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Deriving a 1D Seismic Velocity Model for West-Central Montana

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1. Introduction & Motivation

- In seismically active areas with infrequent large-magnitude earthquakes, high-quality seismic data is critical for determining seismic velocity models. Here, we present the **first** 1-D crustal seismic velocity model for west-central Montana, constrained by seismic phase arrivals from the 2017 M 5.8 earthquake that occurred near Lincoln, Montana.
- To derive the seismic velocity model, we analyze continuous seismic data recorded by 11 three-component, broadband stations in the University of Montana Seismic Network (UMSN), which was strategically deployed to record the Lincoln aftershock sequence.
- We manually pick P-wave arrival times from several hundred well-recorded earthquakes and then invert these data for velocity structure using the program VELEST.
- This final 8 layer model characterizes the velocity structure of the crust appropriate to an area in western Montana of about 40,000 km^2 (200 km x 200 km). The derivation of this model improves the accuracy of hypocenter locations and advances our understanding of the region's crustal structure.

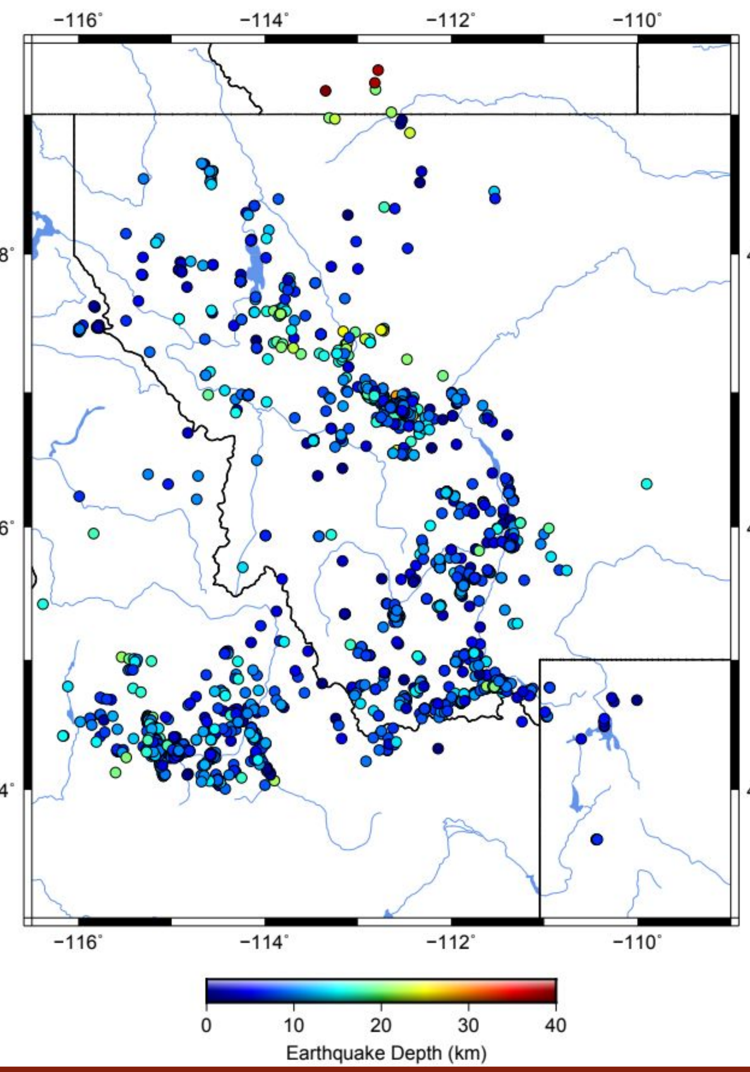


Figure 1.
2900 earthquakes that occurred in western Montana from 2006 to 2020 (above M1.5).

2. University of Montana Seismic Network (UMSN)

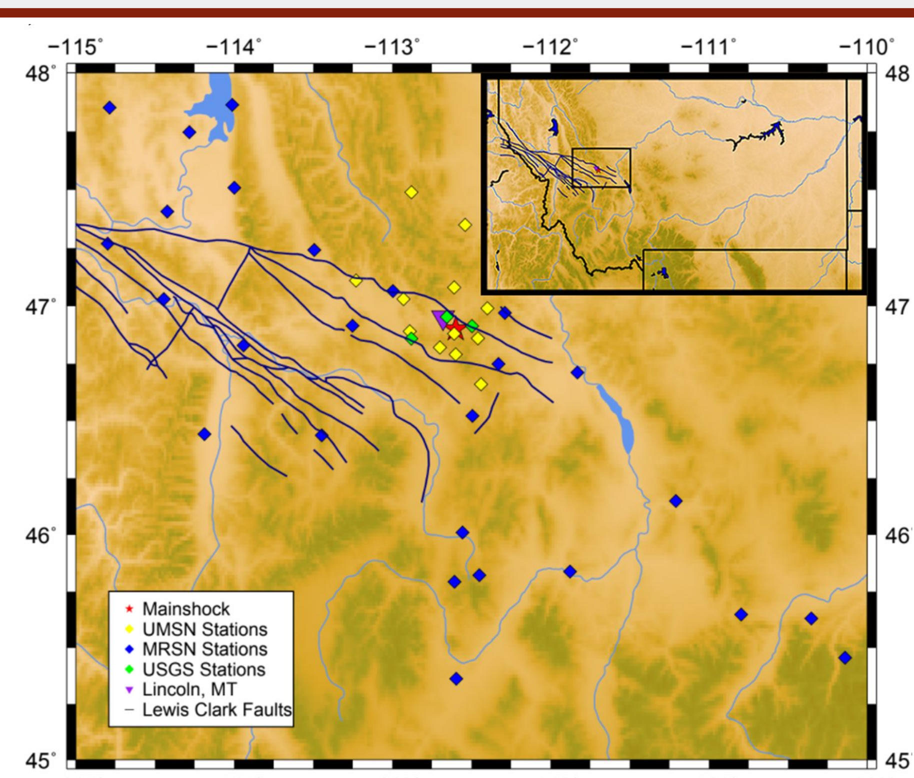


Figure 2.
Seismic station locations that collected data used in the inversion process. Red star denotes the mainshock of the 2017 event while yellow diamonds denote UMSN stations.

- UM stations consist of 11 MBB-2 digital, broadband, 3 component seismometers.
  - Not only is this is a significant upgrade in technology compared to the short period, analog seismic stations used to create previous velocity models for the state, but a vast improvement in seismic station coverage as well.
- The installation of the UMSN began with three stations around the epicenter in the month following the Lincoln mainshock. Seven additional stations were deployed in 2018, followed by one additional station in 2019 with one station re-deployed to a new location in 2020.
- UM seismic stations are strategically placed around the epicenter of the 2017 earthquake to collect the best quality data (see figure at left).
  - Other seismic stations that were included in deriving the velocity model were from the Montana Regional Seismic Network and the U.S Geological Survey.
    - Five MRSN stations lie within 54 km of the Lincoln mainshock.
    - Additionally, the USGS deployed three temporary broadband seismic stations within two days of the mainshock.

3. Methods & VELEST

- We use the software program, VELEST, to produce a 1D velocity model.This is achieved through the inversion of the damped least-square matrix of earthquake travel time partial derivatives to minimize the difference between predicted and observed arrival times.(Kissling et al. 1995).
  - In order to obtain effective results with VELEST, the following data inputs are required:
    - Seismic station coordinates & elevations.
    - Earthquake hypocenters & arrival times.
    - A reference velocity model to initiate the inversion process.
- We manually collect seismic data from the UMSN and supplement with telemetered data from the MRSN.
  - The local model is derived with 2500 earthquakes that occurred within a 200 km radius of the 2017 epicenter, producing 24380 P wave arrivals..
  - These earthquakes occur from July 2017 through May 2020 and have a magnitude greater than or equal to M1.0.

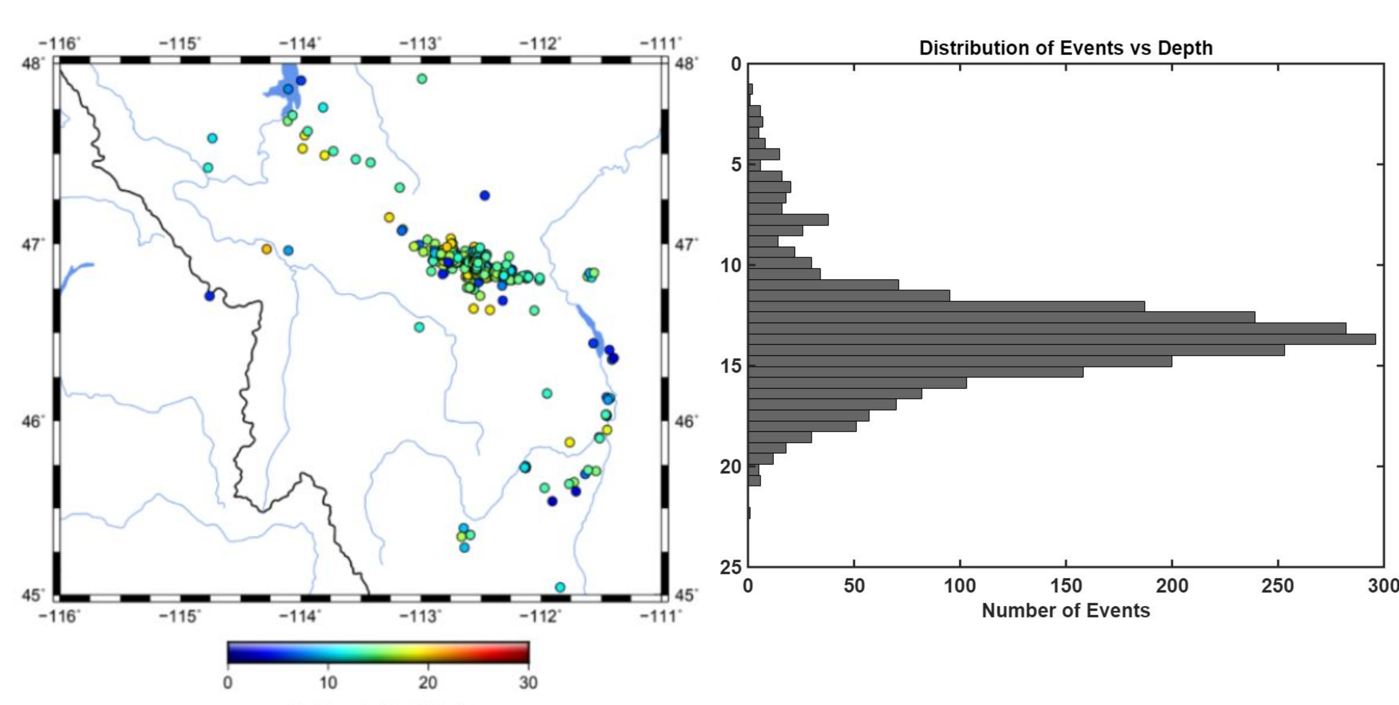
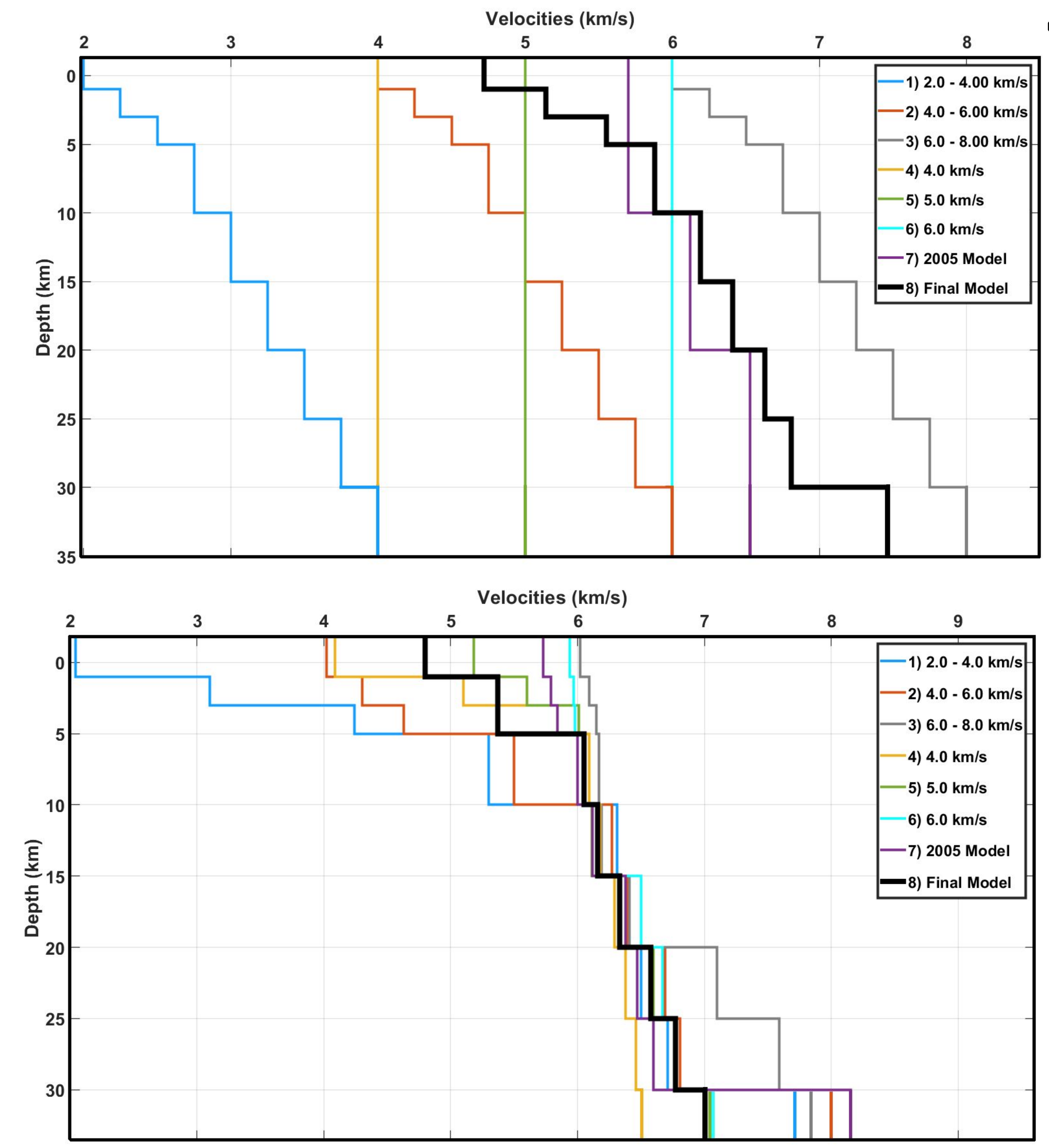


Figure 3.
Left figure: 2500 earthquakes used for the west-central model. **Right figure:** Depth distribution of the 2500 earthquakes.

4. The 1D Seismic Velocity Model for West-Central Montana



- We use a suite of initial solutions to explore the model space.
  - This includes homogeneous & heterogeneous layered models and the last model derived for western Montana in 2005 (Zeiler, 2005).
  - Due to the lack of events occurring at depths beyond 25 km, we opt to constrain the model from 1.80 km above sea level to 30 km below the surface.
  - We aim to determine the upper mantle structure by applying our methodology to a regional dataset (see Figure 1 for an example) to derive an updated regional model for all of western Montana.
- To find the best fit final model, we use the average of the 7 starting models (colored lines) as the input to the final model (black line).
- The preferred 8 layered final model reports seismic velocities of:
  - 4.80 km/s at the surface.
  - 6.16 km/s to 6.58 km/s for the mid crust.
  - 7.00 km/s near the lower crust.
- The final model yields a residual time-travel error of 0.07 s, a reduction of 84% from the initial value of 0.43 s.

Figure 4.
Top Figure: Suite of initial models used as input to VELEST. The eight starting models have been labeled in order: models 1-3 consist of nine layers of heterogeneous seismic P-wave velocities, models 4-6 consist of nine layers of homogeneous velocities, and model 7 is the 3-layered velocity model from Zeiler et al. (2005). The final model input (black line, model 8) is calculated from the mean of the final outputs for the first seven starting models. **Bottom Figure:** Velocity solutions derived from the eight starting models shown in Top Figure.

5. Estimation of Uncertainties

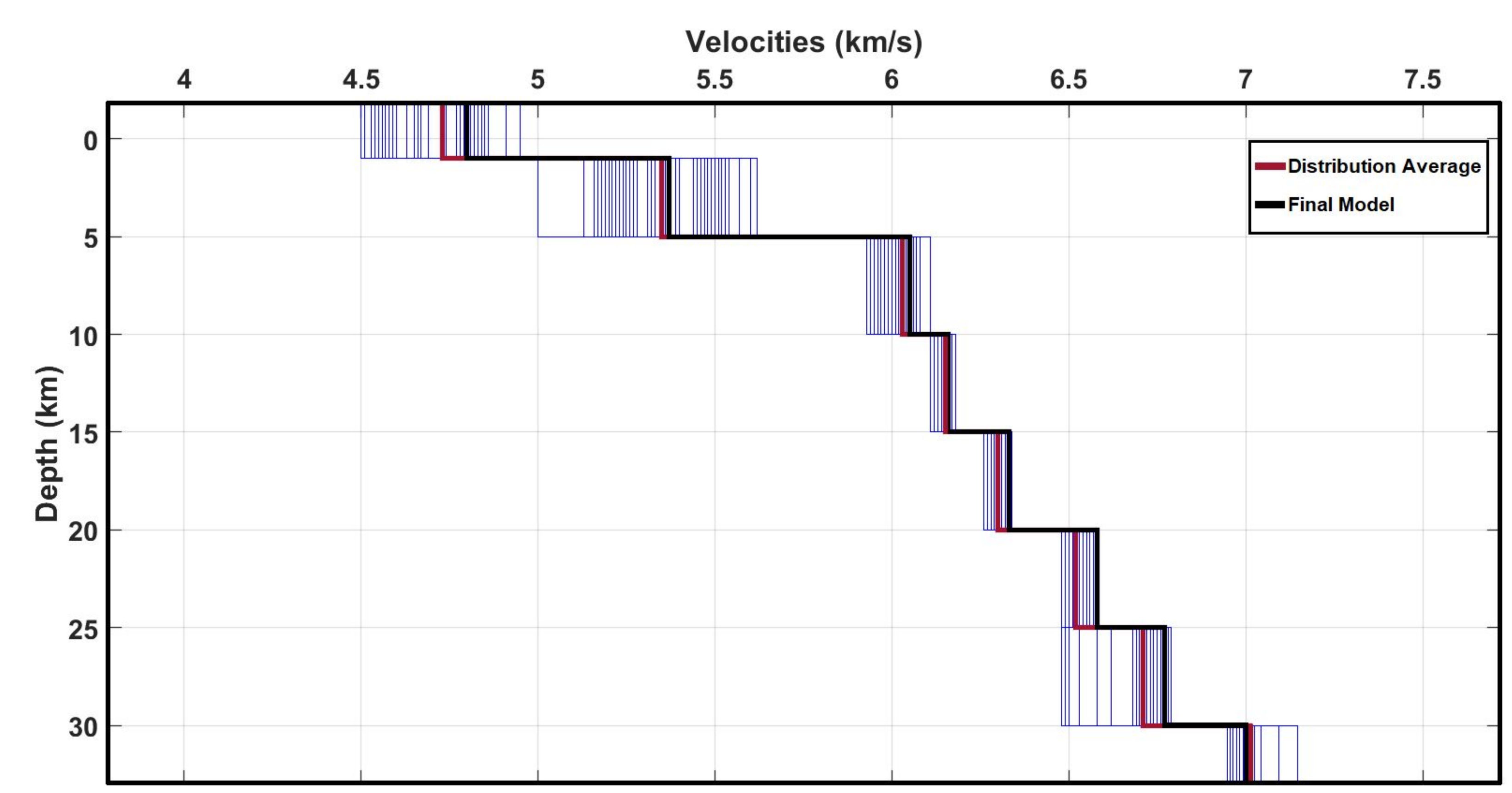


Figure 5. Distribution of 100 models (blue lines) generated by a random selection of 2000 earthquakes. The red line indicates the average of the 100 models, which is compared to the final model (black line).

- To determine distributions of error for the local model, we generate a suite of 100 solutions by randomly selecting a sample of 2000 earthquakes from the full dataset (2500 earthquakes) for each run of the inversion algorithm.
- We then compute the average (red line) to provide an estimate of uncertainty in the velocity for each layer depth compared to our derived final model for west-central Montana (black line).
- We find little variation (< 0.05 km) between the average and final model from depths of 1.0 km to 20.0 km. The greatest variation between the computed average and the final, preferred model is 0.07 km which can be found at the surface (-1.80 km) and the lower crust (25.0 km).

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