CALIBRATION OF 3D UPPER MANTLE STRUCTURE IN EURASIA USING REGIONAL AND TELESEISMIC FULL WAVEFORM SEISMIC DATA

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ABSTRACT

We present progress in the development of a new approach to develop and evaluate earth models at the regional scale that utilizes full waveform seismograms.

We have implemented an approach which relies on a cascade of increasingly accurate theoretical approximations for the computation of the seismic wavefield, with the goal to develop a model of regional structure for a subregion of Southeast Asia (longitude 75 to 150 degrees and latitude 0 to 45 degrees). The selected area is highly heterogeneous, presenting a challenge for calibration purposes, but is well surrounded by earthquake sources and includes high quality broadband digital stations.

In previous years, we developed preliminary models based on successively more sophisticated theoretical approaches to time domain inversion of long period seismograms, in the framework of normal mode theory: 1) a 3D model based on the Nonlinear Asymptotic Coupling Theory (NACT), which includes the consideration of 2D kernels in the vertical plane containing source and receiver. This model was developed for a larger region (longitude 30-150 degrees and latitude -10 to 60 degrees); 2) a 3D model based on the "NBorn" approximation. This approach combines the 3D Born approximation with the path average approximation (PAVA) and allows to accurately account for large accumulated phase delays on paths that sample large scale smooth anomalies. The resulting model has a horizontal resolution of about 200 km.

In parallel, a regional version of the Spectral Element Method (SEM) code, in spherical geometry, RegSEM.1, was completed. This code uses Perfectly-Matched Layers (PMLs) at the borders of the region, and includes general 3D anisotropy, Moho and surface topography, ocean bathymetry, attenuation, and ellipticity. Because each SEM run (i.e., for one event) is time consuming, we proposed implementing an approach in which the wavefields for several events are computed simultaneously. This approach was introduced by Capdeville et al. (2005) and tested on synthetic data at the global scale, but never applied to real data or at a regional scale.

In the past year, we completed the codes and procedures that allow us to invert a collection of summed seismograms over the sub-region of Eurasia already considered for the NBorn inversion. Contrary to the NACT and NBorn cases, for which we collected teleseismic data, RegSEM, as currently implemented, requires sources and receivers to be included in the region of study. We thus collected an entirely new dataset, consisting of 96 events with $6.0 < Mw < 7.0$ observed simultaneously at 6 broadband global seismographic network (GSN) stations during the time period 1995 to 2007, with an epicentral distance between 5^{o} and 45^{o}. We have completed the first successful tests of the method, which consisted of comparing the results of an inversion performed using a standard tomographic approach, where the waveform data correspond to individual source station paths, with an inversion using, as data, summed events at the six stations considered. The resulting 3D models are very similar, indicating that, at least at the wavelengths and periods considered, no substantial loss of information occurred in the event summation process. In these preliminary experiments, the short period cut off was 60 sec and the lateral resolution of the model was ~200km (spherical spline level 6). We present the results of these and other tests aimed at evaluating the potential and limitations of this method as we increase the frequency range to shorter periods, and experiment with different starting crustal models.

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OBJECTIVES

The primary objective of this research is to develop and apply an approach that utilizes increasingly advanced theoretical frameworks and numerical methods in order to obtain improved regional seismic structure calibration. Specifically, a large-scale regional Eurasian model has been developed from a large dataset of seismic waveforms using the path-average approximation (PAVA) and Non-linear Asymptotic Coupling Theory (NACT) (Li and Romanowicz, 1995), which are well-developed normal-mode based approaches. In these approaches, 1D and 2D waveform sensitivity is considered, respectively, in the vertical plane containing the great-circle path between source and receiver. We have refined this model in a smaller region using a linear implementation of Born single-scattering theory (Capdeville, 2005), which more accurately represents the 3D sensitivity of the seismic wavefield, for the inverse part of the problem, and using a non-linear modified 3D Born approximation for the forward part of the problem (Panning et al., 2008). Additionally, we have developed and implemented a regional version of the Spectral Element Method (RegSEM, Cupillard, 2008), a numerical approach that accurately models both wave propagation in a complex 3D earth (e.g., Faccioli et al., 1996; Komatitsch and Vilotte, 1998; Komatitsch and Tromp, 1999). Finally, we have implemented and tested a novel approach using RegSEM with stacked sources (Capdeville et al., 2005) to further speed computation.

A further objective of this research is to perform validation and improved calibration of the model described above using a variety of approaches and datasets, including ground truth datasets from the Knowledge Base. Specifically, we have been using broadband waveform modelling to tighten the crustal model on specific regional paths.

RESEARCH ACCOMPLISHED

Development of an "N-Born" Model.

In previous years, we developed a starting 3D upper mantle shear wave radially anisotropic model (Figure 1a) using NACT (Li and Romanowicz, 1995) from a global dataset of surface wave waveforms crossing the region of interest (longitude 30 to 150 degrees and latitude -10 to 60 degrees). This region is highly heterogeneous, presenting a challenge for calibration, but it is well surrounded by earthquake sources and a significant number of high quality broadband digital stations exist. We started from the existing waveform database that was collected at Berkeley over the last 10 years for the construction of global mantle tomographic models (Li and Romanowicz, 1996; Megnin and Romanowicz, 2000; Gung et al., 2003; Panning and Romanowicz, 2006), and added data from ~20 new events in the period up to to 2005. We now have 38826 3-component waveforms from 393 events recorded at 169 stations. The data has been processed using an automated algorithm, which removes glitches, and checks for many common problems related to timing, poor instrument response, and excessively noisy windows. A weighting scheme has been applied to insure even distribution of data across the region. This model is parameterized laterally in spherical spline level 6, which corresponds to lateral resolution of ~200 km. And the corresponding radially anisotropic model is parameterized in the spline level 5, which corresponds to a lateral resolution of ~400 km.

The next step in our study, finalized in 2007 (e.g., Cao et al., 2007ab), has been to perform an iteration of our 3D model using the "non-linear" Born approximation (N-Born), which is modified from the more standard 3D "linear" Born approximation by including a "Path Average" term (e.g., Panning et al., 2008). This term allows the accurate inclusion of accumulated phase shifts which arise in the case when the wavepath crosses a spatially extended region with a smooth anomaly of constant sign. The linear Born terms account for single scattering effects outside of the great circle path and are modeled according to the expressions of Capdeville (2005). With PAVA, multiple forward scattering is accounted for on the great circle.

Because the calculation of the 3D Born sensitivity kernels is very expensive computationally, we have selected a smaller subregion (longitude 75 to 150 degrees and latitude 0 to 45 degrees), where the lateral heterogeneities are more significant than the surrounding regions. In order to further reduce the length of the computation, we require that both events and stations must be within the large region (longitude 30 to 150^{o} E and latitude -10 to 60^{o} N) and only the ray paths along the minor arcs are selected. We calculated 3D Born sensitivity kernels for 162 events using the method of Capdeville (2005) and the computing facilities (Jacquard) of the National Energy Research Scientific Computing Center (www.nersc.gov). When we generate synthetics for the N-Born inversion, we use N-Born in the subregion and NACT outside of the subregion. The adopted damping scheme for isotropic and radially anisotropic models is the same as that used in the NACT inversion. Figure 1 compares the isotropic part of the starting 3D (NACT) model and of the 3D "N-Born" model obtained after one iteration. The starting crustal model is CRUST2.0, and we invert for perturbations to the Moho topography together with volumetric perturbations in the upper mantle.

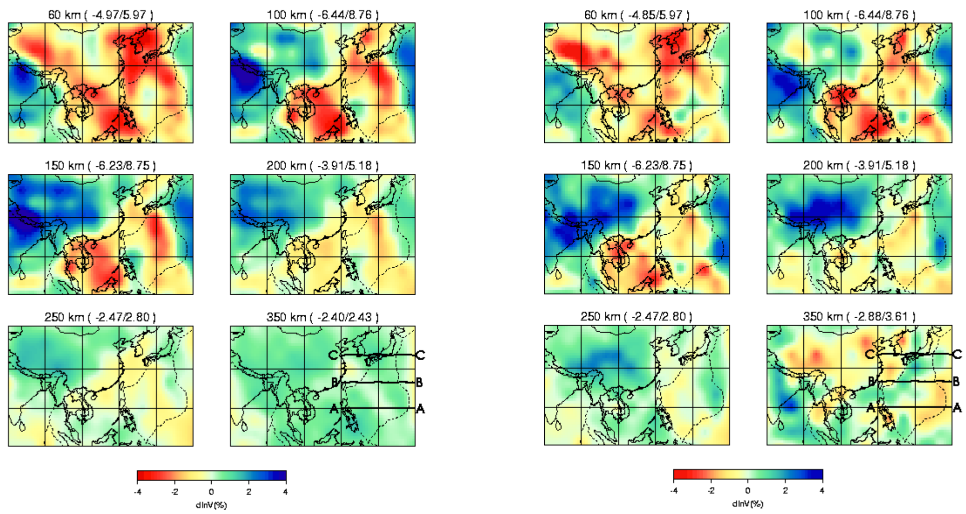


Figure 1. a) Isotropic part of the starting NACT-derived 3D upper mantle model shown in a subregion (Lon 75 to 150 degrees and lat 0 to 45 degrees with map grid interval of 15 degrees). This model was derived using NACT in a somewhat larger region than shown, from a teleseismic waveform dataset. The lateral parameterization is in level 6 spherical splines which give a lateral resolution of ~200 km. Values are shown as percent perturbations from the isotropic velocity of the reference model, PREM (Dziewonski and Anderson, 1981). b) N-Born model (isotropic part) derived after one iteration, using the "non-linear" 3D Born approximation in the subregion shown.

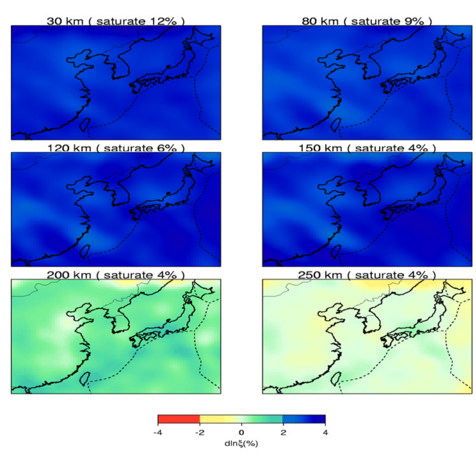


Figure 2. Radially anisotropic part of the N-Born derived 3D upper mantle model of Figure 1. The lateral parametrization is in level 5 spherical splines (lateral resolution of ~400 km). The model is expressed in terms of relative variations in the parameter $\xi = (Vsh/Vsv)^2$.

Both N-Born and NACT derived models can fit waveforms very well, with up to ~83% variance reduction (depending on the choice of damping), and the N-Born residual variance is even lower than that of NACT. While the models agree in general, there are some notable differences between them in detail. For example, beneath the Tibetan plateau, the N-Born model shows a stronger fast velocity anomaly in the depth range 150 km to 250 km, which disappears at greater depth. This indicates that there is no delamination of lithosphere beneath the plateau, as has been suggested by some authors. Likewise, in the anisotropic part of the models, the largest differences are in the deeper layers.

Implementation of RegSEM and a "Summed Events" Procedure

In collaboration with researchers at Institut de Physique du Globe de Paris (IPGP), we have completed a regional version of the Spectral Element code (RegSEM, Cupillard, 2008). The regional SEM incorporates Perfectly Matched Layer (PML) boundary conditions on the lateral borders of the region, which effectively eliminate spurious reflections from the borders. Compared with previous versions, first of all, both Moho topography and surface topography have been included into the process of building the mesh. With reference to a Moho model, we are able to provide realistic velocity contrasts at the Moho discontinuity while introducing any 3D elastic mantle model. Second, anisotropy has been included in the present version of regional SEM (any anisotropic structure can be considered, but we currently have only included radial anisotropy). Finally, this new version of regional SEM has been fully optimized.

Implementation of "Summed-SEM" Methodology

The computation of the forward wavefield using SEM is very accurate, but heavy computationally. It takes 2 hours to compute the wavefield of a single seismic event down to 60 sec (i.e., at long periods) on a modest computer cluster (32 cpu's). To speed up computations and develop the capability of performing many iterations and reaching higher frequencies, we have implemented the approach of Capdeville et al. (2005), in which the wavefield corresponding to many events is computed simultaneously. To do so, all the seismic sources considered are shifted in time to a common origin time, and the wavefield generated by this composite source is calculated once. The observed waveforms, at each station, thus consist of the summed observed seismograms for all events, each of them appropriately shifted in time, and are compared to the predicted synthetic wavefield. While these "summed" waveforms do not have a physical meaning, i.e. there are no identifiable seismic phases, they retain sufficient information to allow retrieval of 3D structure, even in the presence of realistic background noise, at least at long wavelengths. This approach can reducecomputation time by one to several orders of magnitude, depending on the implementation. Capdeville et al. (2005) tested this approach in the framework of global tomography and a synthetic dataset. They showed that, even with realistic noise added to the synthetics, they can retrieve 3D upper mantle structure accurately from a single forward computation involving ~50 events observed simultaneously at ~150 stations worldwide. They used the C-SEM global code of Capdeville et al. (2002) for this development. In their tests, they used accurate numerically computed partial derivatives for the inversion. Their implementation turned out to be quite restrictive, as it is difficult in practice to find a sufficient number of events distributed adequately and observed with good signal to noise ratio at a fixed and large set of broadband global stations.

In the adaptation of this method to our regional case, we have proceeded with the RegSEM code (rather than C-SEM) and have relaxed the restriction of "all events observed by all stations", replacing the single summation over all events by a series of runs, each of which considers the sum of all events observed at a given station. The number of RegSEM runs is then equal to the number of stations considered in the region, which, in general, is significantly smaller than the number of events. In our case, we considered a smaller region within the sub-region of the previous N-Born computation, and initially considered six broadband stations within that region, for which data can be freely accessed from the IRIS Data Management Center (DMC), and collected data from about 100 events in the magnitude range 6–7, also included within this region. Figure 3 shows the region of study and the ray coverage for our initial summed event experiment. Here, we have relaxed the restriction of teleseismic observations. The epicentral distances range from 5 to 40^{o}. In this case, we cannot perform any comparisons with the NACT or N-Born inversions, for which the theory breaks down at short distances, however, we can still perform comparisons with inversions obtained using the simpler Path Average (PAVA) approximation.

Figure 4 shows an example of comparison between "observed" versus RegSEM computed summed waveforms at station XAN, showing that, at these long periods, the starting model predicts the observed waveforms already quite well.

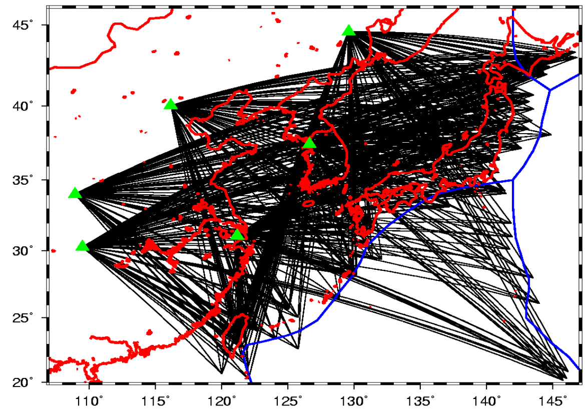


Figure 3: Raypath coverage achieved in the "summed seismogram" experiment. The stations are indicated by green triangles.

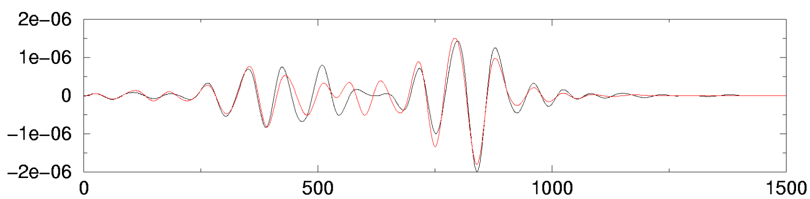


Figure 4. Summed seismogram on the vertical component at station XAN. Black: observed trace, red: synthetic trace computed using RegSEM for the starting 3D model (NBORN) shown in Figures 1 and 2. Both observed and synthetic traces have been filtered with a cut-off period of 60 s.

In order to reduce the computational time in the inverse step of the procedure, we also have opted, at least at this early stage, to compute partial derivatives approximately, using PAVA, in the inversion step of our procedure. We are assuming that, if our starting 3D model (the model derived using N-Born) is sufficiently accurate, these approximate partial derivatives will point us in the right direction and we will at the worst, need to compute a few more iterations to converge to the final model. Eventually, we can implement accurate numerical partial derivatives, whose calculation will also be faster, compared to conventional inversions, due to summation over events.

In order to test the summed event approach, we have first compared the results of an inversion obtained using, on the one hand side, the "summed event" seismograms at the 6 stations considered, and on the other, a "standard" approach, in which we have separately calculated the wavefield using RegSEM for all the events considered, and inverted the corresponding perturbations to the time domain waveforms, as we would do conventionally, using any of our previous inversion methods (PAVA, NACT, N-Born). The only difference in the latter is that now, the forward part of the modelling is computed using RegSEM, rather than mode perturbation theory. The synthetics have been computed down to 60 s period, and the observed seismograms have been filtered accordingly. Figure 5 shows a comparison of the isotropic models obtained using the conventional approach (single event-station paths) versus the summed approach. This figure also shows the inverted model obtained using the conventional approach, but instead of RegSEM synthetics, we use PAVA in both the forward and inverse steps. The two RegSEM models are very similar indicating that the summed event approach works. A striking feature of the RegSEM models is the fast velocity anomaly south of Korea shallow depth (30 km), which is not present in any of the models developed with asymptotic mode perturbation theory., which shows low velocities throughout the ocean basins at this depth. The fast velocity seen in the RegSEM models is likely an artifact, due to the inaccurate crustal model, which does not incorporate the thick sediments present in that region. Since RegSEM models the crust much more accurately than our usual inversions based on mode perturbation theory, these kind of details start to matter, even at periods as long as this test case. Figure 6 shows the radially anisotropic part of the two RegSEM models (conventional procedure, and summed event procedure). Finally, Figure 7 shows the model obtained by conventional inversion of the same dataset, with the same starting model, but using the PAVA approximation in both the forward and inverse steps.

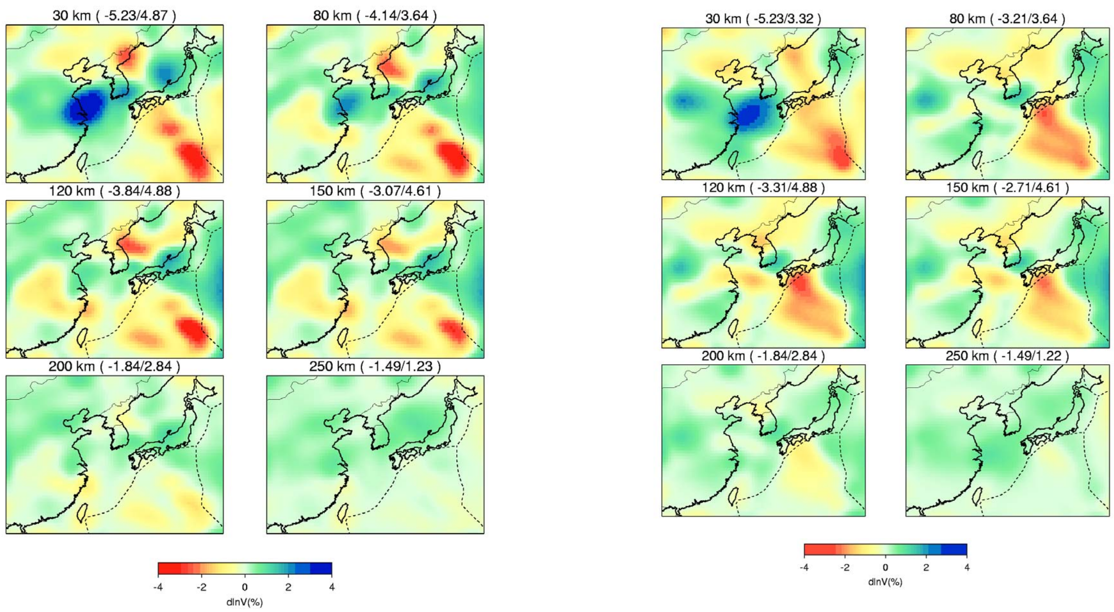
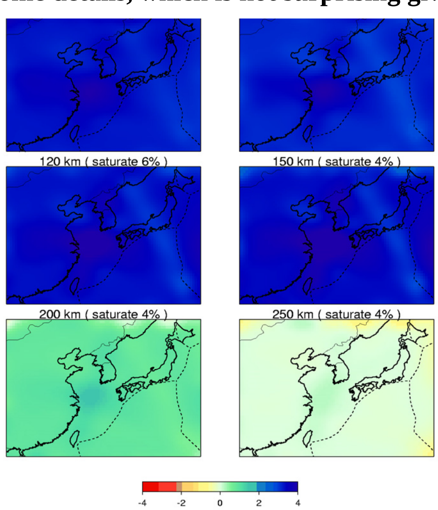


Figure 5. Comparison of upper mantle models obtained after one iteration from the starting NBorn model, using waveform data on the path collection shown in Figure 4, RegSEM for the forward part of the computation, and PAVA for the calculation of partial derivatives. Left: conventional computation using individual source-station paths. Right: "summed-event" computation. The models differ in some details, which is not surprising given that



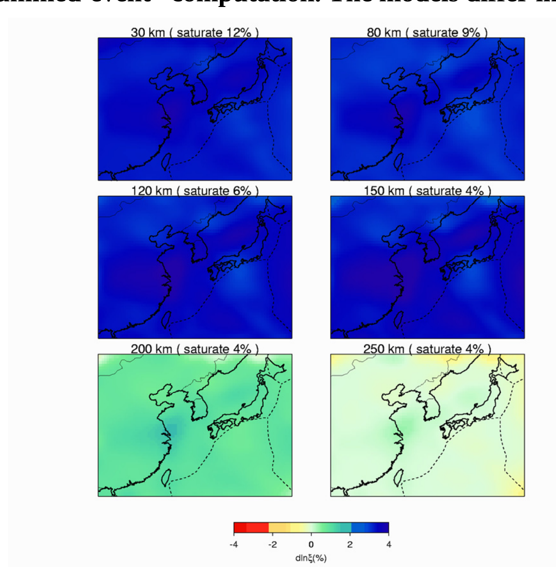


Figure 6. Radially anisotropic part of the models shown in Figure 5. Left: computation on individual paths. Right: results of summed event inversion. Lateral variations are with respect to isotropy, bringing out the ubiquitous Vsh>Vsv structure at shallow depth.

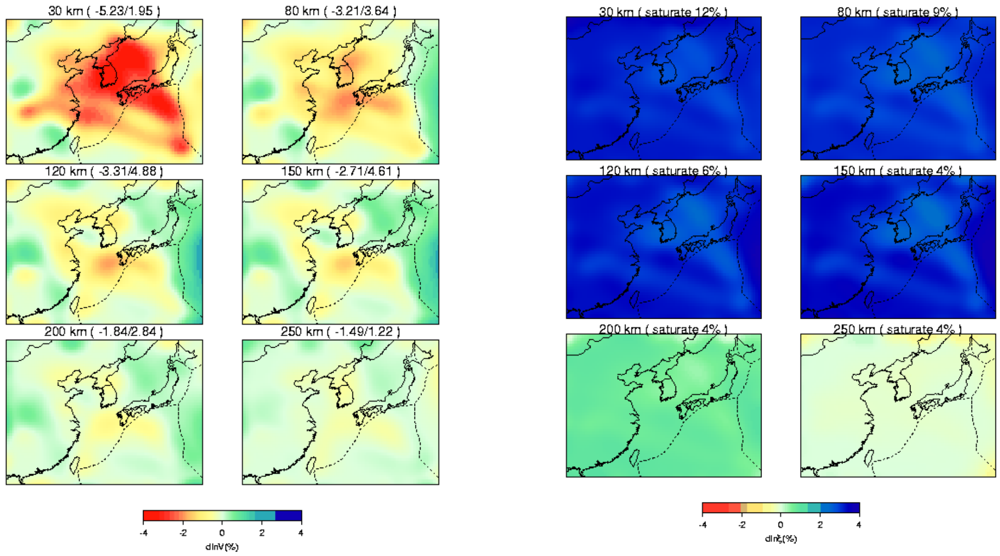


Figure 7: Isotropic (left) and radially anisotropic (right) part of the 3D model obtained after one iteration from the same starting model as used to obtain Figures 5 and 6, and the same dataset, but using PAVA approximation in both forward and inverse steps, and individual source-station paths (no summed events). Here the shallow part of the model is different from those in Figures 5 and 6, as crustal effects are handled approximately through crustal corrections. This explains the very different structure obtained at 30 km depth.

Broadband Waveform Modeling on Specific Regional Paths

In parallel with the implementation of N-Born and summed RegSEM tomography, and in order to refine the starting crustal velocity input model beneath the region of our study, we have continued to perform forward waveform modeling with the method of frequency-wave number integration (FKI). Broadband seismograms are downloaded from IRIS and corrected to absolute ground velocity (cm/sec). We show 2 event locations of events 2000256 (9/12/2000, Mw6.1) and 2003107 (4/17/2003, Mw6.3), and the IRIS station distributions (Figure 8). We start with the 2000256 event, for which the continental ray paths are dominant, to obtain the 1D velocity structure between the source and each receiver. Broadband data are bandpass filtered at 0.005-0.05Hz. We used the Harvard Centroid Moment Tensor (CMT) solution for the source parameters, and the starting model is a 1D layered average crustal velocity structure derived from CRUST2.0. Using the best velocity model we can obtain (Figure 8), we compute Green's functions and perform the moment tensor analysis for two ranges of frequency (0.01-0.05Hz and 0.005-0.03Hz). Then, we select the event 2003107, for which we have similar ray paths as for event 2000256, to perform the moment tensor analysis using Green's function obtained from our 1D simulation (Figure 9). We find a moment tensor solution in good agreement with the CMT solution, whereas the solution obtained using the PREM reference model is very poor. While this example was chosen because we expect that we can use CMT solutions for M > 6 events as good references, this indicates that the additional regional modeling effort is worthwhile and will lead to better moment tensor solutions for smaller events in the area, when we extend the modeling to higher frequencies (0.02-0.05Hz).

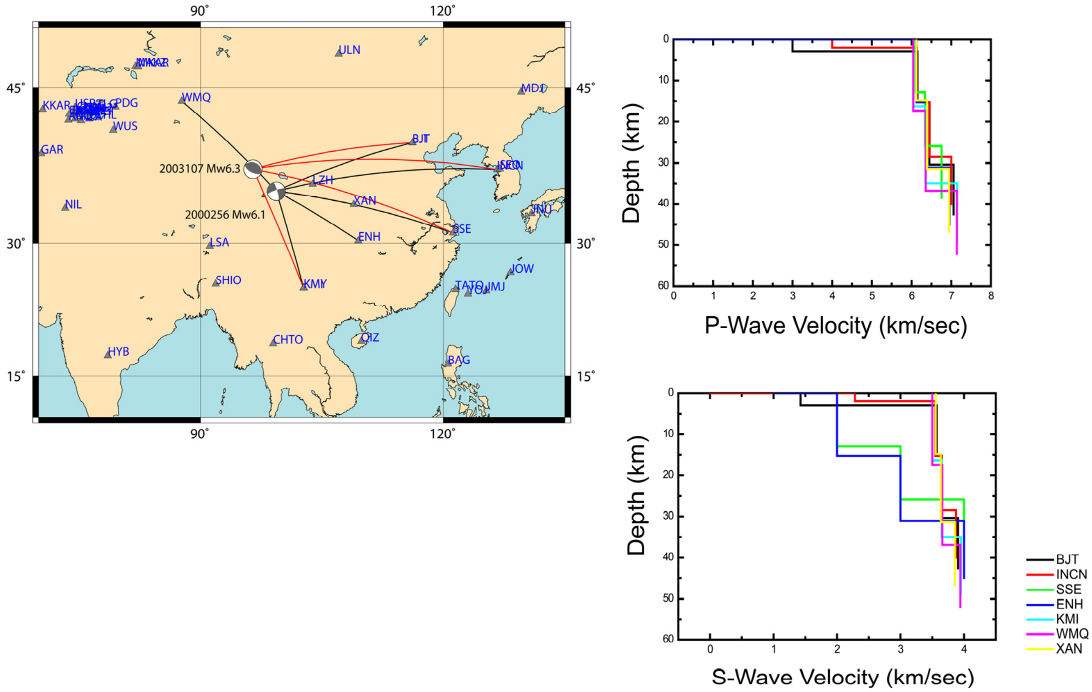


Figure 8. Left: Event 2000256 (9/12/2000, Mw6.1), 2003107 (4/17/2003, Mw6.3) and IRIS station distributions. Source 2000256 (9/12/2000, Mw6.1) is used to obtain the velocity structures. Right: Best P-wave and S-wave velocity structures for the paths between event 2000256 and IRIS stations obtained from 1D forward modeling.

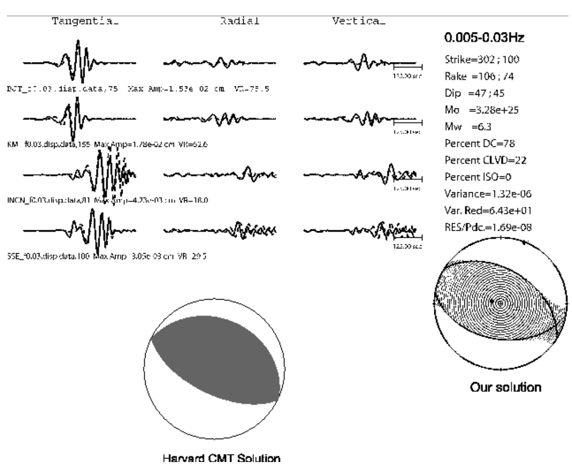
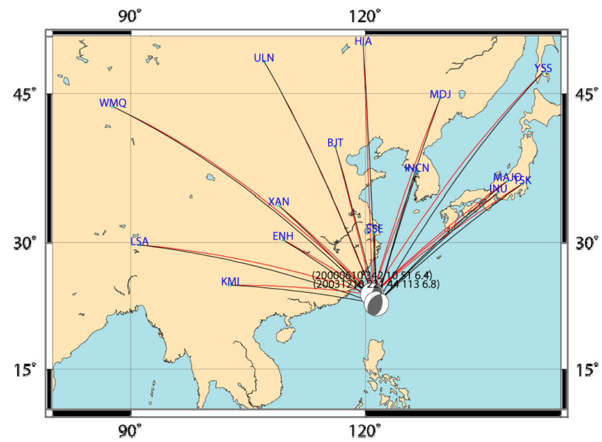


Figure 9: Top: Moment tensor solution for event 2003107 in the 0.005-0.03Hz range using Green's function which were computed from the velocity model obtained using the 2000256 event (Figure 9). Bottom: Global CMT solution from Harvard University.

Figure 10 shows another example, providing coverage of the region from the oceanic side. We note the significant lateral variations in S velocity in the top layer.



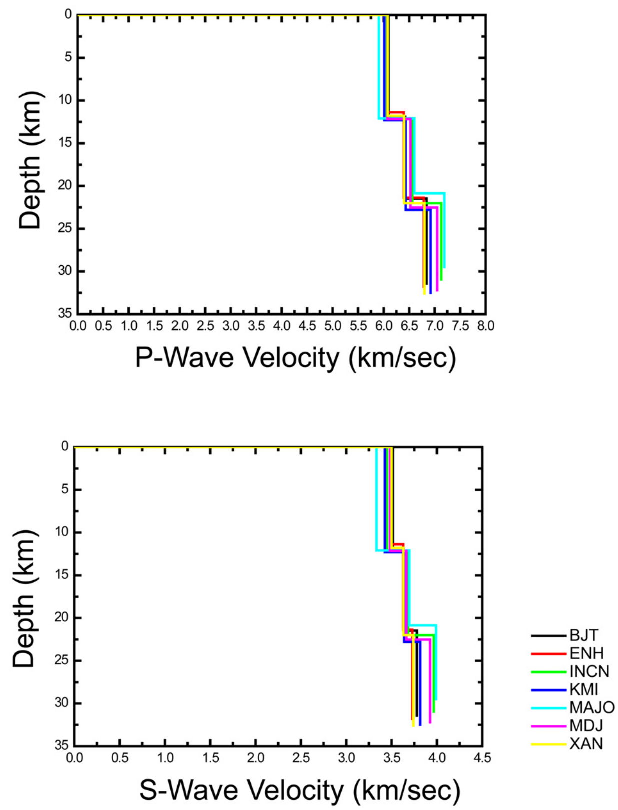


Figure 10. Left: Event pair 2003344 (12/10/2003, Mw6.8) and 2000162 (6/10/2000, Mw6.4) and IRIS station locations. The Global CMT solution for source 2003344 (12/10/2003, Mw6.8) was used to obtain the velocity structure. Right: Best P-wave and S-wave velocity structure for the paths between event 2003344 and IRIS stations obtained from 1D forward modeling.

CONCLUSIONS AND RECOMMENDATIONS

Using better theoretical and numerical approaches in regional tomographic modeling is very important for adequate seismic path calibration. Here we show the progressive implementation of a cascade of theoretical approaches for waveform modeling, culminating in the use of the SEM for forward computations. Our initial tests of the summed seismogram approach using RegSEM synthetics are promising. Further testing involves iterating the model, progressively increasing the frequency range to higher frequencies, and implementing a more accurate crustal model, taking into account, in particular, variations in sediment thickness and the results of our forward modeling of broadband waveforms.

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