Earthquake Catalog Processing and Swarm Identification for the Pacific Northwest

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Abstract

The Pacific Northwest (PNW) of North America encompasses diverse tectonic settings that can produce damaging earthquakes near population centers. Seismicity in this region is often clustered into aftershock sequences and swarms, and their patterns and frequencies differ across subregions or tectonic regimes. Characterizing the seismicity of the PNW requires a catalog of observed earthquakes. Furthermore, applications with the catalog may require earthquake clusters to be identified and regarded separately. Unlike previous studies, we explicate how to overcome challenges when combining catalogs from different countries, particularly in accounting for duplicate events and other discrepancies. We apply this to merge authoritative catalogs for the United States and Canadian portions of the PNW, along with a third dataset with data quality measures. We also perform a window-based search for earthquake clusters, which then get labeled as possible or definite swarms or aftershock sequences. We further split the catalog into its two primary tectonic regimes. We then study the PNW catalog's completeness, and the extent to which this varies between the northern and southern parts of the region. We provide a harmonized international PNW catalog with derived variables describing earthquake clustering and tectonic regimes. This entire processing pipeline has also been fully documented and is supported with software, enabling its use in other seismic regions.

Cite this article as Schneider, M., H. Flury, P. Guttorp, and A. Wright (2023). Earthquake Catalog Processing and Swarm Identification for the Pacific Northwest, *Seismol. Res. Lett.* **94**, 2500–2513, doi: 10.1785/0220220374.

Supplemental Material

Introduction

This article describes the creation of a new international catalog for the Pacific Northwest (PNW) of North America. Our catalog explicitly classifies earthquakes into tectonic regimes and identifies earthquakes occurring in clusters, allowing for more detailed analyses on the key dimensions affecting the region's seismic risk.

PNW seismicity

The tectonic environment of the PNW hosts several distinct tectonic regimes. The Juan de Fuca plate under the Pacific Ocean is subducting under the North American continental plate, which creates a fault capable of generating massive but infrequent megathrust events, the latest of which occurred in 1700 (Ludwin *et al.*, 2005). The geological conditions and processes within the depths of the subducting slab of rock can also produce large and damaging intraslab earthquakes. Numerous shallow faults in the crust of the North American plate also produce crustal earthquakes, which are the most common type of seismicity in the PNW. Furthermore, the subduction zone gives rise to numerous volcanoes; these volcanic earthquakes can occur in spatiotemporal clusters (swarms), which follow patterns distinct from earthquakes triggered by a previous earthquake (aftershock sequences; Llenos and Michael, 2013). The PNW's earthquakes are distributed inhomogenuously across the U.S. states of Washington and Oregon and the Canadian province of British Columbia (Bostock *et al.*, 2019; Gomberg and Bodin, 2021).

Many regions in the PNW with significant seismic hazard lie directly under urban areas (Frankel *et al.*, 2015). To reduce this seismic risk, the U.S. Geological Survey's (USGS) Subduction Zone Science Plan calls for improving seismic hazard assessments and creating regional aftershock forecasts (Gomberg and Ludwig, 2017). The clustering types and tectonic regimes that characterize the PNW affect both the goals.

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We sought to develop an instrumental catalog for the PNW that could specifically address these issues.

Some recent work has investigated the seismicity of the PNW using catalogs from the seismic networks in the United States and Canada. Bostock *et al.* (2019) separately characterized crustal and intraslab seismicity, proposing geological and geophysical factors to explain their different patterns. They used an international catalog that consisted of events from 1984 to 2018 with magnitude (**M**) ≥1, in a region bounded by latitude 39°–51° N and longitude 118°–130° W. In Gomberg and Bodin (2021), a catalog with a different spatial extent and higher magnitude threshold was compiled to study how the productivity of aftershock sequences varied across the PNW. Both the studies used a 3D model for the location of the slab interface (McCrory *et al.*, 2012; Hayes *et al.*, 2018) to split earthquakes into the intraslab or crustal regimes. In Malone (2019), a catalog with an even higher magnitude threshold solely for the US portion of the PNW was used to investigate whether seismicity has decreased in recent decades. The completeness of these catalogs was not assessed prior to their analysis. Other studies on PNW seismicity have focused on smaller subregions (Merrill and Bostock, 2019; Gomberg *et al.*, 2012), quarry blasts (Brocher *et al.*, 2003), or earthquakes in specific tectonic regimes, for example, intraslab only (Thompson *et al.*, 2022).

The few prior studies that have merged catalogs from the United States and Canadian seismic networks included only minimal description of the handling of discrepancies between catalogs. Furthermore, the clustering of earthquakes across the PNW has been studied in just one article (Gomberg and Bodin, 2021), which only investigated aftershocks, ignoring the presence of swarms in the region. The lack of a well-documented international catalog with clusters identified limits the research on PNW seismicity and subsequent seismic risk.

Processing catalogs from multiple sources

A catalog for the international PNW requires combining the catalogs of the Pacific Northwest Seismic Network (PNSN) and Natural Resources Canada's Geological Survey of Canada (GSC) for the United States and Canadian portions of the region, respectively. The presence of considerable seismicity at the national border (particularly around the densely populated Puget Sound) means that using a single country's network may bias the assessment of seismicity in the catalog. Furthermore, no earthquake measurement is error-free, and the quality of an earthquake's reported data is a function of the number of seismic stations that recorded it in a network, as well as the distances and positions of those stations relative to one another (Ammon *et al.*, 2020). Networks routinely provide estimates for the errors for each earthquake's epicentral location, depth, and magnitude, as well as the number of stations that recorded each earthquake, their minimum distance to it, and other variables that characterize data quality (Husen and Hardebeck, 2010). In the PNW, these measurement errors are nontrivial, and vary throughout space and time (Brocher *et al.*, 2003). The PNSN does not make these variables available for public download; we thus used the Comprehensive Earthquake Catalog (ComCat) of the Advanced National Seismic System to retrieve data quality variables for PNSN events.

Merging together three catalogs requires first reconciling different types of discrepancies. Duplicate entries need to be removed both within a single catalog and across each pair of catalogs in all overlapping zones. Furthermore, one must identify earthquakes detected by one network but not another, as well as mismatches in earthquake data between the two catalogs that are supposed to match each other (PNSN and ComCat). The previous studies have not provided sufficient information to make these procedures reproducible (i.e., Bostock *et al.*, 2019 write that they "[took] care to remove duplicate events" without explaining how). We base our approach on the previous work that focuses on combining catalogs, including Mueller (2019), which merges multiple regional catalogs for the USGS's National Seismic Hazard Model. Other studies have combined catalogs across Europe (Grünthal and Wahlström, 2003) or even globally (Nievas *et al.*, 2020), explicating how they check and resolve duplicates. Procedures differ by the tolerances authors set for the time period, magnitude interval, and spatial window with which matching earthquakes are considered duplicates.

Once the catalogs have been harmonized, we use a geophysical model (McCrory *et al.*, 2012), following previous authors (Gomberg and Bodin, 2021), to characterize events as being above the slab interface (crustal regime) or below it (intraslab regime). This allows for each tectonic regime to be analyzed separately.

Window-based detection of earthquakes clusters

Understanding that earthquakes are clustered in time and space is fundamental for modeling catalogs. Seismic hazard assessments generally require a declustered catalog containing only background seismicity or those earthquakes that were not triggered by a previous earthquake. Aftershock forecasting naturally requires aftershock sequences to be identified and separated from other ways that seismicity can be clustered, such as earthquake swarms. Swarms are earthquake clusters where events are not triggered by a previous earthquake, as in aftershock sequences; rather, they occur because of aseismic sources, such as from underground fluids (volcanic magma or groundwater; Roland and McGuire, 2009) or anthropogenic sources (such as wastewater injection; Llenos and Michael, 2013). Swarms manifest in a catalog as brief surges in the seismicity rate for a subregion beyond what is typical for its background seismicity. Although individual swarms have been documented in the PNW for decades (see the Searching for Documented Swarms in Catalog section, available in the supplemental material to this article), the previous studies for the full PNW region have not included the detection or assessment of swarms.

TABLE 1
Target and Auxiliary Catalog Parameters and Number of Events for Initial Catalogs

Catalog	Latitude (°)	Longitude (°)	Magnitude	Time Window (yyyy/mm/dd–yyyy/mm/dd)	Size	Size (Without MSH)
PNSN (target)*	42° N × 49° N	125° W × 116.5° W	**M** 2.0+	1970/01/01–2019/01/01	14,176	7,815
ComCat (target)*	42° N × 49° N	125° W × 116.5° W	**M** 2.0+	1970/01/01–2019/01/01	14,629	8,049
GSC (target)*	42° N × 49° N	125° W × 116.5° W	**M** 2.0+	1985/01/01–2019/01/01	1,118	1,117
ComCat (auxiliary)†	41° N × 50° N	126° W × 115.5° W	**M** 1.3+	1970/01/01–2019/01/01	49,806	37,554
GSC (auxiliary)†	41° N × 50° N	126° W × 115.5° W	**M** 1.8+	1985/01/01–2019/01/01	2,110	2,109

*The latitude and longitude correspond to a rectangular box around the US states of Washington and Oregon, which includes a portion of British Columbia. The time window for Pacific Northwest Seismic Network (PNSN) and Comprehensive Catalog (ComCat) begins in 1970, when the instrumental record of the PNSN began. For Geological Survey of Canada (GSC, which uses a different set of stations than the PNSN), the catalog begins in 1985 because location and magnitude calculations are inconsistent before and after 1985 (C. Brillon, personal comm., 2020). However, additional Canadian events detected by the US networks prior to 1985 are included in the catalog (see the GSC and US catalogs section). We include magnitudes above 2.0 on whichever scale the earthquake was measured in (see the Magnitude scales between catalogs section), following expert advice (S. Malone, personal comm., 2020) and previous literature (Gomberg and Bodin, 2021). For all catalogs, we included only "earthquake" or "quake" event types, excluding explosions and low-frequency events. After downloading the initial catalogs, we omitted events near the active volcano Mt. St. Helens (MSH in last column; see the Detecting spatiotemporal earthquake clusters section).

†The auxiliary zone consists of the target zone plus a 1° margin in latitude and longitude, and a 0.2 lower margin in magnitude (**M** 1.8+). We downloaded data for the ComCat catalog with an even lower magnitude threshold to be able to match to corresponding PNSN or GSC events with different magnitudes (due to either reanalyzed magnitudes or different magnitude scales).

Exact definitions of swarms based on catalog variables do not exist. The previous methods to identify swarms required analysis of very low-magnitude events (e.g., Farrell *et al.*, 2009) or each event's waveforms (e.g., Vidale and Shearer, 2006; Skoumal *et al.*, 2016). Aftershock models can also diagnose a period of swarm-like seismicity by patterns of elevated background seismicity rate or sharp deviations in triggering parameters (Okutani and Ide, 2011; Llenos and Michael, 2013). These approaches are not suitable for our case, because we seek to detect swarms without appealing to events below the magnitude of completeness, or fitting background or aftershock parameters that can be biased in the presence of swarms (Llenos *et al.*, 2009). Thus, we require a different method to identify swarms and aftershock sequences suitable for small and regionally varying catalogs like the PNW. We developed a deterministic procedure that detects spatiotemporal earthquake clusters as multiple earthquakes in a given space–time window. The identified clusters were then hand labeled using expert opinion as swarms or aftershock sequences.

In this article, we describe a novel international catalog for the PNW with earthquakes flagged in swarms and aftershock sequences, and sorted between crustal and intraslab tectonic regimes. After combining catalogs from the PNSN, GSC, and ComCat, we carefully handle catalog discrepancies such as duplicates and mismatches between and within catalogs. We then apply a window-based procedure to identify earthquakes occurring in spatiotemporal clusters for labeling as swarms or aftershock sequences. We release the catalog together with software that accomplishes these tasks, which may benefit other researchers (see the supplemental material). Finally, we visually summarize the resulting PNW catalog and perform the (to our knowledge) first-ever completeness analysis for this region, identifying differences in completeness between the northern and southern areas of the PNW.

Catalog Specifications

We describe here the catalogs collected for the international PNW region. A seismic network's catalog's spatial limits commonly correspond to the region for which the network is authoritative. A catalog often begins at the time when the network started collecting instrumental data or had sufficient station coverage to ensure consistent earthquake detection. The magnitude threshold is usually set to the network's magnitude of completeness or the minimum magnitude for which it can expect to detect earthquakes throughout the spatiotemporal boundaries defined earlier.

These boundaries are based on network operations rather than seismic sources and can bias statistical models made on catalog data (e.g., Zhuang, 2011). The spatial restriction is of particular concern in a region with frequent seismicity on its borders, like the PNW. In these cases, seismicity modelers often fix the temporal range, and consider a target spatiomagnitude zone of interest and an auxiliary zone, which consists of the target zone plus some margin zone around it. We define the target and auxiliary zones for the PNW in Table 1.

We collect catalog data from three sources: the PNSN (authoritative for the US states of Washington and Oregon), GSC (authoritative for the Canadian province of British Columbia), and ComCat, which combines data from all US global and regional seismic networks, prioritizing the authoritative network for each earthquake's location (Malone *et al.*, 1996). Thus, ComCat is designed to have authoritative catalog data for the bordering states of the PNW (California, Nevada, Idaho), as well as for Washington and Oregon. But catalogs are dynamic; so each network's earthquake data can be added or revised when it processes more information (Ammon *et al.*, 2020); this means that ComCat may not contain the most updated catalog data in each individual network. ComCat also provides additional variables related to catalog data quality (see the Processing catalogs from multiple sources section), which are missing from the available PNSN catalog; thus, we need to merge the PNSN and ComCat datasets to get this data for PNW earthquakes.

We used the parameters in Table 1 to download catalog data from PNSN (University of Washington, 1963), GSC (Natural Resources Canada, 1975), and ComCat (Malone *et al.*, 1996) (see Data and Resources). We also used several search parameters specific to ComCat: not specifying earthquakes' depth or azimuthal gap and not restricting earthquakes' review status, impact, catalog, contributor, or product type. Data were downloaded for the auxiliary zone, and earthquakes were flagged as in the target or margin zones with an indicator variable. The description of catalog variables is in the Variables in Final PNW Catalog section, in the supplemental material.

Magnitude scales between catalogs

Earthquake magnitudes are measured by several scales, and this can vary both between networks and within a single network over time. The PNSN almost exclusively used the duration magnitude scale (M_d, Richter, 1935) prior to 2011 and the local magnitude scale (M_l, Lee *et al.*, 1972) afterward due to a change in their waveform analysis software (Malone, 2019). GSC used several magnitude scales throughout the catalog period; but M_l is the dominant scale, accounting for over 98% of earthquakes in this catalog. There are various conversion formulas between different magnitude scales (see, e.g., Grünthal and Wahlström, 2003); we left earthquakes' magnitudes unconverted and included their magnitude scale for future conversion as needed.

We examined magnitude frequencies for 10 yr periods of the PNSN catalog for a signal stemming from the change in magnitude scale in 2011 (see Fig. S1). No difference could be detected following 2011, aside from a smaller number of events, which has been previously reported (Malone, 2019). This suggests that the change in magnitude scales in the PNSN should not affect full-catalog statistics.

Identifying and Handling Catalog Discrepancies

This section describes our approach to identify and resolve common data issues prior to merging catalogs. We algorithmically identified discrepancies between catalogs using similar procedures to Mueller (2019) and Nievas *et al.* (2020). There were three steps in this processing pipeline (see the Terminology for Catalog Matching section, in the supplemental material, for definitions of the terminology used subsequently):

1. identify and remove duplicate records within each of the three catalogs;
2. find the correct match for each PNSN event within the ComCat catalog for subsequent merging by ID. Not all PNSN events could be matched by ID to a partner in ComCat, requiring us to also match by event variables; and
3. process duplicates and discrepancies between GSC and the US catalogs by identifying all events within a catalog outside their authoritative region (e.g., Canadian events in the PNSN catalog). Determine whether these are duplicates for an event within the authoritative catalog (in which case, flag for removal) or separate events that the authoritative catalog did not detect (in which case, keep); see Figure 1.

To find duplicates and match events across catalogs, we used the tolerances for event variables that the USGS takes for combining catalogs for seismic hazard analysis (Mueller, 2019; see Table 2). The tolerances for location and time were doubled before 1990 when PNSN station density was lower (see PNSN station maps in Figs. S6 and S7). We kept the same high magnitude tolerance for both the periods due to the variety of magnitude scales in the catalogs. We used these to first resolve any duplicates and data mismatches, and harmonize event IDs between PNSN and ComCat. After this, we handled duplicates between the US catalogs (PNSN and ComCat) and the GSC catalog, and finally combined the processed US and Canadian catalogs to obtain an international PNW catalog.

PNSN and ComCat

We first checked for and found no duplicate events within the PNSN and the ComCat catalogs, neither by ID nor by value. We then attempted to match the PNSN catalog and ComCat target-zone catalog so they may be merged. In principle, both the event IDs and event variables for ComCat target events should be the same as those in PNSN, because it is the authoritative network for this area. However, numerous discrepancies exist between the PNSN and ComCat events, which can be linked to two causes:

1. The PNSN data were reanalyzed or relisted under a different event ID and not yet updated in ComCat; or
2. ComCat had data from a different network for this event, for example, the Northern California network.

To identify and address these discrepancies, we matched each PNSN event to ComCat. When the PNSN event could be matched by ID, we assessed whether its event variables constituted a strict match, loose match, or mismatch; see results in Table S1. There were 949 events for which event variables did not strictly match and seismologists at the PNSN confirmed that

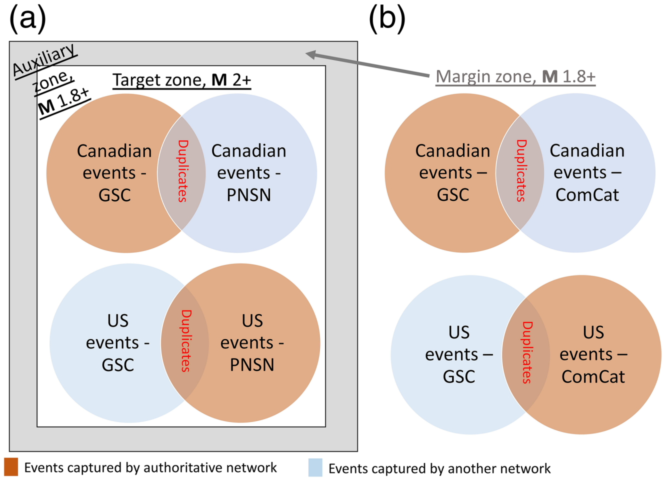

Figure 1. Diagram showing component spatiomagnitude catalogs (colored circles) that comprise the target zone (a) and margin zone (b) of the Pacific Northwest catalog (not drawn to scale). We always prefer data values from the authoritative network for events within its territory (Pacific Northwest Seismic Network [PNSN] and Comprehensive Catalog (ComCat) for US events and Geological Survey of Canada [GSC] for Canada events; orange circles). We also add events detected by other networks that could not be matched to an event from the authoritative network (blue circles), removing duplicates. The margin catalog (b) includes events in a 1° margin around the target spatial zone (**M** 1.8+) and also events of **M** 1.8–2.0 within the target zone. The color version of this figure is available only in the electronic edition.

we should take the value from PNSN. Most of these earthquakes had data that were reanalyzed by PNSN (meaning they will be merged with their older values for data quality variables from ComCat). However, when mismatches existed between PNSN and ComCat's event variables, they were usually not large. Only 1.2% of all PNSN events had a magnitude mismatch with ComCat—the most common mismatch type, most of which were less than 0.5 units.

There were 88 PNSN events that could not be matched by ID to ComCat, and we attempted to match them by value, first strictly, then loosely, and then manually; see results in Table S2. Of the 36 events that could not be matched at all, a PNSN seismologist flagged a single event that was a probable blast and should be removed.

TABLE 2
Tolerances for Each Event Variable Used for Loosely Matching Events Between Catalogs

Variable	Before 1990	1990 and After
Epicenter location	±50 km	±25 km
Time	±20 s	±10 s
Magnitude	±0.5	±0.5

For those PNSN events where a (strict, loose or manual) match was found in ComCat and confirmed by a seismologist, we changed the event ID in ComCat to correspond to its match in PNSN. Most of these unpartnered events were at a state border, and ComCat had used another seismic network's event values rather than PNSN's. There were 35 PNSN events that were unmatchable to an event in ComCat, which PNSN seismologists advised to keep in the catalog. Because these events will not merge with a corresponding entry in ComCat, their data quality variables will be missing.

GSC and US catalogs

We first searched for duplicates in GSC by strictly and loosely matching all earthquakes to each other, and found 15 pairs of duplicate events. These were confirmed by a GSC seismologist to be duplicates, and we were instructed which event to remove from each pair.

To combine catalogs across national borders, one needs to remove duplicates between them. This first step required finding the earthquakes in each national catalog that occurred outside its authoritative zone (e.g., US events that were detected by GSC). If such an event duplicates an event in the authoritative catalog, then it is flagged for removal; however, if it is not detected by the authoritative catalog, it is a valid additional earthquake that we include in our final combined catalog. We split the GSC catalog into the spatiomagnitude target and margin zones for comparison with PNSN and ComCat, respectively (see Table 1). The margin zone has all earthquakes above magnitude 1.8 in the spatial difference between the auxiliary and target zones—a 1° latitude–longitude margin around the target zone. It also includes earthquakes of magnitudes 1.8–2.0 in the target area (see Fig. 1). We matched events by value as the networks used different ID systems.

Target zone (comparison with PNSN). We searched for duplicates between the GSC target zone and the PNSN catalog. Given that magnitude scales varied between catalogs, we considered GSC events within the spatial bounds but below the target **M** 2.0 threshold for comparison with PNSN. We further split the catalog into US and Canadian events using an official dataset for the United States–Canada border (National Oceanic and Atmospheric Administration [NOAA] Office of Coast Survey, 2020). Within the target zone, there were 1051 GSC events located in the United States, 914 of which could be loosely or manually matched to a PNSN event using tolerances in Table 2 (see results in Table S3 and Schneider, 2021 for further details).

We then matched the remaining GSC events (both loosely and manually) to a PNSN catalog with lower minimum magnitude of **M** 1.5 (taking all other parameters for the target catalog in Table 1). Several more GSC events had matches in the ComCat margin catalog and thus were outside the boundaries of the target zone. The remaining unmatchable GSC events were examined by PNSN seismologists, who identified them either as probable blasts or as having a partner in the PNSN catalog that was outside even the margin zone, flagging them for removal. There were 14 US GSC events that had no match in the PNSN and therefore will remain in the catalog.

We also checked whether Canadian PNSN events were already detected by the GSC catalog. Of the 89 Canadian events in the PNSN, only 30 could not be matched to an GSC event, neither strictly loosely nor manually. Of these, nine events were matched by a GSC seismologist to a GSC event under the target zone's magnitude threshold (thus, flagged for removal). 19 PNSN events took place before 1985 (when the GSC catalog begins), and two more events could not be matched to a GSC partner; so these 21 Canadian events in PNSN will remain in the final catalog.

Margin zone (comparison with ComCat). We compared the GSC margin zone's catalog with the corresponding ComCat catalog for the margin zone. Within the margin zone, there were 467 GSC events in the United States. We could loosely or manually match the majority of these events to the ComCat catalog (see results in Table S4). Of the 84 unmatchable events, PNSN seismologists either identified their partners in ComCat outside the margin zone or as probable blasts for all but 38 events, which then remained in the final catalog.

We also searched for Canadian ComCat margin events that matched an event in the GSC margin catalog. Of the 684 ComCat margin events located in Canada, we loosely or manually matched 276 events and flagged 194 events for removal, because they were under the margin's magnitude threshold. Of the 214 unmatchable events, a GSC seismologist identified several probable blasts and a few other partners in GSC events not in our downloaded catalog. The remaining 207 Canadian events in the ComCat margin catalog remained in the final catalog.

Identifying and Handling Earthquakes in Swarms

Swarms are spatiotemporal clusters of earthquakes that can affect models of a catalog, for example, for seismic hazard assessment or aftershock forecasting, and must thus first be detected in the catalog. We used the following two-step strategy to identify swarms for the PNW. In the first step, we search for all earthquake clusters based on spatiotemporal windows and rules; each cluster is then inspected by an analyst (and study coauthor) and categorized as a possible or definite swarm or aftershock sequence. The second step is a literature search to find previously reported PNW swarms and identify these in the catalog.

Detecting spatiotemporal earthquake clusters

Although some authors have used a purely visual approach (Holtkamp and Brudzinski, 2011) to identify swarms, this can be formalized using prespecified spatiotemporal windows to collect earthquakes into clusters, as in classical declustering procedures (e.g., Reasenberg, 1985). We propose the following simple and region-specific procedure to identify earthquakes in spatiotemporal clusters. Our procedure is similar to the CURATE method (Jacobs *et al.*, 2013), in which prespecified spatial and temporal parameters are applied to find candidate clusters, followed by boundary checking. All parametric (window-based) cluster detections will result in different clusters under different parameter values; we ran sensitivity studies using different window parameters and ultimately chose parameters resulting in the most liberally selected clusters. Our aim was to first detect all seismicity that may be clustered, which was then validated and classified by expert opinion in the second stage. Neither cluster detection nor swarm classification has a unique solution for a given catalog, so we used expert review to offer a more authoritative (though less reproducible) result for the PNW.

We performed the following procedure solely on the PNSN target catalog.

1. Split the region into five areas, as is common in seismicity analysis across large regions with disparate seismicity patterns (Veen and Schoenberg, 2008). We delineated these areas to minimize separating regions of concentrated seismicity, creating areas that nearly align with those used in Brocher *et al.* (2003, see their fig. 5) and considered known fault distributions to the extent possible (see Fig. 2).
2. Find temporal clusters: Identify clusters of three earthquakes occurring within an area within a seven-day period; this constitutes a temporal cluster. After this criterion is met, continue checking whether the next event that come after the second-to-last earthquake in the cluster also occurs within seven days of it (thus continuing to make three consecutive earthquakes in seven days). All the events meeting this criterion will belong to the same temporal cluster until the criterion is no longer met.
3. Find spatiotemporal clusters: Restrict the temporal clusters to those in which at least three events are within an area of 50 km^2 of one another.
4. Find spatiotemporal-depth clusters: Categorize clusters as shallow or deep if all but a maximum of two events took place above or below 30 km, respectively (this cutoff was chosen from a visual examination of the catalog's depth distribution; see Fig. S2). A mixed cluster is a cluster that is neither a shallow nor deep cluster. For shallow and deep clusters, remove events that were not within the majority depth categorization (at most two events) from the cluster. For mixed clusters, keep all events. See the Note for Step 4 of Swarm Identification Procedure section, in the supplemental material, for special conditions for handling clusters of size five.
5. Inspect area boundaries: Visually check the border regions of the five areas for whether any visible spatial clusters

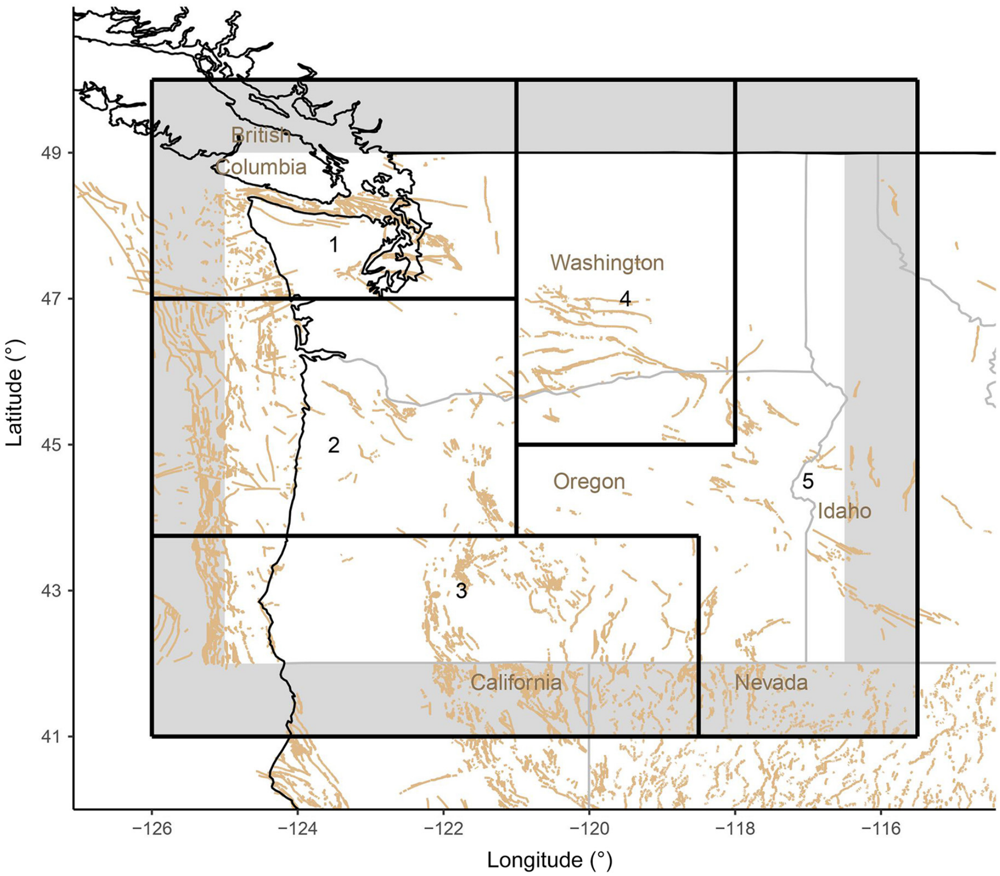

Figure 2. Map of the auxiliary Pacific Northwest (PNW) split into areas for cluster identification. The brown lines show faults from the U.S. Geological Survey (USGS) Quaternary Fault and Fold Database (Survey, 2023). Clusters were only searched for in the target zone (white background) and not margin zone (gray background). The color version of this figure is available only in the electronic edition.

existed that met the criterion of three events in seven days within 50 km^2.

6. Perform visual and criterion recheck: Visually inspect all identified clusters and remove earthquakes that are not located where the cluster is concentrated (obvious spatial outliers). Dissolve any of the remaining clusters in which the criterion of three events in seven days within 50 km^2 is no longer met.

We summarized clusters with maps and plots of magnitudes and times (see Figs. S3–S5).

Before running the cluster detection procedure, we had to address seismicity near Mt. St. Helens—an active volcano in Washington that also lies by several faults. The volcano generated several prolonged periods of swarm activity during our catalog period. Volcano-induced earthquakes are often indistinguishable from tectonic events in active volcanic zones and can dominate catalog statistics, so we exclude events near Mt. St. Helens from our catalog. Specifically, we removed any events within a circular area of radius 10 km from the volcanic center at (122.1956° W, 46.1914° N), following other studies of PNW seismicity (Malone, 2019).

Swarms in the PNW

Through our window-based procedure, we detected 322 distinct clusters in the target catalog, involving 2620 events. PNSN seismologists classified each detected cluster as a possible or definite swarm or aftershock sequence, using a six-point scale, shown in Figure 3 (left). To make these classifications, they primarily used the clusters' spatial clustering, magnitude–time distribution, the range of depth values, and the difference between the highest and the second highest magnitudes. To manage complexity, we drew a dichotomy between swarms and aftershock sequence, that is, not considering whether a swarm may have earthquakes that triggered their own aftershocks.

In total, 68 clusters (consisting of 418 events) were confirmed as swarms, whereas 42 clusters (consisting of 147 events) were classified as possible swarms. In addition, 97 clusters (consisting of 546 events) were classified as either possible or definite aftershock sequences. Comments were provided for each cluster, indicating whether it contained subclusters that should be classified separately or individual events that did not belong to the bulk of the cluster. We made the appropriate splits or removal of events, ensuring that the resulting clusters still maintained the criteria in steps 2–4 (i.e., still had its first 3+ events within 50 km^2 in a consecutive seven-day period), dissolving any (sub)cluster not meeting these criteria. For all resulting clusters, we assigned the scale value given to a cluster to each event in the cluster.

Numerous swarms have also been previously documented in the PNW; however, because of the longer time duration or lower magnitudes of their events, they may not have been detected by our window-based search. Thus, we also searched for catalog events that are part of swarms documented in the published sources. Using the search procedure documented in the Searching for Documented Swarms in Catalog section, in the supplemental material, we found nine documented

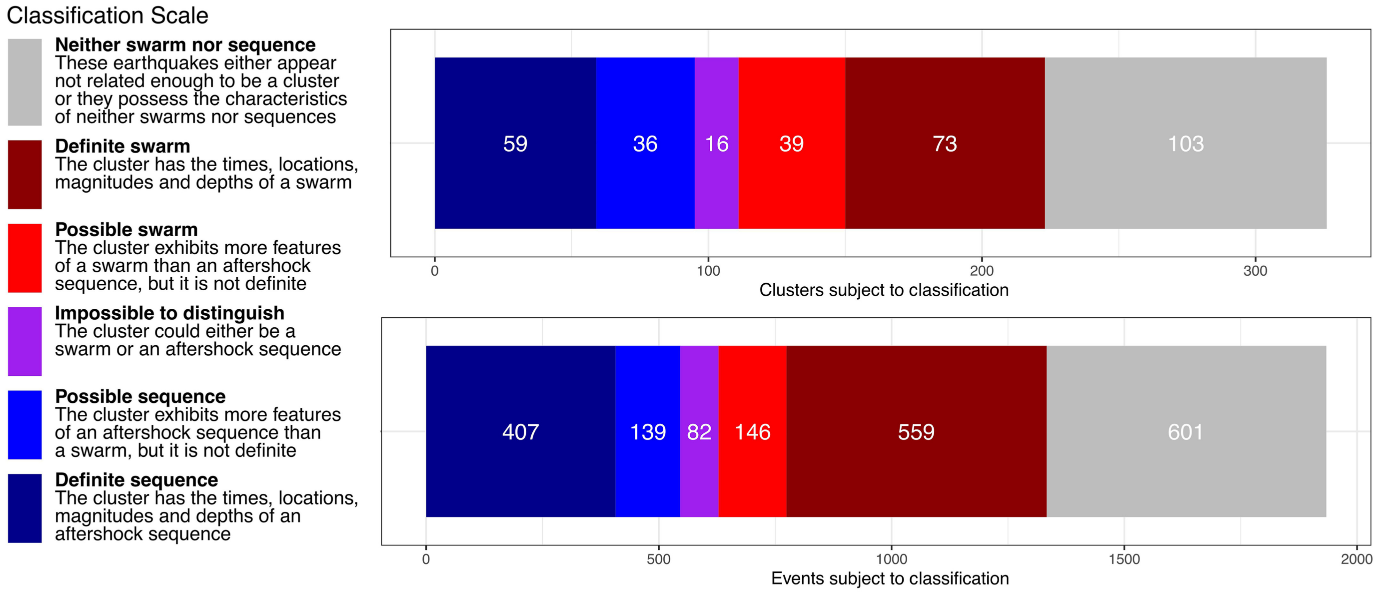

Figure 3. Swarms and aftershock sequences detected in the PNSN catalog (target zone only), classified using a six-point scale. The values include both the window-based search and hand-labeling procedure as well as our literature search for events in documented swarms. The color version of this figure is available only in the electronic edition.

swarms that contained an additional 177 events (see Table S5).

The results of this two-step search for swarms and aftershock sequences are summarized in Figure 3, and all definite and possible swarms and aftershock sequences are mapped in Figure 4. There were more (possible) swarms identified than aftershock sequences, which also contained more events in total.

Merging and Assessing Catalogs for the PNW

Merging PNSN, ComCat, and GSC

The Identifying and Handling Catalog Discrepancies section describes the process of identifying partners for all PNSN events in the ComCat catalog either by ID or by value. All the ComCat events that matched a PNSN event by value had their event IDs changed to the corresponding PNSN IDs. Of the 7815 PNSN events in the target catalog, 7646 had a partner found in ComCat. We merged the two catalogs by ID, which added ComCat variables to the matchable PNSN events. The remaining 169 events remained in the catalog but without ComCat variables.

We then added ComCat margin events to form an auxiliary PNSN–ComCat catalog. Of the 9578 margin events from ComCat, 116 were found to match to a PNSN target event; after removing these duplicates, 9462 margin events joined the catalog, leading to an auxiliary PNSN–ComCat catalog of 17,208 events.

Finally, we combined the joint PNSN–ComCat catalog with GSC events in Canada and GSC events in the United States not detected by PNSN or ComCat (639 events). The component catalogs that comprise the full international PNW catalog (see Fig. 1) are given in Table 3. This final catalog has been removed of duplicates (whether strictly, loosely, or manually matched), taking the authoritative catalog's values (17,847 total events in the international auxiliary zone).

Classifying events by tectonic regime

We had collaborators use a three-dimensional model (McCrory *et al.*, 2012) to calculate the distance between each event's hypocenter and the estimated location of the slab interface. As in Gomberg and Bodin (2021), we classified an event into the crustal regime if it was at least 10 km above the modeled slab interface, due to the uncertainty in the location of the interface. The McCrory (2012) model only goes out to longitude 121° W; we assumed that all events east of this were crustal events, following previous literature (Gomberg *et al.*, 2012); we also classified the events to the southwest of the modeled interface as crustal. This resulted in 7112 crustal events in the target zone. All the events that were below the estimated slab interface were classified as intraslab events (626 events in the target zone); further restricting to events that were at least 10 km below the estimated interface would reduce this to less than 150 events, so we did not do this, though we provide each event's interface distance in the catalog. All events that were between 0 and 10 km above the estimated slab interface were grouped into an "Other" category.

Assessing PNW seismicity

The derived variables found in the final catalog are described in the Variables in Final PNW Catalog section, in the supplemental material. We map the auxiliary (target and margin) catalog for each demarcated area in Figures 5 and 6, which show all

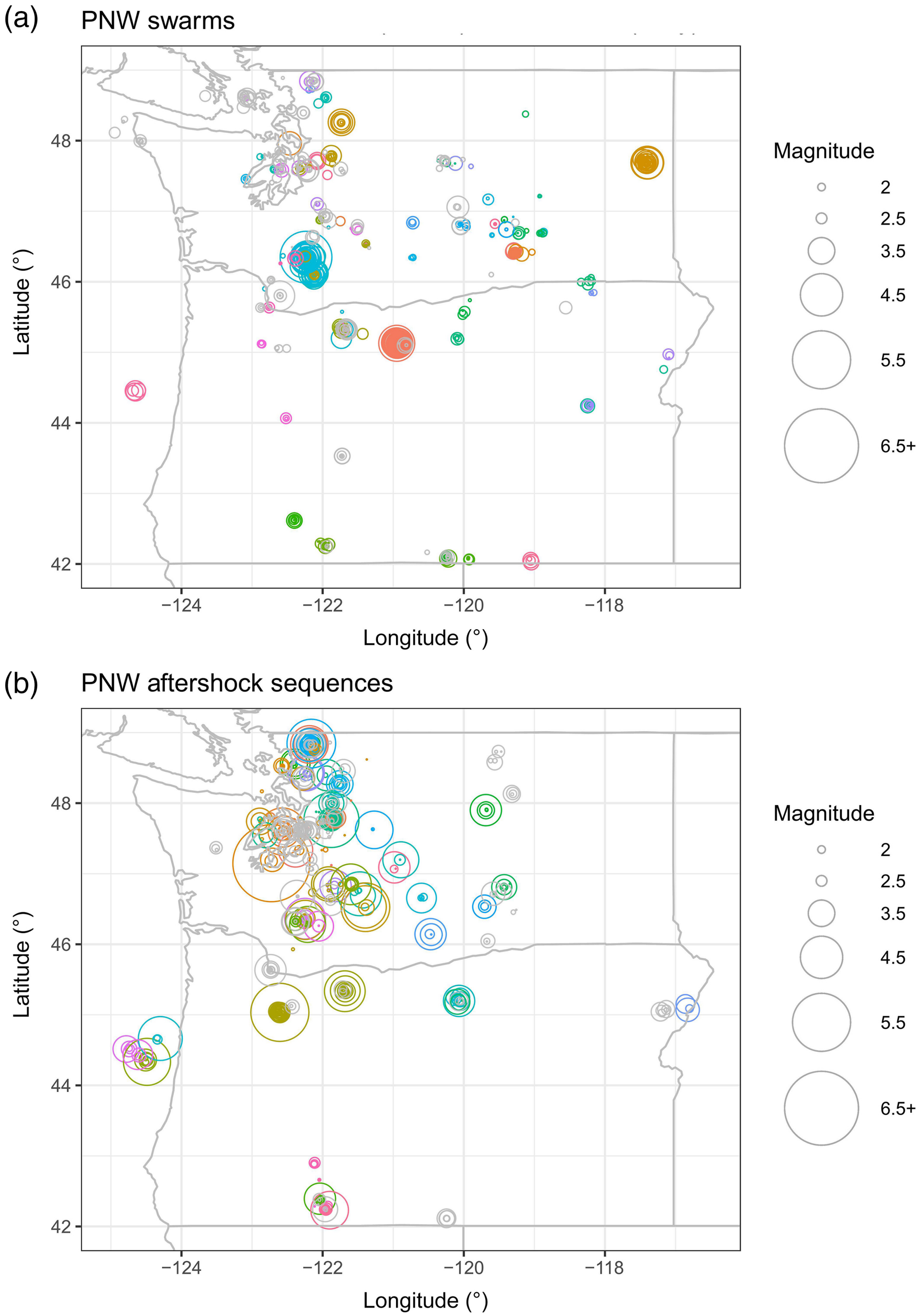

Figure 4. (a) All swarms and (b) aftershock sequences mapped with circle size scaling with magnitude (PNSN target zone only). All definite swarms and aftershock sequences are plotted in colors and all potential swarms/aftershock sequences in grayscale. The color version of this figure is available only in the electronic edition.

earthquakes (including swarms) with tectonic regime shown by color. In Washington and British Columbia, there is considerable seismicity in the Puget Sound area and Vancouver Island, with smaller concentrations in central and southwestern Washington. In Oregon, seismicity is much sparser with smaller seismically active zones in the Willamette Valley, and in several parts of southern and offshore central Oregon. Our results align with PNW catalog maps and summaries in the literature (e.g., fig. 1 of Gomberg and Bodin, 2021).

Confirmed and otherwise documented swarms were found throughout the region (see Fig. 4). Swarms are concentrated both in areas of high seismicity (Puget Sound), medium seismicity (southwestern Washington), and low seismicity (southeastern Washington). In total, there were 559 events in 73 confirmed or documented swarms (7.14% of the target catalog) and 146 events in 39 possible swarms (1.87% of the target catalog).

Crustal earthquakes make up the vast majority of the target zone's earthquakes (90.9%), with intraslab events making up 8.0% and the remainder classified as Other (proportions are similar for the auxiliary zone). Intraslab earthquakes are concentrated in the western edge of the region, where the Juan de Fuca plate subducts under the North American plate, though earthquakes of both the regimes overlap in the densely populated zones around the Puget Sound and southwestern British Columbia. This agrees with the results given in Bostock *et al.* (2019) (see their figs. 3 and 4), which also displays the higher concentration of intraslab seismicity of western Vancouver Island, which lies outside our region.

Complete PNW catalogs

Before analyzing a catalog, it is critical to assess its completeness or the spatial zone, time period, and the minimum

TABLE 3
Deduplicated Components of the Final International Pacific Northwest Catalog (Target, Margin, and Auxiliary, See Fig. 1)

Catalog	Size
PNSN US events in the target zone	7,725
GSC Canadian events in the target zone	64
PNSN Canadian events in the target zone (not represented in GSC)	21
GSC US events in the target zone (not represented in PNSN)	14
Total in target zone	7,824
ComCat US events in the margin zone	9,255
GSC Canadian events in the margin zone	523
ComCat Canadian events in the margin zone (not represented in GSC)	207
GSC US events in the margin zone (not represented in ComCat)	38
Total in margin zone	10,023
Total in auxiliary (target + margin) zone	17,847

magnitude for which the catalog can be expected to contain all earthquakes that occurred. When catalogs are missing data systematically (e.g., due to limited station coverage in certain zones), this can bias models fit to them; so it is pivotal to establish the boundaries of a catalog's completeness over space, time, and magnitude.

We observed a discrepancy in PNSN station coverage between the northern part of the region (Washington and northern Oregon) and the southern part (the rest of Oregon) for much of the catalog period. Figures S6 and S7 show the locations of PNSN stations at the start of each year (1970–2018) in three-year increments; there were no stations south of 45° N until 1980, and station coverage remained much lower than in the north until recently.

This difference suggested that catalog completeness would be different between the northern and southern regions. For simplicity, we sought a latitude threshold to split the target zone and examined cumulative number plots for 1° latitude bands from 42° to 49° N (see Fig. S8), looking for approximate linearity to indicate that earthquake detection is stationary in time. From 45° N and above, seismicity appeared to increase linearly, starting as early as the 1970s, with bands from 45° to 46° N showing departures from linearity early in the period. Thus, we opted to split the region at 45° N. We did not consider a spatial split by longitude, because station coverage seemed similar in the eastern and western regions (above 45° N), due perhaps to the population centers in western Washington and northwestern Oregon and a nuclear power plant in eastern Washington (Gomberg *et al.*, 2012; Malone, 2019).

After assessing that the Gutenberg–Richter relationship held for the full catalog in each region (see Additional Texts and Figures for Completeness Study section, in the supplemental material), we investigated for which periods and magnitude levels their catalogs are complete. We examined plots of magnitudes over time to determine the time period of completeness. Earthquakes in the PNW North did not have sizable gaps in time for lower magnitudes, starting from around 1980 (Fig. S11, top two panels). We show the PNW North's magnitude–frequency distribution for different time periods and magnitude cutoffs in Figures S12 and S13 using years when station density rapidly increased in the PNW North (Michael, 2014). In each plot, we add the best-fit Gutenberg–Richter line with a and b parameters estimated by the maximum-likelihood estimation (MLE; using standard procedures to estimate the MLE (Aki, 1965) and its standard errors (Shi and Bolt, 1982))

We identified the magnitude of completeness by looking for the magnitude at which the observed catalog frequencies are below the ones predicted by the Gutenberg–Richter line. We also used the maximum curvature method (Wiemer and Wyss, 2000), in which the magnitude of completeness is the magnitude bin with the greatest number of earthquakes. Both the methods supported the catalog being complete down to **M** 2.0 and potentially lower, perhaps as early as 1970. However, given that the GSC catalog only begins in 1985 and for consistency with the previous studies (Bostock *et al.*, 2019; Gomberg and Bodin, 2021) and expert opinion (S. Malone, personal comm., 2020), we opted to use a start year of 1985 and a magnitude of 2.0 for the complete PNW North. The b-value for this catalog had an MLE of 0.935 with a standard error of 0.013.

Completeness is less clear for the PNW South. The magnitude time plot (Fig. S11, bottom) shows that earthquake detection was irregular until at least 2004. Even though more PNSN stations were installed after the Klamath Falls aftershock sequence of 1993 (Malone, 2019), there are months-long gaps in earthquake detection in the late 1990s and early 2000s. Whether this is due to a lack of seismicity or insufficient earthquake detection would require additional data sources to infer and is outside the scope of this work. After the Goose Lake aftershock sequence of 2004, the distribution of earthquake magnitudes became arguably more regular, though seismicity remained sparse overall.

We examined magnitude frequency plots for the PNW South (Figs. S14–S17) at different magnitude cutoffs and time periods chosen based on rises in seismicity levels (i.e., separating out the Klamath Falls and Goose Lake sequences); we started at 1993 because station coverage was prohibitively limited beforehand. The fit of the Gutenberg–Richter curve to the catalog varied greatly based on the magnitude cutoff and within each time period; and, thus, it is difficult to determine a single magnitude of completeness. Based on the trends in Figure S11 (bottom two panels) and discussions with colleagues (A. Michael, personal comm., 2021), we use a start year of 2004 (right before the Goose Lake sequence) and suggest

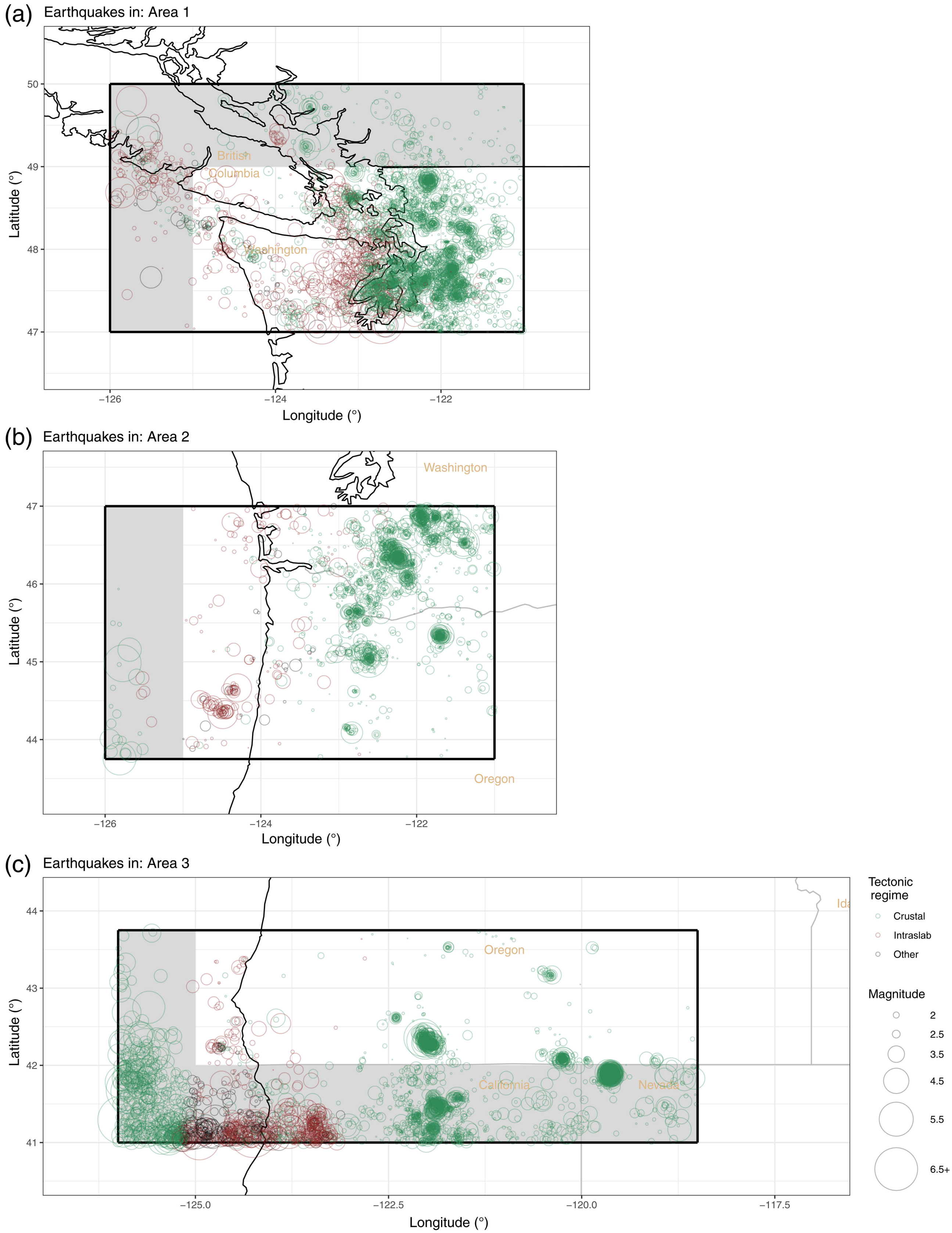

Figure 5. PNW auxiliary catalog for areas 1–3, western half of PNW (panels a–c, respectively); see Figure 2 for area map. Earthquakes are colored by their tectonic regime and swarms and aftershock sequences are included. The target zone has white background, and the margin zone has gray background. The color version of this figure is available only in the electronic edition.

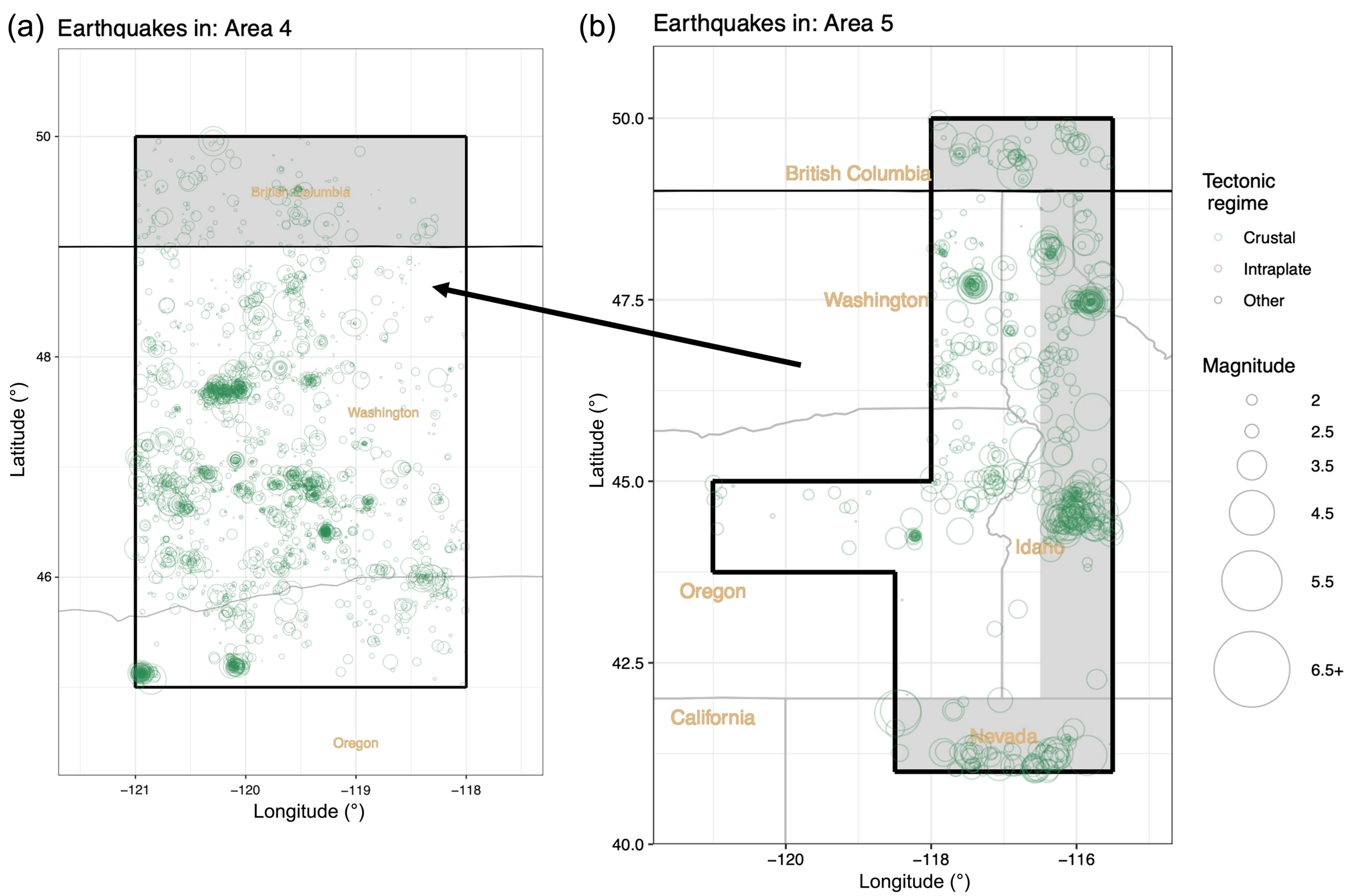

Figure 6. PNW auxiliary catalog for areas 4–5, eastern half of PNW (panels a and b, respectively); see Figure 2 for area map. Earthquakes are colored by their tectonic regime and swarms and aftershock sequences are included. The target zone has white background, and the margin zone has gray background. The color version of this figure is available only in the electronic edition.

three different magnitudes of completeness, resulting in the following b-value MLEs (and standard errors):

1. **M** 2.0, potentially incomplete; $\hat{b}_{\mathrm{MLE}} = 0.882(0.036)$;
2. **M** 2.3, arguably complete; $\hat{b}_{\mathrm{MLE}} = 0.981(0.055)$; and
3. **M** 2.5, highly likely complete; $\hat{b}_{\mathrm{MLE}} = 1.07(0.079)$.

Conclusions

We combined three data sources to collect a new catalog for the international PNW, both for a target zone around Washington and Oregon, and for a surrounding auxiliary zone. We used authoritative sources for the United States and Canada, and merged in a third data source that contained data quality variables, specifying how we detected duplicates and mismatches between the three catalogs. We then performed the first-ever study of the completeness of the PNW catalog. Although the previous literature assumed a constant magnitude and time period of completeness across the region (Bostock *et al.*, 2019; Gomberg and Bodin, 2021), we found that completeness in the southern zone was difficult to isolate from the catalog.

Furthermore, we addressed key issues in the catalog related to earthquake clustering and tectonic environment. We used a window-based and region-specific approach to detect spatiotemporal earthquake clusters. Each cluster was then hand-labeled as a possible or definite swarm or aftershock sequence by a seismologist. We also did a literature review for documented PNW swarms, which were then flagged in the catalog. The final catalog also classifies the earthquakes into the primary tectonic regimes (crustal and intraslab) and provides distances to the subducting slab interface.

Our PNW catalog can serve a variety of future work. We saw evidence of time-varying completeness, especially in the south, which can be accommodated by a time-varying b-value (Guttorp and Hopkins, 1986; van der Elst, 2021). It may also be worthwhile to investigate whether completeness changes between the crustal and intraslab regimes, given their importance for seismic hazard and aftershock forecasting.

The cluster identification procedure described in the Detecting spatiotemporal earthquake clusters section may be improved using cluster analyses that would be adaptive to different patterns in each area of the PNW (see Fig. 2), for example, based on the empirical distributions of interevent distances and interevent times. Rather than fixing thresholds for the entire PNW, a semiparametric clustering algorithm can join events that lie within thresholds based on percentiles of each area's interevent time and distance distributions. It would also be useful to achieve an algorithmic (and thus reproducible) classification of earthquake clusters as swarms or aftershock sequences, rather than purely using expert opinion. This may be based on characteristic properties of aftershocks (e.g., Båth's law; Shearer, 2012) and swarms (e.g., statistics discussed in Zaliapin and Ben-Zion, 2013). Furthermore, it is important to consider how catalog data quality affects cluster detection and classification, which can be done using the location and magnitude error variables in our catalog. Given the relevance that swarms and aftershock sequences have for the PNW's seismic risk (Gomberg and Ludwig, 2017), detecting them with rigorous methods deserves more research attention.

Data and Resources

Pacific Northwest Seismic Network's (PNSN) database was available at https://pnsn.org/events?custom_search=true. Geological Survey of Canada's (GSC) database was available at https://earthquakescanada.nrcan.gc.ca/stndon/NEDB-BNDS/bulletin-en.php. Comprehensive Catalog (ComCat) database was available at https://earthquake.usgs.gov/earthquakes/search/. Data regarding maritime borders were retrieved from https://nauticalcharts.noaa.gov/data/us-maritime-limits-and-boundaries.html. The supplemental material includes the final Pacific Northwest (PNW) catalog, a document outlining the structure of our catalog processing programs and a folder of these R programs. All websites were last accessed in May 2020.

Declaration of Competing Interests

The authors acknowledge that there are no conflicts of interest recorded.

Acknowledgments

This research was supported by the U.S. Geological Survey under Grant Number G20AP00061. This work was also supported by the University of Washington (UW), Department of Statistics and the **M** 9 project at UW (National Science Foundation). The authors gratefully acknowledge J. Renate Hartog and Camille Brillon for assistance with handling catalog discrepancies and cluster labeling, Patricia McCrory and J. Luke Blair for classifying the catalog into tectonic regimes and Steve Malone, Joan Gomberg, Andy Michael, Jeanne Hardebeck, Morgan Page, and Nicholas van der Elst for fruitful discussions. The authors also thank two anonymous reviewers for helping us improve this article. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S. Geological Survey. Mention of trade names or commercial products does not constitute their endorsement by the U.S. Geological Survey.

References

Aki, K. (1965). Maximum likelihood estimate of b in the formula log N= a-bM and its confidence limits, *Bull. Earthq. Res. Inst. Tokyo Univ.* **43,** 237–239.

Ammon, C. J., A. A. Velasco, T. Lay, and T. C. Wallace (2020). *Foundations of Modern Global Seismology*, Academic Press, Cambridge, Massachusetts.

Bostock, M. G., N. I. Christensen, and S. M. Peacock (2019). Seismicity in Cascadia, *Lithos* **332,** 55–66.

Brocher, T. M., C. S. Weaver, and R. S. Ludwin (2003). Assessing hypocentral accuracy and lower magnitude completeness in the Pacific Northwest using seismic refraction detonations and cumulative frequency-magnitude relationships, *Seismol. Res. Lett.* **74,** no. 6, 773–790.

Farrell, J., S. Husen, and R. B. Smith (2009). Earthquake swarm and b-value characterization of the Yellowstone volcano-tectonic system, *J. Volcanol. Geotherm. Res.* **188,** no. 1/3, 260–276.

Frankel, A., R. Chen, M. Petersen, M. Moschetti, and B. Sherrod (2015). 2014 update of the Pacific Northwest portion of the US national seismic hazard maps, *Earthq. Spectra* **31,** no. 1_suppl, S131–S148.

Gomberg, J., and P. Bodin (2021). The productivity of Cascadia aftershock sequences, *Bull. Seismol. Soc. Am.* **111,** no. 3, 1494–1507.

Gomberg, J., B. Sherrod, M. Trautman, E. Burns, and D. Snyder (2012). Contemporary seismicity in and around the Yakima fold-and-thrust belt in eastern Washington, *Bull. Seismol. Soc. Am.* **102,** no. 1, 309–320.

Gomberg, J. S., and K. A. Ludwig (2017). Reducing risk where tectonic plates collide: U.S. Geological Survey Fact Sheet 2017–3024, *Tech. Rept.* doi: 10.3133/fs20173024.

Grünthal, G., and R. Wahlström (2003). An Mw based earthquake catalogue for central, northern and northwestern Europe using a hierarchy of magnitude conversions, *J. Seismol.* **7,** no. 4, 507–531.

Guttorp, P., and D. Hopkins (1986). On estimating varying b values, *Bull. Seismol. Soc. Am.* **76,** no. 3, 889–895.

Hayes, G. P., G. L. Moore, D. E. Portner, M. Hearne, H. Flamme, M. Furtney, and G. M. Smoczyk (2018). Slab2, a comprehensive subduction zone geometry model, *Science*, **362,** no. 6410, 58–61.

Holtkamp, S., and M. Brudzinski (2011). Earthquake swarms in circum-Pacific subduction zones, *Earth Planet. Sci. Lett.* **305,** nos. 1/2, 215–225.

Husen, S., and J. Hardebeck (2010). Earthquake location accuracy, Community Online Resource for Statistical Seismicity Analysis, doi: 10.5078/corssa-55815573.

Jacobs, K. M., E. G. Smith, M. K. Savage, and J. Zhuang (2013). Cumulative rate analysis (CURATE): A clustering algorithm for swarm dominated catalogs, *J. Geophys. Res.* **118,** no. 2, 553–569.

Lee, W. H. K., R. Bennett, and K. Meagher (1972). A method of estimating magnitude of local earthquakes from signal duration, *U.S. Geol. Surv. Open-File Rept.* doi: 10.3133/ofr72223.

Llenos, A. L., J. J. McGuire, and Y. Ogata (2009). Modeling seismic swarms triggered by aseismic transients, *Earth Planet. Sci. Lett.* **281,** nos. 1/2, 59–69.

Llenos, A. L., and A. J. Michael (2013). Modeling earthquake rate changes in Oklahoma and Arkansas: Possible signatures of induced seismicity, *Bull. Seismol. Soc. Am.* **103,** no. 5, 2850–2861.

Ludwin, R. S., C. Dennis, L. McMillan, and J. Clague (2005). Dating the 1700 Cascadia earthquake: Great coastal earthquakes in native stories, *Seismol. Res. Lett.* **76,** no. 2, 141.

Malone, S., D. Oppenheimer, L. Gee, and D. Neuhauser (1996). The council of the National Seismic System and a composite earthquake catalog for the United States, *IRIS* Newsletter **1,** 6–9.

Malone, S. D. (2019). An ominous (?) quiet in the Pacific Northwest, *Seismol. Res. Lett.* 90**,** no. 2A, 463–466.

McCrory, P. A., J. L. Blair, F. Waldhauser, and D. H. Oppenheimer (2012). Juan de Fuca slab geometry and its relation to Wadati-Benioff zone seismicity, *J. Geophys. Res.* **11,** no. B9, doi: 10.1029/2012JB009407.

Merrill, R., and M. Bostock (2019). An earthquake nest in Cascadia, *Bull Seismol Soc Am*, **109,** no. 5, 2021–2035.

Michael, A. J. (2014). How complete is the ISC-GEM global earthquake catalog? *Bull. Seismol. Soc. Am.* 104**,** no. 4, 1829–1837.

Mueller, C. S. (2019). Earthquake catalogs for the USGS national seismic hazard maps, *Seismol. Res. Lett.* **90,** no. 1, 251–261.

Natural Resources Canada (1975). Canadian national seismograph network, available at https://earthquakescanada.nrcan.gc.ca/stndon/NEDB-BNDS/bulletin-en.php (last accessed May 2020).

Nievas, C. I., J. J. Bommer, H. Crowley, and J. van Elk (2020). Global occurrence and impact of small-to-medium magnitude earthquakes: a statistical analysis, *Bull. Earthq. Eng.* **18,** no. 1, 1–35.

National Oceanic and Atmospheric Administration (NOAA) Office of Coast Survey (2020). Maritime limits and boundaries, Data retrieved from NOAA Office of Coast Survey, available at https://nauticalcharts.noaa.gov/data/us-maritime-limits-and-boundaries.html (last accessed May 2020).

Okutani, T., and S. Ide (2011). Statistic analysis of swarm activities around the Boso Peninsula, Japan: Slow slip events beneath Tokyo Bay? *Earth Planets Space* **63,** no. 5, 419–426.

Reasenberg, P. (1985). Second-order moment of central California seismicity, 1969–1982, *J. Geophys. Res.* **90,** no. B7, 5479–5495.

Richter, C. F. (1935). An instrumental earthquake magnitude scale, *Bull. Seismol. Soc. Am.* **25,** no. 1, 1–32.

Roland, E., and J. J. McGuire (2009). Earthquake swarms on transform faults, *Geophys. J. Int.* **178,** no. 3, 1677–1690.

Schneider, M. (2021). Improving uncertainty quantification and visualization for spatiotemporal earthquake rate models for the Pacific Northwest, *Ph.D. Thesis*, University of Washington.

Shearer, P. M. (2012). Self-similar earthquake triggering, Båth's law, and foreshock/aftershock magnitudes: Simulations, theory, and results for southern California, *J. Geophys. Res.* **117,** no. B6, doi: 10.1029/2011JB008957.

Shi, Y., and B. A. Bolt (1982). The standard error of the magnitude-frequency b value, *Bull. Seismol. Soc. Am.* **72,** no. 5, 1677–1687.

Skoumal, R. J., M. R. Brudzinski, and B. S. Currie (2016). An efficient repeating signal detector to investigate earthquake swarms, *J. Geophys. Res.* **121,** no. 8, 5880–5897.

Survey, U.S. Geological (2023). Quaternary fault and fold database for the United States, available at https://www.usgs.gov/natural-hazards/earthquake-hazards/faults (last accessed April 2023).

Thompson, M., J. R. Hartog, and E. A. Wirth (2022). Effect of fixing earthquake depth in ShakeAlert algorithms on performance for intraslab earthquakes, *Bull. Seismol. Soc. Am.* **93,** no. 1, 277–287.

University of Washington (1963). Pacific northwest seismic network, available at https://pnsn.org/events?custom_search=true (last accessed May 2020).

van der Elst, N. J. (2021). B-positive: A robust estimator of aftershock magnitude distribution in transiently incomplete catalogs, *J. Geophys. Res.* **126,** no. 2, e2020JB021027 , doi: 10.1029/2020JB021027.

Veen, A., and F. P. Schoenberg (2008). Estimation of space–time branching process models in seismology using an EM–type algorithm, *J. Am. Stat. Assoc.* **103,** no. 482, 614–624.

Vidale, J. E., and P. M. Shearer (2006). A survey of 71 earthquake bursts across southern California: Exploring the role of pore fluid pressure fluctuations and aseismic slip as drivers, *J. Geophys. Res.* **111,** no. B5, doi: 10.1029/2005JB004034.

Wiemer, S., and M. Wyss (2000). Minimum magnitude of completeness in earthquake catalogs: Examples from Alaska, the western United States, and Japan, *Bull. Seismol. Soc. Am.* **90,** no. 4, 859–869.

Zaliapin, I., and Y. Ben-Zion (2013). Earthquake clusters in southern California II: Classification and relation to physical properties of the crust, *J. Geophys. Res.* **118,** no. 6, 2865–2877.

Zhuang, J. (2011). Next-day earthquake forecasts for the Japan region generated by the ETAS model, *Earth Planets Space* **63,** no. 3, 207–216.

Manuscript received 2 December 2022
Published online 11 July 2023