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REGIONAL MODEL CALIBRATION FOR IMPROVING SEISMIC LOCATION

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ABSTRACT

Accurate seismic event location is integral to the effective monitoring of the Comprehensive Nuclear-Test-Ban Treaty (CTBT), as well as being a fundamental component of earthquake source characterization. To account for the effects of crustal and mantle structure on seismic travel times, and to improve seismic event location in the Middle East and North Africa (MENA), we are developing a set of radially heterogeneous and azimuthally invariant travel-time models of the crust and upper mantle for each MENA seismic station.

We begin by developing an average one-dimensional velocity model that minimizes the *P*-phase travel-time residuals from regional through teleseismic distance at each station. To do this we (1) generate a suite of 1-D velocity models of the earth, (2) compute travel times through the 1-D models using a *tau-p* formulation to produce standard travel-time tables, and (3) minimize the root-mean-square (rms) residuals between the *P*-phase arrivals predicted by each model and a groomed set of ISC *P*-phase arrival times (Engdahl et al., 1991). Once we have an average one-dimensional velocity model that minimizes the *P*-phase travel-time residuals for all distances, we repeat steps 1 through 3, systematically perturbing the travel-time model and using a grid search procedure to optimize models within regional, upper mantle, and teleseismic distance ranges. Regionalized models are combined into one two-dimensional model, using indicator functions and smoother methodologies to reduce distance and depth discontinuity artifacts between the individual models.

Preliminary results of this study at a subset of MENA stations show that we are improving predictability with these models. Cross-validating the travel-time predictions with an independent data set demonstrates a marked reduction in the variance of the travel-time model error distributions. We demonstrate the improvement provided by these 2-D models by relocating the 1991 Racha aftershock sequence. We will extend our investigation to additional MENA stations, and will use our model in tandem with nonstationary empirical corrections (nonstationary Bayesian kriging) to further improve our ability to accurately predict travel times and locate seismic events in this region.

Key Words: 2-D models, travel times, kriging, seismic event location

OBJECTIVE

An accurate velocity model of the earth is a fundamental component of seismic event location. Global velocity models such as *ak135* (Kennett *et al.*, 1995) minimize a set of worldwide travel-time residuals and are primarily meant for prediction of teleseismic travel-times. However, global models are often inadequate for prediction of travel-times at regional and near teleseismic distances, where the effect of crustal and mantle structure on seismic travel-times is considerable. In order to improve the travel-time predictions at regional and near teleseismic distances in the Middle East and North Africa (MENA), we are developing two-dimensional, station-specific velocity models that are optimized to predict travel times. We will use our travel-time models at each station in tandem with nonstationary spatial corrections (nonstationary Bayesian kriging) to further improve our capability to accurately locate all seismic events in this region.

RESEARCH ACCOMPLISHED

Data

We focus our initial travel-time modeling efforts on 27 of the International Monitoring System (IMS) seismic stations in the Middle East and North Africa. The locations of the IMS stations used in this study are shown in Figure 1. The data we use are a set of *P*-phase arrival times from earthquakes recorded at those each of those stations. The earthquakes are a relocated subset of those contained in the *ISC Bulletin* (Engdahl *et al.*, 1998). To minimize the error introduced by a misidentification of phase arrival time, we use only high-confidence *P*-phase picks. The data set has also been declustered - a statistical grooming procedure that reduces the impact of outliers, enhances numerical stability, and lessens computation demands. We divide the groomed data set into a modeling data set and a cross-validation data set. The cross-validation data set represents 10% of the total data set.

Method

For the purposes of this study, the data are parsed into three earthquake-station distance ranges: regional (1°-13°), upper mantle (13°-30°), and teleseismic (30°-90°). Sensitivity analyses were performed to identify those properties of the crust and mantle to which seismic travel-times in each distance range were most influenced. Of the 11 properties investigated in the sensitivity analyses, crustal thickness, upper and lower crustal *P*-wave velocity and upper mantle velocity had the largest affect on travel-times. The eight model parameters we use to describe model space are listed below in Table 1. We develop an adaptive grid search method that efficiently samples the space of reasonable models, allowing the four most influential model parameters (as identified in the sensitivity analyses) to vary.

Table 1: Grid search model parameters of the 1-D velocity models

MODEL PARAMETERS VARIED IN THE GRID SEARCH
Crustal thickness 30-55 km
Crustal *P*-wave velocity
Upper crust 5.5-7.0 km/s
Lower crust 6.6-8.0 km/s
Upper mantle velocity 7.9-8.1 km/s
ADDITIONAL MODEL PARAMETERS
Sediment thickness 4 km
Sediment *P*-wave velocity 4 km/s
Thickness of mantle lid 25 km
P-wave velocity gradient in the mantle lid 0

We calculate travel times through each regionalized *P*-wave velocity model using a ray-tracer that employs the single-valued *tau-p* formulation similar to that of Buland and Chapman (1983). An earth-flattening transformation is used to account for the sphericity of the earth, which preserves the kinematic properties of the rays. The resulting travel-time tables are populated with travel-times, parameterized by distance and depth.

To test the predictive power of each model, we compute the root-mean-square and mean residuals between the declustered *P*-phase arrivals at each station and the arrivals predicted by each 1-D regionalized model. We repeat the calculation for the declustered *P*-phase arrivals at each station and the arrivals predicted by the *ak135* model (Kennett *et al.*, 1995). To compute these residuals we interpolate between grid nodes to calculate the predicted travel-time for the earthquake-station path. Then each predicted time is subtracted from the observed arrival time. We find that a suite of models predict the travel-time arrivals equally well. To further optimize our models, the 50 models that provide the lowest rms residuals are further minimized against the *ak135* model. The model that most closely approximates *ak135* is designated as the preferred model.

The preferred one-dimensional regional models are then merged into one two-dimensional model over the entire distance range of the model, from regional out to teleseismic distances (Figure 2). Merging is accomplished using indicator functions to reduce distance and depth discontinuity artifacts between the individual models (Figure 2). The result is a radially heterogeneous and azimuthally invariant travel-time model of both the crust and upper mantle. This methodology provides optimal models for the three distinct ray-bottoming depths, allowing increased predictability and a smooth travel-time curve.

To test the predictive power of the 2-D models, we compute the rms and mean residuals between the declustered *P*-phase arrivals at each station and the arrivals predicted by both the optimized 2-D model and the *ak135* model. Station-specific analyses of the capability of our 2-D models to predict the observations help us identify regions where the model needs to be improved or alternative models need to be applied.

There are several caveats associated with our technique that merit mention. First, since the travel-time modeling process is non-linear and the number of model parameters is limited, the solution is non-unique. In addition, these two-dimensional models are azimuthally invariant and radially segmented to facilitate statistical averaging. As a result, the models do not account for azimuthal changes in structure and can only account for average changes in radial structure. Our two-dimensional models are thus likely to have better predictive power in areas with dense GT event coverage. Stations with small azimuthal deviations benefit most from these corrections. To predict corrections in aseismic regions, three-dimensional models will likely be required.

Results

For the majority of the 27 IMS stations for which we have computed 2-D models, our 2-D model predicts the observations very well, showing significant variance reduction; for a small number of stations, the 2-D model only slightly reduces the variance. We have selected four IMS MENA stations to illustrate in more detail our method and results: *AAE* (Addis Ababa, Egypt), *ANTO* (Ankara, Turkey), *AQU* (Abruzzo, Italy) and *TBT* (Canarias, Spain) (Figure 1). The results from these individual stations are fairly representative of results from the remainder of stations included in our initial modeling study.

The map in the upper-right-hand corner of Figure 3 shows the azimuthal distribution of a typical modeling data set. This particular data set was recorded at station *AAE*. The data have been parsed into three earthquake-station distance ranges: regional (white circles; 1°-13°), upper mantle (gray circles; 13°-30°), and teleseismic (black circles; 30°-90°).

We tested the predictive power of each *P*-wave velocity model at stations *AAE*, *ANTO*, *AQU* and *TBT* by computing the rms and mean residuals between the declustered *P*-phase arrivals at each station and the arrivals predicted by each 1-D regionalized model. We repeat the calculation for the declustered *P*-phase arrivals at each station and the arrivals predicted by the *ak135* model (Kennett *et al.*, 1995). The 50 models that provide the lowest rms residuals are further minimized against the *ak135* model. For each station, the model that most closely approximates *ak135* is designated as the preferred model. This piece-wise optimization of the travel-time curve markedly improves predictability, especially at regional and teleseismic distances.

Figure 3 shows a cartoon illustrating our preferred regionalized models at station *AAE*. *P*-wave velocity *versus* depth profiles for each distance range at each station are shown in Figure 4. The preferred one-dimensional regional models are then merged into one two-dimensional model over the entire distance rage of the model, from regional out to teleseismic distances (Figure 2). The profiles in Figure 4 all display some distance and depth discontinuity artifacts between the individual models, illustrating the importance of using indicator functions when merging the regionalized models into one 2-D model.

To test the predictive power of the 2-D models, we compute the rms and mean residuals between the declustered *P*-phase arrivals at each station and the arrivals predicted by both the optimized 2-D model and the *ak135* model. Those results are shown in Tables 2a and 2b below.

Table 2a: rms residuals (seconds squared)

STATION	data *vs ak135*	data *vs* best 2-D model	Reduction
AAE	2.67838	2.05136	23%
ANTO	2.16813	1.68400	22%
AQU	2.13796	1.76301	18%
TBT	2.76454	1.69335	39%

Table 2b: mean residuals (seconds)

STATION	data *vs ak135*	data *vs* best 2-D model	Improvement
AAE	2.12126	0.86341	59%
ANTO	1.18942	-0.00094	92%
AQU	1.22124	-0.02453	96%
TBT	0.99596	-0.25633	74%

Histograms of the distribution of residuals are shown in Figure 5. Table 2 and Figure 5 demonstrate a clear reduction in travel-time variance between *ak135* and our preferred 2-D models. In addition, our 2-D models provide a mean residual closer to 0. These results suggest that we are improving predictability with these models.

CONCLUSIONS AND RECOMMENDATIONS

Summary

An accurate velocity model of the earth is a fundamental component of seismic event location, which in turn is integral to the effective monitoring of the Comprehensive Nuclear-Test-Ban Treaty (CTBT). Because global velocity models can be inadequate for prediction of travel-times at regional and near teleseismic distances, we are developing two-dimensional, station-specific velocity models that are optimized to predict travel times for IMS stations in the Middle East and North Africa.

We develop an adaptive grid search method that efficiently samples the space of reasonable *P*-wave velocity models of the earth. Optimized 1-D regionalized models for each IMS station are better able to predict travel-time arrivals than *ak135*. Regionalized models are being mathematically combined into one 2-D model, using indicator functions and smoother methodologies to reduce distance and depth discontinuity artifacts between individual models. We find that this piece-wise wise optimization of the travel-time curve improves predictability, especially at regional and near teleseismic distances.

Further research

These are preliminary results from an initial set of IMS seismic stations; we are in the process of incorporating the remainder of the IMS stations into our study. A station-specific analysis of the capability of our 2-D models to predict the observations will help us identify regions where the model needs to be improved or alternative models need to be applied. We will further optimize our regionalized models by performing a finer adaptive grid search centered near the residual lows identified in our initial analysis. We will also experiment with those additional model parameters we have identified as mechanisms to fine tune the model, such as positive and negative velocity gradients in the upper mantle.

We will test the predictive capability of each 2-D model by cross-validating the data. Our cross-validation data set at each station consists of 10% of the groomed modeling data set. We expect that cross-validating the travel-time predictions by using arrivals from this set of independently located events will demonstrate a marked reduction in the variance of the travel-time model error distributions.

A subset of events from the 1991 Racha earthquake sequence recorded at stations *KAS*, *ARU*, *SVE*, *KVT*, *GAR*, and *KHO* will be used to demonstrate improvement in earthquake location using our 2-D models over our 1-D models and over a generalized earth model such as *ak135*.

Finally, we will use our travel-time models at each station in tandem with nonstationary spatial corrections (nonstationary Bayesian kriging) to further improve our capability to accurately locate all seismic events in this region.

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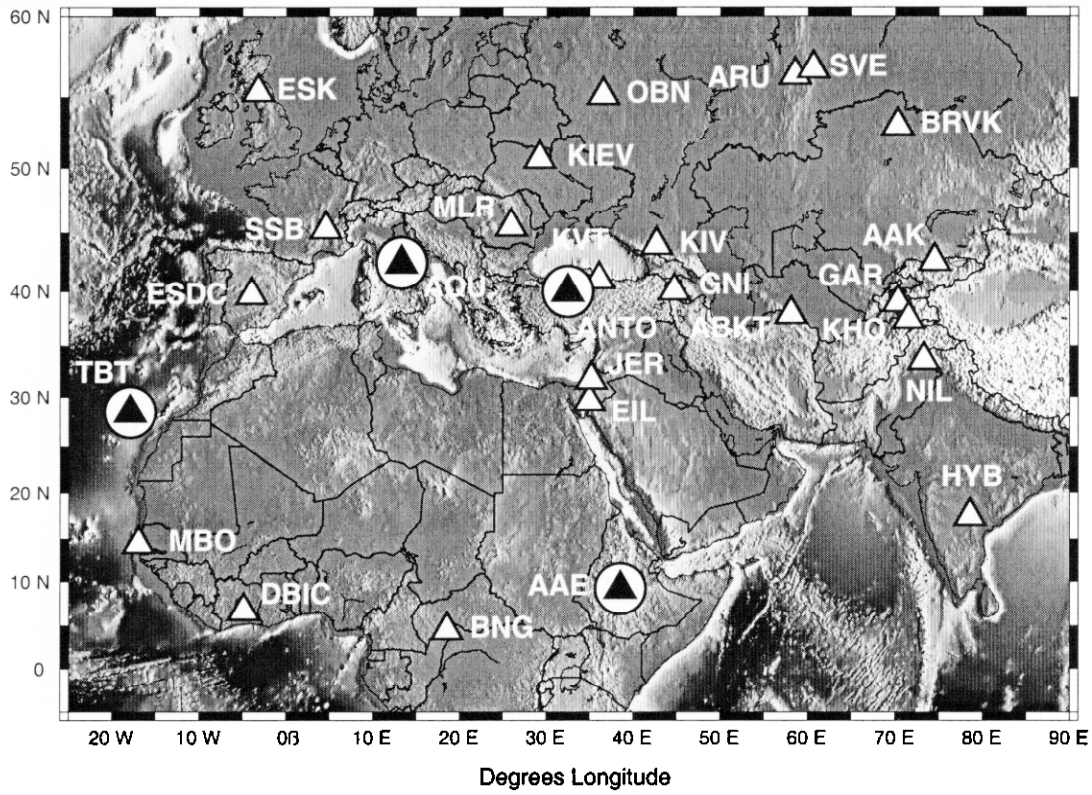

Figure 1: Location of the 27 International Monitoring System (IMS) seismic stations in the Middle East and North Africa for which we have developed 2-D travel-time models. We will present detailed modeling results from the four IMS stations highlighted by the encircled triangles.

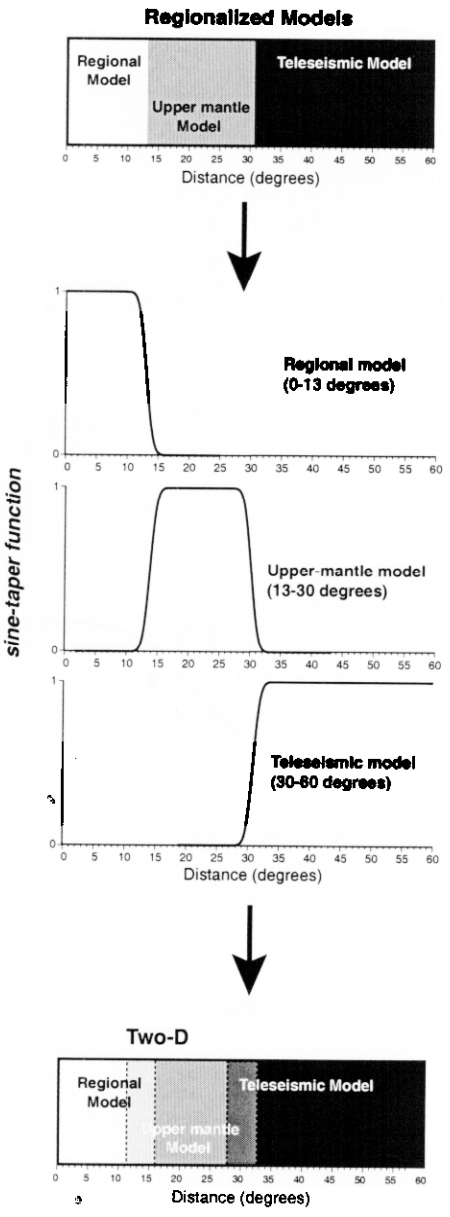

Figure 2: Cartoon depicting the merging of regionalized 1-D models into a 2-D model. Merging is accomplished using indicator functions to reduce distance and depth discontinuity artifacts between the individual models. The result is a radially heterogeneous and azimuthally invariant (see Figure 3) travel-time model of the crust and upper mantle. This methodology provides optimal models for the three distinct ray-bottoming depths, allowing increased predictability and a smooth travel-time curve.

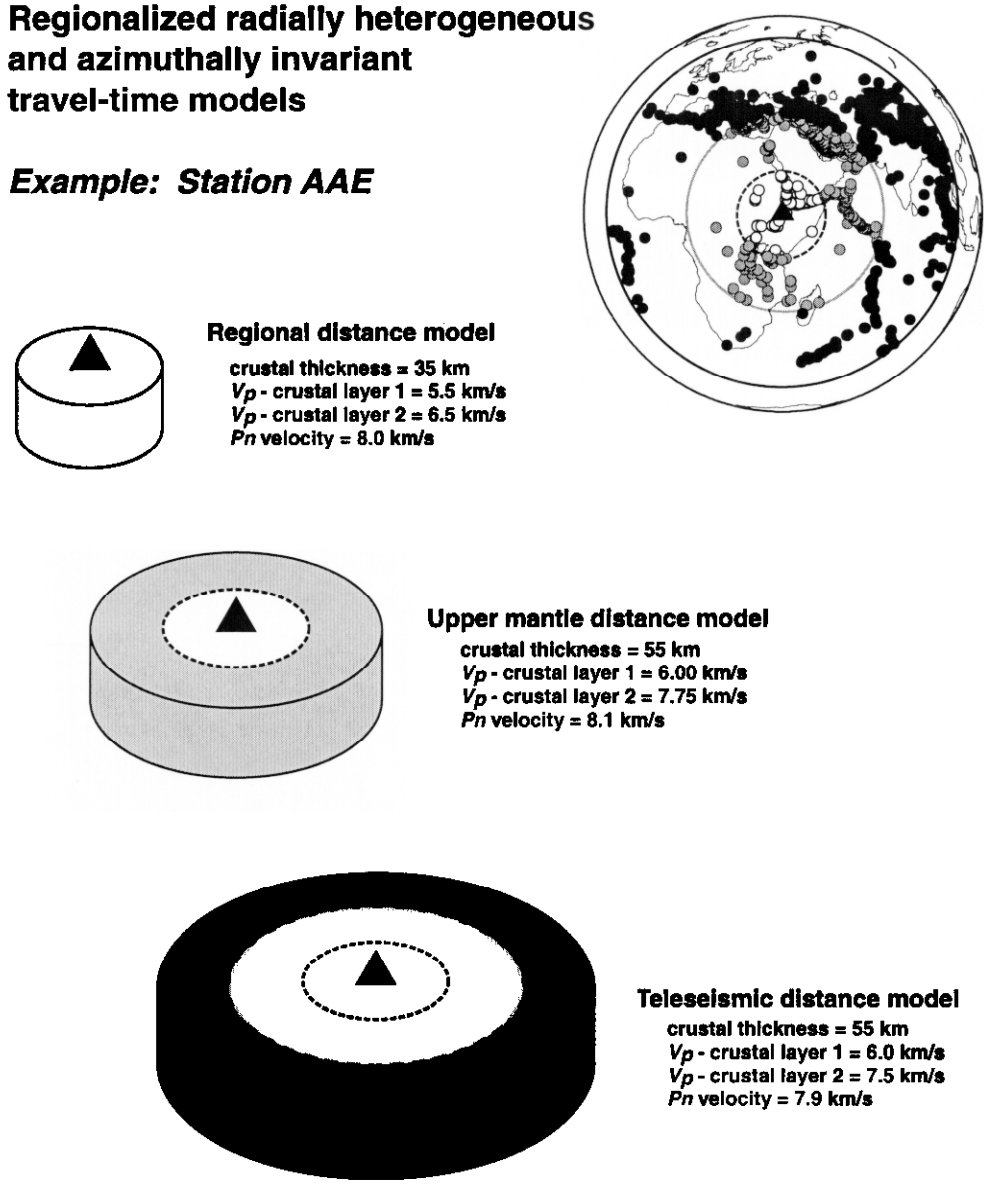

Figure 3: The map in the upper-right-hand corner shows the azimuthal distribution of a typical modeling data set. This particular data set was recorded at station *AAE*. The data have been parsed into three earthquake-station distance ranges: regional (white circles; 1°-13°), upper mantle (gray circles; 13°-30°), and teleseismic (30°-90°). This figure also illustrates the best regionalized radially heterogeneous and azimuthally invariant travel-time models at the IMS seismic station *AAE*.

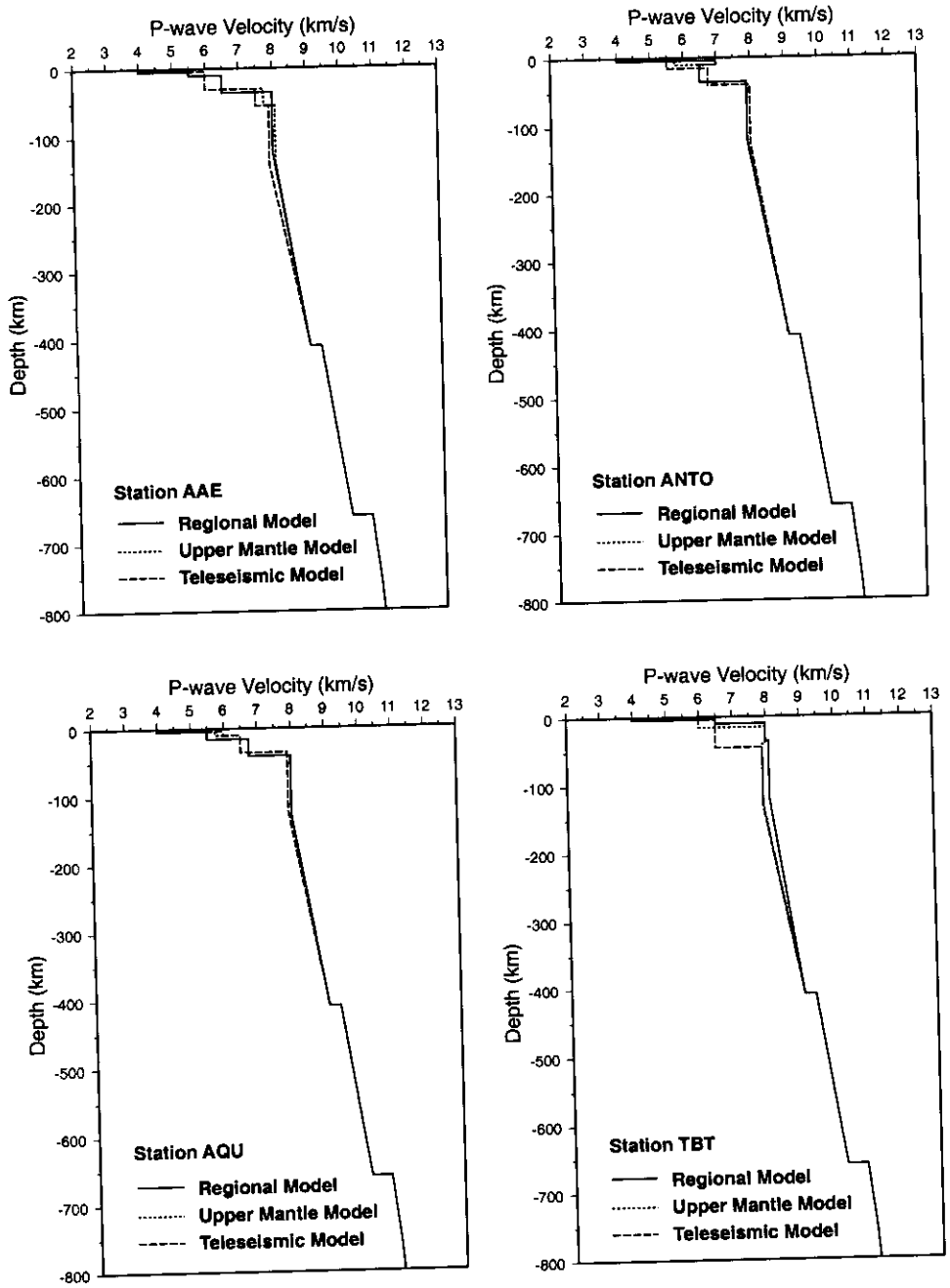

Figure 4: Preferred regionalized models for stations *AAE*, *ANTO*, *AQU*, and *TBT*. The *P*-wave velocity *versus* depth profiles for each distance range at each station are shown. The solid line corresponds to the regional-distance model; finely dashed line corresponds to the upper mantle-distance model; coarsely dashed line corresponds to the teleseismic-distance model.

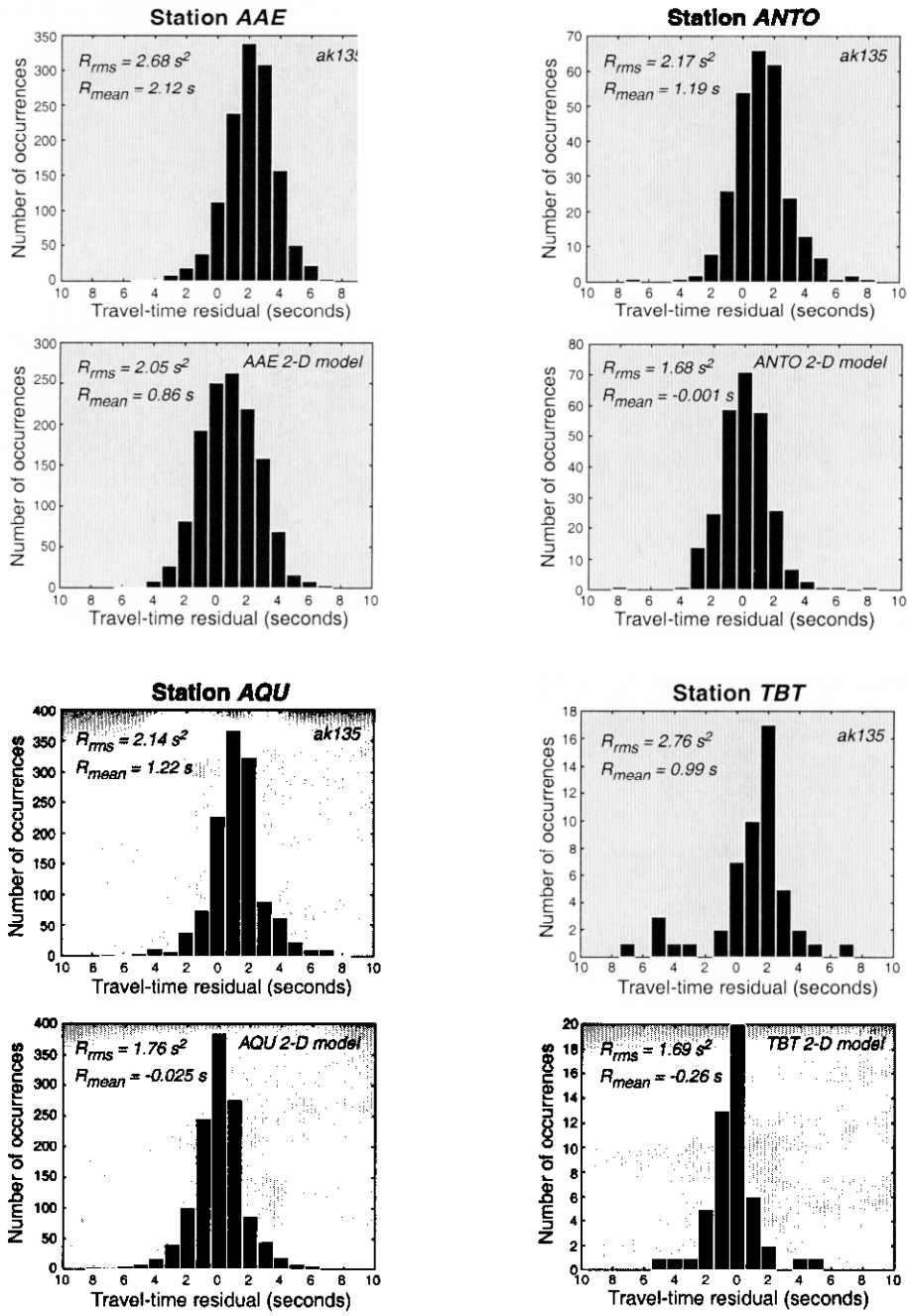

Figure 5: Distribution of travel-time residuals predicted by a global velocity model (*ak135*) and 2-D models computed for IMS seismic stations *AAE*, *ANTO*, *AQU*, and *TBT*. R_{rms} = rms residual (seconds squared); R_{mean} = mean residual (seconds).