Full wavefield simulations in an anisotropic media applied to the study of the Northern Appalachian Anomaly

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Abstract

The Northern Appalachian Anomaly (NAA) is an unusual low velocity zone located at the eastern edge of the thick, cool and tectonic stable North American craton. Over the past 20 years, several studies about this anomaly came up with different ideas of what it could be. Besides being located in a tectonic stable area, previous studies could not detect any significant change in the shear wave splitting pattern or in the asthenosphere thickness caused by the NAA. Based on the idea that this thermal anomaly is generated by the presence of mantle upwelling, a simplified anisotropic model of the Earth was built to simulate a shear wave propagating though it. This paper uses a preexisting MATLAB script to simulate full wavefield propagation, allowing the testing of the hypothesis that wave diffraction masks changes in the mantle anisotropy. A post-processing script, also written in MATLAB, was developed to measure the shear wave splitting and the travel time along an array of 80 different stations at the top of the model. As a result, we were able to compare the measurements after simulations with the ones predicted by the ray theory and understand if the wave diffraction effect is the reason why past studies did not detect changes in shear wave splitting in the area.

Introduction

The Northern Appalachian Anomaly (NAA) is a narrow (~400 km wide) low velocity anomaly in the upper mantle (100 – 300 km) localized in New Hampshire (centered at N42.81, 72.17W). The North American craton is immediately west the NAA, an area representing cold, old and thick lithosphere [Menke et al., 2016]. Compressional

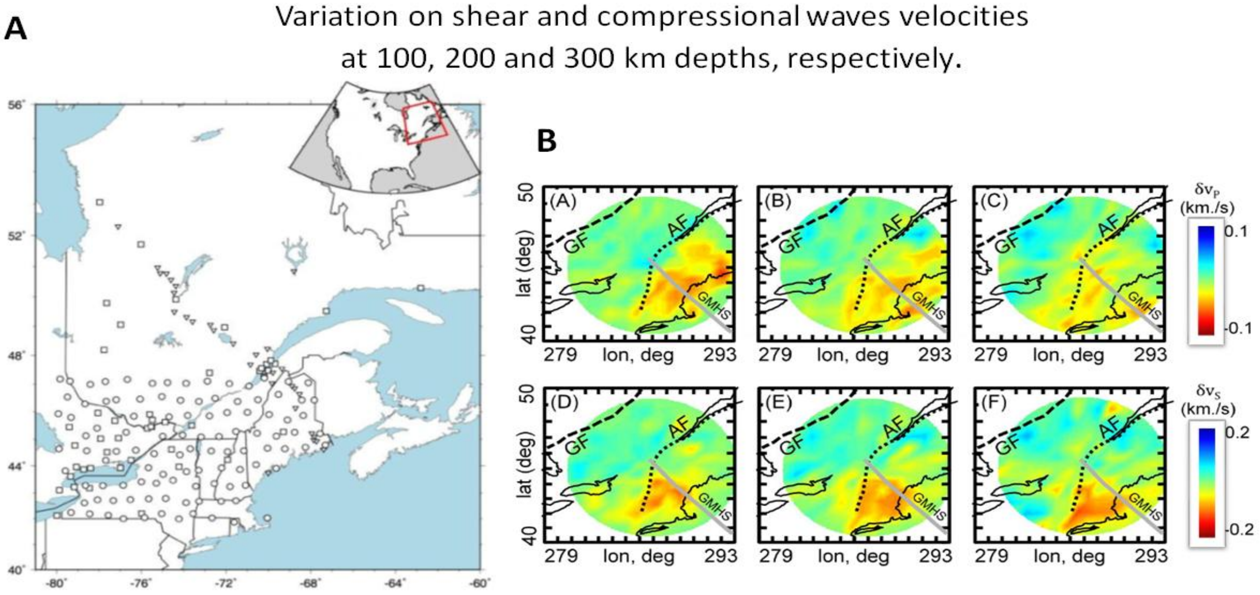

Figure 1: Part A of the figure shows the stations used for the study. It includes permanent stations (squares), Earthscope 141 Transportable Array stations (circles) and Earthscope Flexible Array QMIII stations (triangles). Part B shows the Appalachian Front (AF), Grenville Front (GF) and Great Meteor Hotspot (GMHS) track in the compressional wave and shear wave pertubations for 100, 200 and 300 km (Menke et al.,2016).

and shear wave teleseismic travel time data show that the anomaly produces a shear wave velocity contrast of 10% relative to the surround areas, which implies a 700°C temperature contrast in the upper mantle. The ratio obtained from teleseismic data in the area is compatible with a modern thermal anomaly [Menke et al., 2016] possibly due to localized mantle upwelling. In addition, tomograpic inversion of the travel time data produced maps for different depths in the New England (Figure 1) and the results showed that the anomaly gets wider when the depth increases which gives some information about the shape of the anomaly. Those maps also showed that the anomaly is set between 100 and 300 km of depth.

Earthquakes radiate seismic waves that travel through the Earth, and several earthquakes per day produce distant ground motions that are detected with modern instruments anywhere on the globe. Seismology is the main method used to study the Earth's structure and composition. It is also directly concerned with understanding the physical processes that cause earthquakes and seeking ways to reduce their destructive impacts on humanity (Shearer, 2009).

The tomographic technique uses travel times of P waves and S waves from earthquakes ("teleseisms") that are far away the seismic stations. The location and size of the observed travel time anomalies depend on the lateral variation of the velocity structure, and on the backazimuth and slowness of the incoming teleseismic wave fronts (Waldhauser et al., 2002). Figure 1 shows the teleseismic survey in the New England area and the NAA for 100, 200 and 300 km depth.

Since a strong thermal anomaly suck as the NAA is not expected in this tectonically quiescent geological setting, an early explanation for that was that it is a fossil structure due to Great Meteor Hotspot, which crosses the area about 100 million years ago. Using data from the Missouri to Massachusetts Broadband Seismometer Experiment (MOMA), Li et al. (1998) estimated the topography of the 410 km discontinuity and concluded that there is no significant asthenospheric upwelling across it. This result and the fact that the NAA is not parallel to the Great Meteor Hotspot track (even thought is close to it) leads us to discard the hotspot theory. A new idea came up to explain the presence of a thermal anomaly that would generate so high shear wave velocity contrasts. Once the NAA gets wider in deeper depths, it is characterized as a modern anomaly, and presents such high contrasts levels, it may be interpreted as a hot mantle flow zone, which means a small-scale mantle upwelling [Menke et al., 2016]. The goal of this project is to simulate wave field propagations in a flow mantle model to obtain results that might present features that could be expected in real data.

Commonly-used seismic simulation methods assume the earth is isotropic for computational simplifications. However, anisotropy is present in many parts of the Earth. Consider the wavefront generated by a point source in a homogeneous anisotropic material. The rays travel in straight lines out from the source, but the wavefront is not spherical because velocity varies as a function of ray angle (Shearer, 2009). Figure 2 shows what happens in an anisotropic material.

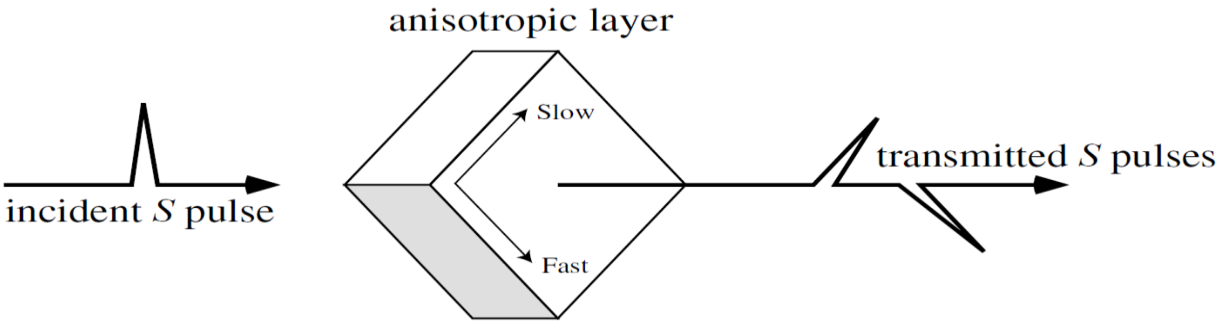

Figure 2: Shear wave being polarized in two components (fast and slow) when it propagates through an anisotropic media (Shearer, 2009).

In an anisotropic media, a shear wave propagating through it will polarize in two different axes perpendicular to each other (Figure 2), a fast axis and a slow axis. If the time separation between the split shear waves is greater than the duration of the original pulse, then two distinct arrivals will be observed and the difference in time between them can be measured. The delay times between the split shear waves are typically 1 to 2 seconds (Shearer, 2009). Shear wave splitting is capable to tell how anisotropic a material is measuring two parameters: the direction of fast polarization and the delay between the two pulses. An important observation about the NAA is that previous studies (Long et al., 2006) could not detect changes in the shear wave splitting pattern (Figure 3) which would be expected for an anomaly capable of producing 10% of contrasts in shear wave velocity.

Because of its simplicity and applicability to a wide range of problems, seismic ray theory (analogous to optical ray theory) continues to be used extensively today. These applications include most earthquake location algorithms, body-wave focal mechanism determinations, and inversions for velocity structure in the crust and mantle. Ray theory is intuitively easy to understand, simple to program, and very efficient. It is relatively straight forward, however, it has several important limitations. It does not easily predict any “nongeometrical’’ effects, such as head waves or diffracted waves (Shearer, 2009). Our goal in applying full wavefield simulations is to understand whether diffraction can mask a shear wave splitting signal from a localized anomaly such as the NAA, even while allowing the corresponding travel time anomaly to be observed.

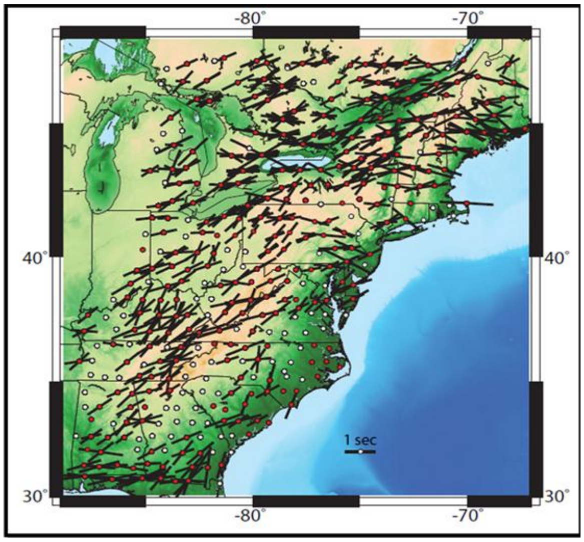

Figure 3: Shear wave splitting pattern in the United States (Long,2016).

Method

The continental margin below New England could be thought as an anisotropic medium, which means the velocity of propagation is not the same in all the directions. The mantle upwelling can be imagined as a model in which the fast direction is always parallel to the flow lines. As an anisotropic medium the mantle would make the S-waves to polarize in different components for the slow and fast direction, making the receivers to record different travel-times for those. The shear wave splitting analysis is the technique that uses the recorded phases of the S-wave to measure the difference in travel time providing information about the anisotropy of the medium. The main purpose of this project is to use MATLAB to simulate full wavefield propagations in an anisotropic medium that is reasonable with a mantle upwelling idea and to estimate both the S wave travel time and S waves splitting times for an incident teleseism observed on an array or receivers on the Earth’s surface.

The advance in computational techniques in the last few years made possible the calculation of robust simulations such as the one used in this paper. Boyd (2006) has created a second-order finite-difference code for an anisotropic and elastic wave simulation in 3D, written in MATLAB that is based on the idea of a full wavefield, not on the ray theory concepts. The number of loops was minimized making the solution efficient and able to interact with the user temporally and spatially (it can compute 60000 nodes per second in each times step). The solution derives from setting the acceleration of a mass, its position and forces action on the mass (Shearer, 1999). Boyd (2006) verified this solution comparing the results with analytical and solution for simple cases and the code was able to successfully discriminate among possible isotropic structures in receiver functions. The stress tensor has to be defined for each node in the 3D space. The source set for the simulation is a Gaussian pulse at the bottom of the model. The code also gives the option to choose among three kinds of waves: P wave, radial shear wave or a transverse shear wave; to choose between isotropic or anisotropic medium; to choose between elastic or inelastic medium; and to set the number of nodes in the 3 spatial directions. In the second part of the code the simulation is ran and the three components of displacement are calculated for each node in space for a moment in time.

The Earth model used in this paper was a 2D simplification of a hypothetical model of mantle upwelling which is associated with the Northern Appalachian Anomaly. To build this model, we used three different forms of the elastic tensor of olivine, the main mineral in the upper mantle. The first one represents an isotropic media, in which the velocities for all the directions of propagation will be the same; the second one is a orthorhombic tensor for a media in which the horizontal direction is the fast axis; and the third one is an orthorhombic tensor for a media in which the vertical direction z is the fast axis. A linear combination of these three tensors was used in a way that the fast direction axis is nearly parallel to the flow lines that represent the mantle upwelling (figure 4).

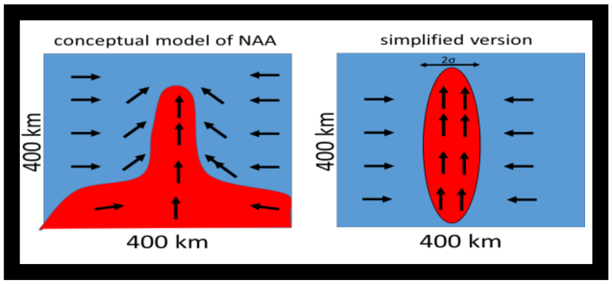

Figure 4: In the left part of the figure is the conceptual model of the mantle upwelling that would have caused the NAA. In the right the simplified version that was built on MATLAB.

The strength of the anisotropy was adjusted so that the maximum splitting was about 1 second per 100 km of propagation, and the strength of the low velocity zone was adjusted to be 1 second late per 100 km of propagation. The slow anomaly is Gaussian in shape, with half-widths characterized by standard deviations and both the slow anomaly and the background are anisotropic. However, for the case of vertical incidence that we consider here, only the background has significant splitting. All results shown here are for a 400 km by 400 km rectangular grid with a 4 seconds period source pulse, with a polarization angle of 45 degrees with respect to the x-axis. (Computations were actually conducted on a 100 km by 100 km grid with a 1 second period source pulse and scaled up, a process which is exact).

In order to compute the splitting in time between the x and y displacement components, 80 stations separated by 5 km each were set along the Earth model. The same procedure was made for each station: The seismograms for both components were read from the file generated by the simulation. In this project, we developed a code that compares the two horizontal components and calculates their splitting using cross correlation. The code performs a grid search over fast direction azimuth, choosing the azimuth and time lag that maximizes the cross correlation between the two rotated components. The splitting time is the time lag is the time necessary to best align the two seismograms. The code also calculated how the travel time of the fast and slow waves varies along the array of stations. Each seismogram was compared with a fixed seismogram (in this case the first one) using cross correlation. The time lag necessary to align them represents the difference in travel time across the model.

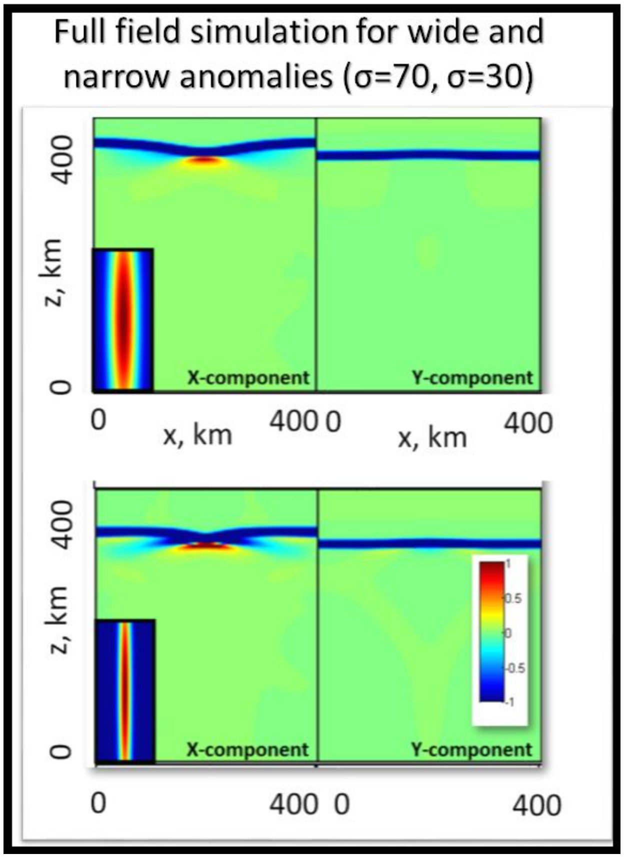
Full field simulation for wide and narrow anomalies (σ=70, σ=30)

Figure 5: Wavefield simulation for wide and narrow anomalies and the wave diffraction effect for both of them.

Results

In order to understand how the wave diffraction affects the measurements, the wavefield simulation was run for anomalies with different half-widths, as quantified by the standard deviation σ (figure 5 shows the procedure was follow for three values of σ, respectively in the figure 6). The figure 6 shows a compilation of the splitting results; the aligned traces in a cross section for the 80 stations; and the travel time profile for each the three values of σ. The first plot of the figure 6 is the splitting along the 80 stations in the top of the Earth model. The red line represents the splitting that was measured after the wavefield simulation whereas the black line represents the splitting expected according to the ray theory. The second is the displacement in time in both components (red for the x component and black for the y component) combined in a cross section after the alignment. It means that the splitting time was already removed to make the traces from the two components aligned to each other and verified that the splitting values were well measured. The third plot is the travel time profile along the 80 stations. The black line is again the result predicted from ray theory; the red line is the result measured after the simulation based on the one rotated horizontal component; the blue line is the travel time measured after the simulation calculated based on the other component.

Conclusions

The results presented in the last section show the comparison between the measurements after the simulation and the ones predicted by the ray theory. We understand that the simulation used in this paper is based on a finite difference solution, which is more realistic than the ray theory results because it considers the wave diffraction effect. The figure 6 shows that the width of the anomaly affects how much the wave diffraction influences the results. For σ=70, the black and red line almost match. This shows that the wave diffraction barely affected the measurement, which means that for very wide anomalies (>140 km wide) ray theory is a good approximation for the wave propagation. For σ=30, the difference between the results after the simulations and the predicted one starts to be visible. Finally, for σ=15, the difference between them is extremely large, which suggests the wave diffraction effect is even higher. For narrow anomalies, the splitting measured by the simulation is wider, flatter and lower in amplitude than the splitting predicted by ray theory. Diffraction reduced the amplitude of the splitting delay time next to the borders of the anomaly and amplified it in the middle.

Diffraction effect are important only for heterogeneities that have half-widths of 30 km or less.

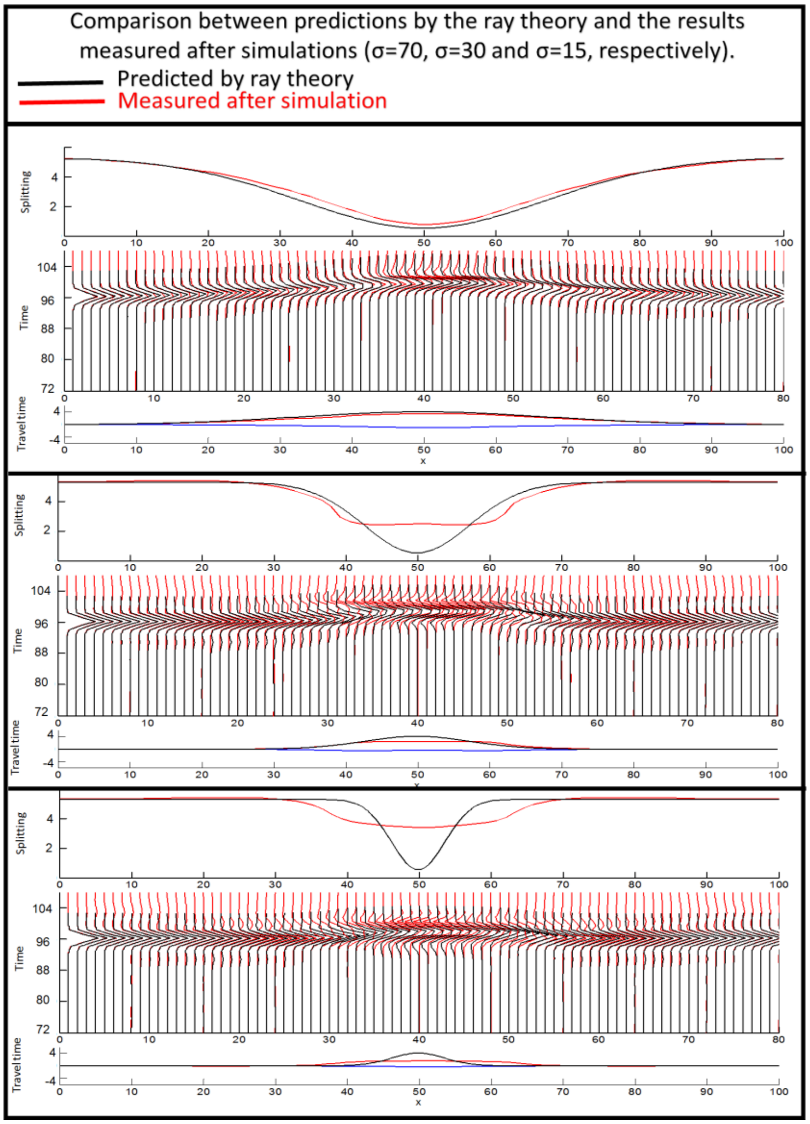

Figure 6: Results for the three values of sigma that represent anomalies with different widths. First graph shows the splitting and the last one the travel time for each value of sigma. The figure compare the predicted results from the ray theory and the ones measured after the wavefield simulation.

Acknowledgments

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