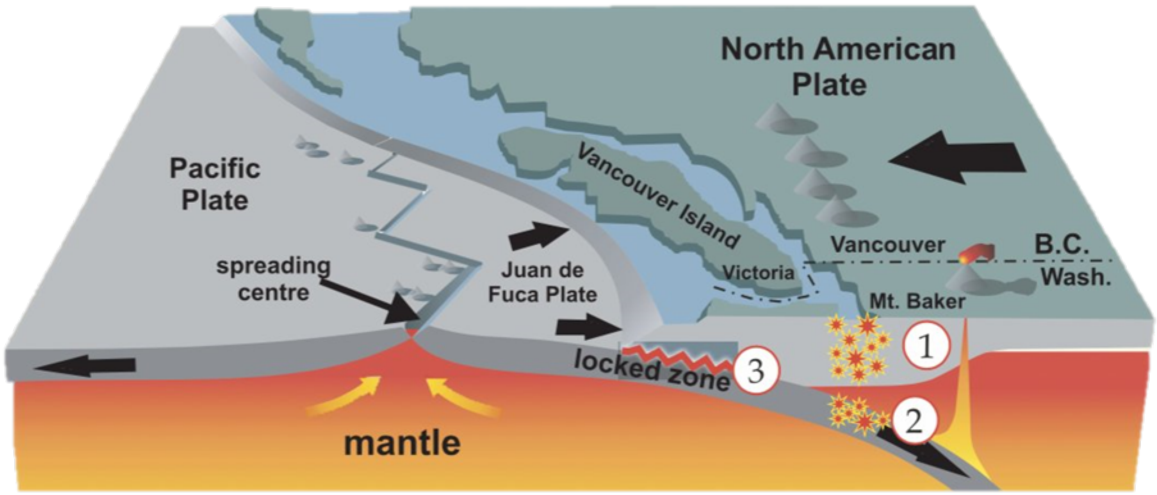


Figure 1: This image of the Cascadia Subduction Zone demonstrates the location and depth of three types of earthquakes: Crustal surface earthquakes occur at a depth less than ~ 35 km (circle 1); Deep slab earthquakes occur at depth of 40 to 60 kilometers below the surface (circle 2), and megathrust earthquakes occur where plate boundaries collide (circle 3). (Government of Canada, 2011)

This study looked at two similar subduction zone regions, the Cascadia Subduction Zone (CSZ) in the Pacific Northwest (Figure 2) and the Chile Nazca Subduction Zone in South America (Figure 3). Both subduction zones have segments with a very young oceanic crust (< ~5 MY) and subduction rates of 2-8 cm/year (USGS Subduction Zone Science, 2020). Both subduction zones experience all three of these types of earthquakes; Cascadia, however, has not experienced a major subduction earthquake since 1700, whereas Chile has experienced 3 major subduction earthquakes (M8.2-8.8) since 2010 (Government of Canada, 2021a; Staisch, Walton, & Witter, 2019).

The Cascadia Subduction Zone (Figure 2), is an 1,100 km-long tectonic boundary between the continental North America plate and the oceanic Explorer, Juan De Fuca and Gorda plates, extending from northern Vancouver Island down to northern California (Government of Canada, 2021b; USGS Pacific Coastal Marine Science Center, 2021). Here the oceanic plates are subducting beneath North America at approximately 2-5 cm/year (Government of Canada, 2021b). For a detailed description of this subduction zone, see, for example (Government of Canada, 2021b; USGS Pacific Coastal Marine Science Center, 2021).

The Chile Subduction Zone (Figure 3) is located along the coastal margin of Chile and is part of a long subduction margin where the oceanic Nazca plate is subducting beneath the western edge of the continental South America plate along the entire 5,900-kilometer length of South America (Henig, Blackman, & German, 2010; Patton, Ammirati, Stein, & Sevilgen, 2019). Subduction rates vary from 6.5-8.0 cm/year along this margin. For a detailed description of this subduction, see, for example (IRIS, No date; Henig, Blackman, & German, 2010). In this study, we considered earthquakes that occurred along the Chile portion of this margin, where the subducting plates age is most similar to that of Cascadia.

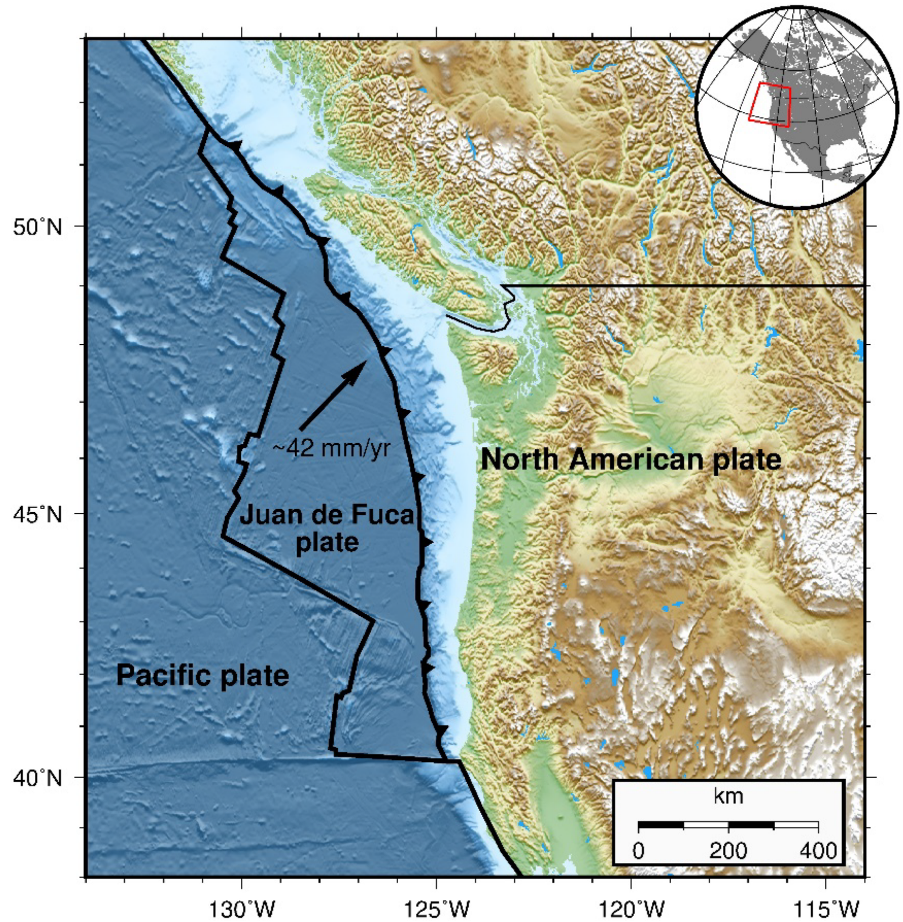


Figure 2: Black variegated line shows the ~1,100 km long Cascadia Subduction Zone, located between the Juan De Fuca and North America plates, where the Juan de Fuca plate is subducting beneath the North American plate at ~42 mm/year.

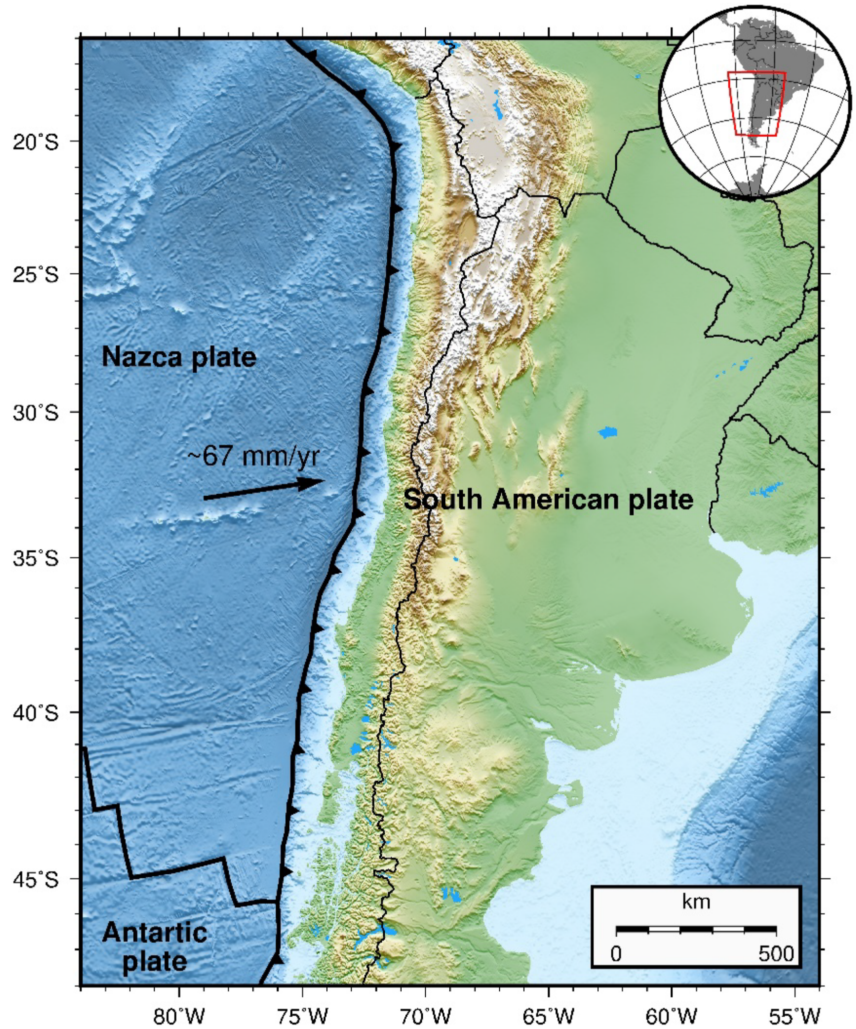


Figure 3: Black variegated line shows the ~5,900 km long Chile Subduction Zone, located between the Nazca and South America plates, where the Nazca plate is subducting at approximately 67 mm/year beneath the South America plate.

Earthquake intensity is the qualitative measurable severity of ground shaking, controlled by several factors, with earthquake magnitude and distance from the epicenter generally being most influential, with higher intensities close to the rupture and lower values further from the earthquake (USGS Earthquake Hazards Program, 2020). Earthquake depth, surface geology, distance from the earthquake rupture, as well as building characteristics are additional factors that influence the intensity people will experience (USGS Earthquake Hazards, 2022)

To gain a greater picture of this ground shaking, capturing the macroseismic intensities provides an estimate of the effect and impact of shaking that people experienced, the USGS uses a citizen science platform to capture this information through the “Did You Feel It?” (DYFI) website (USGS Earthquake Hazards Program, 2020). In general, these reported macroseismic intensities are assigned a numerical value based on (and calibrated to) the Modified Mercalli Intensity (MMI) scale, which is an increasing level of intensity ranging from no felt shaking (MMI=1) to catastrophic destruction (MMI=10) (USGS Volcano Hazards, 2021). The USGS DYFI data is, however, an intensity calculation based on the weighted sum of the eight various DYFI questionnaire indices aggregated (not the average) and is represented by a Community Decimal

Intensity (CDI) rating for either 1-kilometer or 10-kilometer block/grid area. Details on the CDI rating calculation and additional information can be found on the USGS Earthquake Hazards Program webpage (USGS Earthquake Hazards Program, 2020).

The USGS uses information captured through the online DYFI questionnaire to create Shake and Intensity maps, and various plots, such as the Intensity vs. Distance plot (USGS Earthquake Hazards Program, 2020). Intensities used in the USGS's Intensity vs. Distance plots use an 'Intensity Prediction Equation' (IPE) that captures intensities from the DYFI questionnaire's responses and compares them against weighted intensities and distances from the reported magnitudes (USGS Earthquake Hazards Program, 2020).

The DYFI have been collected since 2004, when the online USGS DYFI platform became available to users around the globe (Quitoriano & Wald, 2020). Although there are other earthquake intensity datasets, for example, NRCan in Canada and the Seismological Service of Chile for Chile, (Wald D. J., Quitoriano, Worden, Hopper, & Dewey, 2011), we only consider the USGS intensity data for consistency. The same data collection form is used in both areas, so the resulting intensity values will be directly comparable.

Increasing our understanding of how intensities from specific earthquake events affect people, infrastructure, and the environment contributes to earthquake scenario development, earthquake risk assessment, and community risk and emergency management planning. This research is part of the Canadian Government's Public Safety Geoscience Program; ultimately, our aim of this project is to contribute to better preparedness for future large earthquakes in Canada.

METHODS

This project involved three main components. First, a literature review of the *USGS DYFI Scientific Background* documents was conducted to provide an understanding of the systems and processes used by the USGS for data collection and to determine how best to use the DYFI data for this research. Second, felt earthquakes within search criteria were identified, and DYFI data from the *USGS Search Earthquake Catalog* (ComCat) were acquired for Intraslab (deep) felt earthquakes that occurred within the subducting oceanic plates (Juan de Fuca, Explorer and Gorda in Cascadia, and Nazca in Chile) from January 1, 1960, to Jan 1, 2020. Most of the intensity data in this study are from 2004 onward, after the USGS DYFI portal became operational to global contributors (Quitoriano & Wald, 2020). A small number of significant historical events (going back to 1960) were added to the USGS DYFI database and are used in this study. Lastly, the third component involved running conversion analytics and generating data visualization through plots created in MS Excel. The following expands upon the key components of this data collection and analysis.

Identifying Earthquakes & Acquiring DYFI Data from ComCat

Identifying intraslab earthquakes of interest for this project involved searching the USGS ComCat (USGS Earthquake Hazards Program, 2021) database for earthquakes felt or experienced by people, of magnitude 4.5 and greater, within the oceanic plates that are subducting beneath the North and South America plates from 1960 to 2020.

The tectonic settings within the regions of interest (Figure 2 & Figure 3) control the earthquake depth (Hayes & Crone, 2021; Duo, McGuire, Liu, & Hardebeck, 2018). Shallow events of depths less than 35 km primarily occur within the overriding continental plate, or unsubducted oceanic crust (as seen in Figure 1) (Adams & Halchuk, 2004; Hayes & Crone, 2021). Meanwhile, deeper (depth > 35 km) earthquakes are likely occurring within the subducting slab. We therefore set the depth parameters in ComCat to separate the deep (Intraslab) from the shallow (Crustal) earthquakes in our search. We considered earthquakes at less than 35 kilometers deep to be crustal and those greater than 35 kilometers intraslab (Hayes & Crone, 2021).

ComCat Search for Intraslab Earthquakes

As a starting point, we searched to identify the intraslab (deep) 'felt' earthquakes in the Cascadia subduction zone (Figure 2) and in the Chilean subduction zone (Figure 3). With the knowledge that there have been only a handful of large, deep earthquakes in the Cascadia subduction zone over the past 60 years, we carried out an initial search on ComCat to identify intraslab earthquakes in the Cascadia subduction search region (Figure 4A) during this period. The Cascadia intraslab results (useful datasets for M4.8-6.8 earthquakes) formed the basis for search parameters (M4.8-6.8) used in our Chile data collection

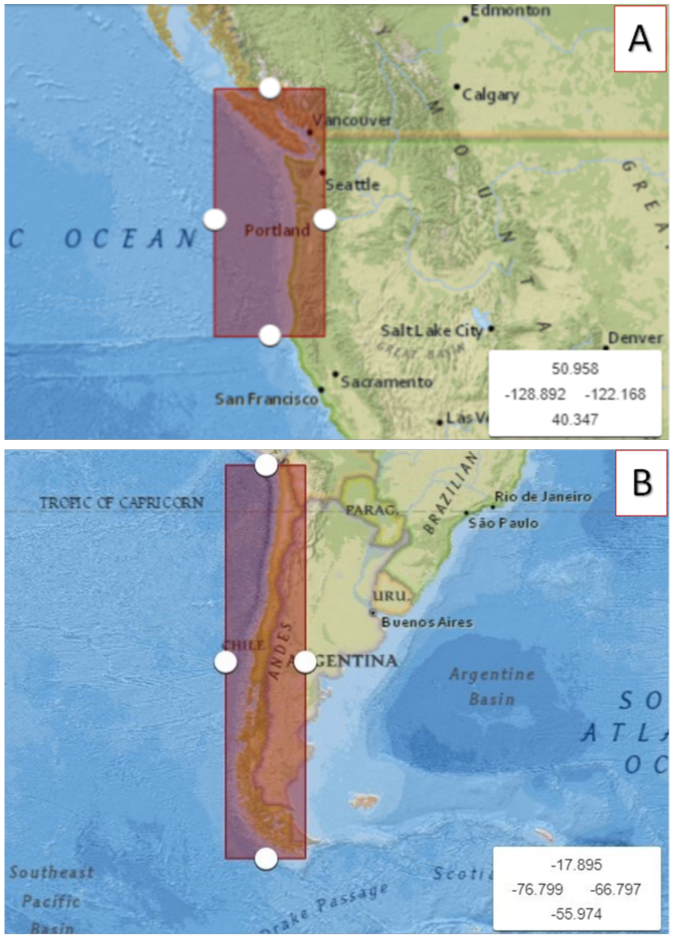


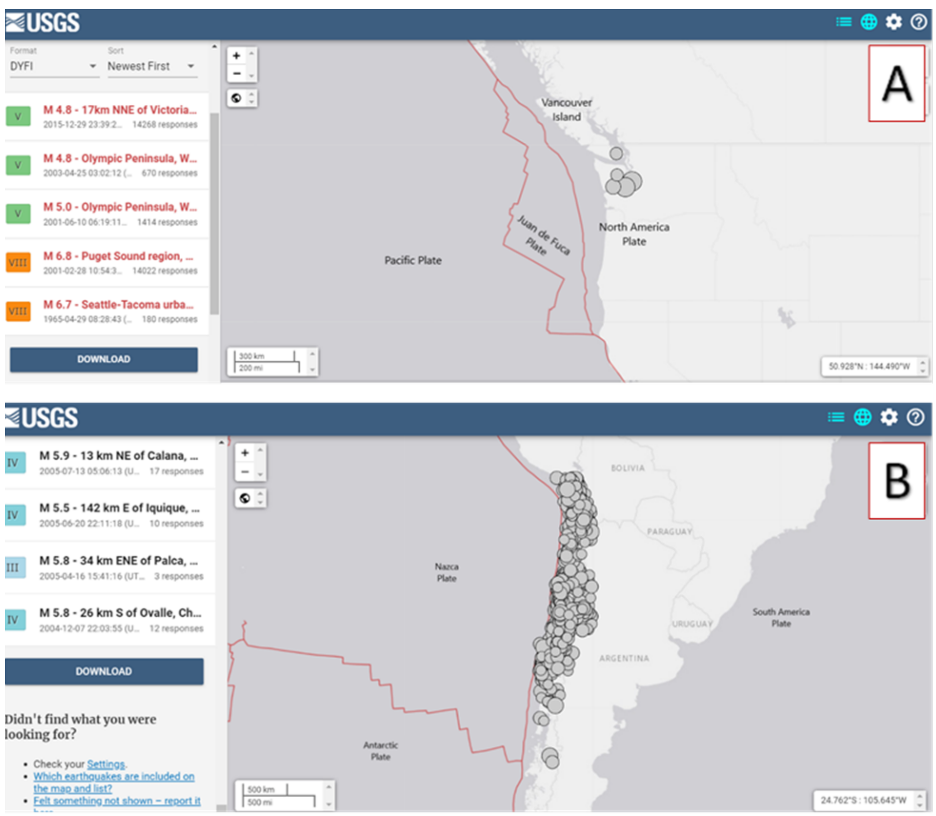
Figure 4: Geographic ComCat search areas capturing the boundaries of the Cascadia Subduction Zone (Image A) and the Chile Subduction Zone (Image B).

Figure 5 shows results of this search for these two zones. The results section of this document highlights the total events found, omitted, and used for this study.

The ComCat search results are summarized in Appendix A & Appendix B and contain the USGS source information for each earthquake. We include hyperlinks to the USGS webpage for each specific earthquake, based on their USGS earthquake ID. The links allowed for quick access to each earthquake's specific webpage and was useful for the retrieval of the DYFI data associated with each event, and validating specific information associated with each earthquake.

The ComCat search engine provided high-quality intensity data. There were, however, some limitations with the ComCat search platform. For example, delineating the geographical search area in ComCat created a very rough (rectangular) outline of the Chile subduction region (Figure 4B), which caused the search to pick up earthquakes outside the region of interest, e.g., within Nazca Plata and bordering countries. We filtered out events that did not occur in the Chile subduction zone. We then further filtered the database to only include earthquakes based on the four magnitudes found from the Cascadia search, i.e., magnitudes 4.8, 5.0, 6.7, and 6.8. Verification of events involved individually setting the search criteria for each of the exact four magnitudes in the ComCat search engine. For example, we discovered only two M6.8 events greater than 35km depths that occurred from 1960 to 2020 within the Chile subduction zone.

Ensuring that we compared the same magnitude and depth of the Cascadia earthquakes with that identified by the Chile ComCat search, required setting depth ranges for each magnitude, by filtering out events that did not fall within our set ranges. The depths of the Cascadia earthquakes were 52.5 km and 50.2 km (M4.8), 40.2km (M5.0), 59.0 km (M6.7), and 51.8 km (M6.8). Therefore, the depth range for M4.8 Chile earthquakes was set to include events that fell within +/- 10 kilometers of the average depth of the magnitude 4.8 Cascadia earthquakes. Filtering depth range for magnitude 5.0 Chile earthquakes was set to approximately +/- 3 kilometers from 40.2 kilometers (38 to 42 km) to keep within the +/- 2-kilometer limit of the crustal earthquake zone. A filtering distance range was not required for the magnitude 6.7 and 6.8 earthquakes, as there were only two Chile earthquakes for each of these magnitudes, and both had limited responses; therefore, we decided to include all data. All events fell within +/- 10 km from the Cascadia event of the same magnitude, however.



SEARCH CRITERIA	*INSLAB (DEEP)*
Magnitude	> M4.5 & < M6.9
Depth	> 35km
Time Period	1960/01/01 to 2020/01/01

Figure 5: ComCat Search parameters used for deep earthquakes, Image A, showing the Cascadia earthquake search results (Image A) and Image B showing the Chile search results (Image B).

Acquiring Raw Data from the ComCat Catalog

Acquiring raw data associated with each earthquake, based on their USGS ID, required sourcing, downloading, and processing the DYFI data from the USGS ComCat database (USGS Earthquake Hazards Program, 2021). The data were obtained in three main formats: .PNG/.JPG (plots), CSV (raw DYFI), and JSON (intensity vs distance). We note that for privacy reasons the USGS does not include individual response locations but rather provides responses that are aggregated by postal code, large city, or geo-location into 1-km to 10-km grid cells for each earthquake (Quitoriano & Wald, 2020; USGS Earthquake Hazards Program, 2020). In their recent paper, Quitoriano & Wald (2020) discuss how aggregating responses help to combine multiple responses and provide a way to interpolate missing intensity markers detailed in the DYFI questionnaires. The general steps taken were to download CSV and JSON files for each earthquake. We then converted all files to Excel format for data manipulation, cleanup, calculations, and plotting procedures. All downloaded intensity versus distance data for each earthquake event has been stored in folders under the naming conversion "event year_ID_magnitude" (e.g., 2015_uw61114871_M4.8). Appendix C details the folder directory structure for this study.

Validation & Quality Control of the ComCat Search Results

The USGS ComCat website stores graphed DYFI data in multiple file formats and, as previously mentioned, we were specifically interested in the 'intensity versus distance' DYFI data in the JSON formats. The JSON files we used contain intensity versus distance data that were aggregated in blocks, and binned into 10-km grids cells (USGS Earthquake Hazards Program, 2021; Quitoriano V. , personal communication, June 15, 2021).

We reviewed individual events by their USGS catalog ID and determined if they were suitable for use, by validating the quality and quantity of DYFI responses and omitting events with limited or poor-quality (fewer than four DYFI responses) data. We discuss the details of filtering and removal of DYFI in the results section.

Processing, Analytics & Plotting DYFI Data

The process we used to investigate whether the felt intensity patterns between Cascadia and Chile subduction zones are comparable, involved binning data by distance and plotting events of the same magnitude and depth on one graph. The following outlines the procedures used to process, graph, and edit the acquired USGS ComCat DYFI intensity versus distance data.

1) **Plotting values by Magnitude:**
   To get a first glance at the intensity versus distance data, we plotted all felt intraplate earthquakes for each specific magnitude (M4.8, M5.0, M6.7, and M6.8) for events that occurred within Chile and Cascadia subduction zones as separate events. For example, all the M5.0 Chile and Cascadia events were plotted as separate earthquakes as seen in Figure 6. The data used in our analyses are available in Excel format (see Appendix A and Appendix B for details and links).

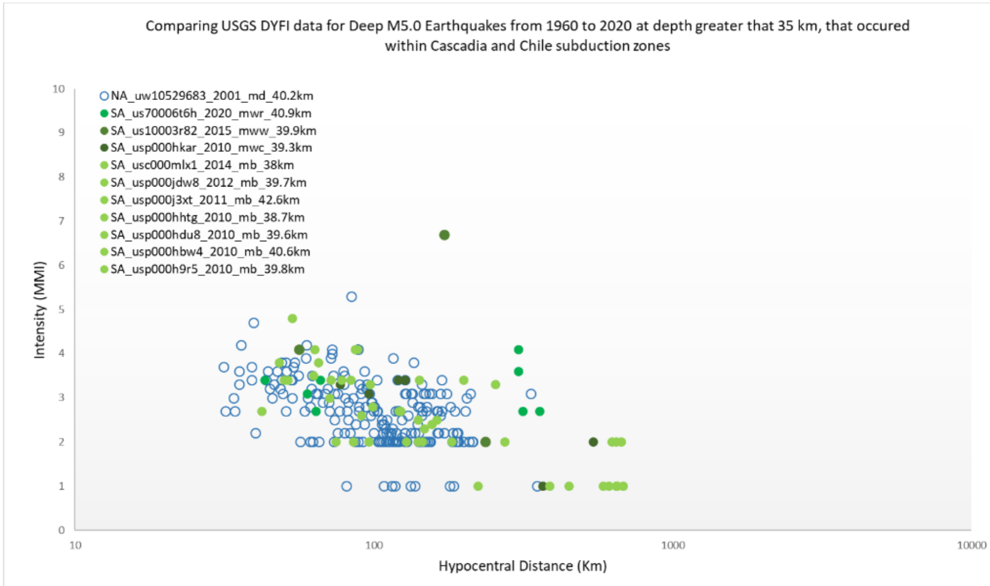
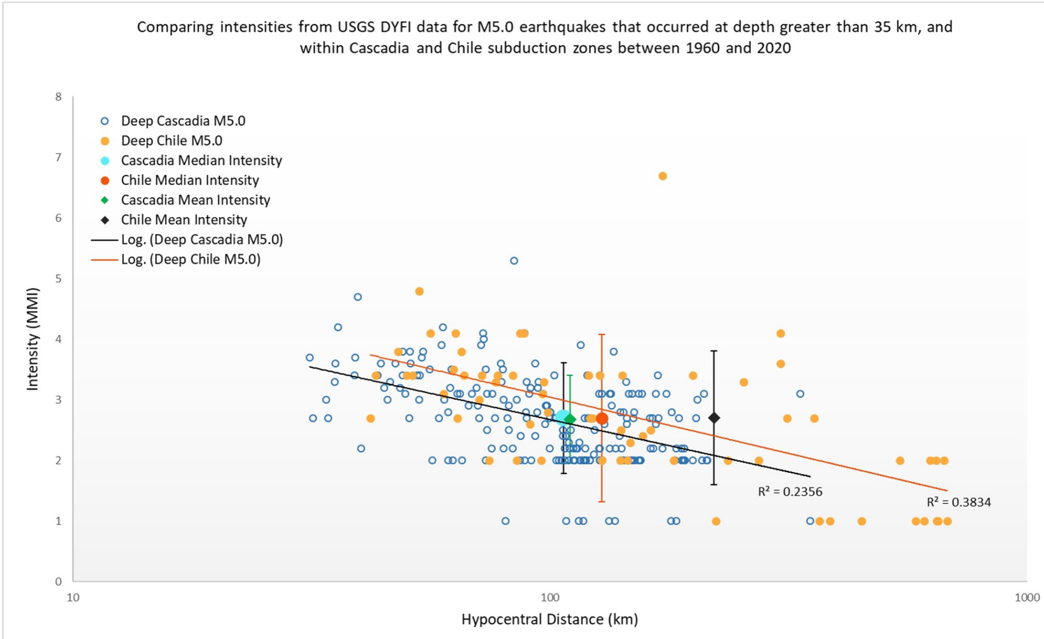


Figure 6: An example of one of the combined plots with associated data, showing the individual intensity responses for Chile (SA) earthquakes (various green colour coded dots indicate magnitude type) & Cascadia (NA) earthquakes (blue colour coded dots) used in this study.

2) **Combining Chile and Cascadia intensity and distance values by magnitude**:
In this next step, we combined the intensity vs distance values of each magnitude (e.g., 4.8, 5.0, etc.) from Chile and Cascadia into a combined plot. For example, we plotted the DYFI intensities for M5.0 earthquakes in Chile and Cascadia as separate series (Figure 7). The same plots also included the mean and median intensities for the entire Cascadia and Chile dataset (all distance values) and the related standard deviations. This plot provides a rough view of the felt intensity patterns across each magnitude for Chile and Cascadia faults zones, without binning intensity values by distance.
   - The standard deviation of the mean for all Chile and Cascadia responses used the STDEV.P function in excel, providing the one standard deviation for all responses.
   - We calculated the standard deviation of the median using the formula $Median\ STDEV = Mean\ STDEV \times \left(\sqrt{Pi} \div 2\right)$, which provided the median for all responses.



Deep Cascadia M5.0			Deep Chile M5.0							
Distance	Intensity		Distance	Intensity			Chile Median Intensity	Chile Median Distance	Cascadia Median Intensity	Cascadia Median Distance
134.9	2.9		59.8	3.1		Value	2.70	128.60	2.70	107.00
115.1	1		304.6	3.6		STDEV	1.38	252.16	0.91	62.93
89.3	2.7		66.1	3.4						
140.3	2.8		314.5	2.7			Chile Mean Intensity	Chile Mean Distance	Cascadia Mean Intensity	Cascadia Mean Distance
142.8	2.8		43.1	3.4		Value	2.71	220.92	2.68	110.22
50.8	2.7		358.7	2.7		STDEV	1.10	201.19	0.73	50.21

Figure 7: An example of a combined plot with associated data, showing all Chile & Cascadia earthquake response values combined on one graph. The table below the plot, shows the calculations use for the mean and median.

3) **Curve fitting mean intensity over binned distance: Generating binned distance plots**
These rough estimates (step 2) only generated a singular mean/median and did not provide a realistic picture of the responses. The plot in Figure 7 (step 2) calculated the mean and median values for all response values spanning over the entire distance range, from as close as ~50 km out to ~1000 km. Therefore, to get a better estimate for the mean and median intensities, we binned intensity values into smaller distance ranges. Using a similar approach to that of the USGS, we binned distance values, which captured the average intensity for binned distances and generated a mean of intensities for each binned distance. This provided better data for curve fitting.

We created a combined binned distance plot for each magnitude by taking the values from the combined magnitude plots (Figure 7). Our first step in achieving this was to create a list of bin distance values that captured the range of distances for intensity values of each magnitude for both Cascadia and Chile events (Figure 8).

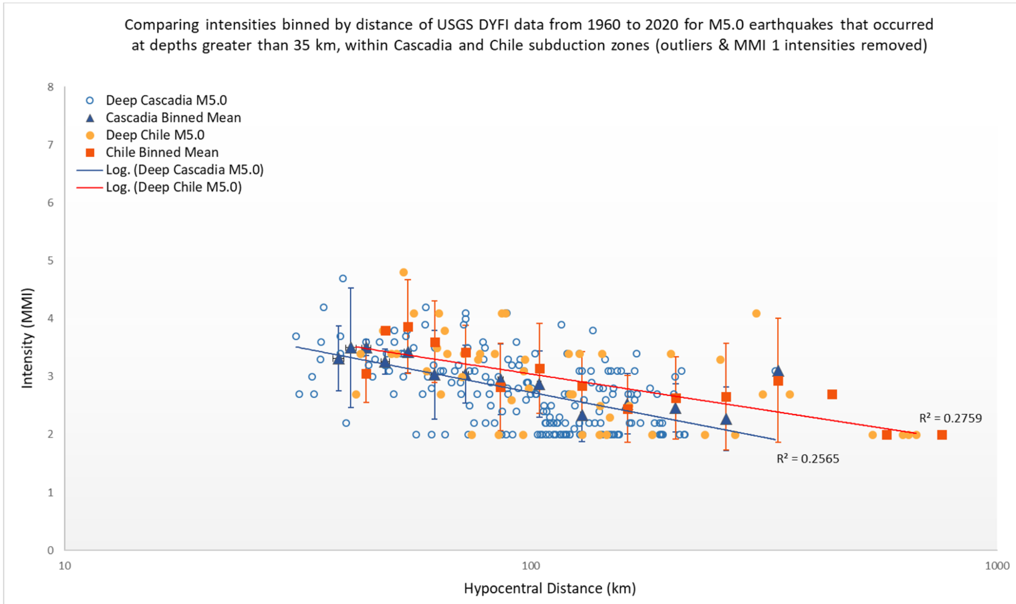


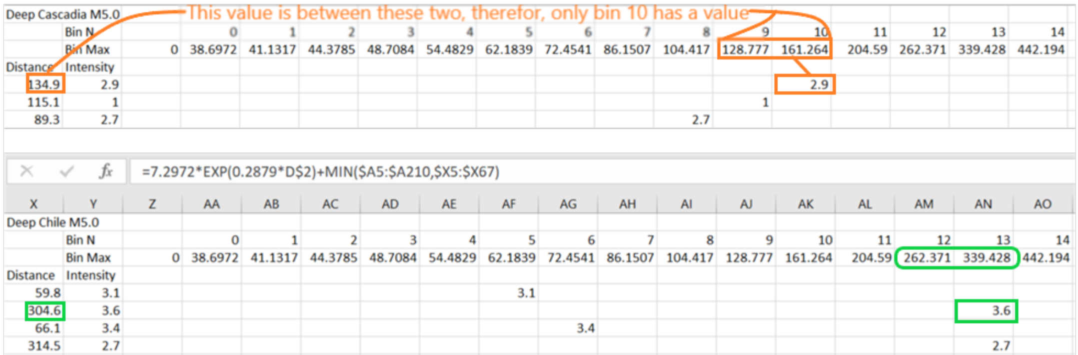
Figure 8: An example of a curve-fitting plot, which combined DYFI data from the entire dataset for 10 Chile M5.0 earthquakes and the 1 Cascadia M5.0 earthquakes, where we binned intensity values by distance.

The formula used to bin distance is similar to that found on the USGS Background information for DYFI data (USGS Earthquake Hazards Program, 2020). We calculated the left edge (upper limit) of each bin using the formula:

$$d_n = 7.2972 * e^{0.2879*n} + d_{min}$$

Where n is the bin number, and d_{min} is the distance of the closest DYFI report. The exponentially increasing bin size and shift applied by using d_{min} ensure that the bins are smaller around the bulk of the responses (Figure 9) and that bins that are more distant capture the sparser reports. We then checked each DYFI report's distance value against this array and only selected the intensity values where their respective distances were lower than the bin max and higher than the previous bin max. Therefore, each column showed values from the distances that fit in each bin.

To calculate the mean and standard deviation of each bin we used built-in average and STDEV.S functions in Excel and only selected values that have a numerical value in each bin, blank bins were not included. We did not calculate the median, as it was not necessary for our purposes. We then took the calculated bin distance values sheet and created intensity binned by distance plots (Figure 8). Conducting this process for the Cascadia and Chile Intraslab earthquakes allowed us to observe similarities and differences in the two regions' intensities vs distance.



Deep Cascadia M5.0																	
	Bin N		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Bin Max	0	38.6972	41.1317	44.3785	48.7084	54.4829	62.1839	72.4541	86.1507	104.417	128.777	161.264	204.59	262.371	339.428	442.194
Distance	Intensity																
134.9	2.9												2.9				
115.1	1											1					
89.3	2.7										2.7						

=7.2972*EXP(0.2879*D$2)+MIN($A5:$A210,$X5:$X67)

X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO
Deep Chile M5.0																	
	Bin N		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Bin Max	0	38.6972	41.1317	44.3785	48.7084	54.4829	62.1839	72.4541	86.1507	104.417	128.777	161.264	204.59	262.371	339.428	442.194
Distance	Intensity																
59.8	3.1							3.1									
304.6	3.6															3.6	
66.1	3.4								3.4								
314.5	2.7															2.7	

Figure 9: The logic and formula used for the curve fitting plots, and binned distance calculations for mean intensity. The orange outlined boxes show that the distance values (134.9) are less than bin 10's max and greater than bin 9's max; therefore, the intensity value in bin 10's column – all other columns are blank (no values). Similarly, for the row in green, the distance is greater than bin 13 and less than bin 12, so only bin 13 has a value and the other values are blank (no value).

4) **Remove outliers, MMI = 1 values and edit combine plots**:
The final step in this study involved reviewing each plot to infer a comparison in intensities between the intraplate earthquakes in the Cascadia and Chile subduction zones. As a first cut, we looked for clusters of intensities around similar distance ranges. We flagged plots, for further investigations, that indicated a similar cluster pattern.

Furthermore, when reviewing each plot, it became clear that there were several outliers. To clean up the results, we removed outliers (i.e., some extremely distal responses that give intensity measures > 4, e.g. an unrealistic MMI = five at 1000 km). Lastly, further review of the plots showed that MMI = one values in all plots influenced the overall trend. We noticed that these (not felt) values were more common in Cascadia, and not used as often in Chile. We decided to remove all MMI 1 values, as they served no purpose in our analyses.

RESULTS

ComCat Catalog Intraslab Earthquake Search Results

The USGS ComCat search engine proved successful in locating intraslab earthquakes within the Cascadia and Chile subduction zones. For example, Figure 5 shows the results of our Cascadia search, where five deep earthquakes of a magnitude greater than 4.5 occurred with the Cascadia region and over 1000 earthquakes within the Chile region (Figure 2).

Search results from the Cascadia subduction zone identified the five earthquakes of four different magnitudes, two at M4.8 and one of each M5.0, M6.7, and M6.8. The Cascadia intraslab results formed the parameters to use in our Chilean subduction zone search. This meant that we set the Chile search magnitude parameter to search for events greater than 35 km deep, with at least four responses, and ranging from magnitudes M4.8 to M6.8. After filtering out events outside of the Chile subduction zone, 157 earthquake events were extracted. Appendix A and B provides summary version of the earthquakes and show the number of response values for events used in this study.

Results of Data Interrogation & Plotting

Here we provide a short discussion on each step of the data analysis and conclusions (following the headings used in the method section) to help facilitate similar research by others in the future. Overall, three main plots were generated for each of the four magnitudes (M4.8, M5.0, M6.7, & M6.8). These plots allowed us to view and interrogate the trends and comparability of felt data for the two subduction zones. In general, plots show good overall agreements between felt patterns in Chile and Cascadia. The following section shows the three plots generated for each magnitude.

Combined by Magnitude Plots - Separate Earthquakes by USGS ID

Our first combined plots (Figure 10) show each Cascadia and Chile earthquake plotted separately, based on their event ID (USGS ComCat search ID). In these plots, we show the depth and magnitude type of each earthquake in the legends. All four plots in Figure 10 show the expected trend of decreasing intensity with distance. Plots M4.8, M5.0, and M6.8 all show a similar clustering of values from approximately 50 kilometers to 500 kilometers. The observed 50-km minimum for felt reports is expected for these deep earthquakes, and represents the hypocentral distance to the closest communities. All plots show a plateau at intensity MMI-1 and a slightly smaller one at MMI-2, and as, the USGS intensity grading system considers MMI values as a ‘not-felt’ response; we removed these values in further analyses.

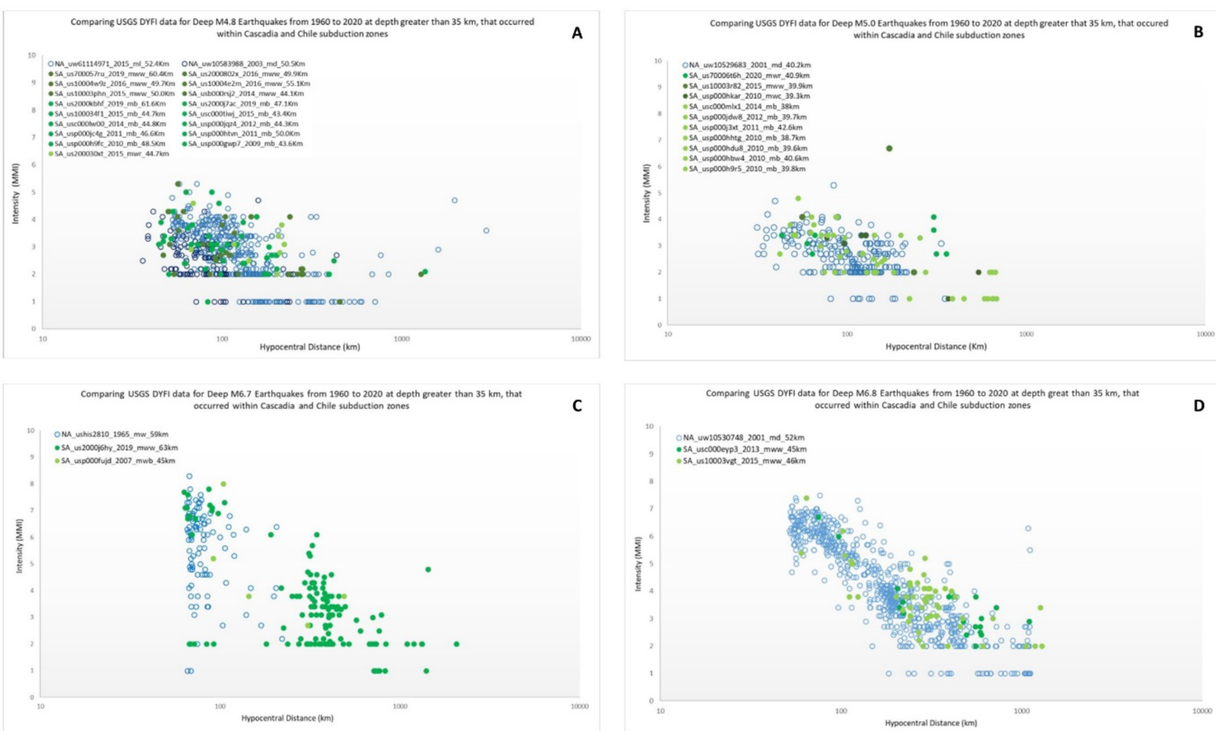


Figure 10: Combined DYFI intensity response data for earthquakes in Chile (SA) and Cascadia (NA) from 1960 to 2020; showing clustering patterns of the individual events for magnitude 4.8 (image A), 5.0 (image B), 6.7 (image C), and 6.8 (image D), indicating a comparable intensity pattern between the Chile and Cascadia subduction zones. Colour coded dots show the response values based on magnitude type (blue dots represent Cascadia (NA) and the different green coloured dots show Chile (SA) responses.

These initial plots provided a rough estimate of individual earthquakes' response patterns for each of the magnitudes while viewing the possible comparability of intensity responses for the two subductions zones. In Table 1, we can see the number of response values per magnitude earthquake for both Chile and Cascadia. For all magnitudes, there were more Chilean earthquakes, yet fewer response values with each earthquake, except for M6.7.

Table 1: Highlighting the number of Chile and Cascadia earthquakes and response values plotted for each magnitude.

Cascadia	Earthquakes	Response Values	Chile	Earthquakes	Response Values
M4.8	2	479	**M4.8**	17	86
M5.0	1	206	**M5.0**	10	63
M6.7	1	96	**M6.7**	2	143
M6.8	1	650	**M6.8**	2	71

Combined by Magnitude Plots - Combined Earthquakes

We have included the following plots generated in Step 2 in this report, as this step shows the process used to create the final curve fitting plots. We combined all the response values for the Cascadia earthquakes and the Chilean earthquakes for each of the four magnitudes. We then plotted the combined data as two series, one for all Cascadia events and one for Chile events for each of the four magnitudes. We generated trend lines and a single mean and median for all values from the Chile and Cascadia earthquakes over the complete hypocentral distance range. Figure 11 plots show the downward trend with all magnitudes, and have similar slopes, indicating that the data are comparable. For example, even though the R^2 values are low, the sloping trend in Figure 11B indicates consistent responses for both magnitude 5.0 Cascadia and Chile data, with Cascadia R^2 value of 0.24 and Chile is at 0.38. This slope comparability is evident in each of the three other magnitude plots.

Additionally, the mean and median intensity for all responses values was calculated and provided a general view of the distribution of intensities. In general, these distribution values for Chile and Cascadia data are similar. For example, we can see that for magnitude 4.8 earthquakes (Figure 11A), the mean and median values are relatively similar (Cascadia: 99.5 km, 2.9 MMI; Chile 101.9 km, 2.8). There is some variability in the intensity patterns for the other three magnitudes, likely due to the differences in reports' hypocentral distance range for the two different regions (particularly M6.7).

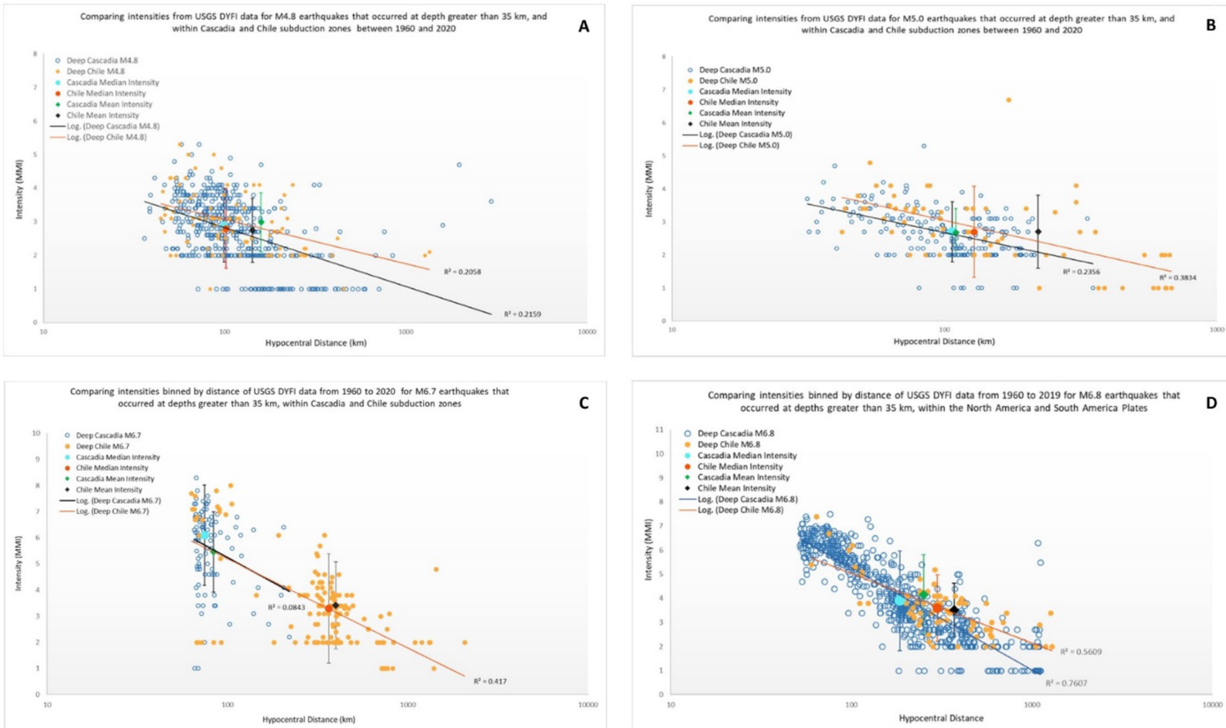


Figure 11: Combined plots for earthquakes in the Chile and Cascadia subduction zones; showing clustering patterns of all response values for each magnitude 4.8 (image A), 5.0 (image B), 6.7 (image C), and 6.8 (image D), and the mean and median of all response values, indicating comparable intensity patterns between Chile and Cascadia.

Combined by Magnitude Plots - Curve Fitting

The curve fitting plots were generated to view a best-fit distribution. In these plots, we binned intensity values into smaller distance ranges, which captured the average intensity for binned distances and generated a mean intensity for each binned distance (Figure 12). We also removed the values of insignificance, the MMI-1 (not-felt) values, and outliers. We deemed outliers to be intensity values that appear unrealistic for the earthquake's documented magnitude. For example, in Figure 11B there is an intensity value of approximately 6.8 MMI at 170 km, for a 5.0 magnitude earthquake, and an intensity of 3.6 MMI at approximately 3,000 km for an M4.8 earthquake (Figure 11A). Removing the outliers helped add clarity to the plots and provided a better distribution of the data. Table 2 shows the total number response values plotted and the number of values (e.g., MMI=1 and outliers) removed for each of the four magnitudes.

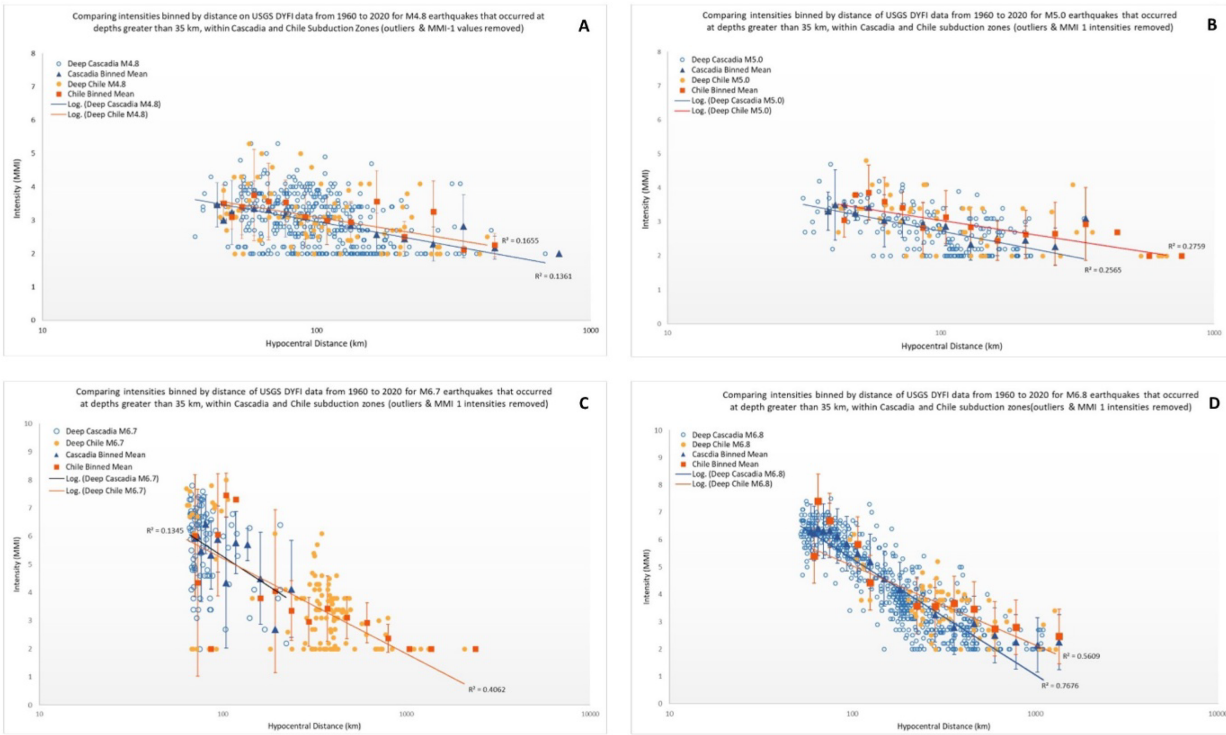


Figure 12: Curve fitting plots for earthquakes in the Chile and Cascadia subduction zones, showing clustering patterns of all response values for each magnitude 4.8 (image A), 5.0 (image B), 6.7 (image C), and 6.8 (image D), and the values for mean and median intensities binned by distance.

Table 2: Showing the number of response values plotted (before MMI=1 and outliers removed) and the number of responses values (MMI=1 and outliers) removed for each of the four magnitudes.

Cascadia	Response Values	Values Removed	Chile	Response Values	Values Removed
M4.8	479	60	**M4.8**	86	9
M5.0	206	18	**M5.0**	63	13
M6.7	96	4	**M6.7**	143	9
M6.8	650	37	**M6.8**	71	0

CONCLUSION & FUTURE RESEARCH

This study compared felt intensity information from deep, intraplate earthquakes in the Cascadia and Chilean subduction zones. The goal was to assess whether felt intensity information from large (M8-8.8) subduction earthquakes in Chile can be used as a proxy for similar events in Cascadia. Overall, the result of this study shows good agreement between felt patterns of deep earthquakes in the two subduction zones, signifying confidence that Chilean intensity data can be representative for megathrust earthquakes in Cascadia.

There were a few limitations in our study, which included the availability and quantity of comparable data. There were limited earthquakes of the same magnitude, as well as an unequal number of response values between Chile and Cascadia, and these factors contributed to our study's comparability limitations. The differences in the quantity of response data between Cascadia and Chile are seen in all plots. All four magnitudes in this study had more response values per event from the Cascadia earthquakes than that of the Chile events. Having a more even distribution of response values between Chile and Cascadia could provide a more robust view of the intensity pattern seen in this study.

The USGS DYFI catalog was invaluable to our study, as it provided us with a vast amount of intensity data for our research. This study not only highlights the value in understanding intensity patterns to be used as a proxy for future large subduction earthquakes in Cascadia, but also highlights the value of the USGS DYFI citizen-based dataset (a globally consistent dataset) in the field of earthquake intensity research.

There is an opportunity to expand this research, by incorporating other earthquake intensity datasets (NRCan in Canada and the Seismological Service of Chile for Chile) (Wald D. J., Quitoriano, Worden, Hopper, & Dewey, 2011). The data collection form or method for deriving intensity rating may differ between datasets, however, and thus data may not be directly comparable. Furthermore, expanding this study into looking at other subduction zones and global DYFI platforms (e.g., Chile or Japan database) would be valuable future research. Additionally, the data we consolidated for this study are a detailed subset of the USGS ComCat database, which contains information for 5 Cascadia and 157 Chilean subduction earthquakes, and this information would benefit from being converted into a relational or non-relational database management system (e.g., Non-SQL or Cloud database). Such a database could be utilized to perform and generate more statistical analysis of our findings.

The next steps for this intensity comparison study have expanded into a companion project (Rutherford & Cassidy, 2022) where we used this same process to investigate shallow (crustal) earthquakes in both Cascadia and Chile.

In conclusion, the results of this study indicate that ground shaking (felt intensity) patterns for deep intraslab earthquakes in Chile and Cascadia are similar. This is useful information for the scientific, engineering and emergency management communities, and suggests that intensity information from large subduction earthquakes in Chile can be applied to Cascadia.

ACKNOWLEDGMENTS

Firstly, we would like to thank Vince Quitoriano (United States Geological Survey (USGS)) for assisting us in navigating the ComCat platform and working with us to acquire DFYI data for felt earthquakes used in this study. We also thank Collin Paul (Earthquake Seismologist with Natural Resources Canada) for developing scripts and analytics, as well as editing contributions to the method section of this report. We thank Alison Bird (Earthquake Seismologist with Natural Resources Canada) for the thorough and thoughtful review of this manuscript. Lastly, we are grateful for the map images in Figure 2 and Figure 3 which Carlos Herrera (Ph.D. Candidate the University of Victoria) kindly produced all the while preparing for his Ph.D. Defense.

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APPENDIX A

Cascadia intraslab earthquakes from 1960 to 2020 used in the intensity comparison study between Cascadia (North America) and Chile (South America) subduction zones.

USGS ID	Event Time	Latitude	Longitude	Depth (km)	Magnitude	Mag-Type	Location	Plate Location	Responses	USGS Links
uw61114971	2015-12-30: T07:39:29	48.5865	-123.3003	52.42	4.8	ml	17km NNE of Victoria, Canada	North America	14,268	https://earthquake.usgs.gov/earthquakes/eventpage/uw61114971/executive
uw10583988	2003-04-25: T10:02:12	47.6705	-123.25	50.513	4.8	md	Olympic Peninsula, Washington	North America	670	https://earthquake.usgs.gov/earthquakes/eventpage/uw10583988/executive
uw10529683	2001-06-10: T13:19:11	47.1675	-123.5025	40.245	5	md	Olympic Peninsula, Washington	North America	1414	https://earthquake.usgs.gov/earthquakes/eventpage/uw10529683/executive
ushis2810	1965-04-29: T15:28:44	47.4	-122.3	59	6.7	mw	Seattle-Tacoma urban area, Washington	North America	180	https://earthquake.usgs.gov/earthquakes/eventpage/ushis2810/executive
uw10530748	2001-02-28: T18:54:32	47.149	-122.7267	51.798	6.8	mw	Puget Sound region, Washington	North America	14,022	https://earthquake.usgs.gov/earthquakes/eventpage/uw10530748/executive

Note: Response values are the aggregation of individual response values, based on a 10-kilometer grid cell.

APPENDIX B

Chile intraslab earthquakes from 1960 to 2020 used in the intensity comparison study between Cascadia (North America) and Chile (South America) subduction zones.

Magnitude 4.8 Earthquakes

USGS ID	Event Time	Latitude	Longitude	Depth (km)	Magnitude	Mag-Type	Location	Plate Location	Responses	USGS Link
us700057ru	2019-08-24: T02:33:00	-31.0978	-71.3676	60.4	4.8	mww	57km SSW of Ovalle, Chile	South America	8	https://earthquake.usgs.gov/earthquakes/eventpage/us700057ru/executive
us2000kbhf	2019-04-06: T21:33:03	-30.0596	-71.3739	61.6	4.8	mb	12km SSW of Coquimbo, Chile	South America	8	https://earthquake.usgs.gov/earthquakes/eventpage/us2000kbhf/executive
us2000j7ac	2019-01-22: T16:19:26	-30.1362	-71.5813	47.1	4.8	mb	30km SW of Coquimbo, Chile	South America	3	https://earthquake.usgs.gov/earthquakes/eventpage/us2000j7ac/executive
us2000802x	2016-12-12: T01:40:25	-30.9368	-71.4241	49.9	4.8	mww	43km SSW of Ovalle, Chile	South America	7	https://earthquake.usgs.gov/earthquakes/eventpage/us2000802x/executive
us10004w9z	2016-03-09: T13:28:11	-30.4412	-71.3451	49.7	4.8	mww	22km NW of Ovalle, Chile	South America	3	https://earthquake.usgs.gov/earthquakes/eventpage/us10004w9z/executive
us10004e2m	2016-01-13: T12:20:39	-19.2847	-70.1676	55.1	4.8	mww	90km S of Arica, Chile	South America	8	https://earthquake.usgs.gov/earthquakes/eventpage/us10004e2m/executive
us10003phn	2015-10-18: T12:48:43	-35.969	-72.668	50.0	4.8	mww	31km W of Cauquenes, Chile	South America	7	https://earthquake.usgs.gov/earthquakes/eventpage/us10003phn/executive
us100034f1	2015-08-24: T05:13:49	-29.882	-71.252	44.7	4.8	mb	2km N of La Serena, Chile	South America	3	https://earthquake.usgs.gov/earthquakes/eventpage/us100034f1/executive
us200030xt	2015-07-28: T18:05:12	-34.9564	-71.8116	44.7	4.8	mwr	51km WNW of Molina, Chile	South America	16	https://earthquake.usgs.gov/earthquakes/eventpage/us200030xt/executive
usc000tiwj	2015-01-25: T08:47:05	-34.756	-71.813	43.4	4.8	mb	43km WSW of Santa Cruz, Chile	South America	13	https://earthquake.usgs.gov/earthquakes/eventpage/usc000tiwj/executive
usb000rsj2	2014-07-13: T03:16:52	-32.949	-71.255	44.1	4.8	mww	7km S of Quillota, Chile	South America	69	https://earthquake.usgs.gov/earthquakes/eventpage/usb000rsj2/executive
usc000lw00	2014-01-02: T22:39:44	-32.961	-71.386	44.8	4.8	mb	9km N of Villa Alemana, Chile	South America	28	https://earthquake.usgs.gov/earthquakes/eventpage/usc000lw00/executive
usp000jqz4	2012-08-28: T08:11:25	-32.418	-71.169	44.3	4.8	mb	Valparaiso, Chile	South America	10	https://earthquake.usgs.gov/earthquakes/eventpage/usp000jqz4/executive
usp000jc4g	2011-12-12: T20:23:59	-34.756	-71.866	46.6	4.8	mb	Libertador General Bernardo O'Higgins, Chile	South America	20	https://earthquake.usgs.gov/earthquakes/eventpage/usp000jc4g/executive
usp000htvn	2011-01-30: T21:48:28	-29.881	-71.503	50.0	4.8	mb	Offshore Coquimbo, Chile	South America	20	https://earthquake.usgs.gov/earthquakes/eventpage/usp000htvn/executive
usp000h9fc	2010-03-15: T21:25:32	-21.288	-69.929	48.5	4.8	mb	Tarapaca, Chile	South America	7	https://earthquake.usgs.gov/earthquakes/eventpage/usp000h9fc/executive
usp000gwp7	2009-04-29: T16:24:40	-29.999	-71.392	43.6	4.8	mb	Offshore Coquimbo, Chile	South America	5	https://earthquake.usgs.gov/earthquakes/eventpage/usp000gwp7/executive

Magnitude 5.0 Earthquakes

USGS ID	Event Time	Latitude	Longitude	Depth (km)	Magnitude	Mag-Type	Location	Plate Location	Responses	USGS Link
us70006t6h	2020-01-01: T16:51:32	-30.2857	-71.5582	40.88	5.0	mwr	42km SSW of Coquimbo, Chile	South America	10	https://earthquake.usgs.gov/earthquakes/eventpage/us70006t6h/executive
us10003r82	2015-10-24: T21:24:45	-31.442	-71.4883	39.92	5.0	mww	37km NW of Illapel, Chile	South America	6	https://earthquake.usgs.gov/earthquakes/eventpage/us10003r82/dyfi/intensity
usc000mlx1	2014-02-10: T04:13:44	-38.4428	-73.1942	38.03	5.0	mb	28km N of Carahue, Chile	South America	14	https://earthquake.usgs.gov/earthquakes/eventpage/usc000mlx1/dyfi/responses
usp000jdw8	2012-01-23: T21:55:16	-36.338	-73.031	39.7	5.0	mb	offshore Bio-Bio, Chile	South America	14	https://earthquake.usgs.gov/earthquakes/eventpage/usp000jdw8/executive
usp000j3xt	2011-06-29: T08:22:13	-32.237	-71.337	42.6	5.0	mb	Valparaiso, Chile	South America	24	https://earthquake.usgs.gov/earthquakes/eventpage/usp000j3xt/executive
usp000hkar	2010-09-06: T03:20:46	-37.785	-73.423	39.3	5.0	mwc	Bio-Bio, Chile	South America	19	https://earthquake.usgs.gov/earthquakes/eventpage/usp000hkar/executive
usp000hhtg	2010-08-09: T12:13:43	-38.717	-73.149	38.7	5.0	mb	Araucania, Chile	South America	31	https://earthquake.usgs.gov/earthquakes/eventpage/usp000hhtg/executive
usp000hdu8	2010-06-11: T08:54:19	-34.753	-71.822	39.6	5.0	mb	Libertador General Bernardo O'Higgins, Chile	South America	13	https://earthquake.usgs.gov/earthquakes/eventpage/usp000hdu8/executive
usp000hbw4	2010-04-25: T15:42:23	-37.526	-72.879	40.6	5.0	mb	Bio-Bio, Chile	South America	13	https://earthquake.usgs.gov/earthquakes/eventpage/usp000hbw4/executive
usp000h9r5	2010-03-20: T10:04:37	-34.406	-71.723	39.8	5.0	mb	Libertador General Bernardo O'Higgins, Chile	South America	10	https://earthquake.usgs.gov/earthquakes/eventpage/usp000h9r5/executive

Magnitude 6.7 Earthquakes

USGS ID	Event Time	Latitude	Longitude	Depth (km)	Magnitude	Mag-Type	Location	Plate Location	Responses	USGS Link
us2000j6hy	2019-01-20: T01:32:52	-30.0404	-71.3815	63	6.7	mww	10km SSW of Coquimbo, Chile	South America	789	https://earthquake.usgs.gov/earthquakes/eventpage/us2000j6hy/dyfi/intensity
usp000fujd	2007-12-16: T08:09:17	-22.954	-70.182	45	6.7	mwb	Antofagasta, Chile	South America	45	https://earthquake.usgs.gov/earthquakes/eventpage/usp000fujd/dyfi/intensity

Magnitude 6.8 Earthquakes

USGS ID	Event Time	Latitude	Longitude	Depth (km)	Magnitude	Mag-Type	Location	Plate Location	Responses	USGS Link
us10003vgt	2015-11-07: T07:31:43	-30.8796	-71.4519	46	6.8	mww	39km SW of Ovalle, Chile	South America	210	https://earthquake.usgs.gov/earthquakes/eventpage/us10003vgt/dyfi/intensity
usc000eyp3	2013-01-30: T20:15:43	-28.094	-70.653	45	6.8	mww	56km NNE of Vallenar, Chile	South America	122	https://earthquake.usgs.gov/earthquakes/eventpage/usc000eyp3/dyfi/intensity

Note: Response values are the aggregation of individual response values, based on a 10-kilometer grid cell.

APPENDIX C

Folder locations documentation for the - Earthquake Intensity Comparison Study

Project database compiled by: Jessica Rutherford (Research Scientist Contractor with Gyp-Sea Natural Science Consulting). Email: jmr.rutherford@gmail.com

Data and information on this project have been transferred to the Pacific Geological Centre server.
For specific information contact: Dr. John Cassidy at email address: john.cassidy@nrcan-rncan.gc.ca

Main Folder	Project Folders	Subfolders/Files	Content
Chile Cascadia Intensity Project (Rutherford & Cassidy, 2022)	Deep Earthquake Intensity Study (Cascadia Chile)	Final Deep Combined Plots Old Versions (Working Anaysis of Combine Plots) USGS Data Deep Cascadia Earthquakes USGS Data Deep Chile Earthquakes Deep_M4.7_CombinedChileCascadia_Graphs.xlsx Deep_M4.8_CombinedChileCascadia_SeperatePlots.xlsx Deep_M5.0_GraphsCombined_SeperatePlots.xlsx Deep_M6.7_CombinedChileCascadia_SeperatePlots.xlsx Deep_M6.8_CombinedChileCascadia_SeperatePlots.xlsx Images_DeepRevisedPlots(Dec30,2021).pptx Images_DeepRevisedPlots(Dec302021).jfc.pptx Images_DeepRevisedPlots(Jan-12-2022)..pptx Revised_M4.8_DeepCombined_2022.xlsx Revised_M5.0_DeepCombined_2022.xlsx Revised_M6.7_DeepCombined_2022.xlsx Revised_M6.8_DeepCombined_2022.xlsx Cascadia_M4.7_events Cascadia_M4.8_events Cascadia_M5.0_events Cascadia_M6.7_events Cascadia_M6.8_events JSON to CSV to Excel Old Version of Graphs Images ComCat_Search_DeepCascadia.xlsx ComparisonStudy_ProcessSteps.txt DeepCascadiaEarthquakes_USGSLinks.xlsx FileDownload_tracking.xlsx Chile_4.7M_events Chile_4.8M_events Chile_5.0M_events Chile_6.7M_events Chile_6.8M_events json_to_csv ComCatDeepChileSearchResults ComCatSearch_DeepChile_Earthquakes ToDo_email	These folders contain all data, documents, and images used in the Deep earthquake intensity comparison study. Information in these folders includes working and final plots, images, and documents. Raw data downloaded from the USGS COMCAT platform are in the folders (USGS Data Deep Cascadia/Chile Earthquakes). They also contain the raw data, JSON file conversion files, and scripts. 'Old Versions…" folders with old plots and analytics have been left in these folders for future reference. Final Excel documents and images of plots for figures used in this Open File report are in the "NRCan Open File Publication Documents" folder (see below).
Chile Cascadia Intensity Project (Rutherford & Cassidy, 2022)	Chile Cascadia Intensity Study - NRCan Open File Documents	Crustal Earthquakes Deep Earthquakes Previous versions of publication sections Reference Source Publications Documents for Appendix Final Open File Document Images In Report Previous Section Versions	The "Deep Earthquakes" folder contains the drafts and final reports, images/figures, and appendix sections for the NRCan Open File report. There are previous drafts of the report sections, which highlight the edited and changes made for the final report.