ADVANCING SEISMIC EVENT LOCATION THROUGH DIFFERENCE CONSTRAINTS AND THREE-DIMENSIONAL MODELS

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ABSTRACT

Current seismic event location based on kriged travel-time correction surfaces requires high-quality ground truth (GT) for optimal success. Unfortunately in many important regions of the world, including China, it is rare to find more than a handful of events over vast areas whose locations are known with an accuracy of 5 km (GT 5) or less. To mitigate this we are developing a technique for applying relative constraints among travel-time correction surfaces for stations within a network, in effect turning GT 15 or worse into GT 5 or better. This method is based on the hypothesis that for two stations recording the same event, the effect of the event mislocation is eliminated through residual differencing. By exploring the relative travel-time residual differences among events recorded at combinations of station pairs within a network, we can build a set of relationships among residual surfaces that can be fixed to absolute levels by incorporating ground truth information. Nonlinear inversion is used to then find the best-fit surfaces. Using the Northern California Earthquake Data Center (NCEDC) catalog to develop and test our method, we have demonstrated that for well-picked events the travel-time residual differences for events co-linear with a given station pair vary smoothly for crustal P phases. Numerical tests show that the residual relationships are usable over a broad azimuth range, allowing us to include more events than for a strictly co-linear requirement. We plan to extend the method to incorporate regional phases on a variety of available catalogs. To this end, the preliminary z-format Annual Bulletin of Chinese Earthquakes (zABCE) catalog has been relocated with IASPEI91 using our merged global database to test Asia residual data. Data are also being integrated from regional Nepal and Bhutan datasets.

A second innovation we are working on is the use of travel times from three-dimensional (3-D) velocity models in the generation of correction surfaces instead of simple one-dimensional (1-D) Earth models. The National Nuclear Security Administration (NNSA) software design allows us to build empirical correction surfaces from any set of travel-time tables. This capability enables us to better predict travel times in aseismic regions, and it should remove bias in travel times estimated in seismic regions (facilitating improved correction surfaces and reducing bias in earthquake locations). Despite the increase in processing speed and capacity, large global seismic catalogs are still produced primarily by using 1-D velocity models. 3-D velocity models, however, are improving in both resolution and reliability. Studies have demonstrated their superiority over 1-D models in terms of improved location and reduction in uncertainty. It therefore seems appropriate that routine seismic event location methods should migrate to the 3-D velocity model standard. However, we must consider the increased processing time to produce 3-D locations even when using faster computers. It is important to assess the accuracy of 3-D travel-time tables and the ray-tracing algorithms used to create them. We must weigh, in combination with the added computational burden, the merits versus costs of such a transition. Our effort will focus on performing relocation tests on a catalog scale (or at least a large subset), and on analyzing computational times to determine if using 3-D tables for regional location on a routine basis can be justified in an operational setting.

In addition to testing the operational feasibility of using 3-D models in routine location, we are building and testing 3-D models from several sources. Internally, we use LITHO3D, a Matlab-based tool developed at Los Alamos National Laboratory (LANL), to construct 3-D models from published and unpublished velocity and attenuation information.We are currently testing a number of 3-D models for Asia, including the model developed at Massachusetts Institute of Technology (MIT), the Lamont Consortium model, and the LANL model. Early results suggest that the external models perform well under circumstances for which they were designed. Limited Pn performance testing in two specific geographic locations shows similar favorable results for both the MIT and Lamont models.

OBJECTIVE

The objective of this work is to improve seismic event location throughout Asia. This will be accomplished through improving the usefulness of poor-quality ground truth data and by building and improving 3-D velocity models of the region. An essential element of the former is constrained spatial correlation of residual differences between stations, in contrast to the implementation of Rodi et al. (2003) that is based on spatial correlation of residuals between stations, as observed by Steck et al. (2001a), (2001b), and (2001c). For 3-D model building and testing, high quality ground truth is needed, as is the ability to correctly calculate regional phase travel times from 1-D, 2-D, and 3-D models.

RESEARCH ACCOMPLISHED

Correction Surface Differences

Current seismic event location based on kriged travel-time correction surfaces requires high-quality ground truth for optimal success. Unfortunately in many important regions of the world, including China, it is rare to find more than a handful of events over vast areas whose locations are known with an accuracy of 5 km (GT 5) or less. To overcome this limitation, we are developing a technique for applying relative constraints among travel-time correction surfaces for stations within a network, with the goal of in effect turning GT 15 or worse into GT 5 or better. This method is based on the premise that for two stations recording the same event and phase, the effect of the mislocation of the event is reduced through differencing the residuals. By exploring the relative travel-time residual differences among events recorded at combinations of station pairs within a network, we can build a set of relationships among residual surfaces that can be fixed to absolute levels by incorporating available GT information. This does not require high correlation between corrections, merely a stable relationship amongst the given set of events. Biases can exist between stations, possibly arising from different site geology. We have begun to implement a nonlinear inversion to find the best-fit surfaces. Using the Northern California Earthquake Data Center catalog to develop and test our method, we have demonstrated that for well-picked events the travel-time residual differences for events co-linear with a given station pair vary gradually, with little scatter, for crustal P phases. Numerical tests show that the residual relationships are usable over a broad azimuth range, allowing us to include more events than for a strictly co-linear requirement (Rowe, 2003). Our plan is to extend this method to incorporate regional phases on a variety of available catalogs. The zABCE catalog offers significant potential in Asia for this method due to its station density. We are currently relocating the zABCE with IASPEI91 and using our merged global database to assure a consistent treatment of base model and station correction. The use of our merged arrival tables may also improve some locations. Data are also being integrated from regional Nepal and Bhutan catalogs (Sheehan, et al., 2004). Figure 1 shows roughly 45,000 original zABCE event locations. Approximately three million arrivals are associated with these events after our global database merge. Figure 2 shows that stable residual difference relationships between events are present for station pairs in this dataset.

3-D Models

A second innovation we are working on is the use of travel times from 3-D velocity models in the generation of correction surfaces instead of simple 1-D Earth models. NNSA's software design allows us to build empirical correction surfaces from any set of travel-time tables. This capability enables us to better predict travel times in aseismic regions, and should remove bias in travel times estimated in seismic regions (facilitating improved correction surfaces and reducing bias in earthquake locations). Despite the increase in available processing speed and capacity, large global seismic catalogs are still produced primarily by using 1-D velocity models. 3-D velocity models, however, are improving in both resolution and reliability. Studies have demonstrated their superiority over 1-D models in terms of improved location and reduction in uncertainty. It therefore seems appropriate that routine seismic event location methods should migrate to the 3-D velocity model standard. However, we must consider the increased processing time to produce 3-D locations even when using faster computers. It is important to assess the accuracy of 3-D travel-time tables and the ray-tracing algorithms used to create them. We must weigh, in combination with the added computational burden, the merits versus costs of such a transition. Our effort focuses on performing relocation tests on a catalog scale (or at least a large subset), and on analyzing computational times to determine if using 3-D tables for regional location on a routine basis can be justified in an operational setting.

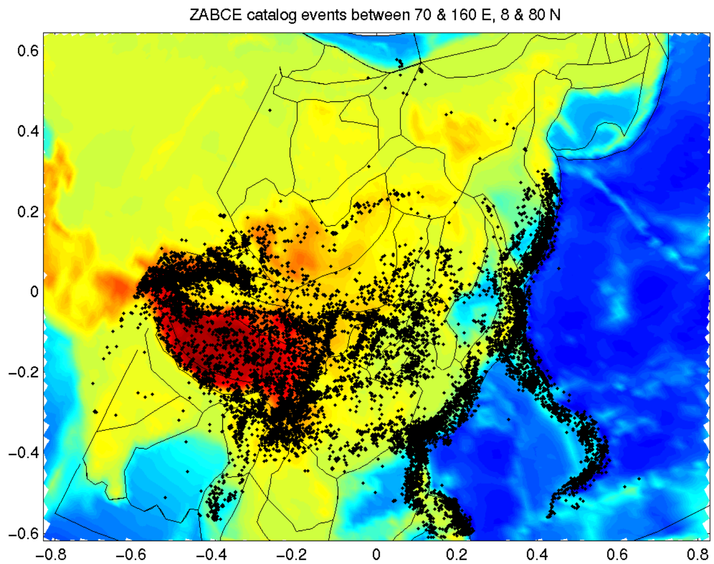

Figure 1. Seismicity plot from zABCE catalog.

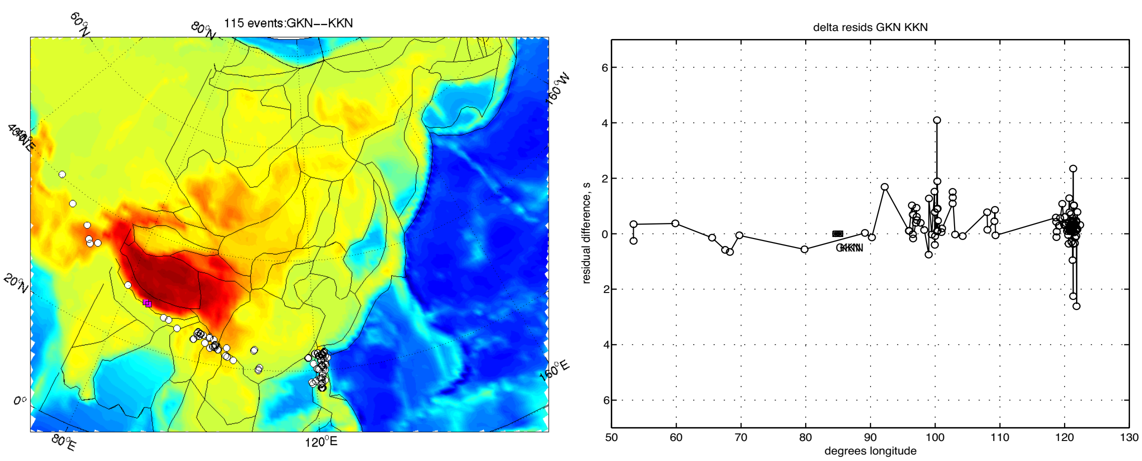

Figure 2. Co-linear seismicity for GKN-KKN station pair from zABCE (left). Residual differences plotted versus distance from stations (projected onto a line of latitude). Note that while the differences cluster around zero mean, such behavior is not required. What we are looking for is a stable relationship, not necessarily zero mean, which is to say it does not require a high correlation between residuals from the station pair.

In the examples, relocations were performed on a 750 Mhz Sun Blade 1000 with 1 Gbyte of RAM. The 3-D travel time table file, in Parametric Grid Library (PGL) format, was 65 Mbytes in size. Figure 3 shows processing times for individual origins having different numbers of associated phases and stations in the selected station list (used in parameter files to limit those stations used). Each event was run five times individually, taking the average and standard deviation. The computation times reported are a sum of the base time required by LocOO/PGL to load and execute a default set of base model station/phase pairs, plus the time required to load the 3-D information associated with the different stations needed, plus the time to perform the location once all data are read in. To show only the time required for the 3-D aspects of the relocation, we took the difference between the average 3-D time and 1-D time for the different numbers of stations available for an event. There is a clear increase in time with the number of stations needed to be loaded/processed for the 3-D relocation (Figure 4, left). Projecting to 100 stations by fitting a line (through zero) to the data (Figure 4, right), we see that the overhead for 3-D location of such an event will be about 16 seconds. The average “reported” events/day for global catalogs (ISC, EDR, and REB) are around 50-85 events/day. Of course, this is only a small portion of the actual events relocated in any given day, but the time required to use 3-D model appears manageable.

Correctly locating seismic events requires a good estimate of the geophysical parameters of the material through which the seismic energy travels. Toward this end, we are developing a geophysical model for China and East Asia (CEA). Our current model was derived as a patchwork of geologically distinct provinces, each of which is assigned a geophysical profile. The profiles are joined and a 3-D model is generated using LITHO3D (Aprea et al., 2001). Two additional geophysical models were obtained from MIT (Sun, 2004) and the Lamont-Doherty Earth Observatory (LDEO) consortium (Richards et al., 2003). We are working to compare these two models with the CEA model and may adopt one in lieu of our ad-hoc CEA parameters where warranted. Figure 5 compares the estimated depth to Moho for the MIT model and our CEA model. The MIT collection of 1-D “layercake” velocity-depth profiles (Figure 5, right) are defined through Monte Carlo perturbation of initial profiles, to minimize travel time misfit for a region near every integer latitude-longitude point, whereas the 1-D “layercake” velocity-depth profiles for the CEA model are constant within a province.

While testing these models using TauP (Crotwell et al., 1998) we see that the LDEO model does a good job of predicting the Pn arrivals, although it incorporates (and provides) no structural information such as crustal thickness or significant discontinuities. The lack of crustal and mantle discontinuities in LDEO model results in the inability to estimate arrival times for other phases that are often important in earthquake location. Unlike the CEA and MIT models, the LDEO model is characterized by velocity gradients (Figure 6) derived to fit travel times for first-arriving P-waves from mantle refractions at regional distances. Like the CEA model, it is characterized using one profile for each large, geologically distinct province. Shallow velocities for each of the LDEO provinces are shown in the map.

To test components of the various models for Asia, we have gathered GT 0-20 information for two nuclear test sites in Asia: the former Soviet test site in Kazakhstan (KTS), and the Chinese site at Lop Nor. Figure 7 (for Lop Nor) shows picks and predictions for the WH3Lc (LANL; Whitted et al., 1999), MIT, and Lamont models. The picks for MKAR and MAKZ are plotted together and suggest that nuclear tests recorded at MAKZ can be used to calibrate models for MKAR. No nuclear tests from KTS have been recorded on either station and seismicity is sparse. There have been numerous chemical shots at KTS that were recorded on MAKZ. Figure 8 shows seismograms for several of these tests, with labels indicating the shot size in tons. Two-ton shots are clearly seen at MAKZ on several occasions. Detailed investigation of high signal-to-noise-ratio (SNR) chemical tests indicates a very small amplitude Pn phase followed a few seconds later by a prominent lower crustal phase which we have tentatively identified as PmP. At low SNR, this secondary phase will be picked as the first arrival. For KTS, Figure 9 shows picks and predictions for the KZ45 (Jih and Wagner, 2000) and MIT models. All models do a decent job of predicting Pn. For our purposes it is advantageous to be able to predict all regional phases from a single model. Of the models tested, the WH3Lc and MIT models do the best job of predicting all observed regional phases for their respective regions.

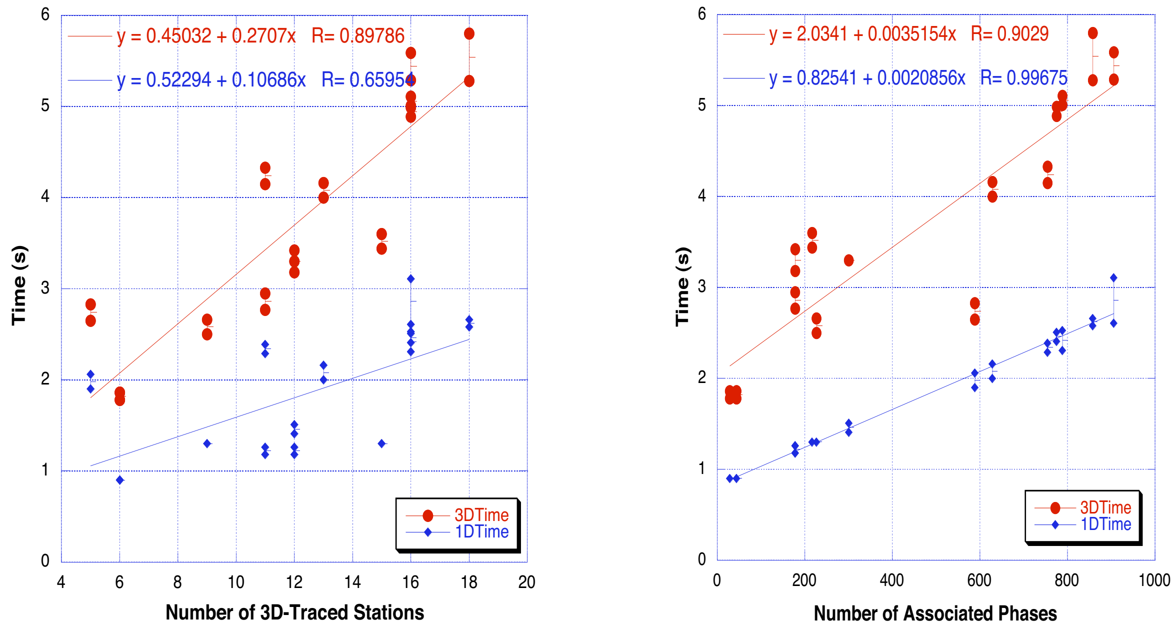

Figure 3. Computation times for 1-D and 3-D locations. Left plot shows dependence on number of 3-D ray-traced stations. Right plot indicates dependence on the number of associated phases. Note that only the stations having 3-D travel time tables built for them are used in the relocations (both 3-D and 1-D).

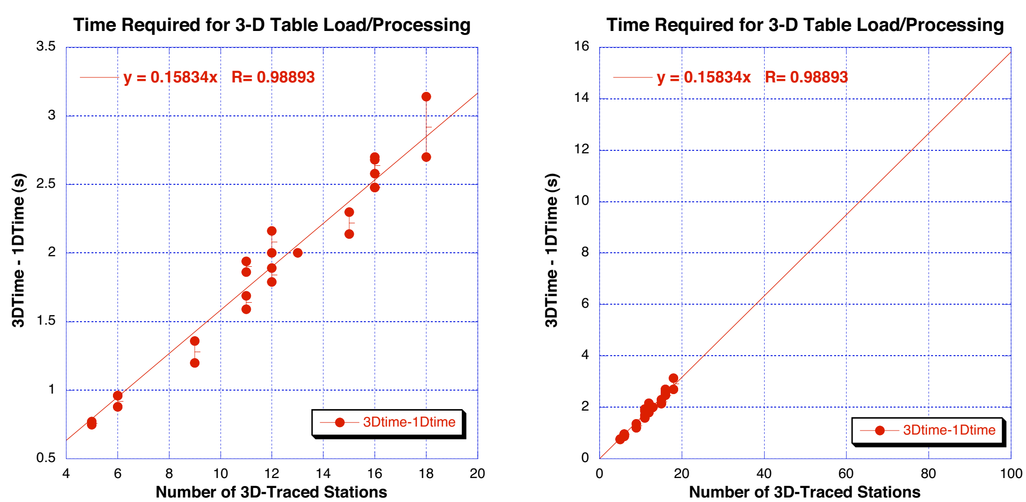

Figure 4. Differences in time between 3-D and 1-D relocations, to highlight the additional burden of 3-D travel-time table usage. The left plot shows actual tests, while the right plot shows a prediction to a 100-station location based on the tests.

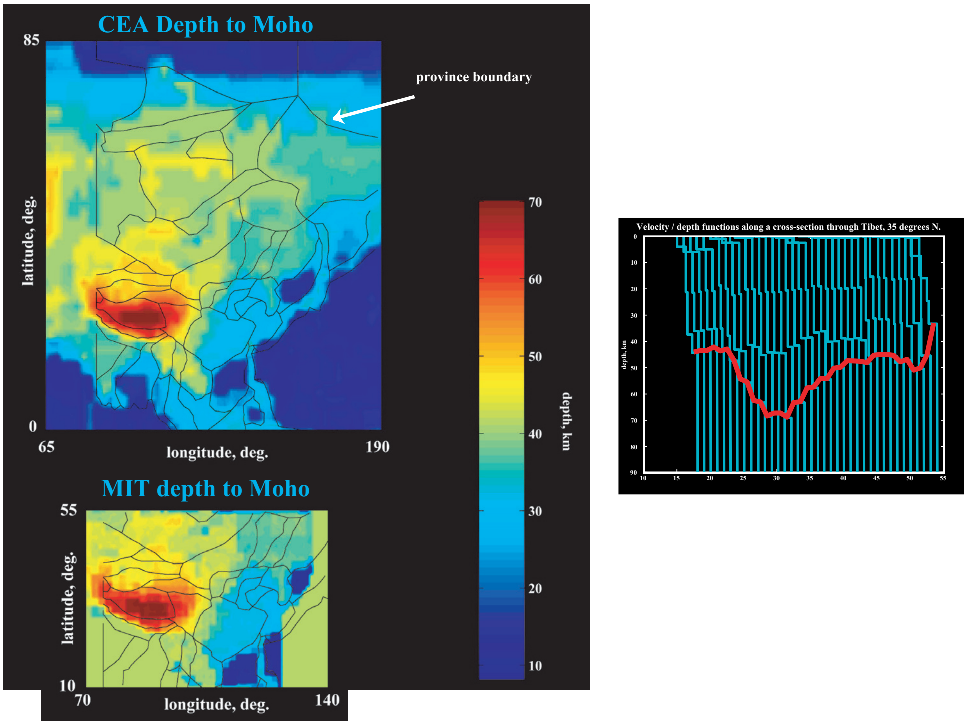

Figure 5. Comparison of Moho depths between the LANL CEA model and the MIT model. Also shown are velocity profiles along latitude 35 north for the MIT model. The red line indicates Moho.

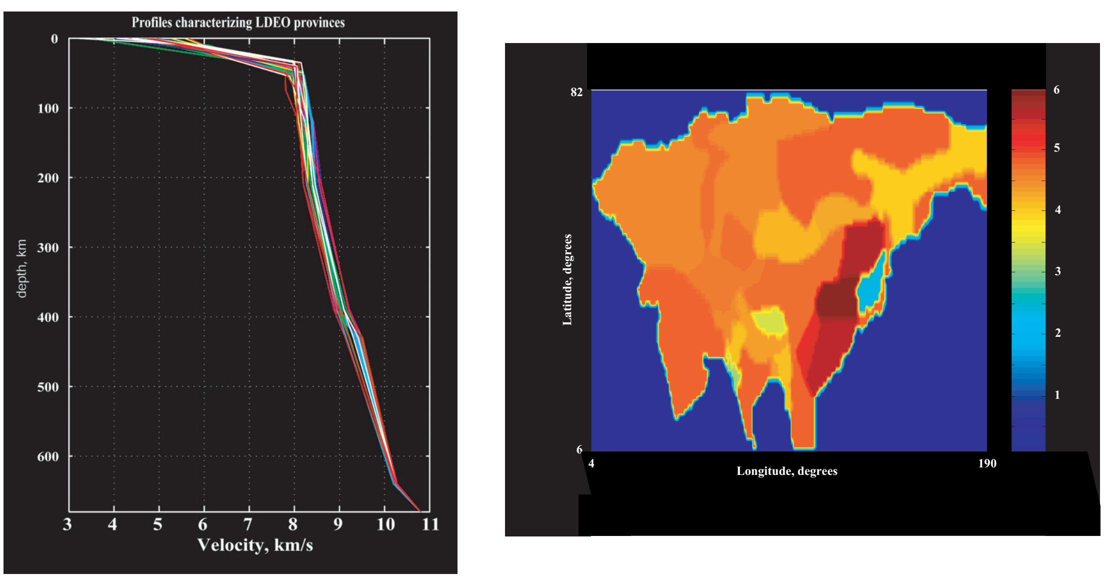

Figure 6. Plots showing some elements of the LDEO model. Left are velocity profiles with depth, right shows the LDEO provinces and shallow velocity structure.

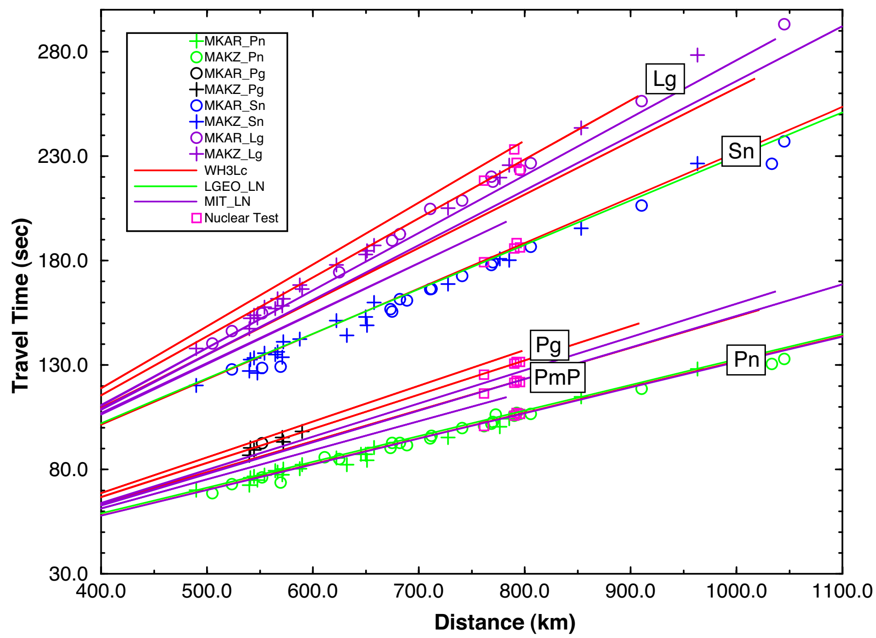

Figure 7. Travel time picks at both MKAR (circles) and MAKZ (plus signs) comparing the WH3Lc, LDEO_LN, and MIT_LN models for a surface source. Text phase labels call out picks and not necessarily model predictions.

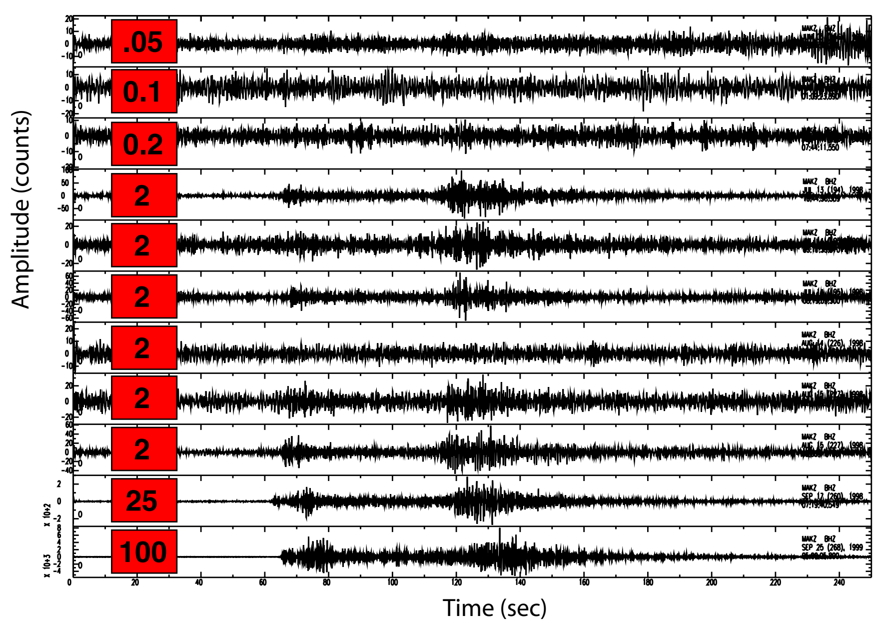

Figure 8. Selection of seismograms recorded at MAKZ for chemical shots at KTS ranging in size from .05 to 100 tons. Notice variable noise levels for the suite of 2 ton shots.

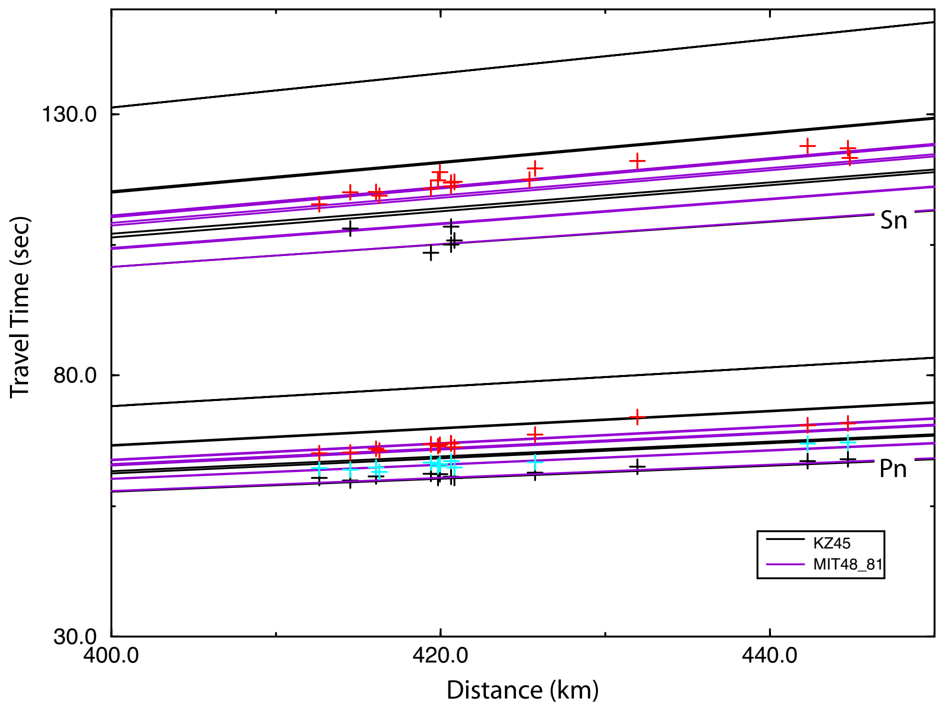

Figure 9. Comparison of KZ45 and MIT48_81 models with picks at MAKZ for the chemical shots at KTS. Arrival time symbols as in previous figure. Only Pn and Sn curves are labelled, as the travel time curves for later phases become interleaved. PmP is the second time curve for each model, Pg and Lg are the third. Picks are shown with plus signs (black = Pn and Sn; red = Pg and Lg) and squares (light blue = PmP).

CONCLUSIONS AND RECOMMENDATIONS

Initial investigations into the use of travel-time residual difference constraints for purposes of leveraging poor GT into good GT suggest that while some challenges exist, the potential payoffs are substantial. This approach extends the idea that nearby stations should show spatial correlation between their respective correction surfaces. Here, we require only that the differenced correction surfaces show some specific spatial correlation properties; the correction surfaces alone need not be correlated. We have begun exploring the usefulness of the 3-D Asia models provided by the consortium teams. For some test sites, the best-fitting models, some of which come from these Asia products, have been identified for MAKZ/MKAR. We have found also that feasibility testing of location using 3-D raytracing is favorable for catalog-scale location efforts. One recommendation coming out of this work is that better tools are needed to predict regional phases, such as Pg and Lg, from 1-D, 2-D, and 3-D models. Some research and development effort should be devoted to this goal.

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