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Mapping of Microseismic Aftershock Sequences Following the 2017 Lincoln, Montana M 5.8 Earthquake

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MAPPING OF MICROSEISMIC AFTERSHOCK SEQUENCES FOLLOWING THE 2017 LINCOLN, MONTANA M 5.8 EARTHQUAKE

By

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Abstract

The Rocky Mountains of western Montana have long been experiencing tectonic compression and extension that has shaped much of western North America. This activity consistently produces seismic events, like the 6 July 2017 M 5.8 earthquake 11 km southeast of Lincoln, MT, which can be used to advance understanding of crust and mantle dynamics and structure. Seismic mapping is vital to understanding structure and tectonic activity in western Montana as well as in analogous locations across the world. Recently deployed seismometers from the University of Montana as well as the Montana Regional Seismic Network (MRSN) from the Montana Bureau of Mines and Geology (MBMG) and temporary stations from the United States Geological Survey (USGS) have been collecting continuous data for several years that can be analyzed using the QuakeMigrate software. Continuous waveform data from the University of Montana Seismic Network (UMSN) has not previously been searched for earthquakes (outside of the USGS event catalog) and potentially contains hundreds or thousands of additional small seismic events not previously detected by the more sparsely distributed regional networks. An updated catalog, based on the concentrated deployment of UMSN stations around the Lincoln aftershock sequence, will allow for an updated structural analysis of west-central Montana with unprecedented precision, as well as detailed analyses of aftershock evolution and crustal stress state. Large events, like the Lincoln, Montana event in 2017, garner significant attention but are rare. Smaller events, while they may not be felt at the surface or even register in some seismometers, are much more common and therefore can provide a more thorough understanding of the Earth's subsurface dynamics and structure, thus motivating the need for a detailed catalog. We are currently using QuakeMigrate to create an earthquake catalog using data from the 12 stations in the UMSN, stations from the MRSN, and temporary USGS stations near Lincoln to detect and locate aftershocks following the M 5.8 Lincoln, Montana mainshock. The catalog will include origin times, hypocentral locations, and magnitudes of earthquakes that have occurred since the Lincoln, Montana mainshock on 6 July 2017. This catalog aims to provide accessible seismic event data for west-central Montana beginning on 6 July 2017 until the conclusion of 2021.

Introduction

A series of moderate to major seismic events have been recorded throughout the 20th and 21st centuries in western Montana, most recently with the 6 July 2017 M 5.8 event occurring 11 km southeast of the small town of Lincoln, Montana (McMahon et al. 2019; Smith, Martens, & Stickney 2021; Stickney 2022). The epicenter of this event is within 100 km of two major cities – Helena, the capital city of Montana, and Missoula, the state's second largest city, and the event itself was felt at distances as far as 800 km from its epicenter (McMahon *et al.,* 2019). Eleven larger magnitude events have been recorded in the state of Montana since 1897, early on by eye-witness accounts and more recently by seismic instrumentation (Stickney, 2022). These include the M 6.6 Clarkson event of June 1925, the M 6.2 and 6.0 events near Helena in October 1935, and the M 7.3 Hegben Lake event of August 1959, which was the largest ever recorded in Montana (e.g., McMahon *et al*., 2019). Additionally, a M 5.6 event occurred near Dillon, Montana in 2005 (e.g., Stickney 2022). Despite the scarcity of these large events relative to regions more commonly associated with earthquakes like southern California or Alaska, few states experience more frequent seismic activity than Montana. A majority of earthquakes are small in magnitude and cannot be felt at the surface, but because of their much greater frequency, can be highly useful for understanding subsurface structure.

Studies including analysis of seismicity caused by volcanic activity and intrusions in Iceland and probabilistic locating of induced earthquakes in the Netherlands have used QuakeMigrate software (Smith *et al.,* 2020), but the software has not yet been used in Montana. Customized QuakeMigrate programs and additional supplemental programs written for this project allow for use of this software anywhere in the world with adequate waveform data available. Our analysis of the Lincoln area uses the QuakeMigrate software developed during a project in Iceland (Drew *et al.* 2013) customized to the Montana region to provide further insight on research completed by McMahon *et al.* (2019) on locating aftershocks related to the Lincoln mainshock in 2017. Their study included 14 stations in the region with data exclusively from 2017, which was later expanded upon by Smith, Martens, and Stickney (2021).

The hypothesis introduced by Smith, Martens, and Stickney (2021) states that a bookshelf faulting structure may be present where the Lewis and Clark Line interrupts the Intermountain Seismic Belt (ISB) in Western Montana. The Lewis and Clark Line (LCL) is a west and northwest trending 400 km long series of strike-slip, dip-slip, and oblique-slip faults throughout Idaho and western Montana (Wallace, Lidke, & Schmidt, 1990). The Intermountain Seismic Belt closely follows the eastern extent of the Rocky Mountains in North America extending from southern Utah and Nevada into northwestern Montana (MBMG, n.d.) and is characterized by scattered, shallow Quaternary-fault seismicity along with less frequent, larger scarp-forming events (Arabasz & Smith, 1981). The Lincoln event occurred at the junction of the LCL and the approximately 100 km wide ISB. Smith, Martens, and Stickney (2021) made manual phase-pick refinements and computed focal mechanisms for 414 aftershocks of the 2017 mainshock using stations around the Lincoln area from the UMSN, MRSN, and USGS network. An unexpected north-northeast trending left-lateral strike slip fault was identified, consistent with the findings of McMahon et al. (2019). This fault orientation is near perpendicular to the trend of the LCL, contradicting the expectation of active faults following the trend of the LCL. New data and an increased sample size of microseismic events may help further constrain or qualify the bookshelf faulting hypothesis. Additionally, a publicly accessible catalog with a lower magnitude of completeness for aftershocks following the Lincoln event in 2017 will enable further study in the area for more seismic-related research.

Motivation and Scientific Objectives

Many significant and damaging earthquakes have occurred in Montana since the 20th century began, with the most damaging being the Hebgen Lake Earthquake in 1959 causing $11 million in damage, massive landslide, and at least 28 deaths (e.g., McMahon et al., 2019; Stickney 2022). Due to the abundance of tectonic activity in the Rocky Mountains and west-central Montana, it is likely that similar events will occur in the future. Awareness of local scientists to fault lines allows for in-depth study and analysis of a given fault in terms of its potential to produce significant earthquakes. Increased communication of general information about earthquakes alongside seismic hazards to the public could contribute to less damage or loss of life when another large event does occur in the region. While earthquakes cannot yet be predicted, activity levels of faults and their hazard potential can be determined based on frequent, small earthquakes like those mapped in this study. Reconstructions of past geology and environments in Montana can also benefit from the identification of fault lines, whether active or inactive, due to displacement or unconformities sometimes present at fault lines. This research will produce a catalog of events that can be further analyzed and mapped to better develop understanding of fault structure in west-central Montana for any applicable purpose. We use a recently updated velocity model and newly developed QuakeMigrate software to provide more precise and accurate hypocentral locations and local magnitudes than has been done before. Furthermore, we include continuous waveform data from the UMSN, which has not been incorporated into routine earthquake detections and locations by the USGS and MRSN, because the UMSN is not telemetered unlike other regional networks.

Scientific Objectives

- Apply QuakeMigrate and ObsPy software to detect and locate earthquakes in west-central Montana using UMSN, MRSN, and USGS data
- Accurately detect and locate as many events as possible between the day of the Lincoln mainshock (6 July 2017) and the end of 2021
- Store the hypocentral locations and magnitudes of all earthquakes and aftershocks in a comprehensive catalog
- Share catalog for public access and further research

Methodology

The procedure for customizing QuakeMigrate to output results in the desired area consists of steps that are outlined in detail in this section and in Figure 3. We downloaded continuous waveform data from the Incorporated Research Institutions for Seismology (IRIS) based on station and channel availability in the specified geographic area around Lincoln, MT using an ObsPy method in a program we developed (in Python) separately from QuakeMigrate. We then customized four Python scripts from the example versions included in QuakeMigrate to complete the necessary stages for earthquake location in west-central Montana with appropriate parameters to match the data being used. The code was then tested – parameters were edited repeatedly to optimize earthquake locations and reduce uncertainty as much as possible. Following the completion of the test runs, each program is currently being run for successive six-month intervals through the third of four QuakeMigrate stages beginning on 6 July 2017 and ending on 31 December 2021. Once the fourth stage is complete, the outputted files with data for each event will be passed into another independently developed Python program to be formatted and have selected data sent to a comprehensive text file that we refer to here as the earthquake catalog. The catalog is not completed at the time of submission of this report, yet all current source code can be found in the supporting information.

QuakeMigrate provides a series of example programs written in Python to create a look-up table, detect P-wave and S-wave arrivals over a given time frame, trigger the possible seismic events from the detected arrivals, locate the event hypocenters, and estimate the magnitudes of events based on times of arrival and waveform amplitudes of all stations that recorded a given earthquake. The scripts must be customized to the specific location(s) and desired parameters a user requires for mapping their own data. The QM software was used to identify and locate events instead of manual phase picking due to the over three-year period of analysis and the possibility of thousands of events occurring over that time. Manual phase picking and location would take significantly longer and would be subject to human error on a greater scale. A catalog already exists for the Lincoln aftershock sequence, though it was created based only on USGS and MRSN stations. UMSN stations, which are not telemetered, are not included in the automated and routine detection and location algorithms used by the USGS, MBMG, and University of Utah. Based on the USGS catalog, Smith et al. (2021) manually refined automated phase picks from the UMSN data at the times of known events. They did not, however, search the continuous data for additional small earthquakes that may be absent from the USGS catalog. The aim of this research is to identify and locate additional, previously undetected events by integrating the UMSN data with other datasets in the retroactive construction of a new catalog. Because the UMSN data is densely and strategically distributed around the Lincoln aftershock sequence, our hypothesis is that hundreds to thousands of additional microearthquakes may be identified by including the additional, high-quality data.

The UM network consists of 12 state-of-the-art seismometers surrounding Lincoln, Montana. The first three of these stations were deployed in August of 2017 directly following the M 5.8 mainshock to accurately record aftershocks. Seven more stations were deployed in 2018, followed by one in 2019 and another in 2020. Three of the twelve stations remain currently active in 2022. Several stations were decommissioned in 2021 due to waning aftershock activity and for maintenance. The Nevada Creek station (NVMT) station ended data collection on 11/17/2018 and the Granite Butte station (GBMT) stopped recording on 30 July 2020. The conclusion of data collection by UM at GBMT was followed by the deployment of a new instrument with the same station name under the MRSN. Other local stations include those of the Montana Bureau of Mines and Geology, which includes 46 stations around western Montana, extending from just northeast of Libby, MT, as far south as Lima, MT, and as far east as Greycliff, MT. Only 15 of the MRSN stations were used in our study as other MRSN stations do not reside in the chosen geographic area and often did not detect smaller Lincoln-area events. One permanent station in the USGS network and three temporary stations from the USGS deployed directly following the Lincoln event, and removed in October 2017, were also included for a total of 27 stations (Figure 1).

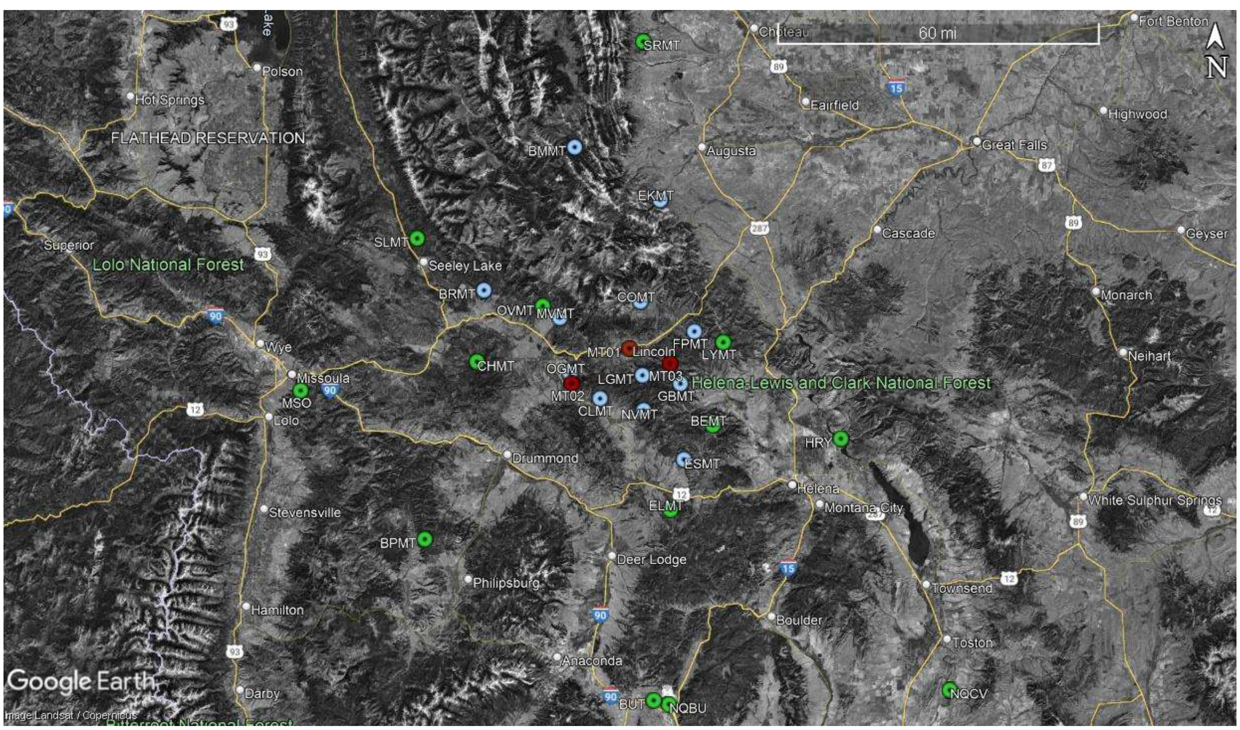

Figure 1. Map of UMSN, MBMG, and temporary USGS field stations included in this project. UMSN stations are in blue, MBMG stations are in green, and temporary USGS stations are in red. View online version to see map in color.

QuakeMigrate Software

QuakeMigrate software is an open-source software package developed originally for use in Iceland that is used for locating earthquake hypocenters and computing earthquake magnitudes and origin times. It operates through the process of coalescence microseismic mapping (CMM), as described in Drew et al. (2013), which is a method that employs successful procedures from two previously developed methods in order to improve accuracy and mitigate uncertainty. QuakeMigrate is especially effective in regions experiencing frequent and intense seismic activity, such as volcanic and geothermal landscapes and locations of hydrofracturing. We use QuakeMigrate to analyze data from various stations and networks following the 6 July 2017 event near Lincoln, MT because of the frequency and intensity of aftershocks that occurred in the region as a result of the M 5.8 mainshock. The process of coalescence microseismic mapping is effective for such regions because it uses data from P-wave and S-wave arrivals while mitigating the risk of misidentification of P-waves and S-waves. QuakeMigrate is designed to allow for modification and customization to include more arrival phases and be used to analyze data anywhere in the world that has sufficient data.

One of the goals for the effectiveness of the software is to use the most reliable features of other earthquake location methods, such as imaging techniques and travel-time inversion while eliminating some of the hindrances that come with those other methods. Imaging techniques use backpropagation of data to identify the hypocentral locations and the origin times of earthquakes using similar methods to seismic reflection profiling. Locating earthquakes through travel-time inversion requires the picking of arrival times followed by inversion of wave travel-times based on the inferred velocity structure in the area. While both methods have been used often and have their strengths, they are subject to a number of sources of uncertainty (Drew et al. 2013). The CMM approach to earthquake location is built upon the strengths of imaging and inversion methods as well as the source scanning algorithm (SSA) method suggested by Kao & Shan (2004). The main variation between the CMM method used in QuakeMigrate and the SSA method is that the CMM method develops signals based on uncertainty of wave arrivals related to a seismic event. The logarithms of signals are summed instead of the signals themselves, so therefore when the signals are mapped, they can be viewed as probability density functions (Drew et al., 2013).

QuakeMigrate locates seismic events in a four-step process. First, a travel-time lookup table (LUT) is developed as a three-dimensional grid based on a user-specified velocity model that can be homogeneous or heterogeneous. The lookup table is made for both P- and S- waves and only needs to be computed once. Next, potential seismic events are detected over a given time interval. Wave-arrival detection is triggered when the ratio of the short-term average (STA) to the long-term average (LTA) increases above a specified threshold. The STA is a continuous calculation of the average amplitude of the waveform data over a short time window, while the LTA is the same over a longer time window. The ratio of these averages can be used to identify potential wave arrivals because it varies with sudden changes in amplitude. The size of these windows and the magnitude of the detection threshold determine the sensitivity of the detection function to changes in the amplitude of the waveform data. The STA/LTA detection function used in QuakeMigrate to detect potential earthquakes, as described in Drew et al. (2013), is:

$$f_D(t) = \frac{W_L \int_0^{W_S} |y(t+\tau)| d\tau}{W_S \int_{-W_L}^{0} |y(t+\tau)| d\tau} \quad (1)$$

The short time window used in the STA is represented by W_s, and the long time window used for the LTA is W_L. The function *y(t)* represents the amplitude of the seismic signal in the waveform data.

Workflow

Using a mass data-download method from ObsPy (Beyreuther et al., 2010), waveform data in miniSEED format was acquired from the Incorporated Research Institutions for Seismology (IRIS) database. Continuous waveform data and metadata files (datalessSEED) were downloaded from the 6 July 2017 Lincoln mainshock through the end of 2021. Initially we found it beneficial to use small, sub-daily portions of data in order to test each of the necessary scripts to assure data was being downloaded appropriately and efficiently. After the ObsPy download program and QuakeMigrate programs were tailored to the Lincoln case study, a loop was used to download data for the UM network over the full period following the Lincoln, MT event until the end of 2021. The custom script for downloading data for the UMSN and MRSN networks as well as each of the customized QuakeMigrate programs (*generate_lut, detect, trigger, locate) are* available in the supporting information. The ObsPy Mass Download method also allows for access to individual response files for each station in the specified geographic area.

The main portion of QuakeMigrate customization for west-central Montana was done with two separate series of the four scripts required to detect and locate events. One series used the UMSN stations, and the other used the MRSN stations located in a rectangular area with a lower left corner at 45.92˚N, -113.94˚W and an upper right corner at 47.94˚N, -111.38˚W. The full catalog is being developed using data from the UMSN, MRSN, and three temporary USGS stations in the same run of the software. During testing, we set the depth range to detect and locate the Lincoln events from 2.5 km above sea level to 30 km below sea level (based on WGS84 model). After troubleshooting code with a randomly selected 8-minute time span (9/15/2018 – 6:00:30 to 6:08:30) and getting a successful event summary figure from the *locate* program for both networks, this time span was increased to 1 hour long, then to 12 hours long and was followed with the comparison of the outputted event summary figures.

A problem arose with the event summary figures originally due to an inadequate trigger threshold, causing the trigger and locate stages to only detect the largest event in the given time period. This problem is discussed in more detail in the description of the trigger stage (see below). With an appropriate trigger threshold (now set to 1.375), the degree of uncertainty for location and magnitude of a given event does not change when using different windows of data. In the first execution of the 12-hour time span, the runtime on the detect stage increased slightly (from approximately 1.5 seconds to approximately 4 seconds per iteration), which was investigated and solved by an increased thread count (4 to 8) and an increased LUT decimation factor ([4,4,4] to [8,8,8]). The decimation factor controls the decimation of the node spacing in the *detect* and *locate* QuakeMigrate programs. We expected to see a greater degree of uncertainty when increasing the decimation factor from 4 to 8 in the detect stage. However, in multiple tests, there was no observed change in uncertainty values for the same located event when run with a decimation factor of 4 and a decimation factor of 8. This is not the case when a decimation is completed in the *locate* stage. In the case where the node spacing is decimated in the *locate* stage as well as in the *detect* stage, runtime of locating each event decreases while the degree of uncertainty for origin time and hypocentral coordinates increases.

QuakeMigrate's *locate* program requires a single instrument-response calibration file (i.e., datalessSEED file) for all stations. The ObsPy Mass Downloader stores these response files in a directory, the name of which is specified by the user, so the response files in this directory must be combined into one file for use in QuakeMigrate. There are various ways to do so, but in this project, we utilized ObsPy's `read_inventory` method (Beyreuther et al., 2010). A manually downloaded datalessSEED file containing the response information for all UMSN stations was used to test code initially and, once the code was functioning properly, the response information for each of the stations in the MRSN network was combined and run through each of the four QuakeMigrate programs. The two network-based files of response information were then combined again into one summary file to use the data from both networks in tandem, producing more event detections and locations.

Combining the datalessSEED files from MRSN and UMSN proved a challenge, as both the MRSN and UMSN include a station at Granite Butte, named GBMT. Each of the stations were deployed at approximately the same location but collected data over different time intervals. The GBMT station in the MRSN network was excluded from this process, as the inclusion of two different stations with the same name produced errors and the MRSN station was deployed after the aftershock activity had waned. Other solutions for this include renaming one of the stations, which would require the renaming of the station in response information and in waveform data files or running the code so it ends on 30 July 2020 with the UMSN station, and picks up that same day following the deployment of the MRSN station. Another option might be to use different instrument location codes, but we did not investigate this.

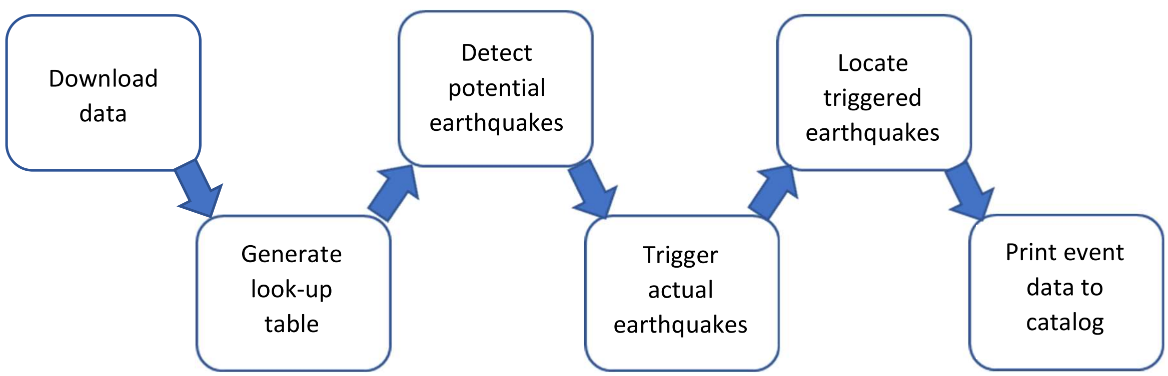

Figure 2. Flow chart depicting the overall process of how QuakeMigrate software is used in this project. Each "step" represents a program written in Python. The QuakeMigrate software package comes with example code for the four steps in the middle, and the programs represented by the first and last steps were independently developed. All source code is available in the supporting information.

Generating the lookup table

The traveltime lookup table (LUT) for the Lincoln, Montana area was created using QuakeMigrate and a heterogenous one-dimensional velocity model developed at the University of Montana (Courtenay Duzet, personal communication). The lookup table creates a three-dimensional grid of evenly spaced nodes to a user-specified depth (in this case, 30 km) across the user-specified area using lower-left corner and upper-right corner coordinates. Various "bounding box" tools[1] exist online to help identify and visualize geographic area on Earth's surface, as used in this project. QuakeMigrate uses the pair of upper right and lower left coordinates and depth to create a volume in which raypaths are mapped from grid nodes to stations at the surface. The lookup table is independent of the time span in which earthquakes and waveform data are analyzed. Using the most currently updated velocity model specific to west-central Montana reduces error from outdated models or models that are developed over a larger area. One important parameter that we experimented with throughout testing was the node spacing, which represents the division of the grid into equal parts of specified dimensions. The node-spacing parameter directly impacts runtime, as more closely spaced nodes (more total nodes) extend runtime. Denser node spacing, however, allows for more precise hypocenter location. Node spacing can be adjusted in the *detect* and *locate* stages as well through the decimation factor parameter (**`lut.decimate([])`**). Appropriate node spacing depends mainly on the size of the area being used for the LUT. The area of the LUT also impacts runtime in the *detect* stage directly – a larger area leads to longer runtimes than a smaller area with the same node spacing due to a greater total number of nodes.

Depth (km)	**P-wave velocity (V_p, km s^{-1})**	**S-wave Velocity (V_s, km s^{-1})**
-1.8	4.80	2.727
1.0	5.37	3.051
5.0	6.05	3.438
10.0	6.16	3.500
15.0	6.33	3.597
20.0	6.58	3.739
25.0	6.77	3.847
30.0	7.00	3.977

Table 1. Velocity model required to generate the traveltime look-up table, created at University of Montana for west-central Montana, via Courtenay Duzet, personal communication (2022).

Detecting events

The main study-specific modifications in the QuakeMigrate *detect* program, which detects events over a specified period using the look-up-table, are (1) the input and output (i/o) file paths, (2) the time period in the form of a start time and an end time, and (3) the timestep. The script was directly modified from the *detect* script in the **`Volcanotectonic_Iceland`** example in QuakeMigrate. The timestep parameter represents the time interval in which the code detects events, between a given start time and end time. The total time between the start and end must be divisible by the timestep. The timestep also impacts runtime of each iteration of *detect* – a smaller timestep yields less run time for each iteration but can produce a greater total runtime. For testing and troubleshooting purposes, the timestep was set to 120 seconds for shorter timespans and 300 seconds for longer timespans, and the program was run over 8-minute, 1-hour, and 12-hour time periods. These same time intervals were used for subsequent programs described in the workflow (*trigger* and *locate*). For final development of the catalog, we are using a 120 second timestep to run the detection through 6-month intervals. Other key parameters that can be changed from the example values include bandpass filters, short-term average (STA) and long-term average (LTA) windows, detection threads, sampling rate, and the look-up table decimation factor. A copy of the customized *detect* program for our catalog (as well as the other customized programs used in the workflow) is provided in the supporting information.

Networks often record data differently from one another, which QuakeMigrate accommodates for in the *locate* stage, yet stations or networks with different sampling rates must have those sampling rates re-scaled in order to be used together (which can also be done through QuakeMigrate). In this study, all sampling rates for stations used from the UMSN, MRSN, and temporary USGS stations were 100 Hz, so re-scaling was not needed. We chose values for the following parameters through use of default values included with QuakeMigrate and through trial-and-error examinations of runtime in the *detect* stage and uncertainty in the hypocentral locations of earthquakes. We use bandpass filters [2, 20, 2] for both P and S arrivals, an STA window of 0.2 seconds, an LTA window of 1.0 seconds, a detection thread value of 8, and a LUT decimation factor of 8. Bandpass filter and STA/LTA values were the default values provided in examples in QuakeMigrate code and changing these values did not improve runtime or uncertainty.

A potential event is detected when the ratio of the STA and LTA (computed using equation 1) exceeds the specified detection threshold. A general rule for choosing the correct STA and LTA windows is that the short window should be long enough to contain "one or two periods of the dominant signal frequency" and the long window should be three to ten times the length of the short window (Drew et al., 2013). Other ways to optimize the values for parameters such as node spacing and to reduce uncertainty when detecting events are outlined in greater detail by Drew et al. (2013).

A notable convention for the *detect*, *trigger*, and *locate* programs is that the specified starttime cannot be set to the exact time in which data becomes available. For example, if the first available miniSEED data is at time 00:00:00.0 for 1 January 2000, the starttime for the *detect*, *trigger*, or *locate* program must be set after that time. In this study, we begin 30 seconds after the first available data. This bug has been acknowledged and solved by the developers of QuakeMigrate but has not yet been added to the software at the time of this study (Connor Bacon, personal communication).

Key parameters that impact runtime in the *detect* stage include the decimation factor, which is a modification of the node spacing outlined in the previous stage, and the timestep over which events should be detected. The timestep represents the amount of time, in seconds, by which the total specified period is divided for the detection process. Larger timesteps lead to longer runtimes per timestep. Additionally, the thread count parameter can be increased experimentally as a higher thread count generally reduces runtime depending on the system the software is run on. increased speed to find the optimal value. The sampling rate of onset functions can be changed as well and has a less significant impact on runtime (Tom Winder, personal communication). We specified a sampling rate of 100 samples per second (sps) in order to match the sampling frequency of the stations in the UMSN and MRSN networks.

Triggering events

The *trigger* program in QuakeMigrate is responsible for filtering real seismic events from other nondescript changes in waveform amplitude that were identified as potential earthquakes in the *detect* stage. Events are "triggered" when the maximum coalescence value exceeds the specified trigger threshold. Coalescence values of potential events are determined by the signal-to-noise ratio (SNR) of a given event as its arrival time uncertainty is shown to be linearly dependent on the inverse of the logarithm of the SNR (Drew et al., 2013). The trigger threshold parameter, which the maximum coalescence must exceed for an event to be triggered, is primarily a reference that can be used to isolate legitimate seismic events from those that are not. Occurrences other than earthquakes that produce a signal on a seismometer include diurnal cultural noise such as disturbances from vehicular traffic (Maryland Geological Survey, 2022) as well as mining explosions and quarry blasts, which are recorded and identified in the USGS catalog (USGS, 2022).

The appropriate trigger threshold can be different for various time periods based on the normalized coalescence values of events that potentially occur in that time period. The process of CMM and the computation for this coalescence function is explained in detail by Drew et al. (2013). A trigger threshold that is below the average coalescence value for the entire given time period may yield only one event for that time interval because the coalescence value will never fall below the trigger threshold. When this occurs, all events will be seen as overlapping and only the largest spike in the normalized coalescence values will be triggered as an actual event (Tom Winder, personal communication). After experiencing this

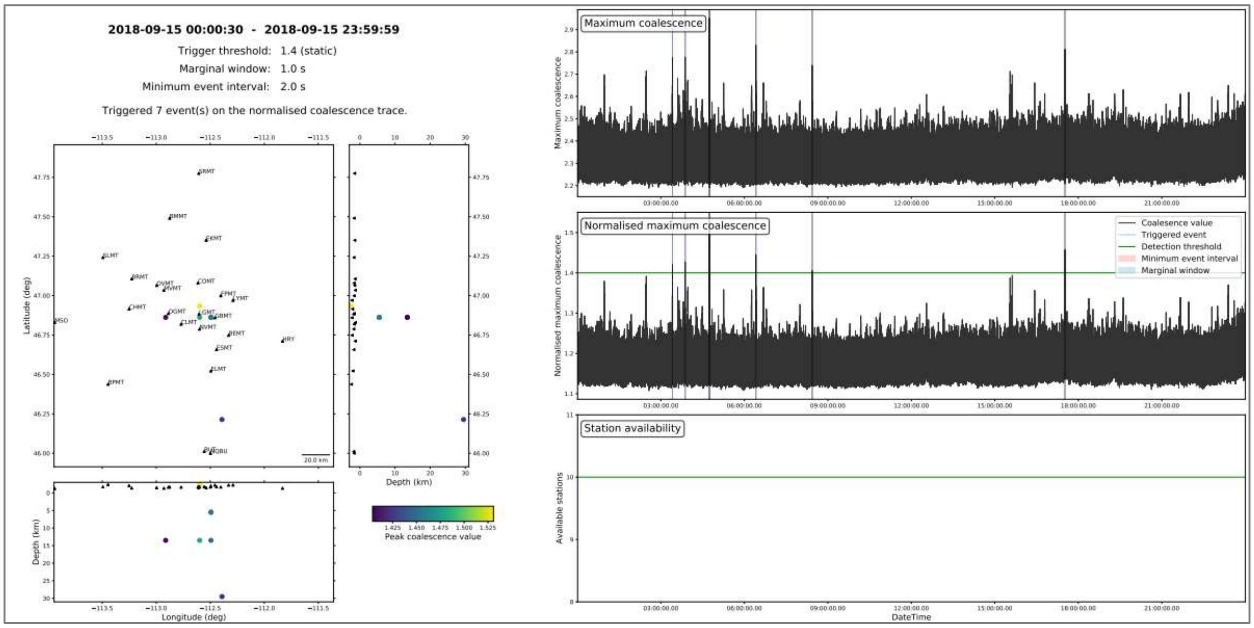

Figure 3. An example event summary plot from the *trigger* stage of QuakeMigrate. The trigger threshold value can be seen as the green line in the Normalized Maximum Coalescence plot. Any disruption that breaches this threshold is considered a seismic event. Each event is plotted on the map to the left and is colored based on its peak coalescence value.

error with a trigger threshold value of 0.45, it was determined that the best solution is to increase the trigger threshold to a value that is on the normalized coalescence value graph found on the right side of the trigger event summary plot for a time interval, which in this case was approximately 1.4. The largest peaks in the normalized coalescence values plot generally represent the events with the best recorded arrivals (Drew et al., 2013), and only the largest peak values in most example runs exceeded a trigger threshold value of 1.4. The threshold value is represented by a green line in the normalized maximum coalescence plot in the trigger summary figures (Figure 3) and can be changed to optimize the identification of only real seismic events. Triggered events are represented by when the normalized coalescence plot increases above the green line of the trigger threshold. The optimal trigger threshold is low enough to allow the coalescence function to exceed it for as many real events as possible while leaving out artefact events and other noise.

Locating events

QuakeMigrate's *locate* stage (`locate.py`) computes the hypocenter of a detected and triggered earthquake in a 3-dimensional space around each possible event found in the *trigger* stage, and it outputs the epicentral coordinates, depth, calculated magnitude, and the degree of uncertainty for each. This program returns the desired information for our catalog in a directory entitled "events," which contains files (*.event) with a series of descriptive and statistical outputs for every detected, triggered, and located event. The program also returns an event summary figure for each event (Figure 4). Event summary figures for each event can be found in the supporting information. In order to calculate magnitudes in the *locate* stage, response calibration information must be provided for each station included in the analysis. The MRSN and UMSN use different seismic instrumentation, which is a consideration whenever using data from multiple networks, and response calibration files provide the software with necessary information about each station so magnitudes can be calculated. The use of these files eliminates the need for most individual changes or specifications for each network in the code, other than sampling rate, as discussed in the *detect* stage description.

In response to the output files that QuakeMigrate produces in the *locate* stage, we developed a Python program (**`event_reader.py`**) to read these event files individually and return only the hypocentral locations, magnitudes, and origin times for each event line by line into a text file in order to create the catalog. An example of the information that will be found in the final catalog once complete is seen in Table 3.

Key parameters that impact runtime in the *locate* program include the marginal window and thread count. The number of stations also linearly impacts runtime (Tom Winder, personal communication), but was negligible here because we did not change the number of stations used between stages. The marginal window parameter is an estimate of uncertainty in the origin time of the event, which itself represents the uncertainty in the velocity model used as well as the spatial uncertainty of the event (QM docs). We observed that a longer marginal window yields a shorter runtime and greater uncertainty. We optimized runtime and uncertainty values through a trial-and-error process at a marginal window of 1.0 second. The default thread count value of 4 was increased to 8, but not further as there was no observed improvement in runtime at greater thread counts than 8. Code was run on the linux-based virtual machine Apgar, maintained by the University of Montana IT and the Martens research group. We used the same bandpass filters, STA/LTA windows, and sampling rate as previously mentioned in the *detect* description. We used default values from QuakeMigrate example code in the **`Volcanotectonic_Iceland`** example for the **`pre_filt`**, **`water_level`**, **`signal_window`**, **`highpass_filter`**, and **`highpass_freq`** parameters.

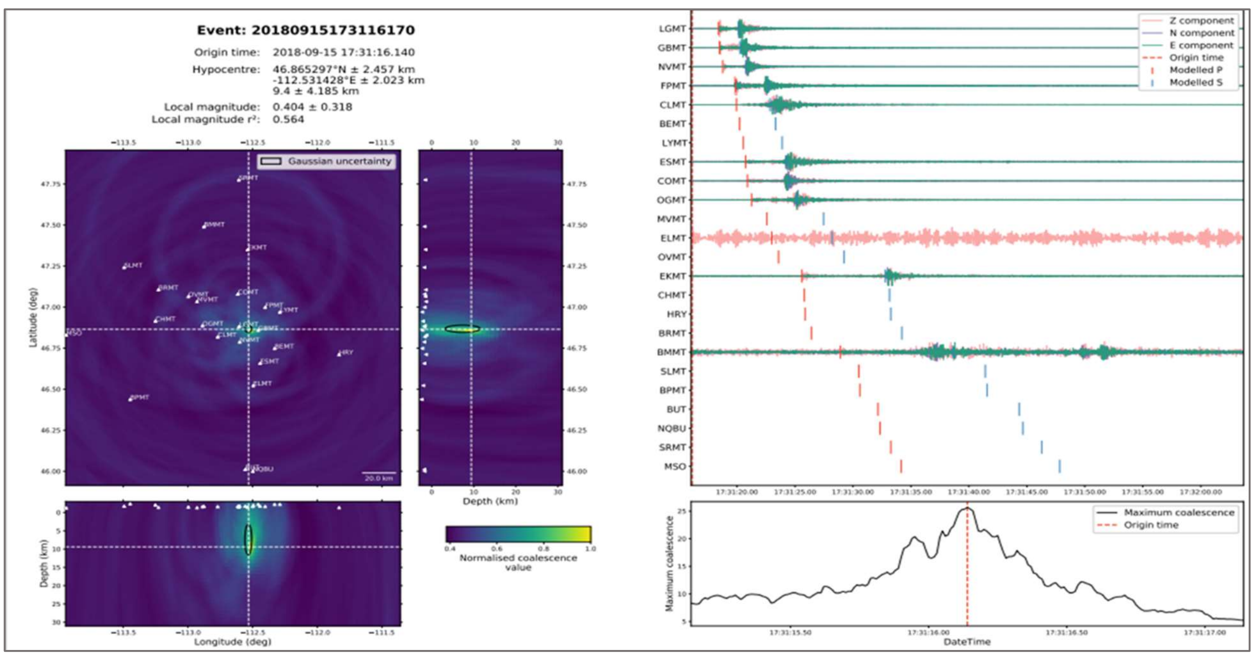

Figure 4. An example of an event summary figure outputted from the *locate* stage of QuakeMigrate. The right side of the figure includes seismograms for each station that detected the event and automated phase picks for each arrival based on the distance from station to calculated hypocenter. MRSN stations that detected the event do not have seismograms because those stations only record the vertical component of displacement, while UMSN stations include the vertical component and both horizontal components. P-wave arrivals found through the vertical component recorded by MRSN stations are included in the data. We will add the MRSN seismogram data in future work if possible. The left side of the figure is a map of the calculated hypocenter in three dimensions relative to station locations and includes a colormap based on peak coalescence values based on location for the event, indicating the event most likely occurred where the coalescence value is mapped to be the highest.

Visualizing fault lines

QuakeMigrate allows the user to add a file containing latitude and longitude coordinates to overlay on the maps of events. This allows for the comparison of event locations to known structural features as well as the possibility for identification of new structural features delineated by earthquakes that may be deeper in the subsurface or not previously observed. The format required to plot fault lines on event summary figures consists of one comma-delimited (.csv) file that contains the paths of the individual files, which contain the geographic coordinates of each fault as well as the line thickness and color desired for the display of each fault line. The format of the overarching file and each individual fault coordinate file is seen in Table 2. Example fault files are provided in the supporting information. Similar application of other geographic and geologic features may also be useful for studies in which county, state, province, or national borders would be useful. Example code in QuakeMigrate related to studies completed in Iceland includes delineation of dikes and other volcanic intrusions.

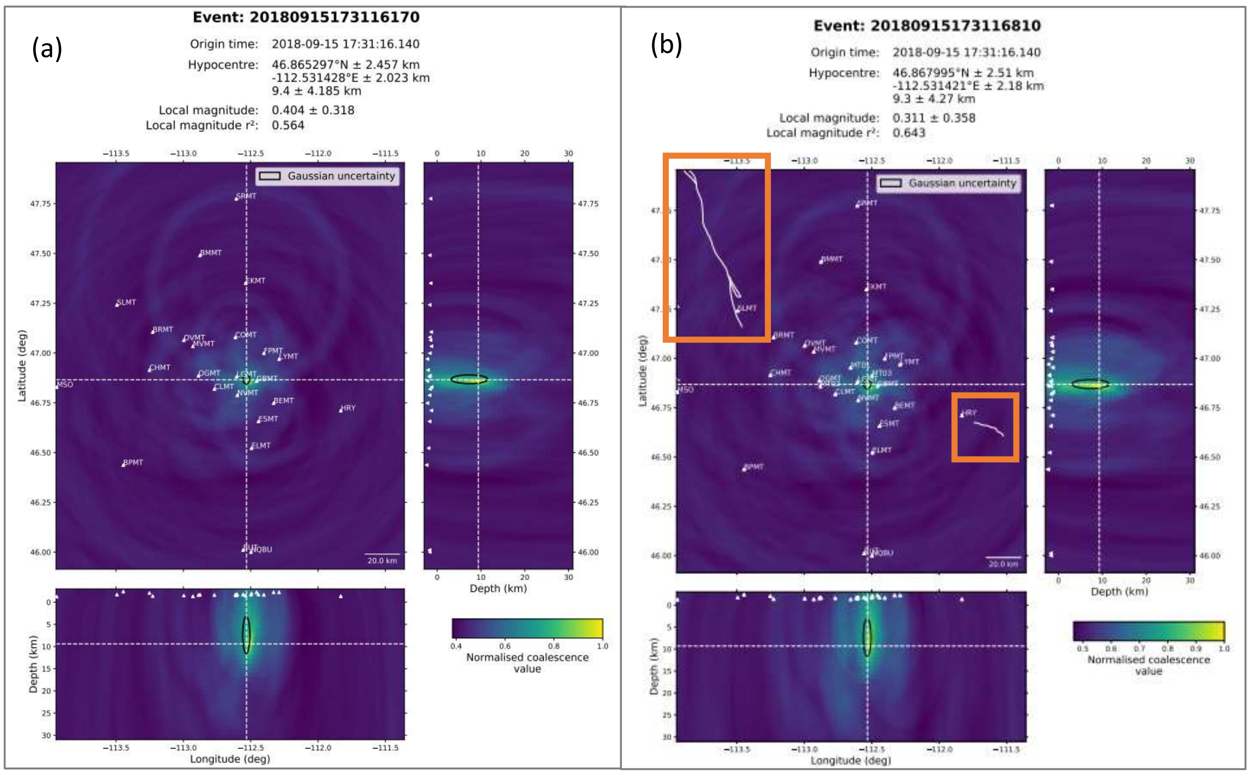

Figure 5. Event summary figure map from *locate* stage without fault lines plotted (a) and the same figure with multiple Quaternary age fault lines plotted (b) seen in orange boxes. Figures (a) and (b) have slightly different uncertainties due to minor changes in the **`marginal_window`** and **`min_event_interval`** parameters specified in the *trigger* stage of QuakeMigrate. Fault data are available via the USGS Earthquake Hazards site (https://www.usgs.gov/natural-hazards/earthquake-hazards/faults).

Main file (.csv) format	../inputs/XY_FILES/ fault_1.csv,black,0.5,- ../inputs/XY_FILES/ fault_2.csv,black,0.5,- ../inputs/XY_FILES/fault_3.csv,black,0.5,- ../inputs/XY_FILES/fault_4.csv,black,0.5,- …

Individual fault file (.txt) format	# fault name -113.9289962,47.2582968 -113.9299113,47.25927347 -113.9314225,47.2605362 -113.9327576,47.26242792 -113.934436,47.26414459 -113.9363589,47.26575459 -113.9372817,47.26689904

Table 2. *Example formatting for files containing coordinates for fault lines visible on event summary figure maps.*

Results and Next Steps

The full catalog, once completed, will represent continuous data analysis of the most likely earthquakes and aftershocks and other earthquakes in the region of the 2017 M 5.8 event between the day of the mainshock (6 July 2017) and through the end of 2021 (31 December 2021). Future analysis using this catalog will aim to identify earthquakes it includes that are not found in the current national earthquake catalog. Additionally, we intend to map the cataloged events and identify clusters and their geographic trends in an effort to further constrain locations of active faults in the region, building on Smith, Martens, and Stickney (2021). We expect to observe multiple events that have not previously been recorded by the USGS national catalog. Some gaps in recorded data and a small number of local stations after the mainshock and before UMSN stations were deployed could contribute to fewer cataloged events than expected. Like other aftershock sequences, the frequency of observed events decays with time after the mainshock. The USGS catalog has recorded 4884 seismic events (which includes several mining explosions and quarry blasts) greater than M 0.0 over the same time period and geographic area as our catalog is being completed in reference to (USGS Composite Earthquake Catalog, 2022).

Date of event	Origin Time	Latitude	Longitude	Depth (km)	Local Magnitude
2018-09-15	03:25:03.38	46.660246	-112.595939	22.9	0.234
2018-09-15	03:36:10.79	46.950574	-111.720672	20.2	0.23
2018-09-15	03:52:23.02	46.85887	-112.444889	11.0	-0.0562
2018-09-15	04:44:25.50	46.904882	-112.535271	11.0	0.615
2018-09-15	04:44:59.50	46.873393	-112.531408	12.6	0.104
2018-09-15	06:09:01.47	47.599341	-112.597465	30.5	-0.154
2018-09-15	06:15:10.65	46.824662	-111.776049	17.5	0.753
2018-09-15	06:25:19.62	46.9352	-111.60799	12.1	0.185
2018-09-15	06:25:26.75	46.889172	-111.936952	13.0	-0.0367
2018-09-15	06:25:37.41	46.856171	-112.4449	11.1	-0.64
2018-09-15	06:40:49.42	46.434456	-113.390741	13.3	0.597
2018-09-15	06:47:08.64	46.932464	-111.424173	13.5	0.206

Table 3. Hypocentral locations of earthquakes occurring on 15 September 2018 as an example of the information included in the catalog. The catalog will be formatted and created through the **`event_reader.py`** program that is not a part of the QuakeMigrate software. The programs currently used to develop the catalog are available in the supporting information. Note: these event details are from program test runs and may not be present in the final catalog when it is completed.

Further analysis using this catalog once complete will be to identify specific events (if any) it includes that are not included in the regional USGS catalog. Additionally, we plan to map events in the catalog in an effort to identify potentially unmapped faults in a similar process as outlined in Smith, Martens, and Stickney (2021), yet with a larger sample size of seismic events and a lower magnitude of completeness. We also aim to use similar methodology to map earthquakes in the Swan Valley region of northwestern Montana to compare earthquake depths to the local brittle-ductile transition zone depth and later compute focal mechanisms for mapped events, which is outlined in more detail in the Discussion.

Discussion and Broader Implications

Bookshelf Faulting along the LCL

Bookshelf faulting is a process that occurs when large shear zones cause smaller faults that are roughly perpendicular to the direction of shearing to rupture or reactivate in order to accommodate for stress in the shear zone (Smith, Martens, & Stickney, 2021). Evidence for this relationship in western Montana is seen through the alignment of earthquake sequences within the LCL. The majority of aftershocks located by Smith, Martens, and Stickney (2021) from the 6 July 2017 event in Lincoln are clustered within 5 to 10 km of the mainshock. Aftershocks were thought likely to rupture on pre-existing faults that are part of the LCL. However, several aftershock clusters as far as 15 km from the mainshock are seen in linear trends that are nearly perpendicular to the LCL. Smith, Martens, and Stickney (2021) infer that these linear trends on which many aftershocks have been observed are faults making up a bookshelf faulting mechanism in the area due to their orientation. These unexpected faults may be areas of crustal weakness reactivated by the recent earthquakes (Smith, Martens, & Stickney, 2021).

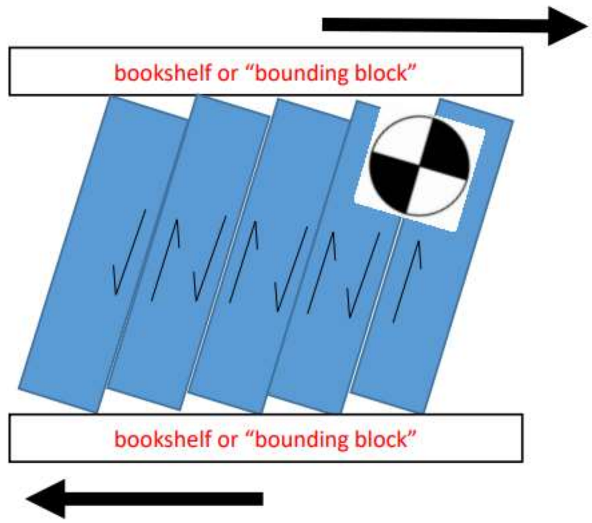

Figure 6. A schematic diagram of bookshelf faulting. The boundaries between the blue rectangles ("books") represent the faults found by Smith, Martens, and Stickney (2021) that accommodate for stress created by shearing of "bookshelves." The entire system shown experiences clockwise rotation about a vertical axis as right-lateral shearing progresses (via Smith, Martens, & Stickney, 2021).

The catalog we are creating can be analyzed to potentially support or extend evidence of bookshelf faulting surrounding the LCL in western Montana. Determination of focal mechanisms and observations of clusters over the greater-than-four-year span this catalog will cover for events near the epicenter of the Lincoln mainshock may expose newly formed or re-activated fault lines that would provide more detail on the hypothesis made by Smith, Martens, and Stickney.

Anomalously Deep Seismicity of the Swan Valley

The collection and analysis of data with QuakeMigrate may be useful for the study of anomalously deep seismic events occurring in the Swan Valley of northwestern Montana (Stickney 2022). Recorded events may be occurring at a greater depth than the average brittle-ductile transition zone across western Montana, raising the question of how the brittle failure associated with the earthquakes could be present there. Hypocentral locations and focal mechanisms of earthquakes could be used to develop a greater understanding of the fault structure and kinematics below the Swan Valley, providing insight as to how these anomalous events may occur.

Hazard Implications

Earthquakes like the Lincoln, MT mainshock in 2017 may seem few and far between, but still can pose significant danger to local towns and communities, no matter how small. Many places that do not experience common large seismic events are not well prepared. Places like Montana are complicated because they experience multiple seismic events every day, but many events are not felt due to very remote locations or small magnitudes. While small earthquakes do not seem to pose much of a threat, they are indicative of activity in the earth's crust that often has the potential to produce large events. Studying and precisely locating even the most minor of events allows for better comprehension of what is going on with the geologic structure of an area, as well as approximately where and how damaging future earthquakes may be.

Conclusions

We are currently developing a catalog of earthquakes and aftershocks of the M 5.8 event on 6 July 2017 near Lincoln, Montana through customization of programs from the QuakeMigrate software package. We use continuous waveform data from the UMSN, MRSN, and three temporarily deployed stations from the USGS seismic network to provide the most comprehensive earthquake dataset for west-central Montana in order to create an earthquake record for over four years directly following the mainshock. QuakeMigrate uses a method called coalescence microseismic mapping to compute earthquake hypocenter locations and origin times. The seismicity that will be present in this catalog is largely related to the concentrations of faults local to west-central Montana, including the Lewis and Clark Line and the Intermountain Seismic Belt.

While thorough seismological studies have been completed for much of the United States and North America, new data is constantly being recorded and potentially contains information from seismic events that have not yet been analyzed. The UMSN has recorded over four years of continuous waveform data in west-central Montana that has not yet been included in national or international catalogs and records and contains high resolution information relating to the M 5.8 earthquake that occurred 11 km southeast of Lincoln on 6 July 2017. Events like the Lincoln event are often unexpected and hazardous especially when they occur near populated areas, and they produce large numbers of aftershock events that can be used to accurately study subsurface structure and dynamics. Analyzing this data from the UMSN alongside other recorded data in the region and the development of a catalog of the data creates opportunity for future study. The process of customizing QuakeMigrate software can be repeated and catalogs can be developed for any location with continuous waveform data. Outlining this process and showing results produced result aims to help others in the future who work to complete related products using QuakeMigrate.

Data and Resources

Continuous waveform data was downloaded from IRIS for the UMSN, MRSN, and USGS stations included in this analysis. Figure 1 was created using Google Earth Pro (downloaded from https://www.google.com/earth/versions/#download-pro). Station locations used for Figure 1 and the analysis were accessed from the interactive IRIS station map (https://ds.iris.edu/gmap/). Code was developed, customized, and run using the PuTTY application to access a virtual machine maintained by the University of Montana IT and the Martens research group. Figure 5 was accessed from Smith, Martens, and Stickney (2021). Fault data are available via the USGS Earthquake Hazards site (https://www.usgs.gov/natural-hazards/earthquake-hazards/faults). All outputs relating to the catalog data including summary figures, data files, and continuous waveform data are available in the supporting information. Results were compared with the current USGS composite earthquake catalog, which is available online (https://earthquake.usgs.gov/earthquakes/search/).

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