AUTOMATED DEVELOPMENT OF 3D LOCAL TRAVEL TIME MODELS

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ABSTRACT

Intuition suggests that use of three-dimensional (3D) seismic travel time models will lead to improvements in event location by minimizing travel time residuals and local bias. Testing this intuition has been difficult in the past because of a lack of 3D modeling and location codes and the effort involved with generating 3D models. Software now available allows us to easily generate 3D velocity models, calculate travel times over a grid, and compute event locations with the grid search method. This paper describes how we have developed and are evaluating a local (100 km x 100 km x 40 km, 1 km grid spacing) velocity model grid for the Nevada Test Site (NTS). A 3D geological model of NTS has been developed from this highly characterized area's voluminous available data: well logs; core and chip samples; gravity, magnetic, and seismic refraction surveys; and surface geology. This 3D geology has been digitized using EarthVision software (widely used in the oil industry). From the digitized geology, we have created a 3D grid file containing simplified geologic units: alluvium, tuff, Paleozoic bedrock, middle crust, and mantle (top of unit defined by the Moho). We then use a script to assign a velocity to each geologic unit in the grid file, with a velocity gradient for the middle crust unit, and generate a 3D grid file of slowness. This slowness file (for P or S phases) can then be used directly by the open-source code NLLoc (Lomax and Virieux, 2000) to generate separate travel time files for each station in the area to each grid point—NLLoc uses the Podvin and Lecompte (1991) finite difference algorithm. Once the set of travel time files is created for each station of the grid, NLLoc is then used to locate events via a grid search algorithm, compute synthetic travel times for an event, and compute location statistics. We are using travel time data (precisely known origin time and location) from the WATUSI surface chemical explosion at the Big Explosion Experimental Facility (BEEF) as ground truth and stations of the University of Nevada, Reno, local network to calibrate the velocities used in the model. Because the calibration is based on a surface event, travel times are particularly sensitive to shallow crustal velocities. The end result (after iteratively adjusting velocities used for the shallow geologic units) is a velocity model with a mean of the travel time residuals very close to zero. The model results in a location error for WATUSI of less than 1 km. The real advantage of the 3D model is demonstrated by the fact that the location determines a shallow depth for the event, a result not obtainable with a simple one-dimensional (1D) layered velocity model.

OBJECTIVES

The seismic velocity structure of the Earth is known to be relatively homogeneous at the teleseismic scale compared to the regional scale (Ritzwoller, et al., 2003). At the regional scale, tectonic style (fold belts, rift structure, sedimentary basins, etc.) plays an increasingly important role because the seismic ray paths are confined to the crust and upper mantle. At the scale of local seismic networks (200 km or less), ray paths are confined mainly to the upper crust, and local geologic heterogeneity becomes even more important for locating events, especially in the case of sparse networks or networks with poor azimuthal coverage. Thus, one objective for improving seismic event locations at the local scale is to develop a 3D velocity model. The objectives of this study are to develop an automated method of producing a 3D velocity model, apply the method to produce a 3D velocity model of NTS, and test and validate this model using local ground truth events.

Development of local three-dimensional seismic velocity models has several objectives:

- The computer code used to locate events needs to be able to accommodate 3D models. For reasons of computational efficiency, most existing location codes (with the exception of special research codes used in particular areas, such as volcanic studies areas) in the past have used 1D (flat layer) velocity models. Recently, however, grid search location codes have become available that accommodate 3D velocity models.

- A 3D velocity grid needs a grid spacing at least on the order of the seismic wavelength, which can be on the order of 1–2 km for shallow sedimentary deposits with low seismic velocities. These relatively small grid spacings may necessitate large grid files, which are challenging but not prohibitive in a computational sense, but can be prohibitive in the sense of actually putting the 3D grid model together. Clearly, is it not practical to assemble a gridded velocity model on the order of 400,000 elements (100 km by 100 km by 40 km) or larger without automated methods. Thus we need to develop an automated method to produce such grid files.

- Grid spacings of 1–2 km may seem to be quite fine in terms of the area covered by a local seismic network, but compared to the level of detail of geologic mapping or characterization at the local level, this scale is very coarse (it is rare for an individual geologic formation to be as thick as 1 km or more). An important question is how to “down sample” (or, using phraseology familiar to signal processing, “decimate”) geologic information into what is important for the velocity model.

- Once a representative grid with geologic elements has been defined, the next objective is to assign seismic velocities to separate units.

- The final objective is to test and validate the model.

RESEARCH ACCOMPLISHED

Development of the Geology Grid Model

To develop and test our approach for automated generation of a local 3D velocity model, we chose the NTS and surrounding region for several reasons:

- Prior to 1992, extensive efforts were put forth to map and characterize the geology of NTS for the underground nuclear testing program. The hundreds of boreholes drilled and logged and extensive mapping and geophysical surveys carried out have resulted in NTS being an extremely well-characterized region.

- Over the past several years much of the geological and geophysical data from NTS has been digitally compiled into a 3D geologic model that includes detailed local topography. This model is digitally archived in a geographical information system (GIS) format compatible with many different GIS software applications. This digital archive and the software application allow us to easily generate grid files of geology from different areas covered by the model.

- The University of Nevada, Reno (UNR), operates a local seismic network within NTS funded by the Department of Energy (DOE) Yucca Mountain Repository program. UNR also operates additional seismic stations in south-central Nevada as part of their Southern Great Basin Seismic Network (SGBSN—refer to http://www.seismo.unr.edu/). Lawrence Livermore National Laboratory (LLNL) has access to both catalog and waveform data from these stations.

- Because of ongoing chemical explosives and ordinance testing at NTS, several large known explosion sources are available as ground truth events that can be used to test and verify the velocity modeling approach.

EarthVision (Dynamic Graphics, Inc.) is a 3D modeling code used extensively at LLNL to build and visualize 3D geologic models (Figure 1). The goal of these models is to characterize and better understand the subsurface geology. You can rotate, slice, peel, and clone 3D structural and property models for effective evaluation and verification. Also built within the framework are 3D property models of the 3D geologic model that are used to evaluate and visualize the spatial distribution of physical properties. Contour maps, isochore maps, and cross sections derived from 3D models provide easily understood representations of faults and stratigraphy. You can seamlessly integrate seismic interpretation in time with your depth model. These precise 3D models are easily updated with new data. We integrate all geophysical and geological data into one database. These models provide the ability to calculate volumes of individual layers or reservoirs.

The 3D geologic model of NTS was constructed using EarthVision software from a much larger model of the southern Great Basin that was generated for an investigation of the 1993 nonproliferation experiment (NPE) explosion. This regional model includes detailed constraints at the Nevada Test Site based on the extensive geologic and geophysical studies. Gross structure of the crust and upper mantle is taken from regional surface-wave studies. Variations in crustal thickness are based on receiver function analysis and a compilation of reflection/refraction studies. Upper-crustal constraints are derived from geologic maps and detailed studies of sedimentary basin geometry throughout the study area. The free surface is based on 10 m resolution elevation data at the NTS and a 90 m digital elevation model (DEM) elsewhere. The Great Basin model extends to a depth of 150 km, and the NTS model goes to a depth of 38.8 km.

The NTS model incorporates much of the detailed geologic data that was collected for the underground nuclear test program. Literally hundreds of boreholes provide subsurface stratigraphic data that is used to constrain the stratigraphic units. Numerous geophysical surveys are also available to aid the definition of the basins. Faults are not included in this model.

In order to make the initial study model computationally tractable, we limited the size aerially to 100 km by 100 km, with depth to 40 km. For a 1 km grid spacing, this results in 400,000 grid elements. The geographical coordinates of the geographically aligned grid are defined by the southwest corner of the upper surface of the grid at latitude 36.753 longitude -116.775. The grid search location code that we chose to use for this study (see below) uses a flat earth geometry, but station corrections can be included to account for topography differences. Because all of the ground truth events that we have are explosions occurring at the ground surface in Yucca Flat, we chose to use the elevation of Yucca Flat, 1200 m, as the surface datum for the velocity model.

The next decision to make concerning the geology model was which units to include, e.g., the number of different geologic units to be used in the model. We made this choice mainly based on what would be a relatively simple starting point and what made sense with respect to what we thought would have the most impact on the seismic velocity structure. The geologic units were divided into the following from upper to lower: alluvium, volcanic tuff, undivided Paleozoic units, lower crust, upper mantle. The EarthVision code was then used to define and extract these units and assemble them into a 3D binary grid file. Each element in the grid was assigned a code for the geology type. Using a scripting code, the binary elements of the grid file were converted into a binary file of seismic slowness (travel time per unit length, or inverse velocity in km/s for a 1 km grid). This slowness file could then be used to compute travel times in the location code, as described below. A representation of the slowness model is shown in Figure 2 with N-S and E-W cross sections going through the center of the model. Representative velocities used in the figure are alluvium 2.0 km/s, tuff 2.5 km/s, Paleozoic 5.0 km/s, lower crust 6.0–6.5 km/s (as a gradient), and upper mantle 7.8 km/s. Values for these velocities were initially chosen based on known studies for relatively shallow depths (McKague 1980; Howard, 1985) and regional seismic studies (Hoffman and Mooney, 1984; Patton and Taylor, 1984). Adjustments to the initial velocities used were made iteratively in the testing and validation process, as described below.

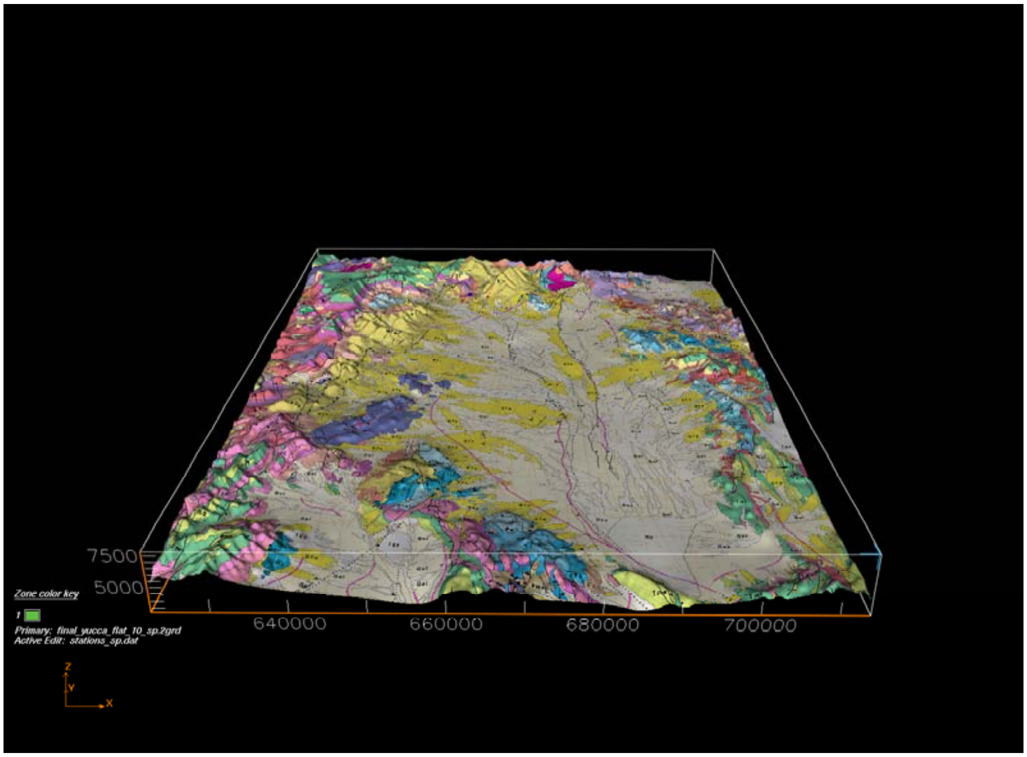

Figure 1. Surface representation of a portion of the NTS geologic model. The elevation is in feet; the horizontal scale is in Nevada coordinates. Surface geology has been draped over the topography.

Incorporation of the Geology Model into the Location Code

The general purpose, probabilistic nonlinear grid search location code NLLoc, developed by Anthony Lomax (Lomax and Virieux, 2000) is ideal for our objectives. The open-source code (refer to http://alomax.free.fr/nlloc/index.html) has the capability to generate 3D travel times from a 3D velocity model via the finite difference algorithm developed by Podvin and Lecompte (1991). Using the input slowness (velocity) model described above, travel times are computed from each station location to every cell in the grid and stored in travel time files. These travel times are then used, via an oct-tree sampling method, to compute the location of seismic events over the grid. A Metropolis-Gibbs sampling method is used to develop probability density functions so that nonlinear effects on the location uncertainty can be examined. The code does not incorporate elevation differences into the travel time model, but station corrections can be included to make a rough approximation to elevation differences affecting travel times.

An additional advantage of the NLLoc software is that it includes a module, called Grid2GMT, which generates scripts for creating maps via the Generic Mapping Tools (GMT) open-source software (Wessel and Smith, 1991). The module makes it particularly easy to generate horizontal and vertical sections (Figures 2 and 3) through the velocity model grid as well as produce similar sections of contoured travel time in addition to the usual maps of station locations and event locations. The capability is particularly important in checking for model artifacts and inconsistencies in large grid files.

Testing, Modifying, and Validating the Model

As can be seen in Figure 2, the distribution of seismic stations is concentrated near the southwest boundary of NTS in the vicinity of the Yucca Mountain nuclear repository with a few additional stations surrounding Yucca Flats (the large yellow area with the word “WATUSI” in it). WATUSI was an 18,000 lb surface explosion detonated at the surface in September 2002. The exact location and origin time of this event are known, it was well recorded on all of the stations, and it is centrally located in the network, thus this explosion provides an excellent ground truth event for testing the 3D velocity model.

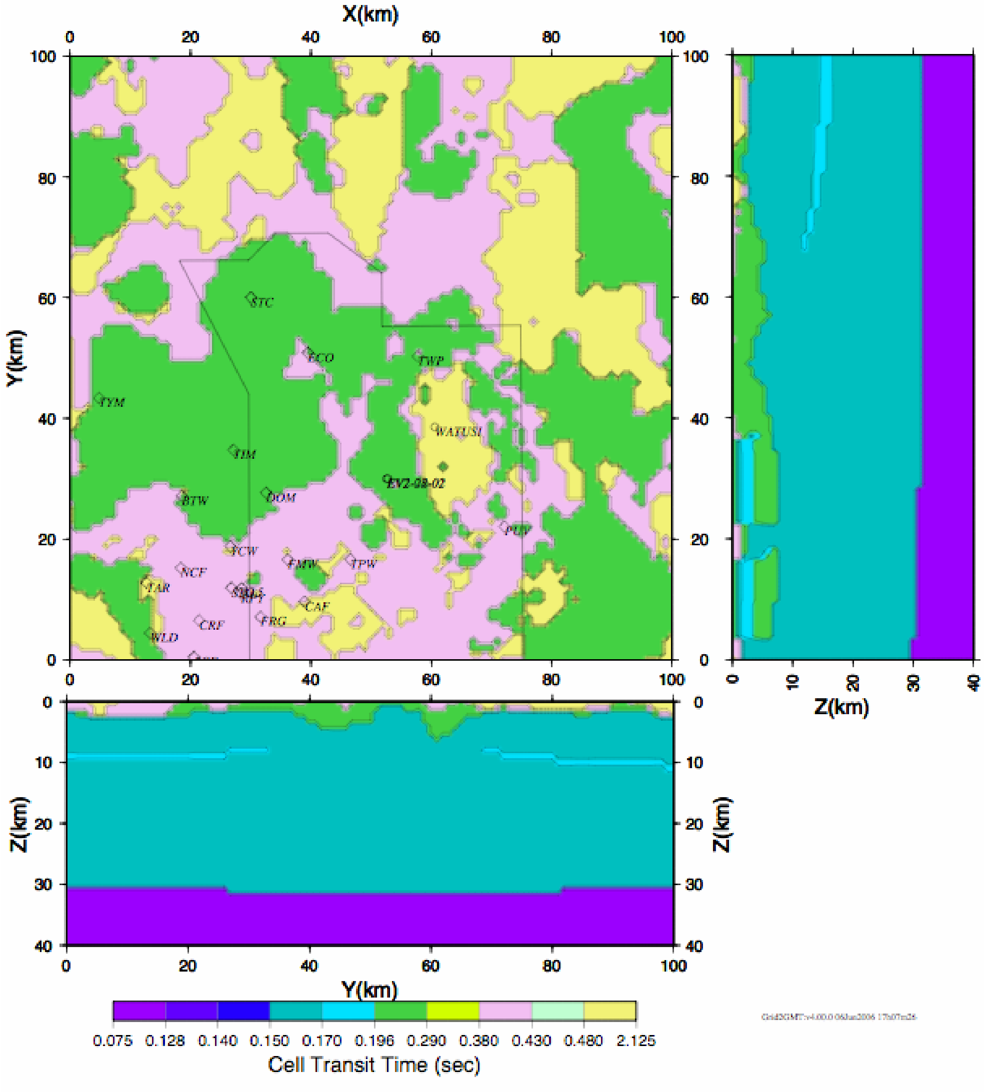

Figure 2. Map view and cross sections (through the middle of the map) of the geologic map grid used in this study. The NTS boundary is shown by straight lines. Diamond symbols are locations of seismic stations’, circles are locations of explosion events used for ground truth. Color contours refer to cell transit time (slowness) assigned to individual geologic units as discussed in the text. The color scheme refers to geology units as follows: alluvium—yellow, tuff—pink, Paleozoic—green, lower crust—blue, upper mantle—purple.

The procedure we used was as follows: the initial velocity model, developed as described above, was used to develop files of travel time from each station to every grid point using the Grid2Time module of NLLoc. These travel time files were then used to compute the travel time from each station to the known location of the WATUSI event. These travel times were then compared with the observed travel times for WATUSI. By comparing travel time differences for different stations with the velocity model along the path between WATUSI and the station (e.g., Figure 3), we can make some guesses about how to adjust the velocity for certain geologic units. We then adjusted the velocities for specific units in the model and repeated the process. If we assume that the picking errors are less than 0.1 s, then our goal in adjusting the velocity model should be to get the mean difference between the observed and predicted travel times to be less than 0.1 s.

In the process of these iterations of the velocity model, we discovered that, because the velocity model has a flat surface with the datum of 1200 m, some of the area (northwest corner of NTS) has a surface above the datum and some (southeast corner) has a surface below the datum. In gridding the velocity model, geology above the datum is missing, and geology below the datum was generated as a different unit with very low velocity (air). This only became obvious after we carefully examined the first run of the model. We corrected this effect by modeling the area below the datum as an upward continuation of the surface geology until the surface datum was reached. In this area (below the datum), stations will need a negative time correction (advance) to account for the elevation difference; in areas above the datum a positive time correction (delay) is needed to account for the additional travel time through the higher topography. Initially, we make these elevation station corrections at a specific station by simply dividing the difference of station elevation from the datum (1200 m) by the velocity of the geologic unit at the surface in the particular area.

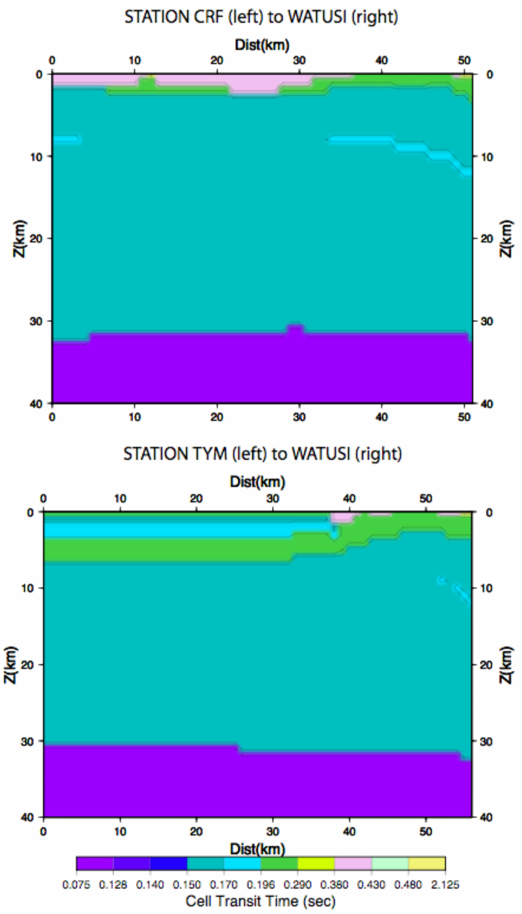

Figure 3. Cross sections through the velocity model (cell transit time is seconds is shown) for paths between the WATUSI explosion (upper right corner) and the station indicated (upper left corner). Color scale and geologic units are the same as for Figure 2.

By plotting the observed and computed travel time with distance, we can compare the differences for each station. By making plots like Figure 3, we can try to determine which part of the model is affecting the travel time and adjust the velocities of geologic units accordingly. Note that we do not change any of the spatial relationships of the model; we only change the velocity assigned to a particular geologic unit. Figure 4 (which is normalized to a velocity of 6.0 km/s) shows considerable variations in travel time (0.6–1.3 s) that are undoubtedly related to velocity heterogeneity. For the model comparison shown in Figure 4, stations DOM, SCF, and TYM have significantly fast arrivals, while stations TWP, PUV, TPW, ECO, and FRG have significantly slow arrivals. Velocity of the alluvial layer under Yucca Flats, where the source WATUSI event is located, generally affects all of the stations equally, while delays or advances at individual stations depend mainly on the geology beneath the station, but also somewhat on particulars of the overall path. The current model (results shown in Figure 4) has a mean travel time residual with respect to the observed travel times of about 0.15 s. When we use this model to locate the WATUSI event using the grid search code NLLoc, the location error of the hypocenter is less than 1 km (the size of a grid element). The nonlinearity of the location solution, however, is notable by the sensitivity of the depth determination to the value of the P/S velocity ratio. (For the current model, we do not use separate P and S velocity models, although the NLLoc code supports this option.) In varying the P/S velocity ratio from 1.80 to 1.95, we found that shallow depths were obtained in the location for values between 1.85 and 1.90, but the depth jumps to 10 km or more for values outside this range.

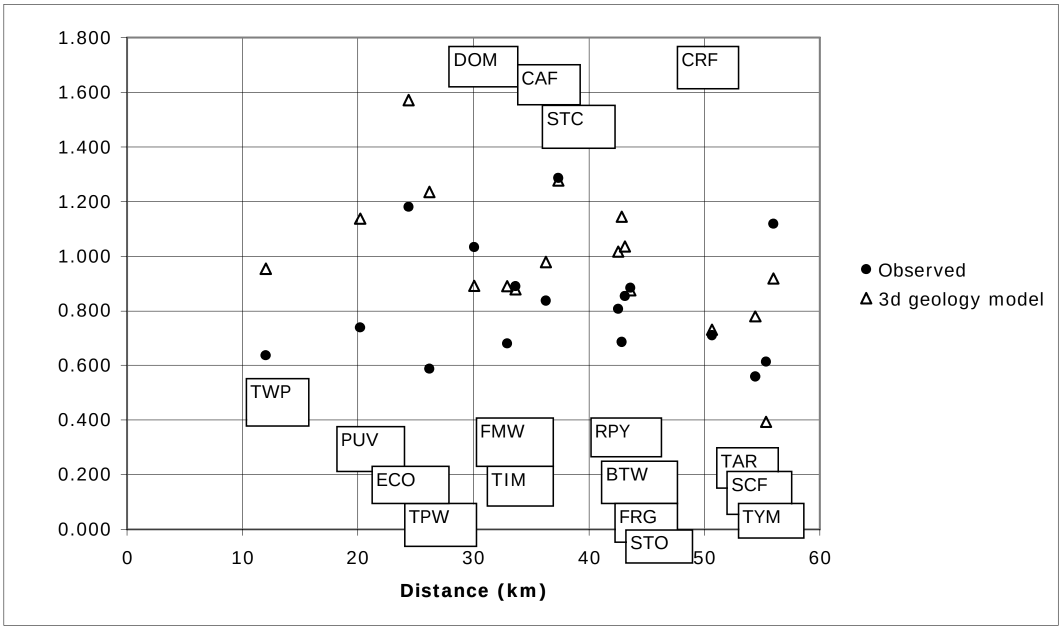

Figure 4. Plot of observed (dots) and calculated (triangles) travel times from the WATUSI explosion to the seismic stations. Calculated travel times are based on the geology-based travel time model. Refer to Figure 2 for station locations. Travel times are normalized to a P wave velocity of 6.0 km/s.

CONCLUSION(S) AND RECOMMENDATIONS

We have demonstrated that local 3D velocity models can be easily generated automatically using commercially available geological modeling GIS software. We can then compute travel times over a 3D grid using the open source software NLLoc. We have begun to assess the value of this modeling approach for improving local seismic event locations in relatively small (100 km x 100 km) areas using NTS as a test case. Visual tools available with NLLoc help us to analyze how seismic velocity in individual geologic units can affect station travel times due to lateral and vertical geologic heterogeneity. Once we have optimized the 3D geologic model (at least for the case of ground truth data we have available), we will be able to study the effects of the network configuration on location results and ultimately assess the value of 3D models over simpler models for location of seismic events at the 40–100 km distance scale with sparse networks.

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