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Title: THE USE OF PROPAGATION PATH CORRECTIONS TO IMPROVE REGIONAL SEISMIC EVENT LOCATION IN WESTERN CHINA

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THE USE OF PROPAGATION PATH CORRECTIONS TO IMPROVE REGIONAL SEISMIC EVENT LOCATION IN WESTERN CHINA

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ABSTRACT

In an effort to improve our ability to locate seismic events in western China using only regional data, we have developed empirical propagation path corrections (PPCs) and applied such corrections using both traditional location routines as well as a nonlinear grid search method. Thus far, we have concentrated on corrections to observed P arrival times for shallow events using travel-time observations available from the USGS EDRs, the ISC catalogs, our own travel-time picks from regional data, and data from other catalogs. We relocate events with the algorithm of Bratt and Bache (1988) from a region encompassing China (latitude 20°-55°N; longitude 65°-115°E). For individual stations having sufficient data, we produce a map of the regional travel-time residuals from all well-located teleseismic events. From these maps, interpolated PPC surfaces have been constructed using both surface fitting under tension and modified Bayesian kriging. The latter method offers us the advantage of providing well-behaved interpolants, but requires that we have adequate error estimates associated with the travel-time residuals. To improve our error estimates for kriging and event location, we separate measurement error from modeling error. The modeling error is defined as the travel-time variance of a particular model as a function of distance, while the measurement error is defined as the picking error associated with each phase. We estimate measurement errors for arrivals from the EDRs based on roundoff or truncation, and use signal-to-noise for our travel-time picks from our waveform data set.

We have found that applying the PPCs reduces travel-time bias and mislocation using only regional data. With a good station distribution, location accuracy can be surprisingly good (within ~7 km) using as few as 3 stations, despite the fact that the closest recording station is typically 10° distant. Most of the events that we use to evaluate the utility of the PPCs are nuclear explosions from the Chinese nuclear test site near Lop Nor, although earthquakes having good epicentral location and/or depth estimates will also be used. We find that the constructed travel-time residual surfaces show some distance dependence, suggesting an inadequate regional velocity model. For this reason we have begun developing an unbiased 1-D regional model for China.

We have been able to construct the empirical PPCs largely due to the relatively high seismicity in China, especially western China. However, the lack of seismic data for some stations and regions in and around China has led us to begin evaluating other methods of predicting PPCs. We are evaluating both the use of rather simple corrections based upon crustal thickness and Pn velocity, as well as tomographic reconstruction of Pn velocity, with subsequent calculation of the PPCs from the inverted Pn velocities. A simple iterative reconstruction method has been applied to about 6000 Pn arrivals at about 55 stations. Results indicate low Pn velocities associated with Tibet and the eastern half of Sichuan province of China.

Key Words: Location, calibration, seismic regionalization

OBJECTIVES

The objective of this research is to improve regional seismic event location in China. To accomplish this objective, we initially developed a suite of empirical propagation path correction (PPC) surfaces (Cogbill and Steck, 1997). While the surfaces developed significantly improved regional location capability, a travel-time residual bias in the 1-D travel-time model (ak135) used made estimating unbiased travel-time variances difficult. Thus, we have now developed a 1-D model to remove travel-time residual bias at regional distances. Using this model we have recalculated the PPCs and eliminated the distance bias. Finally, we are evaluating both the use of rather simple corrections based upon crustal thickness and Pn velocity, as well as tomographic reconstruction of Pn velocity, with subsequent calculation of the PPCs from the inverted Pn velocities.

INTRODUCTION

We have focused our effort to improve regional location of seismic events in China on the development of corrections to P-wave travel-time observations available from the United States Geological Survey Earthquake Data Reports (EDRs), the International Seismological Centre (ISC) catalog, our own travel-time picks from regional data, and data from other catalogs. For this research we have chosen to locate events within a region defined from 20°-55°N latitude and from 65°-115°E longitude, using the EvLoc algorithm (Bratt and Bache, 1988; Nagy, 1996). While our intent is to calibrate all regional seismic stations, many of the stations of interest, particularly those of the International Monitoring System (IMS), have not been in operation long enough to acquire sufficient data for this undertaking. To circumvent this problem we use EDR and ISC stations as surrogates for those of the IMS. In this report we discuss the development of propagation path corrections (PPCs) for 49 EDR/ISC stations and 6 IMS stations and their effect on regional and teleseismic locations in China. Interpolated PPC surfaces have been constructed using both surface fitting under tension (Smith and Wessel, 1990) and modified Bayesian kriging (Hipp et al., 1998). Our principal source of ground truth for verifying results comes from a report by Gupta (1995) that provides accurate locations of a number of Chinese nuclear tests at Lop Nor in western China.

In Cogbill and Steck (1997), we reported on our initial efforts at developing PPC surfaces. Using the *ak135* velocity model (Kennett et al., 1995), we compared regionalized locations at Lop Nor both with and without PPCs. Our results showed that EvLoc generally performed quite well when as few as 3 to 5 stations were available, even if the closest stations were on the order of 10° distant. When PPCs were applied, the locations became more stable, and regional location bias due lateral structure variation was reduced. Grid-search locations (Kennett, 1992) also improved with the use of PPCs, but not as much as with the Bratt and Bache (1988) algorithm. Because the *ak135* velocity model is not currently used by institutions doing global event association and location, we have begun using the *iasp91* global velocity model (Kennett and Engdahl, 1991) and an average regional 1-D model for China (Li and Mooney, 1998).

A critical element of our location effort lies in improving our ability to accurately estimate the errors in travel-time measurements. This is important both in determining the location error ellipse (or confidence region), and in providing accurate estimates of traveltime variance to the kriging codes. To aid in this, we have refined estimates of modeling and measurement errors. The modeling error is defined as the travel-time variance of a particular model as a function of distance, while the measurement error is defined as the picking error associated with each phase. Optimally, signal to noise ratio should be used to determine the measurement error, but this is rarely reported in most catalogs. We have found that many stations of the Chinese Digital Seismic Network (CDSN) have phase picks that are rounded or truncated to the nearest second. We compared these arrival times against regional waveforms and found that we must account for this roundoff or truncation (Figure 1). To use these arrivals for event location, we developed a preliminary measurement error estimate based on the noted roundoff/truncation. For example, if the roundoff is to the nearest second, the measurement error is 1.0 s. If the roundoff is to the nearest 0.5 s, 0.1 s, or less than 0.1 s, the measurement error is set to 0.5 s, 0.2 s, or 0.1 s, respectively. Thus, the best measurement error is 0.1 s. This appears to be most appropriate for high signal-to-noise events. Modeling error is the most difficult of the two types of error to estimate. We begin by using estimates of the modeling error developed from arrivals compiled by the preliminary International Data Center (pIDC) for the global velocity model *iasp*91 (Swanger, 1998, personal communication). This estimate of modeling error does not account for intrinsic biases present in our locations, arising from differences in network geometry and from using a 1-D base model when the true structure is laterally variable.

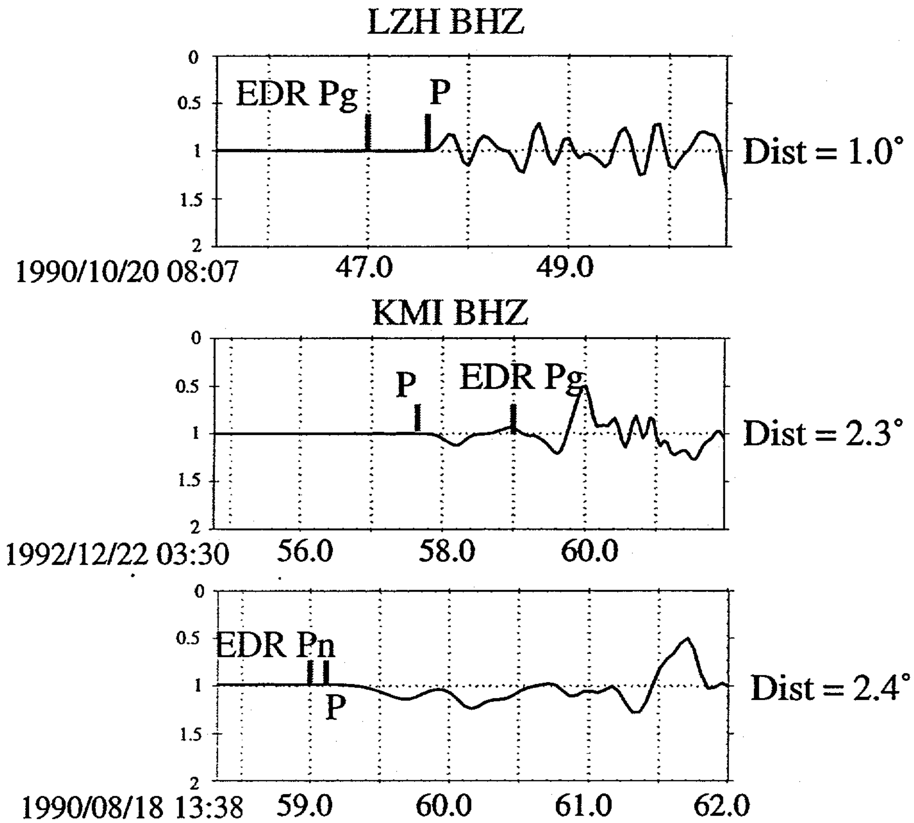

Figure 1: Example waveforms and travel-time picks from our data set and the USGS EDR picks. Note that for these Chinese Digital Stations, the picks are truncated or rounded off to the nearest second (vertical dashed lines).

RESEARCH ACCOMPLISHED

An average 1-D model for China

An inspection of average P-wave residuals plotted versus epicentral distance shows that the *iasp*91 velocity model produces bias in our travel-time residuals at regional distances (Figure 2). This suggests that the *iasp*91 global model is too fast for the China region, particularly for Pn. To find a better model that will reduce this bias, we took an average of seven crustal models based on deep seismic sounding results for China (Li and Mooney, 1998). Our strategy was to assume a three-layer crust with each layer having the average crustal thickness and velocity of the three thickest layers of each of the seven models. Thin sedimentary layers and anomalous mid-crustal zones were thereby eliminated. Figure 2 shows the P-residuals for locations based on our 1-D model and from this it is clear that most residual biases have been eliminated. The average China model features a somewhat thicker crust and faster upper mantle than *iasp*91 (Figure 2). An important question is whether or not a "best" 1-D model exists for locating seismic events in western China. We have performed relocations of nuclear tests from the Lop Nor region using a number of different 1-D models, including those for western China based on deep seismic sounding, and none are able to eliminate the regional bias we see with respect to the relocations of Gupta (1995). It is, however, possible to remove that bias using propagation path corrections (Cogbill and Steck, 1997).

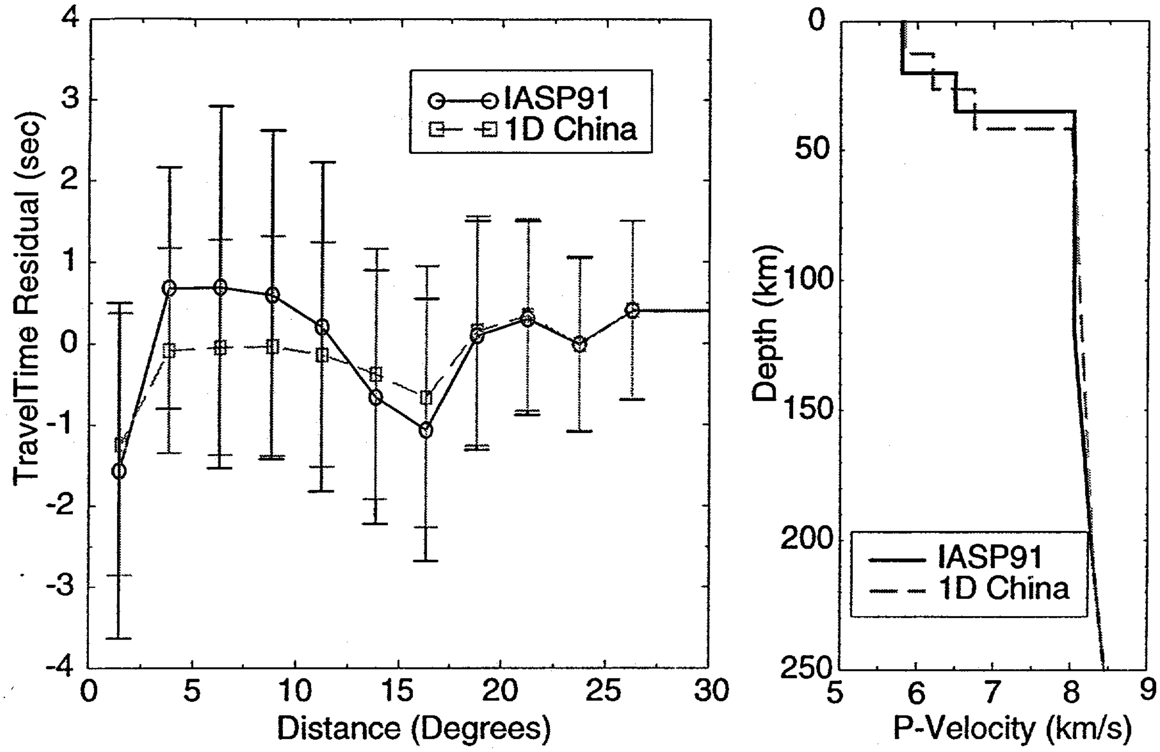

Figure 2: (left) Binned travel-time residuals as a function of distance for IASP91 and our average 1-D China model. Note that except for residuals at a distance of less than 2.5°, residual bias is removed and the standard deviation reduced for the 1-D China model. (right) IASP91 and the 1-D China P-velocities.

Empirical propagation path correction surfaces

We determine P-wave propagation path corrections using traveltime residuals from teleseismically located events with depths less than 34 km. Residuals are used only if the magnitude of the residual is less than 6 s, the event is located by 30 or more defining phases recorded at distances greater than 18°, and the azimuthal gap of the location is less than 180°. By employing the latter two criteria, we restrict ourselves to residuals from events located with an accuracy of about 25 km (E. R. Engdahl, personal communication). More accurate ground truth data are available for the Lop Nor nuclear test site in western China, however. For this region, Gupta (1995) has relocated several nuclear shots using the JED method and Landsat imagery of one of the shots. Ground truth for some of the larger earthquakes in China will also be incorporated as it becomes available. All events are relocated using the EvLoc algorithm (Nagy, 1996) and the 1-D model described above, with the exception of those located by Gupta. The Gupta events are fixed at his locations. Residuals are then tabulated for 49 EDR/ISC stations and 6 IMS stations.

Maps of P-wave residuals for the 55 stations are interpolated using two approaches. The first approach, discussed in some depth in Cogbill and Steck (1997), fits the data to a surface using splines under tension (Smith and Wessel, 1990). This approach has several limitations, including the inability to predict the accuracy of the interpolated PPCs, as well as a tendency to extrapolate poorly. The second approach, called modified Bayesian kriging (Hipp et al., 1998) addresses both these concerns. Using modified Bayesian kriging, the value of the PPC surface goes to zero at distances greater than a specified correlation length away from the data points, and an estimate of the variance associated with the surface is calculated based on user-supplied residual variances and an estimate of the background variance. In results shown here, we used 5° for both the model and data correlation lengths. For station WMQ, Figure 3 shows the kriged P-residual surface and its associated variance, while the surface fit with splines under tension is shown in Figure 4. To test the effect of the PPCs on epicentral location, the events are again relocated in EvLoc using both teleseismic and regional phases. Figure 5 compares the relocations using PPCs to those of the earlier locations and shows that we successfully remove the remaining biases with the 2-D corrections.

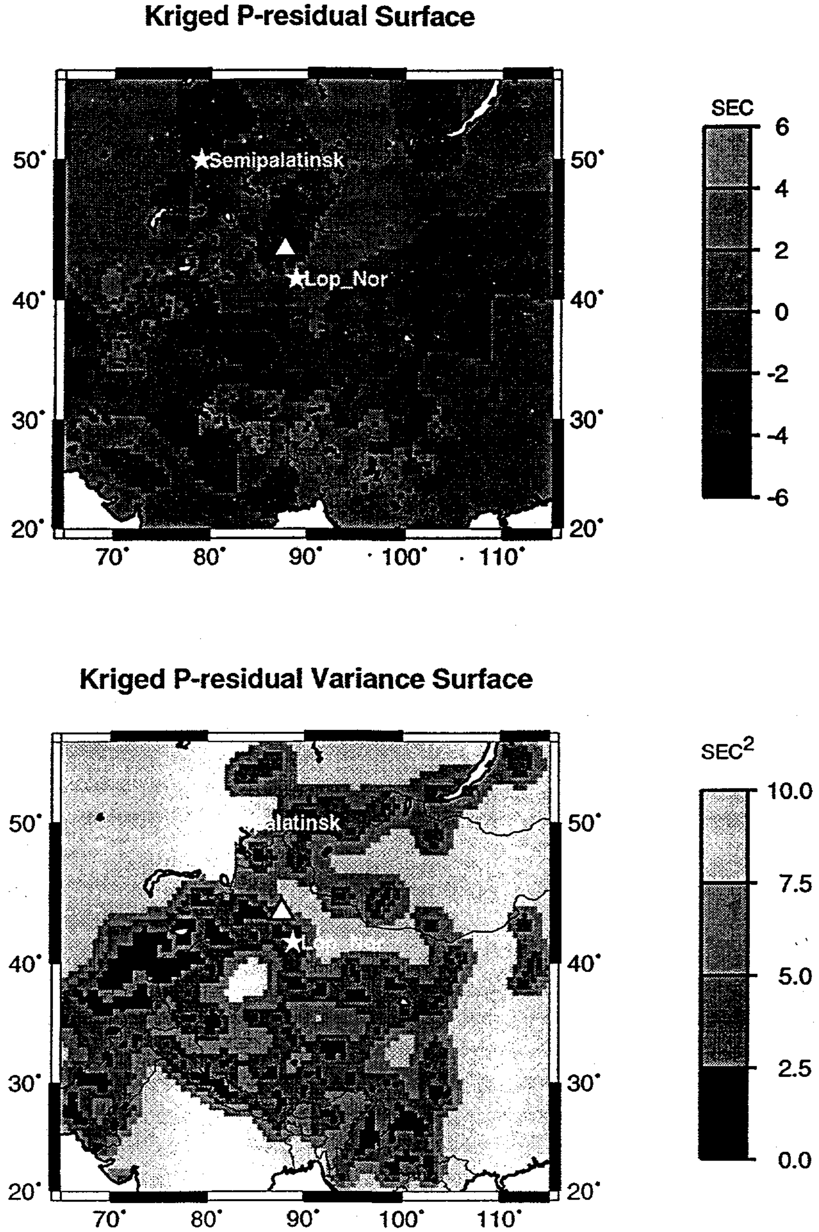

Figure 3. (top) P-residual surface from modified Bayesian kriging. White triangle is station WMQ. White stars show the locations of the Chinese and former Soviet Union nuclear test sites. Black squares show event locations. (bottom) Variance of P-residual surface. A background of 10 sec^2 was assumed.

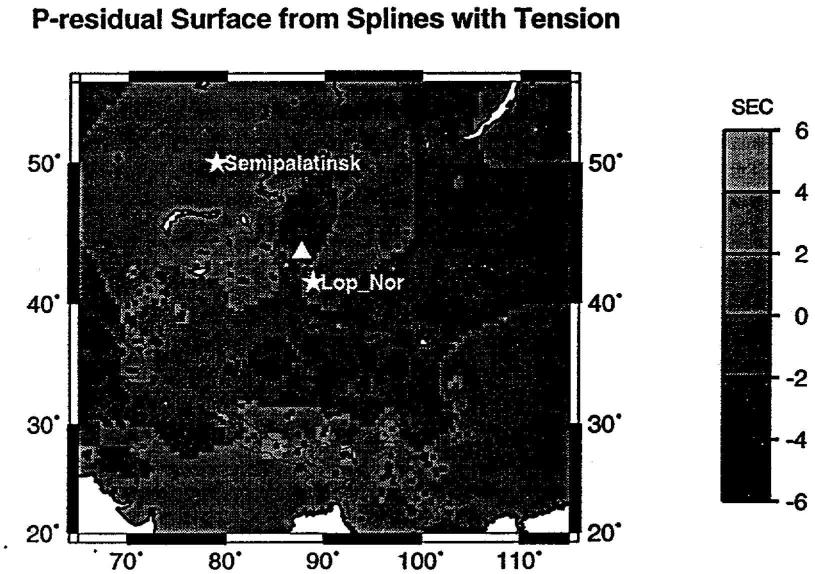

Figure 4. P-residual surface from splines with tension. Note PPC values predicted for regions without any data (e.g. the NW corner of the plot).

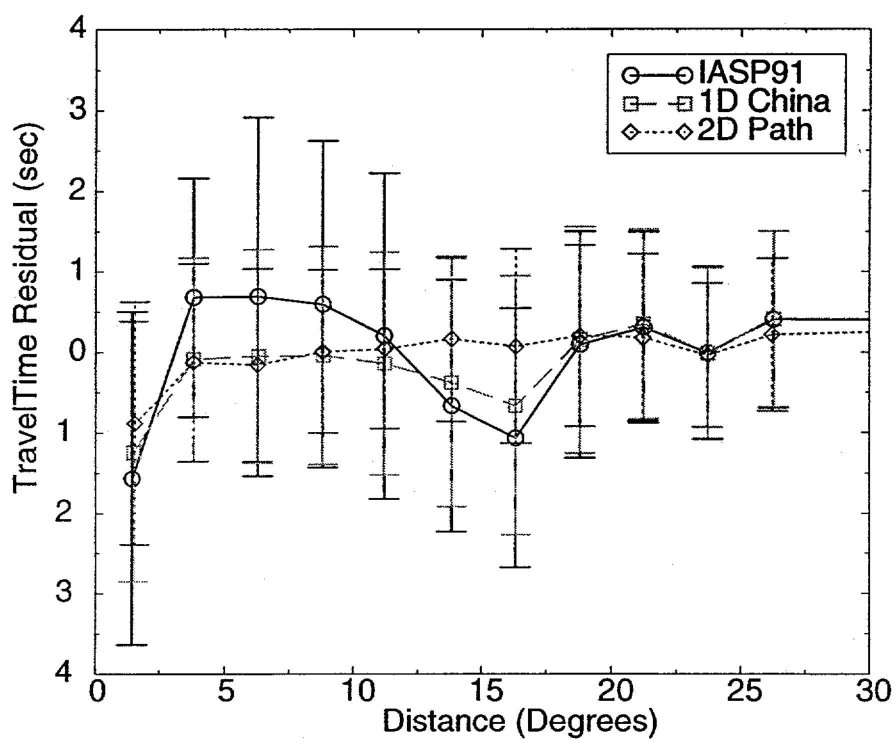

Figure 5: Binned travel-time residuals as a function of distance for IASP91, an average 1-D China model, and implementing the 2-D path corrections. Most remaining bias is removed using the 2-D corrections.

Effect of varying crustal thickness

Crustal thickness variations in the study region are quite large, ranging from 30-70 km (Li and Mooney, 1998). Inasmuch as our PPCs have been developed empirically, we decided to investigate whether the values of the PPCs were at all predictable from changes in crustal thickness. We used the depth-to-Moho data available from the Cornell University data base (Fielding et al., 1993) to estimate the crustal thickness at the locations of all the events used to construct PPC surfaces. The results were surprisingly simple: the travel-time residuals seem to be *completely uncorrelated* with crustal thickness. Figure 6, a plot of crustal thickness at the event location versus the P travel-time residual for station WMQ, is quite typical of the results obtained at all the stations used in this study.

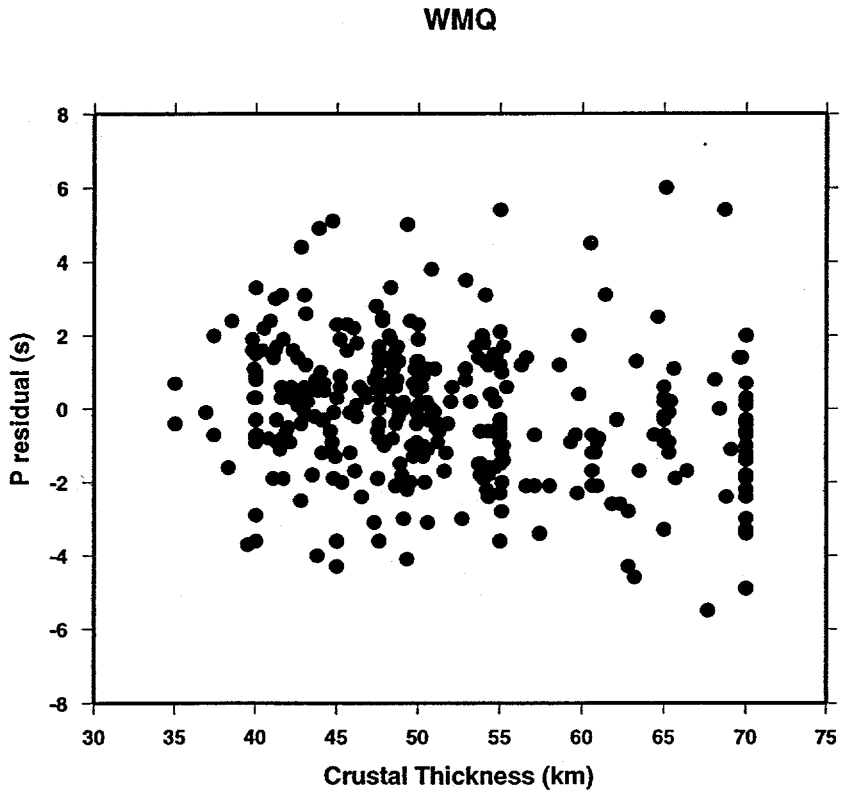

Figure 6. P travel-time residuals versus crustal thickness at the event location, for station WMQ.

Tomographic reconstruction of Pn velocities

We have been able to construct empirical PPCs largely because of the relatively high seismicity in China, particularly in western China. However, the lack of seismic data for some stations and regions in and around China has led us to begin evaluating other methods of predicting PPCs. If we can determine the 2- or 3-D velocity structure of the crust and upper mantle in China, this can be used to generate PPCs for any station/event pair of interest, provided velocity resolution in the region of interest is adequate. Tomographic reconstruction of lateral (2-D) variation in Pn velocity is one such approach that we are currently pursuing. We use Pn residual data from the EDR catalog, applying the same selection criteria as outlined above for empirical PPC surfaces. Here, we further restrict the data to the distance window between 330 km and 1667 km, so that only Pn phases are considered. This yields 6033 Pn residuals from 55 stations. Data from the McNamara et al. (1997) study (about 1500 additional traveltimes) on the Tibetan plateau will be incorporated in the near future.

The Pn residuals are backprojected onto a 1° grid covering the region from 20°-55° N latitude and 65°-115° E longitude. We use a simple SIRT tomographic backprojection algorithm (Humphreys and Clayton, 1988; McNamara et al., 1997), coded in the PERL programming language. While we do remove the average residual for a given station, we do not currently account for variations in crustal thickness throughout the region, or for event statics. Hit quality, based on the number and orientation of rays sampling a given node, is used to down-weight poorly-sampled nodes (Figure 7). Hit quality is defined as: $Wq = (n_T/8)^{.5} * \{1/(8-n_1) + 1/(8-n_2) + ... + 1/(8-n_8)\}/8$, where n_T is the total number of rays sampling a node, and $n_1...n_8$ are numbers of rays in each of 8 equally-spaced azimuth bins around that node. If an individual n_i is greater than or equal to 8, its term inside the curly braces, $1/(8-n_i)$, is set to one. If all $n_1...n_8$ are greater than or equal to 8, then $Wq = 1$. Each slowness image is also smoothed with a 3° radius smoother.

A slowness result for one iteration of the algorithm is shown in Figure 8. In this model, the upper mantle beneath the Tibetan plateau and the western half of Sichuan province are found to be slower than the average, while the upper mantle beneath part of the western Himalaya and the Tarim basin is observed to be faster than normal. These preliminary results, despite the very simplistic approach, agree well with the results of McNamara et al. (1997) and Zhao and Xie (1993), particularly considering that we have not accounted for variations in crustal thickness. Further studies will incorporate crustal thickness, event statics, iteration, and resolution testing. Ultimately, velocity images such as the one presented here will be used to predict PPCs for the China region.

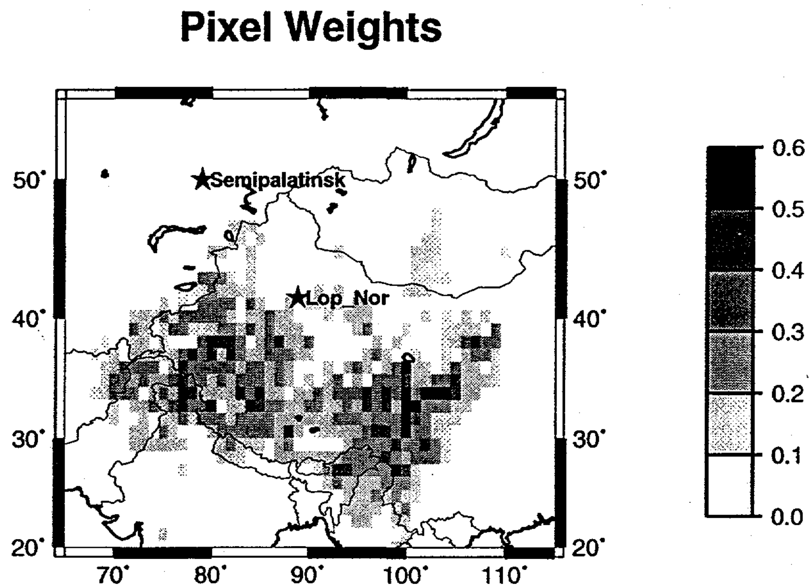

Figure 7. Ray geometry weights used to scale slowness perturbations.

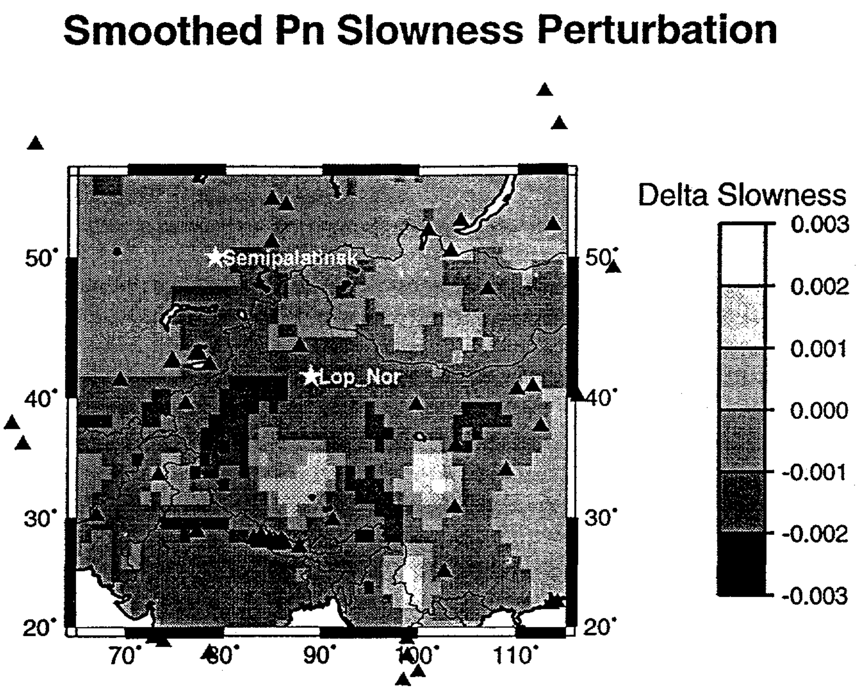

Figure 8. Pn slowness variations from simultaneous backprojection.

CONCLUSIONS AND RECOMMENDATIONS

We have developed empirical P-wave propagation path corrections for 55 seismic stations in and around China. We have shown that these corrections improve regional event location at the Lop Nor nuclear test site. Some distance dependence is observed in our correction surfaces when locations are performed with the *iasp91* velocity model. To remove this bias we have developed a simple 1-D model for China. Application of propagation path corrections based on our average China model successfully eliminates all remaining bias, except at distances less than 2.5°. Because of sparse seismicity in some areas of China, and a lack of data at some critical stations, we have begun looking at alternative methods of predicting PPCs. Initial research on using Moho depth to predict PPCs shows no correlation between event Moho depth and P-wave residual. On the other hand, P-wave tomography reveals some coherent lateral variations in Pn velocities which may be used to predict PPCs.

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