Testing the Effects of Velocity Models for Seismic Location in the DNE18 Virtual Experiment

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ABSTRACT

The Dynamic Network Experiment 2018 (DNE18) was a virtual experiment designed to quantitatively assess current capabilities for multi-modal data ingestion and processing for nuclear explosion monitoring at the local/regional scale. This assessment will allow us to identify and prioritize remaining challenges that need to be met to achieve desired monitoring capabilities. The experiment was a collaborative effort between **Los Alamos National Laboratory**, **Sandia National Laboratories**, **Lawrence Livermore National Laboratory**, and **Pacific Northwest National Laboratory**.

We describe efforts to test various velocity models for any bias or other recognizable patterns using a two-week, analyst-built event (ABE) bulletin. The data set includes over 6000 events manually-built by the analyst using the **Utah Seismic Network** (Figure 1) which includes about **182 seismo-acoustic stations, 152 of which have analyst arrival picks**. There are active mines in the state of Utah, many of which are associated with clusters of events. The ABEs include mostly Pg and Lg arrivals for events within Utah and some just outside the state. Global events were also picked that included teleseismic P and S as well as core phases, etc. although these are not included in this study. **We test local, regional, and global P and S velocity models (1-D, 2-D, 3-D) for their effect on the event locations**, paying attention to overall epicenter shifts and residual reduction. Many of the event clusters are good candidates for application of **relative relocation techniques**.

Overview

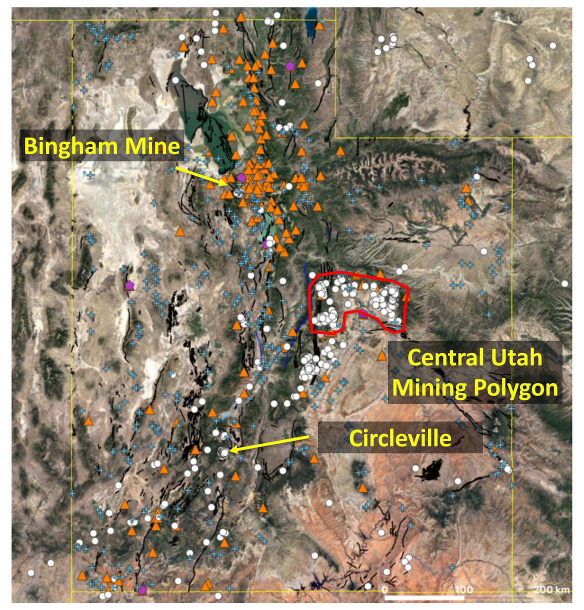

Figure 1: Utah area showing seismic (orange triangles) and infrasound (magenta pentagons) stations available for the DNE18. Possible mines are shown as cyan plus signs. Analyst-built events are shown as white circles. There are clusters of events in the mid-eastern portion of map which appears to correspond to a coal mine. The Bingham mine is in the northwest-central portion, just south of Salt Lake

The analyst-built events (ABE) include mostly Pg and Lg arrivals for events within Utah and some just outside the state. Global events were also picked that included teleseismic P and S as well as core phases, etc. These are relocated as well in this study, but not included in the discussions below.

The ABE using the ak135 1D velocity model (Kennett et al., 1995). This model is a global average 1D model that varies only with depth. The crustal parts of the model include three layers with constant velocity in each layer (both P and S). The Pg and Lg travel time tables associated with ak135 are group velocities of 6.1 and 3.6 km/s, respectively. Some of the events include azimuth and slowness measurements and/or infrasound azimuths and "arrival" times.

There are 6475 events and 82303 associated arrivals – 45% are Lg, 45% are Pg, 3.8% are teleseismic P, 2.3% are regional Pn, 0.8% are regional Sn and 0.8% are pP. Thus, it is clear that the crustal portions of any velocity model are going to affect the locations the most.

Parameters for Relocation

For this study, LANL used a variety of algorithms.

__Single-Event Relocations__

- The **LocOO3D** (v1.10.1e) program (Ballard, written communication), which was developed by SNL for relocating seismo-acoustic events from an Oracle database was used with the RSTT and SALSA3D velocity models.
  - **LocOO3D** can relocate events using 1D LocSAT-type travel time tables, TauP (Crotwell et al., 1999), RSTT (Myers et al., 2010), 3D travel time lookup tables in GeoTess format (Ballard et al., 2016b), and raytracing through a GeoTess model as in SALSA3D (Ballard et al., 2016a).
- A location algorithm based on ***tomoDD*** (Zhang and Thurber, 2006) was used with the ***Syracuse3D*** **Model** (Syracuse et al., 2017) and ***CRUST1.0*** (Laske et al., 2013). This algorithm uses a pseudo-bending ray tracer, which is also used in the development of the Utah 3D Model independently of the DNE18.
- __**Parameters:**__
  - 95% coverage ellipse (LocOO3D)
  - Do NOT allow large residuals
    - Threshold: 3.0 s (weighted RMS)
    - Max Fraction: 0.5 (only allow a fraction of arrivals to be set to undefined when re-running events)
    - Defining Attributes: travel time, azimuth
    - Max Iterations: 30
    - Starting Location:
      - LocOO3D: Event location from input tables (analyst)
      - Syracuse3D (2):
        - Event location from input tables (analyst)
        - Closest station
- __**Velocity Models Used**__ **(if phase is not listed, it defaults to ak135)**:
  - __Fixed Depth__ (depth is held at analyst input depth)
    - ***RSTT*** (Pg, Lg, Pn, Sn)
    - ***SALSA3D*** (v2) (P,Pg,Pn,S,Sn,Lg) (fixed crust from CRUST2.0 (Bassin *et al.*, 2000))
  - __Free Depth__
    - LocOO3D (limited to topography using ETOPO1)
      - ***RSTT*** (Pg, Lg, Pn, Sn)
      - ***SALSA3D*** (v2) (P,Pg,Pn,S,Sn,Lg) (crustal model is CRUST2.0)
      - ***tomoDD*** (depth allowed to float above topography)
        - ***Syracuse3D*** Utah Model (first-P, first-S)
          - Analyst location as starting location
          - Closest station as starting location
        - ***CRUST1.0*** (first-P, first-S)
          - Analyst location as starting
          - Closest station as starting location

__Multiple-Event Relative Relocations__

- The **LocOO3D** (v1.10.1e) program has the ability to set one event as the **Master Event** (e.g., Evernden, 1969) -- Using residuals from one event to correct travel times of other events. We were also able to perform some Multiple-event Relocations using tomoDD in certain areas. ***Model: RSTT***
- ***GrowClust*** (Trugman and Shearer, 2017) is a hierarchical clustering algorithm for relative earthquake location, normally relying on waveform cross-correlation. For this study, we only used the analyst travel time picks. ***Model: ak135***
- ***Bayesloc*** (Myers et al., 2009) estimates the joint probability of event locations, corrections to travel time predictions, precision of arrival time measurements, and phase labels for the arrival times. Bayesloc also accepts probabilistic prior constraints on any of the input parameters. ***Model: ak135***

__Metrics__

For this study, we chose to not focus on any metrics to show quality because we do not have ground-truth (GT) locations for the ABE. We show statistics on differences in average locations per model/set-up relative to the ABE, and sometime to other models/set-ups. Mainly, we will discuss overall patterns and features of the relocations.

References

Ballard, S., J. Hipp, M. Begnaud, C. Young, A. Encarnacao, E. Chael, and W. S. Phillips (2016a). SALSA3D – A tomographic model of compressional wave slowness in the Earth's mantle for improved travel time prediction and travel time prediction uncertainty, *Bull. Seism. Soc. Am.* **106**, 6, doi:10.1785/0120150271.

Ballard, S., J. Hipp, B. Kraus, A. Encarnacao, and C. Young (2016b). GeoTess: A generalized earth model software utility, *Seis. Res. Lett.* **87**, 3, 719-725, doi:10.1785/0220150222.

Bassin, C., G. Laske, and G. Masters (2000). The current limits of resolution for surface wave tomography in North America, *Eos Trans. AGU* **81**, F897.

Crotwell, H. P., T. J. Owens, and J. Ritsema (1999). The TauP Toolkit: Flexible seismic travel-time and ray-path utilities, *Seis. Res. Lett.* **70**, 154-160.

Evernden, J. F. (1969). Identification of earthquakes and explosions by use of teleseismic data, *J. Geophys. Res.* **74**, 3828-3856.

Kennett, B. L. N., E. R. Engdahl, and R. Buland (1995). Constraints on seismic velocities in the Earth from travel times, *Geophys. J. Int.* **122**, 108-124.

Laske, G., G. Masters, Z. Ma, and M. Pasyanos (2013). Update on CRUST1.0 - A 1-degree global model of Earth's crust, Presented at European Geophysical Union 15, EGU2013-2658.

Myers, S. C., G. Johannesson, and W. Hanley (2009). Incorporation of probabilistic seismic phase labels into a Bayesian multiple-event seismic locator, *Geophys. J. Int.* **177**, 193-204.

Myers, S. C., M. L. Begnaud, S. Ballard, M. E. Pasyanos, W. S. Phillips, A. L. Ramirez, M. S. Antolik, K. D. Hutchenson, G. S. Wagner, J. J. Dwyer, C. A. Rowe, and D. R. Russell (2010). A crust and upper mantle model of Eurasia and North Africa for Pn travel time calculation, *Bull. Seism. Soc. Am.* **100**, 2, 640-656.

Syracuse, E. M., H. Zhang, and M. Maceira (2017). Joint inversion of seismic and gravity data for imaging seismic velocity structure of the crust and upper mantle beneath, Utah, United States, *Tectonophysics* **718**, 105-117, doi:10.1016/j.tecto.2017.07.005.

Trugman, D. T., and Shearer, P. M. (2017). GrowClust: A hierarchical clustering algorithm for relative earthquake relocation, with application to the Spanish Springs and Sheldon, Nevada, earthquake sequences. *Seis. Res. Lett.* **88**(2A), 379-391, doi:10.1785/0220160188.

Zhang, H., and C. Thurber (2006). Development and applications of double-difference tomography, *Pageoph* **163**, 2-3, 373-403, doi:10.1007/s00024-005-0021-y.

Single-Event Relocations

__Fixed Depth__

We first relocated all the events using a fixed depth and the RSTT and SALSA3D models. Again, SALSA3D has CRUST2.0 as the crustal model which will be used for the Pg and Lg phase travel time predictions. **Figure 2 shows the relocations for the state of Utah.** The locations from the RSTT and SALSA3D models do appear to have clusters that are relocated in "tighter" patterns, especially near the "Coal Mine" region, Bingham mine, the Wyoming cluster (top mid-right), and some cluster shifts, seemingly to the west of the analyst-defined cluster.

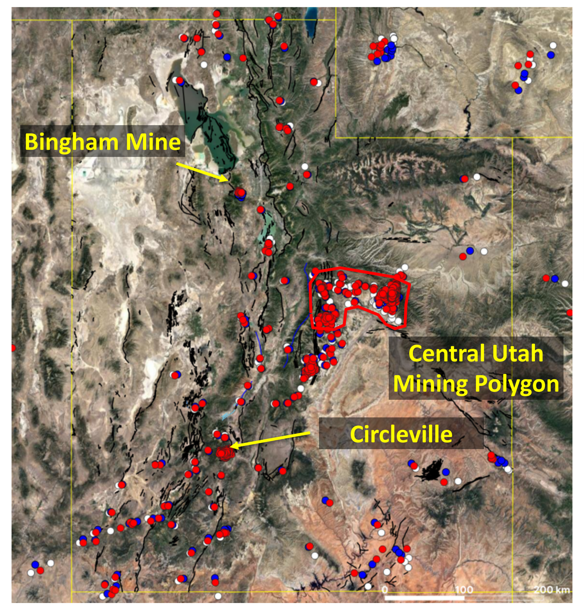

Figure 2: Relocations of the ABE (white) using ***RSTT*** *(blue) and* ***SALSA3D*** *(red) models.*

Fixed-Depth Relocations *(shift relative to ABE Locations)*				
Model	**Count**	**SDOBS (s)**	**Avg Distance (km)**	**Avg Azimuth (deg from North)**
ak135 (ABE)	6475	0.70	-	-
RSTT	6468	0.23	3.66	220.3
SALSA3D/CRUST2.0	6469	0.40	4.88	223.9

__Free Depth__

We relocated the ABEs and allowed depth to be part of the solution (Figure 3). The tomoDD and Hypoinverse solutions were only free-depth and did not appear in the fixed-depth section above. Events relocated using the LocOO3D program utilized the feature of constraining the shallowest depth to topography. Thus, we used ETOPO1 topography from the area to limit "surface" depth for the **SALSA3D** and **RSTT** free-depth locations. The ***tomoDD-Syracuse3D*** and Hypoinverse locations did not have this constraint and depths could possibly be above the topography, sometimes significantly so. The ***tomoDD-CRUST1.0*** did have a 3 km elevation limit to depths applied during relocations. The table below summarizes the number of events relocated, the average RMS/SDOBS, and the average distance and azimuth each model shifted the epicenters.

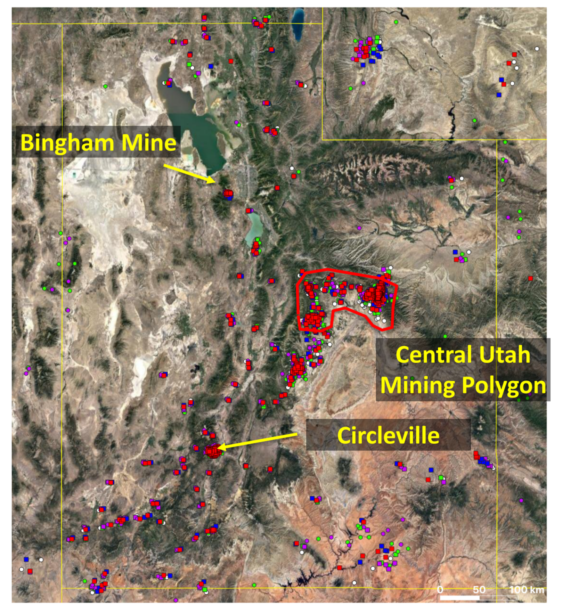

*Figure 3: Free-Depth Relocations for the ABEs. Colors are: White (ABE), red squares (**SALSA3D**), blue squares (**RSTT**), magenta hexagons (**Syracuse3D** – Closest station starting location), magenta squares (**Syracuse3D** – Analyst starting location), green hexagons (**CRUST1.0** – Closest station starting location), green squares (**CRUST1.0** – Analyst starting location).*

Free-Depth Relocations *(shift relative to ABE Locations)*				
Model	**Count**	**SDOBS (s)**	**Avg Distance (km)**	**Avg Azimuth (deg from North)**
ak135 (ABE)	6475	0.70	-	-
RSTT	6231	0.20	3.53	229.3
SALSA3D/CRUST2.0	6307	0.40	5.33	224.3
Syracuse3D-Analyst Start	6106	0.22	2.19	258.8
Syracuse3D-Closest Station	6129	0.22	3.52	247.5
CRUST1.0-Analyst Start	6255	0.35	2.05	244.2
CRUST1.0-Closest Station	6385	0.31	4.35	236.1

Conclusions

Relocations of the events during the two-week, Analyst Built Event (ABE) period demonstrate the sensitivity of locations to local velocity models and relocation techniques. From 1D to 3D models, relocations of clusters of events show the bias of the default ak135 model and the spread of epicenters from several different models. Relative relocation techniques add accuracy, but require some GT constraints to improve confidence of results. Future work involves detailed analysis of error ellipses as well as event depths. In addition, investigation into using other relative relocation techniques (that involve waveform cross-correlation) is warranted.

Contact Information

Publications *Profile*

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Bingham Mine

The Bingham Mine is an active mine, with 20 ABEs for the 2-week picking period. The 20 ABEs have depths fixed at 0 km (sea level). The actual elevation of the mine varies from 1.4 km (deepest) to 2.1 km (shallowest). Fixed-depth relocations are thus too deep at 0 km. However, using SALSA3D and RSTT with fixed depth of 0 km results in two distinct groupings of the 20 events (Figure 4). SALSA3D (i.e., CRUST2.0) results in events across the center of mine, closer to the relocations by the analyst. RSTT results in events being shifted to the south.

Free-depth solutions for the Bingham Mine area (Figure 5) suggest that the 3D models (Syracuse3D, SALSA3D) relocate the events to the northern area of the mine, a possible location of activity at the time of the events (from Google Earth). CRUST1.0 locates the events more to the center of the mine area and RSTT still locates the events to the southern portion of the mine, also a possibility given Google Earth images.

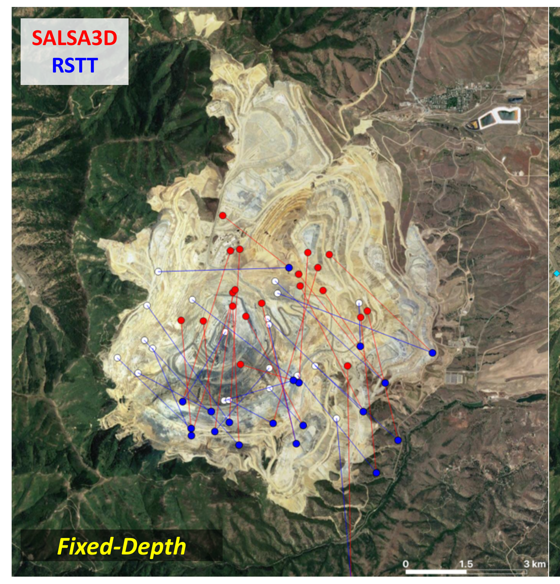

*Figure 4: Fixed-depth (0 km) relocations. Relocations with **SALSA3D** (red) and **RSTT** (blue) result in two distinct grouping, shown with tie lines to the corresponding ABE.*

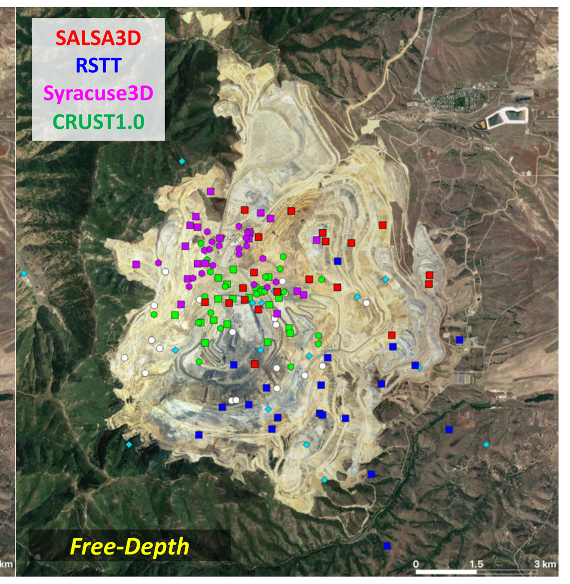

*Figure 5: Free-Depth relocations. **Squares are locations from analyst starting locations, hexagons are from closest station starting locations.** The **Syracuse3D** (both starting location sets) and the **SALSA3D** model suggest activity in the northern part of the mine while **RSTT** locations suggest activity to the south.*

__Relative Relocations__

We relocated the Bingham Mine events using both __Master Event__ and __Multiple Event__ Relative Relocation techniques. Figure 10 shows the results of the relocations, using 3 GT events from 2013 (outside DNE18 data range) as calibrations (K. Pankow, personal communication).

Master Event relocations were performed with __Event #2 as the master__, using the **ak135** and **RSTT** models, with both fixed and free depths. Note shifts of Events #1 and #3.

Multiple Event relocations in Figure 6 used the **Syracuse3D** and **CRUST1.0** models with the ***tomoDD*** software, holding all 3 of the GT events fixed. The Syracuse3D relocations appears the most clustered around an area in a consistent manner.

Figure 7 shows a multiple event relocation using **Bayesloc** with **ak135**. The three GT events were held fixed and add bounds for the relative relocations. These relocations are centered closer to the 3 GT events than the ***tomoDD*** runs.

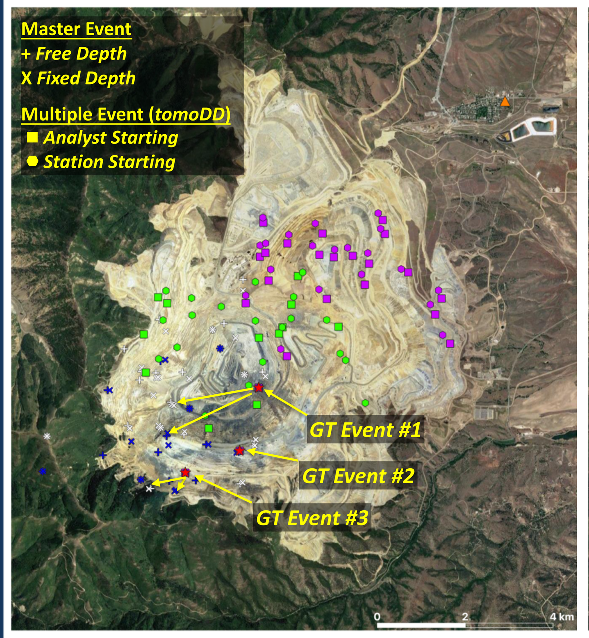

*Figure 6: Relative Relocations using Master Event (**ak135**, **RSTT**) and Multiple Event (i.e., tomoDD) methods (**Syracuse3D**, **CRUST1.0**). Note the GT event shifts for #1 and #3 when using #2 as the Master Event.*

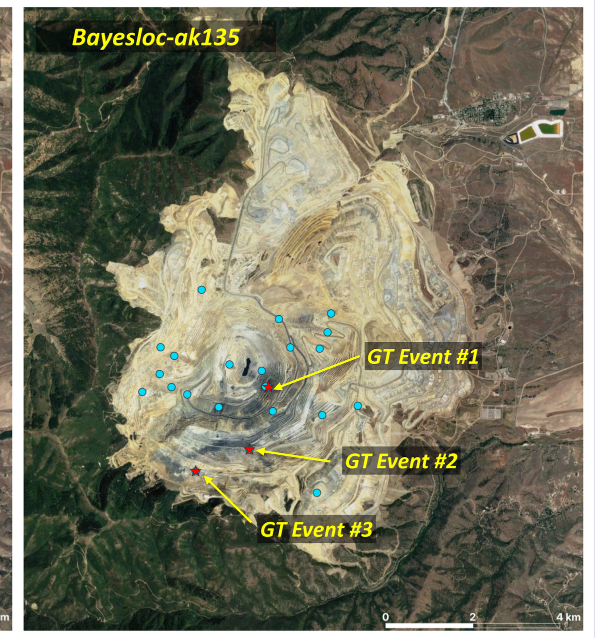

*Figure 7: Relative Relocations using **Bayesloc** (**ak135**). Result are very different compared to the **Syracuse3D tomoDD** run.*

Central-East Utah Mining Polygon

This Coal Mine region (West Ridge Mine) demonstrates a very high seismicity area, especially considering that the data set spans only 2 weeks. This area is mostly __longwall mining__.

__Fixed Depth__: The cluster of events is very dense, with the **SALSA3D** and **RSTT** models basically shifting the cluster to the northwest (Figure 8, left). The cluster size does not appear to be reduced when using **SALSA3D** or **RSTT**. The ABE to the west all appear to shift significantly to the northeast when using **SALSA3D** or **RSTT**.

__Free Depth__: For free-depth solutions (Figure 8, right), results for **SALSA3D** and **RSTT** are similar to the fixed-depth solutions above. Solutions with **RSTT** show a slight separation of events into northern and southern clusters. Comparing the **Syracuse3D** and the **CRUST1.0** models using ***tomoDD*** (Figure 9), it appears that the cluster separation demonstrated using RSTT (Figure 8, right) is also apparent when using the **Syracuse3D** and **CRUST1.0**. More investigation into the cluster is warranted to determine if two clusters are present.

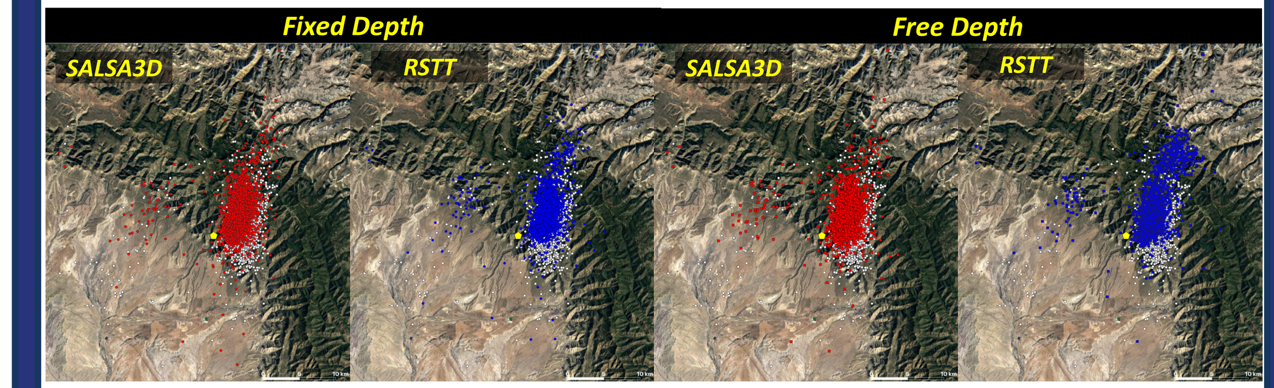

*Figure 8: Fixed-depth (left two) and Free-depth (right-two) relocations. Analyst events are white, **SALSA3D** are red, **RSTT** are blue. **RSTT** shows almost two separate clusters. West Ridge Mine entrance is shown.*

West Ridge Mine

__Master and Multiple Event Relocations__

Figures 9-10 show multiple-event relocations using several techniques.

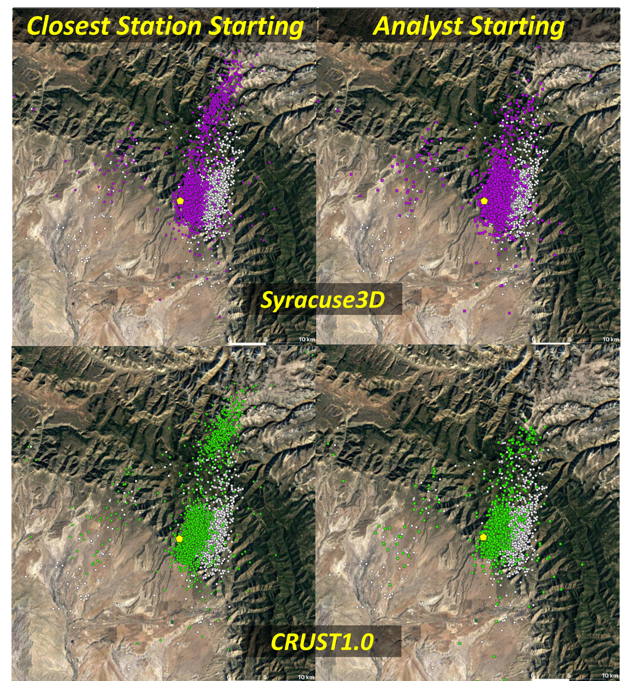

*Figure 9: Free-depth relocations for **tomoDD**. Analyst events are white. Top-left: **Syracuse3D** with closest station starting locations. Top-right: **Syracuse3D** with analyst starting locations. Bottom-left: **CRUST1.0** with closest station starting locations. Bottom-right: **CRUST1.0** with analyst starting locations. The separation into two clusters is readily apparent for either model with the closest station is used as the starting location. Also note the more linear trend to the northern cluster when using the Syracuse3D.*

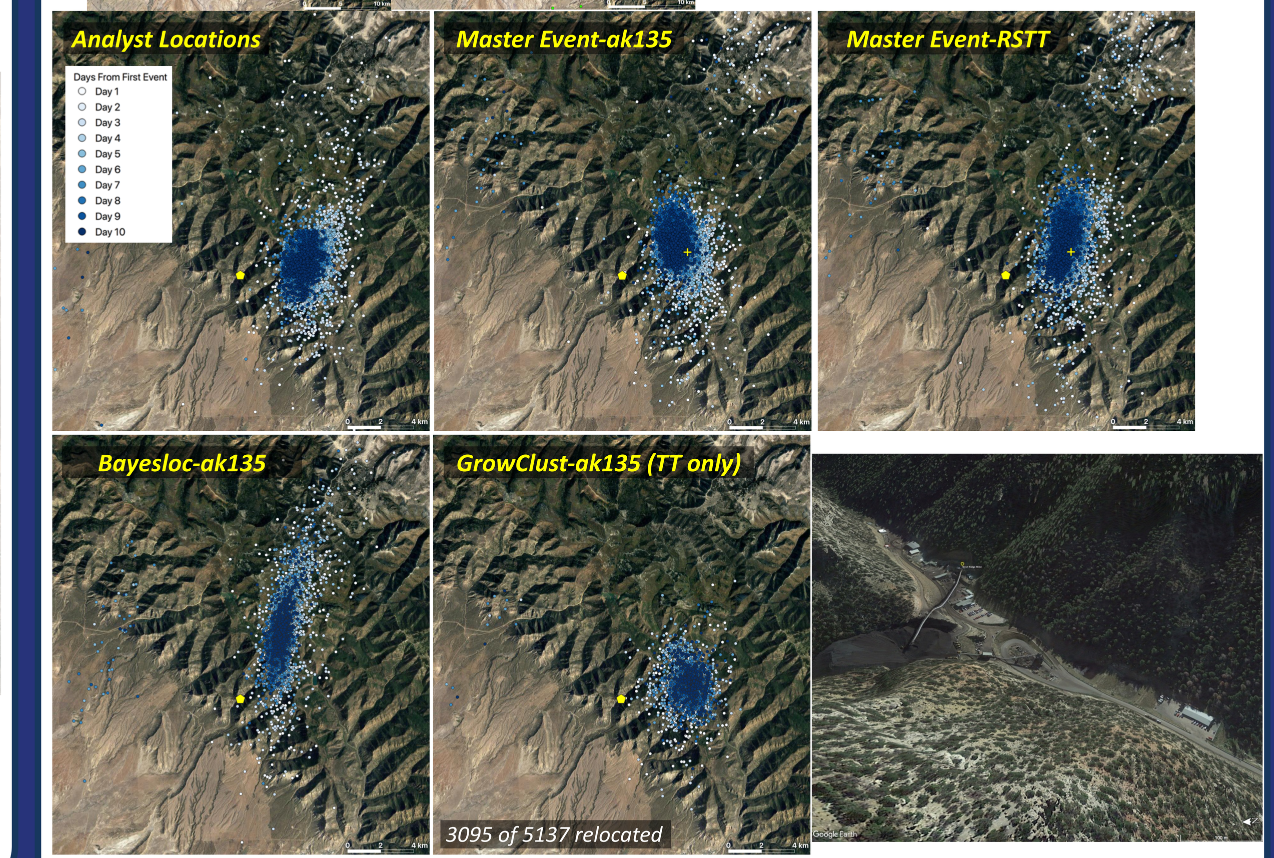

*Figure 10: Master and Multiple Event Relocations in the East Mining Polygon region. Top-Left: Analyst single-event locations using **ak135**, showing relative timing to the first event in the cluster. Top-Middle: Master Event relocations using event indicated (yellow plus) and the **ak135** model. Top-Right: Master Event relocations using event indicated and the **RSTT** model. Bottom-Left: Multiple Event relocations using **Bayesloc** and **ak135** model. Depths set to 0 km with 0.5 km standard deviation. Bottom-Right: Multiple Event relocations using **GrowClust** and **ak135** (no correlations, only travel times). 3095 of 5137 events relocated.*