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3D Crustal Tomography Model of Utah

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Table of Contents

1. Introduction

The ability to accurately locate seismic events is necessary for treaty monitoring. When using techniques that rely on the comparison of observed and predicted travel times to obtain these locations, it is important that the estimated travel times and their estimated uncertainties are also accurate.

The methodology of Ballard *et al.* (2016a) has been used in the past to generate an accurate 3D tomographic global model of compressional wave slowness (the SAndia LoS Alamos 3D tomography model, i.e. SALSA3D). To re-establish functionality and to broaden the capabilities of the method to local distances, we have applied the methodology of Ballard *et al.* (2016a) to local data in Utah. This report details the results of the initial model generated, including relocations performed using analyst picked mining events at West Ridge Mine and three ground-truth events at Bingham Mine. We were successfully able to generate a feasible tomography model that resulted in reasonable relocations of the mining events.

2. Tomography Method and Data

The methodology of Ballard *et al.* (2016a) used to generate the SALSA3D model was used here to generate a tomographic model of Pg wave velocity in the Earth's crust in Utah, specifically in the Wasatch Front. 100 stations from the University of Utah Seismograph Stations (UUSS) network and 1724 seismic events, the deepest of which occurred at 23 km depth, were used in this work. Figure 1 shows the event and station locations and the achieved raypath coverage.

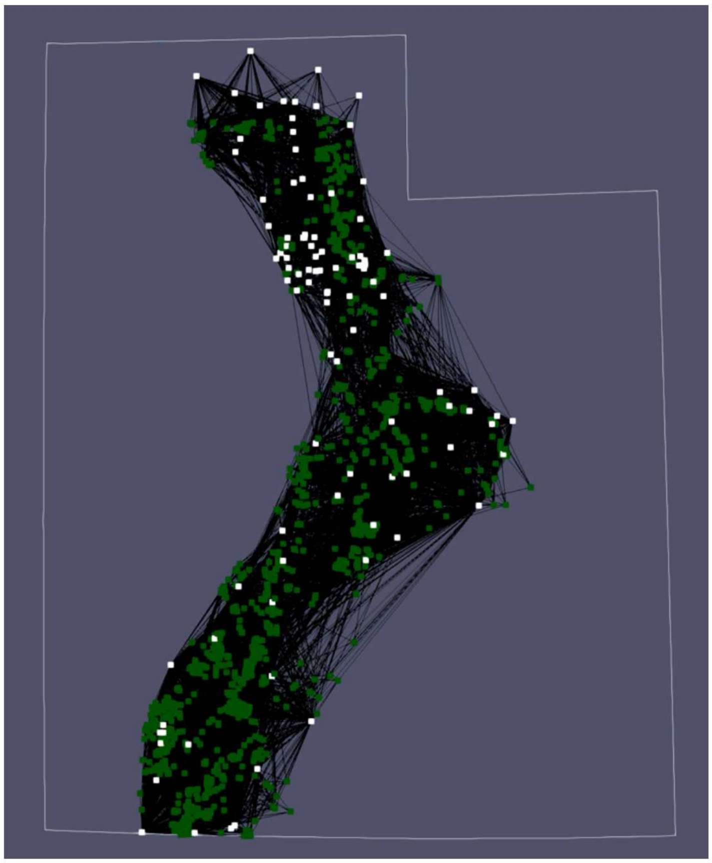

Figure 1. Event (green circles) and station (white squares) locations. Black lines represent the corresponding raypath coverage.

Our starting model in this work consisted of a layerless crust, with crustal thickness and topography extracted from the Crust 1.0 model (Laske *et al.*, 2013). Pg velocity was set to a constant 6.2 km/s throughout the starting model. The initial resolution of the grid generated by the GeoTess framework (Ballard *et al.*, 2016b) was set to a triangle edge length of 0.5 degrees.

3. Tomography Results

Following several iterations and refinements of the grid (see Ballard *et al.*, 2016a for details), the generated Utah Pg velocity tomography model and its corresponding model resolution are shown in Figure 2 at depths ranging from 0 to 20 km.

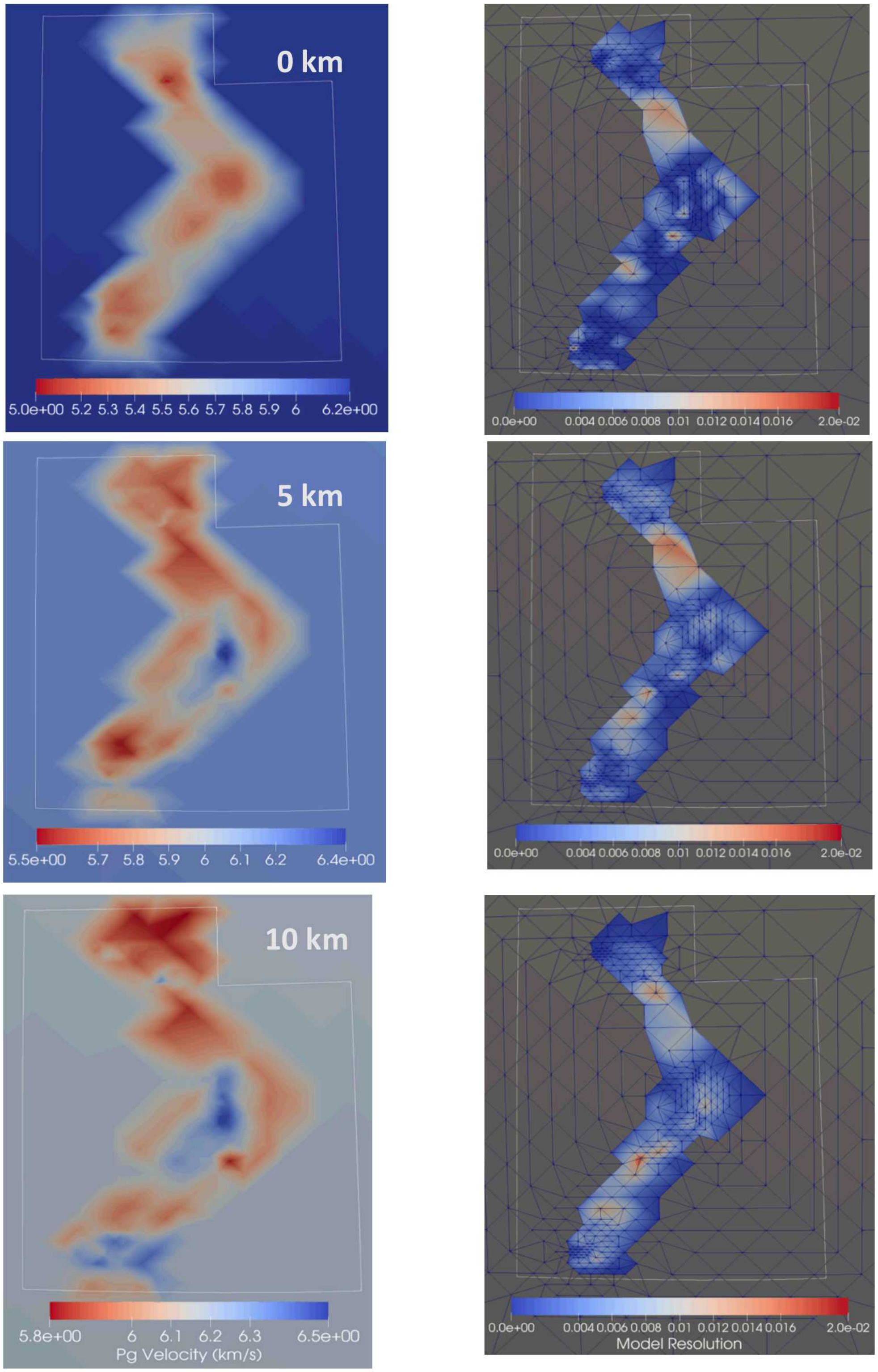

Figure 2. Map of Pg velocity (left column) and grid and model resolution (right column) at depths of 0, 5, 10, 15, and 20 km (continued on next page). In the left column, blue is fast and red is slow. Note the varying velocity scale used to enhance features in the velocity tomography at each depth. In the right column, red is high model resolution and blue is low model resolution, with grid resolution mapped on top.

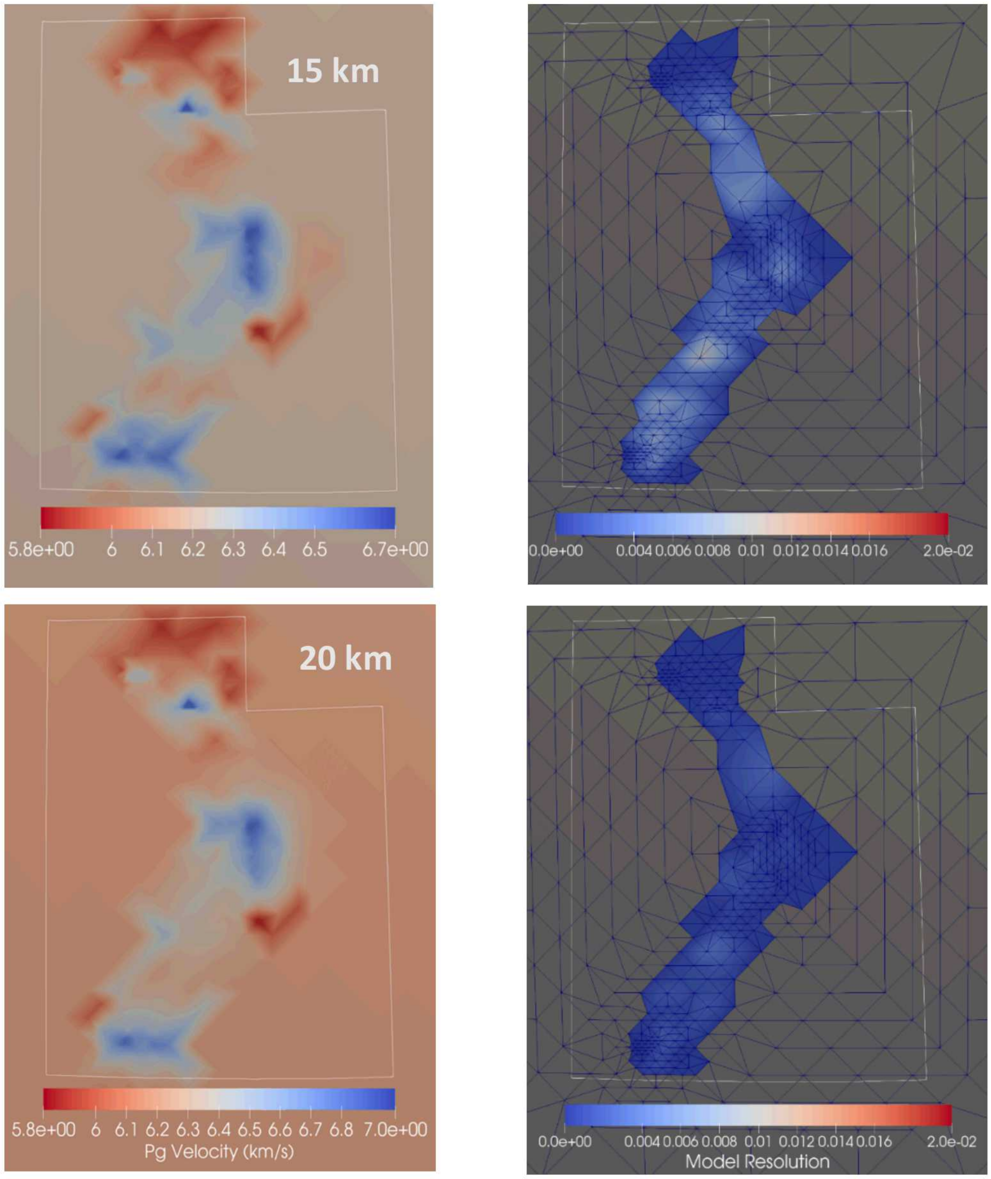

Figure 2. Continued.

Our model appears to be reasonable, consisting of distinct, broad features that persist to depth rather than the "salt-and-pepper" features that indicate overfitting. In our model, we observe slower velocities at shallower depths, with velocity increasing with increasing depth. At 5 and 10 km depth, fast features at the center and southern end of the Wasatch Front, respectively, are seen to persist at various depths.

We note that the corresponding model resolution, which reaches a maximum value of 0.02 at depths less than 15 km, is low when compared with past experiments using the SALSA3D global model, where the maximum resolution was ~0.25 after several refinements. This observation may be caused by the smaller region (Utah vs. the Earth) being examined. More likely, the lower resolution values indicate that our initial model has been overdamped, since higher damping will result in decreased model resolution.

While an overdamped model is typically not ideal, for the purposes of our demonstration our model appears to be acceptable. Our conclusion is further reinforced by the Root Mean Square (RMS) residual versus tomography plot shown in Figure 3.

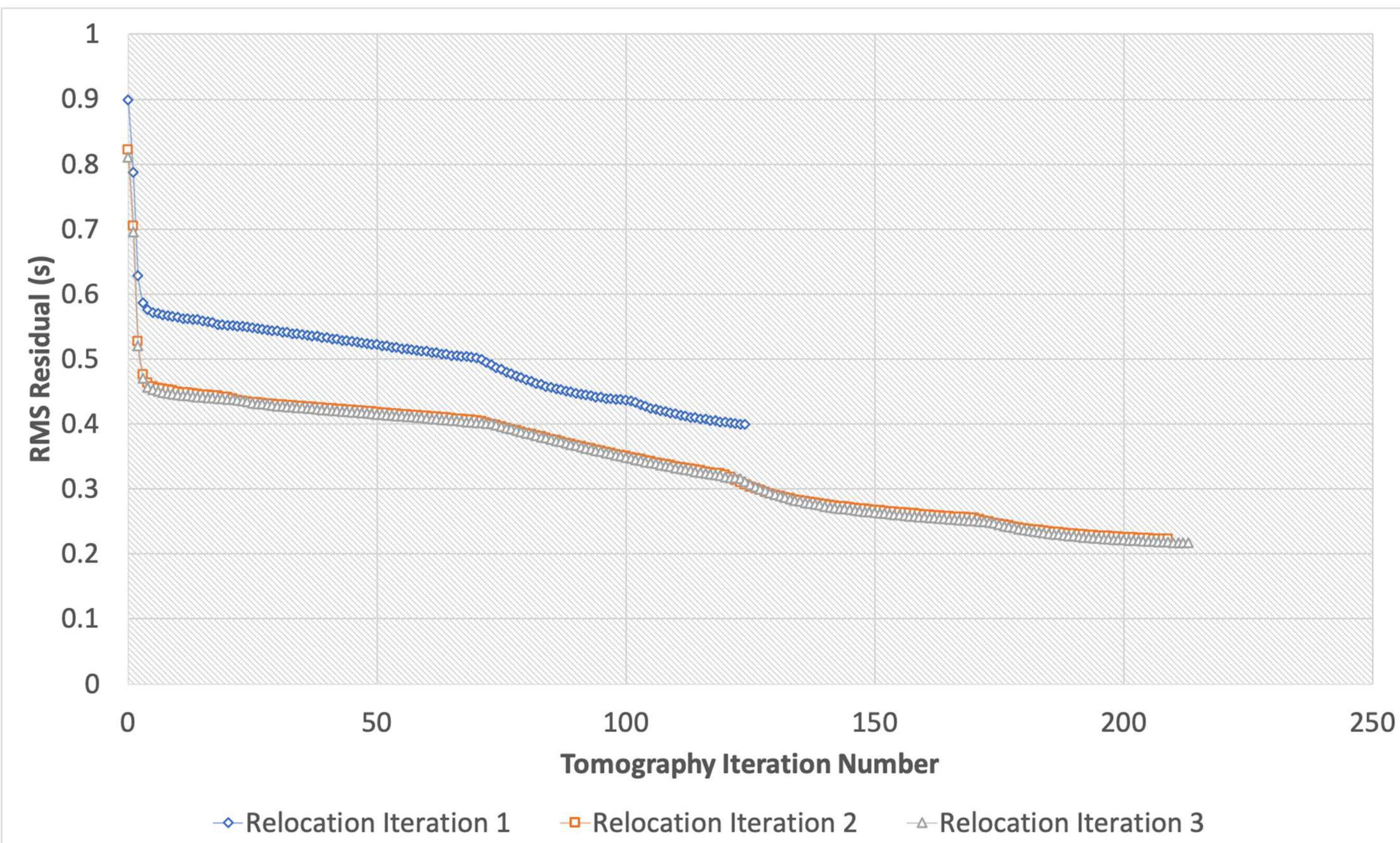

Figure 3. RMS residual versus tomography iteration number over three relocation iterations. The final RMS residual of 0.22 represents a reduction of 76% from the starting model.

In Figure 3, each curve represents the reduction in RMS residual vs tomography iteration number. The three individual curves indicate individual relocation iterations. In each relocation iteration, a tomography model is calculated, the events are relocated such that they are consistent with the calculated model, and a new tomography model is calculated based on the new event locations and the original starting model, grid resolution, and damping parameters (see Ballard *et al.*, 2016a for details).

We observe a large change in the model between the first (orange) and second (blue) relocation iterations, but the changes from the second iteration to the third (gray) are negligible. This observation indicates the event locations and the final model are consistent with each other. The percentage of events that undergo a change in epicenter location with each relocation iteration reinforces this conclusion (Figure 4). After the first relocation iteration, ~98% of events move by 6 km or less. For relocations 2 and 3, event relocations are negligible, with ~94% and ~99% of events having moved by less than 0.5 km, respectively.

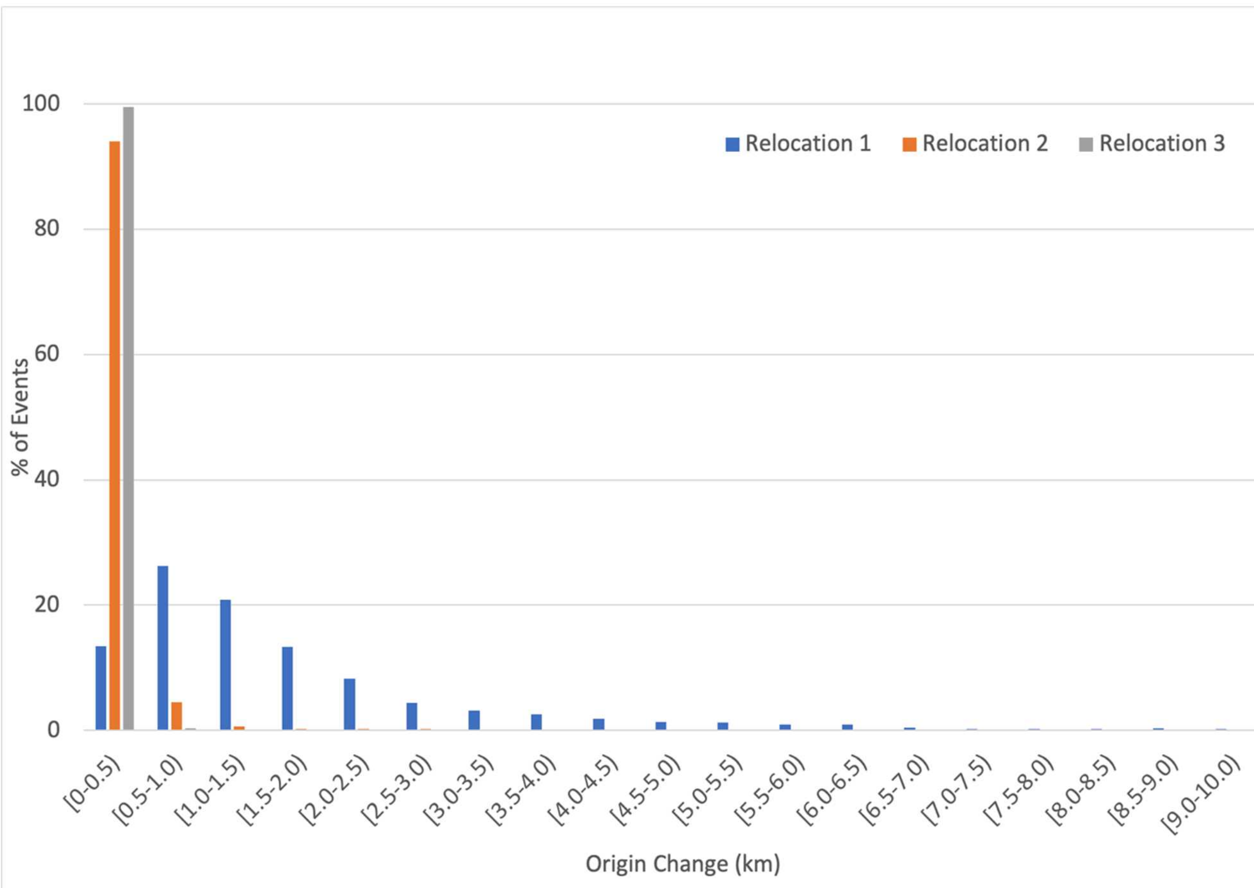

Figure 4. Histogram showing change in epicenter location for events used to generate Utah tomography model.

Overall, the end-to-end tomography procedure reduces the RMS residual of the tomographic data set from 0.90 to 0.22 s (76%) and results in event relocations that are consistent with the final model. These results are consistent with the observations seen for the SALSA3D model (Figures 5 and 6, Ballard *et al.*, 2016a). We note that the decrease in residual is much more drastic than that seen for SALSA3D (Figure 6, Ballard *et al.*, 2016a). This observation is likely the result of our use of a very simplistic starting model. In contrast, the SALSA3D model had a more complex starting model that more accurately reflected known global features.

Absolute station site terms were also determined when we calculated the final model shown in Figure 2. A histogram of these site terms is shown in Figure 5 below.

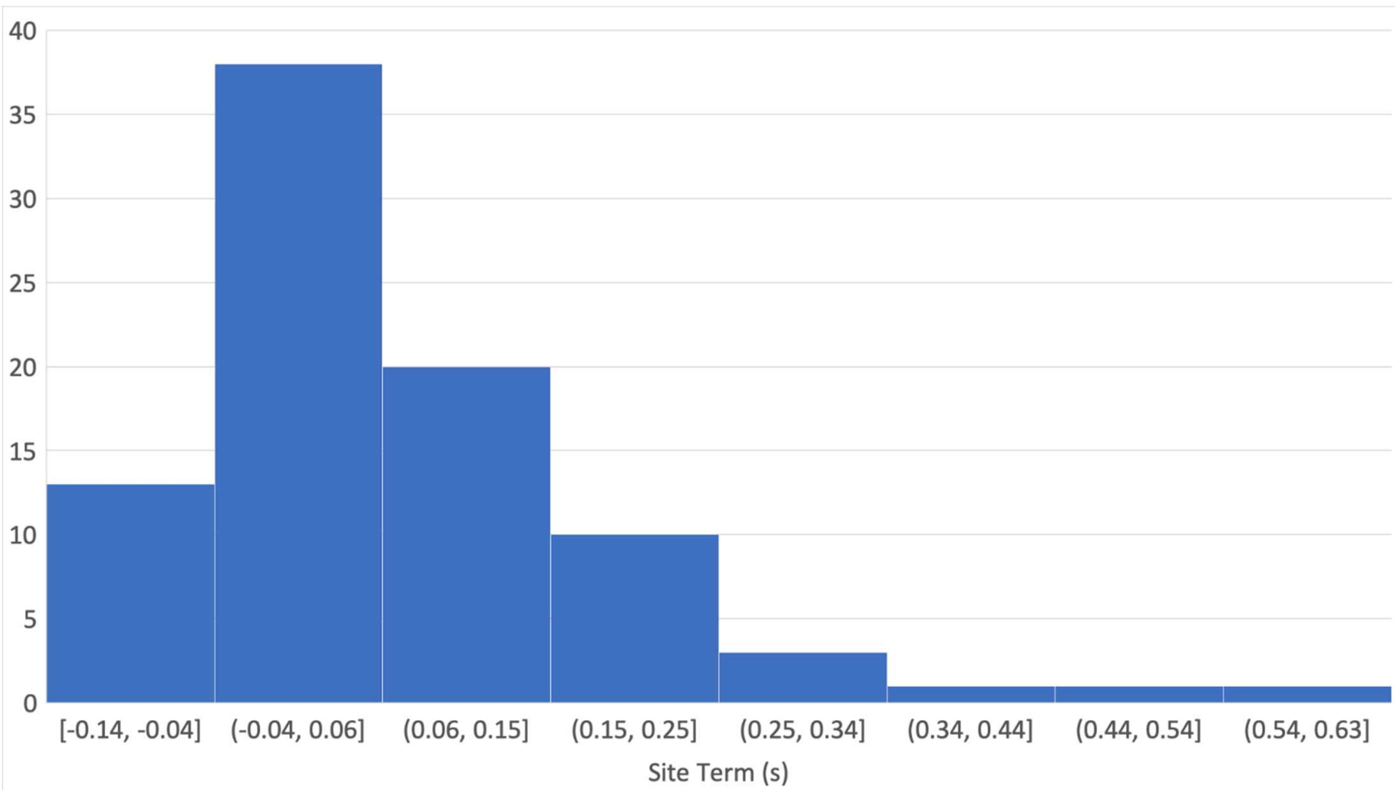

Figure 5. Histogram of absolute site term values in seconds.

The site terms are found to have reasonable values, ranging from ~-0.14 seconds to 0.63 seconds, with the majority of stations having site terms ranging from ~-0.04 to 0.06 seconds.

Finally, the travel time prediction and travel-time prediction uncertainty for UUSS station ALT is shown in Figure 6 as an example.

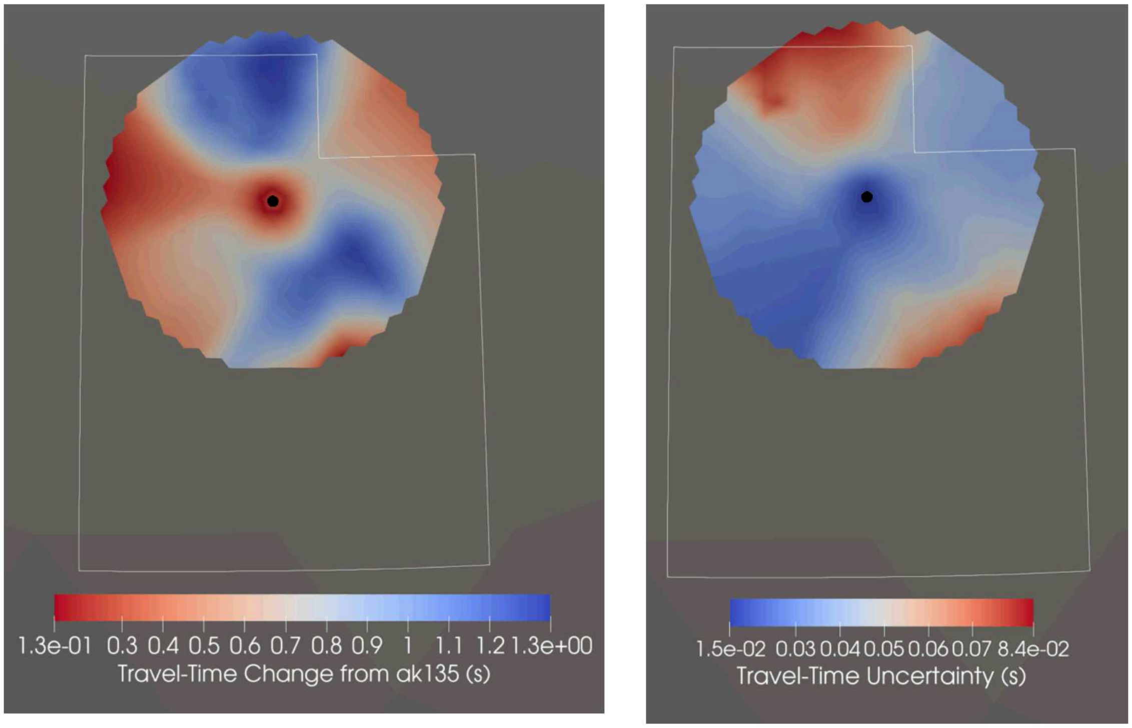

Figure 6. (a) Travel-time prediction and (b) travel-time prediction uncertainty for station ALT at 0 km depth. The black dot at center represents station ALT.

In Figure 6a, the travel time computed using the Ballard *et al.* (2016a) method minus that computed by ak135 is shown at a depth of 0 km, with fast anomalies shown in blue and slow anomalies shown in red. Figure 6b shows the corresponding uncertainty, with higher uncertainties in red and lower uncertainties in blue. For station ALT, we find the highest uncertainties at the NW and SE edges of the travel-time prediction calculation. There is also an area of higher uncertainty (~0.045) to the east of ALT. These areas appear to line up with areas of less dense raypath coverage when compared to Figure 1.

Two observations are of note here. First, the uncertainties in general are very low, ranging from 0.015 to 0.084 s, in comparison with the SALSA3D model which had uncertainties ranging from 0.3 to 2.0 s in Ballard *et al.*, 2016a. Second, some areas with no raypath coverage appear to have unreasonably low uncertainties, e.g. west of ALT.

These issues are likely a result of the damping being set too high during model generation. Higher damping typically results in lower travel time uncertainties as a result of allowing less change in the model.

4. Mining Event Relocations with the Utah 3D Model

To perform an initial validation of the 3D Utah model generated using the tomographic procedure in Ballard *et al.* (2016a), event relocations with fixed depth were performed for events associated with the underground West Ridge Mine and the open pit Bingham Mine.

For West Ridge Mine (Figure 7), a large cluster of analyst-picked events (shown as white dots) originally located to the SE of the mine entrance (shown as a yellow pentagon) are relocated towards the NW, closer to the entrance. Events with a greater number of defining stations are found to relocate nearer the mine entrance.

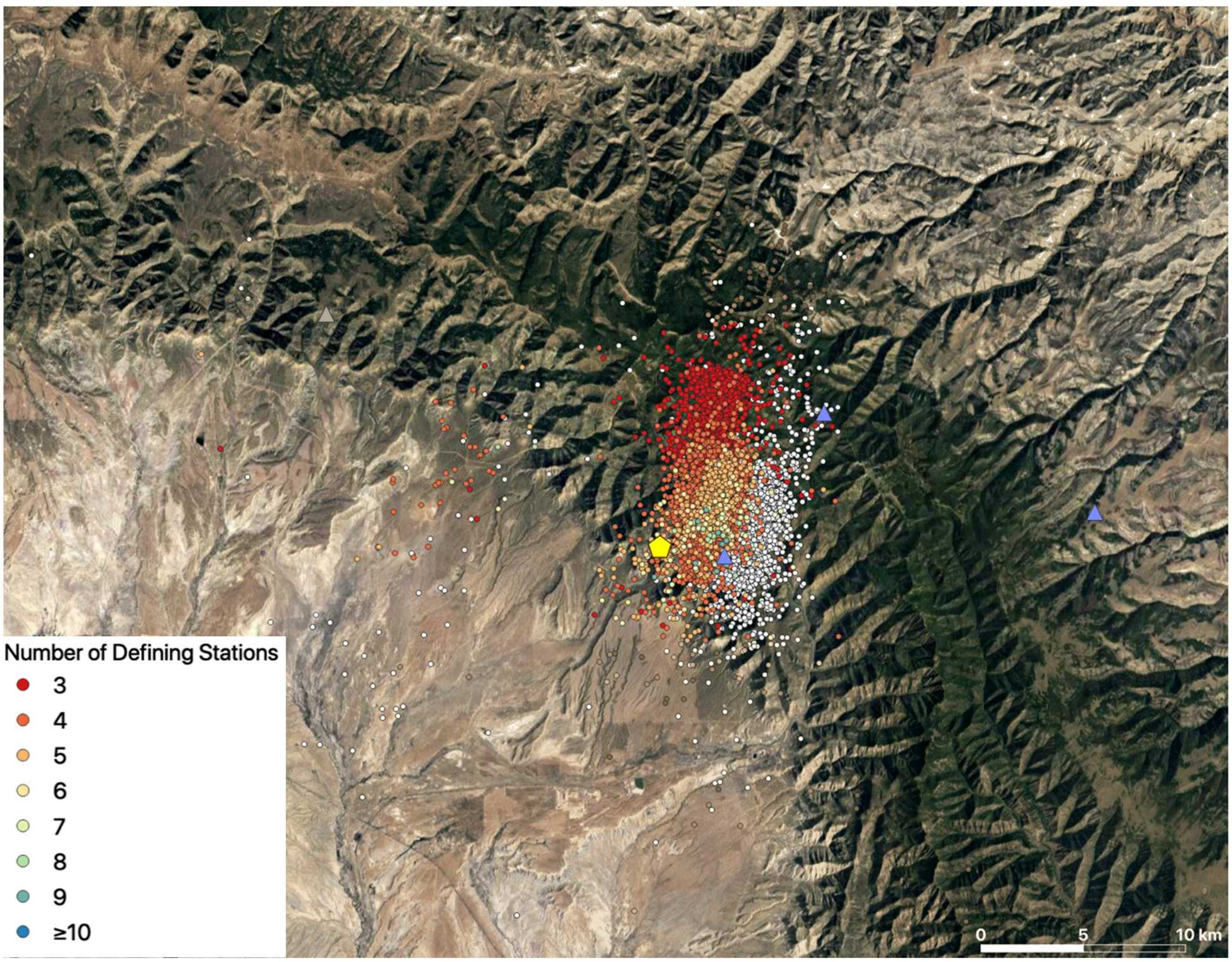

Figure 7. Relocation of events from the West Ridge Mine. Original locations are shown in white. The mine entrance is shown as a yellow hexagon. Nearby stations are shown in blue. Event color indicates the number of defining stations, with cooler colors indicating more stations.

These results appear to indicate that our model is reasonably removing a bias in the original locations and while the scatter of events remains large, other factors (e.g., picking bias) are known to contribute greatly to such scatter.

For the Bingham Mine, we attempt to relocate three Ground-Truth (GT) events indicated by red stars in Figure 8 below and labeled as EVID 1, 2, and 3 from top to bottom, respectively. 95% coverage ellipses were calculated with local 1D errors and are shown in orange.

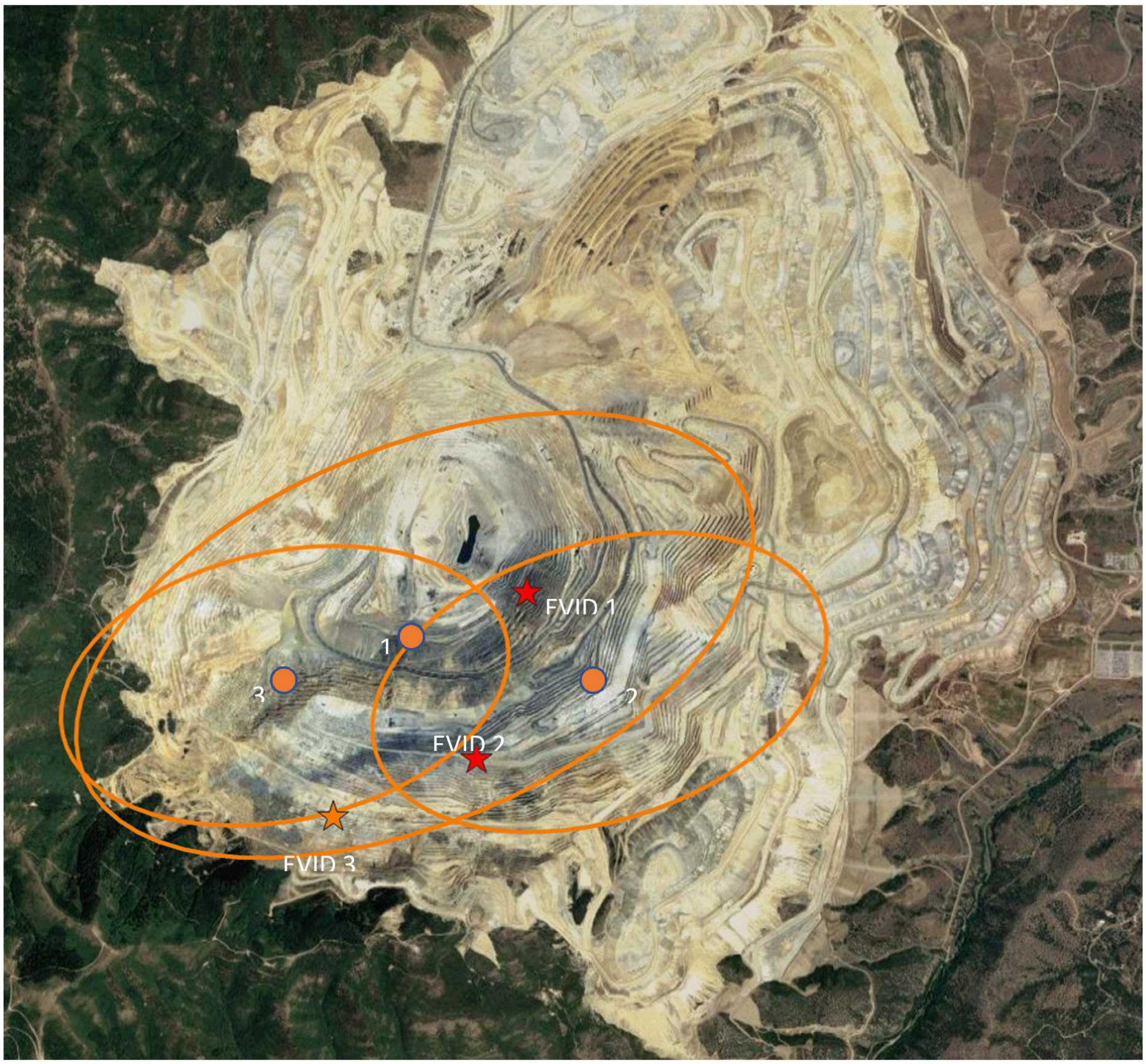

Figure 8. Event relocations of 3 GT events at Bingham Mine with 95% coverage ellipses. GT events are shown as red stars and labeled from top to bottom as EVID 1,2, and 3, respectively. Relocations performed using our model are shown as orange dots. Each event is labeled by their corresponding GT event ID (e.g., event 1 corresponds to EVID 1).

The relocations are all observed to remain within the mining area and appear to be within ~2 km of the true GT event locations. Both EVID 1 and EVID 2 are included within the 95% coverage ellipses, while EVID 3 is only just outside its ellipse. Again, the relocations performed using our model appear to be reasonable.

5. Conclusions

We have applied the tomographic procedure described in Ballard *et al.* (2016a) to generate a 3D crustal velocity model of the Pg wave of the Wasatch Front, Utah along with the associated travel times and travel time uncertainties. This model was generated in order to re-establish the functionality of the algorithm as well as to expand the algorithm to handle tomography at local distances.

We have demonstrated that these goals have been accomplished, with a fully functional tomographic pipeline restored and a reasonable Pg velocity model produced. Further, we demonstrate that our velocity model results in feasible event relocations via testing with analyst-picked and ground-truth mining events.

Improvements in the starting model, the choice of damping parameter, and the value of the a priori uncertainty matrix will be needed to address the issues observed in this current model, particularly the unusually low travel-time uncertainties. These improvements will be tackled in future work.

6. References

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