GEOPHYSICAL RESEARCH LETTERS, VOL. 22, NO. 2, PAGES 121-124, JANUARY 15, 1995

Anomalous mantle structure at the Proterozoic–Paleozoic boundary in northeastern US

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Abstract. Using teleseismic P wave tomography we detect very large (~5%) variation in the compressional velocity of the upper mantle beneath the Proterozoic–Paleozoic boundary in the Northeastern US. In this region, the upper mantle is heterogeneous on the 100 km scale to a depth of 300 km. Below this depth, the mantle appears to be laterally homogenous, at least on the scale of 200–250 km. Given the tectonic history of the region, the large amplitude, short wavelength heterogeneities can not be caused by temperature variations, but may be due to chemical heterogeneity or variations in the amount and orientation of flow-induced seismic anisotropy.

Introduction

Lateral heterogeneity of upper mantle seismic velocity has been documented on a variety of length scales [e.g. Taylor and Toksöz, 1979; Humphreys and Clayton, 1990; Lerner-Lam and Jordan, 1987; Creager and Jordan, 1986; Silver and Chan, 1991; Hu et al., 1994]. This heterogeneity may arise from an array of causes. Globally large tectonic units like oceans and continents are found to differ in their seismic velocity profiles down to the depth of 400 km [Lerner-Lam and Jordan, 1987]. Regions with distinct tectonic histories within continents have significantly different seismic properties that extend as deep as 300 km [Taylor and Toksöz, 1979; Duecker and Humphreys, 1990; Humphreys and Clayton, 1990]. The effect of temperature on seismic parameters is exemplified by the velocity structure of a subducting slab [Creager and Jordan, 1986], and of a plume associated with a hot spot [Nataf and VanDecar, 1993]. Differences in chemical composition such as the presence of water [Zielhuis and Nolet, 1994] or enrichment in chemical elements with higher seismic velocities [Ebel and Hon, 1994], may also cause regional variations in seismic velocity. Finally, regional differences in the extent and direction of preferred orientation of crystals within the mantle lead to a variation in the amount and direction of seismic anisotropy. The anisotropy of seismic velocity causes "apparent" velocity heterogeneity in a variety of environments ranging from a mid-ocean ridge [Blackman et al., 1993] to the archean craton [Silver and Chan, 1991].

The Grenville Province (GP) [Moore, 1986] and the Appalachian Orogen (AO) [Taylor, 1989] flank the eastern part of the archean North American craton. Rocks of those tectonic units preserve a record of two Wilson Cycles. The Adirondack mountains are the most southeastern surface expression of the GP. The eastern edge of the Adirondacks may be considered the surface expression of the boundary between the GP and the AO.

The differences in deep seismic structure of the GP and the AO were first documented 15 years ago [Taylor and Toksöz, 1979; Pesekis and Sykes, 1981]. Faster compressional velocities were found under the GP, and a general correlation was observed between the velocity features at depth and the tectonic units observed on the surface [Taylor and Toksöz, 1979]. These findings have been recently confirmed in the southeastern US by Vlahovic and Powell [1994], who also reported along-strike variations of upper mantle seismic properties within the AO. Heterogeneity of the upper mantle at the GP–AO boundary has been recently studied by Ebel and Hon [1994], who found the uppermost mantle of the GP to be faster then that of the adjacent Avalon terrane by almost 3%. Complexity of the crustal seismic structure and differences in seismic properties of the crust between the Adirondack Mountains and the Appalachians were also documented in western New England by Hughes and Luetgert [1991].

New Teleseismic Data

We use new teleseismic traveltime data derived from the archive of the NY State Seismic Network (NYSSN) operated by LDEO in the northeastern US (figure 1). Signals from the short period (0.5–2 Hz) vertical geophones are digitally recorded at 100 samples/s. Arrival times of P and PKP phases are measured for about 150 earthquakes. Hypocentral locations are from the PDE catalog. Events located at least 30° away and recorded by at least 4 stations are retained for the analysis. The spherically symmetric P wave velocity structure used to compute traveltimes is modified from the IASPEI91 model to reflect crustal velocities of western New England [Hughes and Luetgert, 1991]. Relative traveltime residuals are computed by removing an average delay from each event. Mean station residuals show considerable systematic variation–up to 0.5s (figure 2)–suggesting laterally varying velocity structure. Large (0.2–0.4s) systematic variations in relative delay with angle of incidence and azimuth at individual stations indicate that the heterogeneities responsible for them must lie in the mantle where raypaths diverge (figure 3).

Traveltimes from 90–150 km wide subarrays (5–12 stations) are used to estimate polarization. A similar relative array polarization technique was successfully applied to the California network subarrays [Powell and Mitchell, 1994]. Polarization is obtained by fitting a plane wave described by the components of a slowness vector to the station delays in a least squares sense. The measurement is then related to the geometrical center of mass of the group of stations recording the event. Only horizontal components of the slowness vector could be resolved with reasonable accuracy.

Paper number 94GL02693
0094-8534/95/94GL-02693$03.00

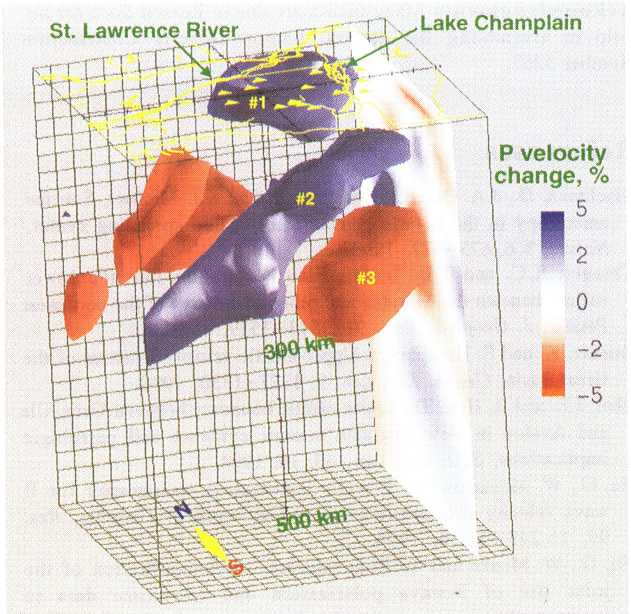

Fig. 4. The central part of the final 3D compressional velocity model is presented in the form of the percentage change from the initial 1D structure. Dimensions of the volume shown are 400×300×500 km. The origin of the axes corresponds to the center of the model. Positions of stations are shown by solid yellow triangles. Viewing azimuth and angle are 195° and 17°, respectively. Colored surfaces enclose areas where velocity perturbation exceeds 3%.

therefore poorly constrained. The shallow fast anomaly under the northeastern Adirondacks (#1, see figure 4), the top part of the fast west–dipping feature (#2) and the deep low velocity anomaly (#3) under the Champlain Valley are reliably imaged.

Discussion

The region of study has been tectonically passive since the time of the Allegenian Orogeny (275 Ma) [Taylor, 1989]. Nevertheless, results of the tomographic imaging present a picture of the upper mantle that is heterogeneous on the scale of about 100 km down to the depth of 300 km. Due to the limited lateral resolution below 300 km the presence of small (less then 100 km) features can not be ruled out there (synthetic tests suggest that larger features should be seen). The lack of velocity perturbation in the deep part of our model implies general homogeneity of the mantle on the scale of 200–250 km below 300 km.

The velocity high #1 under the Adirondacks is well constrained in its southern part, where it does not extend below 50 km. The northeastern extent of this feature is uncertain due to insufficient ray coverage. Maximum deviation from the 1D velocity structure (+9%) is obtained within this anomaly. The shape of anomaly #1 (which is influenced by the B–spline node distribution) indicates a source located very close to the surface. The area of the anomaly is generally coincident with that of a regional gravity high (the Plattsburg anomaly), which is believed to be associated with a buried intrusive mass [Simmons, 1964]. Very high (6.6 km/s) compressional velocity and local gravity lows were found to be associated with anorthosite intrusions in the Adirondacks [Simmons, 1964; Hughes and Luetgert, 1991]. Since anomaly #1 corresponds to a gravity high, the composition of its source most likely is not anorthositic.

Only the top part of the velocity high #2 lies within the volume with a sufficient ray coverage. It is located between 50 and 100 km deep and appears to be longer then it is thick. A likely source of such anomaly is a region with a large lateral velocity gradient, which would strongly affect the polarization part of the dataset. The anomaly underlies the zone separating the GP from the AO on the surface. This region was the site of an arc-continent collision during the Ordovician [Taylor, 1989] and the existence of lateral velocity gradients within this portion of the upper mantle is quite likely.

Interpretation of the velocity low #3 at the depth of 200 km presents a challenge. The anomaly is relatively small (150×100×100 km) and strong (5% velocity perturbation). While elevated temperatures are often associated with low seismic velocity [Creager and Jordan, 1986], #3 is unlikely to be of a thermal origin. The last orogenic event took place in this region 275 My ago [Taylor, 1989]. The Montegerian hot spot that had supposedly passed through this region before creating New England Seamounts did so around 125 My ago [Sleep, 1990]. Thus for at least 100 My this region has been tectonically quiet, and the temperature differences must have had equilibrated. Also, if a $\partial Vp/\partial T$ value of -0.5 m/s/°K [Creager and Jordan, 1986] is used, and a base value of 8.2 km/s is assumed, a temperature anomaly on the order

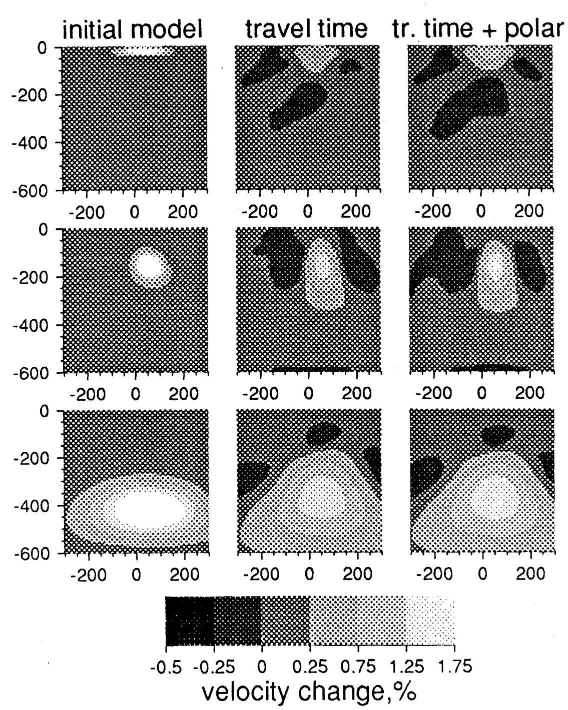

Fig. 5. Resolution tests. (Left) Initial models used to produce synthetic traveltime and polarization data. (Middle) Estimated models using traveltimes only. (Right) Estimated models using both traveltimes and polarization data. Inclusion of polarization data leads to slightly better recovery of amplitude in the upper part of the estimated model.

of 800°K is required for a 5% decrease of compressional velocity.

A relatively localized change in mantle composition or very localized change in the direction or the amount of anisotropy must be invoked to account for the observed reduction of compressional velocity. Assuming peridotitic mantle, the change in composition that would lead to lower velocities most likely would involve an increase in the orthopyroxene content. Another possibility would be the presence of water and, consequently, the existence of partial melt. Delivery of hydrous minerals to the depth of 200 km could have been achieved during the final closure of the Iapetus Ocean during the Devonian, with parts of the oceanic lithosphere being subducted under the already accreted terranes of the AO [see Taylor, 1989].

The observed P-wave delays do not exhibit a clear azimuthal variation that might be attributed to anisotropy. Nevertheless, strong anisotropy is present in the mantle in this area. Silver and Chan [1991] detect shear wave splitting of ~1.0 s with a fast direction of N74°E at the station RSNY in the northern Adirondacks (figure 1). We observe similar splitting (~1.3 sec, fast N85°E) at station ECO in the central Adirondacks. Hence the observed pattern of P-wave delays may be affected by anisotropy as well as by true heterogeneity.

If the slow anomaly #3 is due to the anisotropy, it may represent a region where the orientation of the anisotropy is different then elsewhere in the region. The fast direction of the olivine crystals [100] is parallel to the flow direction within the mantle. Since rays used in this study are subvertical, the region where the fast axis of olivine is relatively horizontal would show up as slow in comparison to areas where there the orientation of the fast axis is random, with a difference of about 8% in P-wave velocity for the case of pure olivine. The amplitude of the anomaly (5%) would then imply a high degree of orientation in the olivine or just a relative excess of it. For comparison, 7% anisotropy was required to explain P-wave traveltime delays over a spreading ridge [Blackman et al., 1993], while Silver and Chan [1991] estimated S-wave anisotropy of the upper mantle under North America to be around 4%.

Whether anomaly #3 is compositional or anisotropic in nature, it could have been created no later than the time of the last large scale deformation in the region, and have remained intact ever since. The same is true for #2 – it is located in the region where last major deformations occurred during Ordovician time. Existence of these velocity anomalies within the upper mantle agrees well with the notion of the "fossil" structure preserved in the subcontinental mantle since the last tectonic episode [Silver and Chan, 1991].

In summary, the upper mantle under the transition zone from the Precambrian Grenville Province to the Paleozoic Appalachian Orogen is heterogeneous (on the order of 5%) on a scale of about 100 km down to a depth of 300 km. This heterogeneity is related to episodes of tectonic activity that took place at least 275 My ago. The tectonic events that created this Proterozoic–Paleozoic boundary have a complex expression (in the sense of having induced relatively short wavelength heterogeneities in chemistry or rock fabric) in the lithospheric mantle. Whether such complexity occurs only at major tectonic boundaries, or is a ubiquitous feature of the cratonic lithosphere is an important issue for the future study.

Acknowledgments Many thanks are due to Russell Such for his help in assembling the dataset. Lamont-Doherty Contribution Number 5267.

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(Received July 14. 1994; accepted September 18, 1994.)