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High-resolution estimates of lithospheric thickness from Missouri to Massachusetts, USA

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Abstract

This paper presents a new three-dimensional (3-D) model, NA00, of the S-velocity of the upper mantle beneath North America. The model differs from its predecessor NA95 in that it exploits seismograms recorded by a recent dense, broadband array, MOMA, and from independent measurements of North American crustal thickness. Model NA00 is derived by fitting the waveforms of broadband seismic S and surface waves recorded by the MOMA array and inverting them together with the database of waveform fits used for NA95 and the crustal thickness estimates. It is demonstrated that including data from the dense, broadband MOMA array yields a resolving power beneath the array that is of unprecedented quality and relatively constant over a large depth range. This improved resolution provides a unique opportunity for quantifying the structure of the upper mantle in and below the lower, thick Precambrian lithosphere. The high-resolution seismic structure of the imaged high-velocity lithosphere is compared with the thermal structure (estimated from heat flow), compositional structure (estimated from xenoliths and electrical conductivity) and the elastic structure (estimated from gravity and topography). There is a remarkable agreement between the seismic, thermal, and compositional estimates. The seismic lithosphere is 180 km thick below Missouri and Illinois, 200 km thick below Indiana, Ohio and Pennsylvania, practically undefined below New York, and 80 km below Massachusetts and the Atlantic continental shelf. The thick lithosphere is underlain by a layer with lower S-velocities that could represent a relatively low-viscosity channel. However, the S-velocities in this layer are much higher than those of typical oceanic asthenosphere.

Keywords: waveforms; tomography; thickness; lithosphere; low-velocity zones; broad-band spectra; S-waves

1. Introduction

The resolution of seismic tomographic models of Earth's upper mantle is currently limited by a combination of data quantity, data quality, and theoretical sophistication. This paper investigates the influence of data quantity on the resolution and demonstrates that spatially densifying the current seismogram observations significantly increases the resolution. We utilize this increase to study the consistency of several estimates of lithospheric thickness, which are based on different types of geophysical and geological data. Finally, we evaluate new high-resolution S-velocity values of the upper mantle below the lithosphere.

From January 1995, through April 1996, 18 broadband seismic stations were deployed in a

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linear array between Missouri and Massachusetts (MOMA) [6,7,13]. In this time period seven earthquakes within the North American plate were recorded that had magnitudes large enough ($5.6 < Mw < 7.3$) to yield a good signal to noise ratio in the MOMA seismograms. The S and surface waves in these seismograms are sensitive to lithospheric structure and can in principle be used to image variations in lithospheric structure and in its depth extent along the array.

For example, the April 14, 1995, Mw = 5.7, event in Texas was recorded at MOMA with a good signal to noise ratio and the great circle paths from MOMA to this event have azimuthal differences of only 8–24° from the strike of MOMA (Fig. 1). The waveforms of S and surface waves from this event have been analyzed to image the average lithospheric structure between Texas and Pennsylvania [18]. However, the epicenters of four of the seven earthquakes are not well aligned with the strike of the MOMA array, so effects on the seismograms from passing through the lithosphere beneath MOMA and from passing through structures outside of MOMA cannot be properly separated. In this study, we circumvent this problem by combining the S and surface waveforms from the seven events with the S and surface waveform database that was used to derive 3-D S-velocity model NA95 [19].

A common problem in long-period fundamental mode surface wave and teleseismic body wave tomographic studies is that the data sensitivity tends to overestimate lithospheric thicknesses. When regional surface waves are combined with regional body waves, lithospheric thickness is generally not overestimated but resolving power of the data may decrease with depth. This decrease possibly leads to artificial negative velocity gradients below high-velocity anomalies. This study

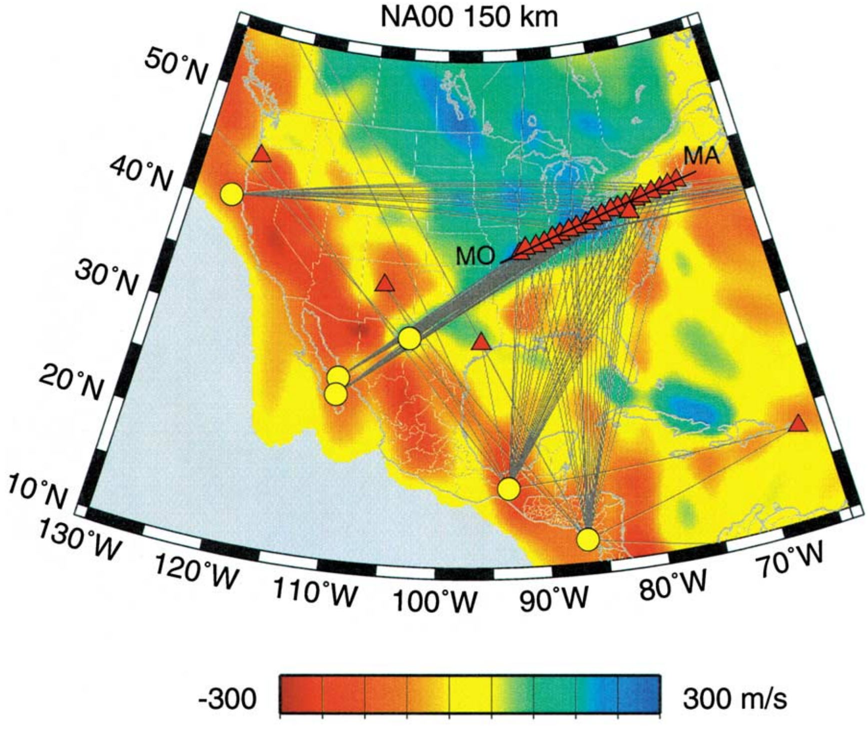

Fig. 1. Map of model NA00 at a depth of 150 km. Superimposed are the great circle wave paths (thin gray lines) that were used for NA00 but not for NA95 [19]. The paths are shown together with corresponding events (yellow circles) and seismic stations (red triangles). The thick black line represents an extended profile from Missouri to Massachusetts along which vertical sections are shown in Fig. 2.

avoids both of these problems by taking advantage of both S and surface waves as well as of the excellent resolving power of the new data set below the MOMA array.

Roughly the western half (Missouri through Ohio) of the MOMA stations are on crust with a Precambrian basement that formed in the mid-Proterozoic [10]. Going east (Pennsylvania and New York), the profile sits on the Grenville and Appalachian provinces [10], respectively, while the eastern 100 km (Massachusetts) of the profile are on the continental margin with the Atlantic Ocean.

2. Data and method

The combined data sets (that used for NA95 and that from the MOMA array) yield 8921 linear constraints on North American upper-mantle S-velocity and crustal thickness from 794 seismograms of 84 earthquakes and 94 stations. Fig. 1 shows the new great circle paths, with corresponding events and stations, for which waveforms of S and surface waves were used that were not used for the derivation of model NA95. We further enhanced this combined data set by adding extra constraints on depth to the Mohorovičic disconti-

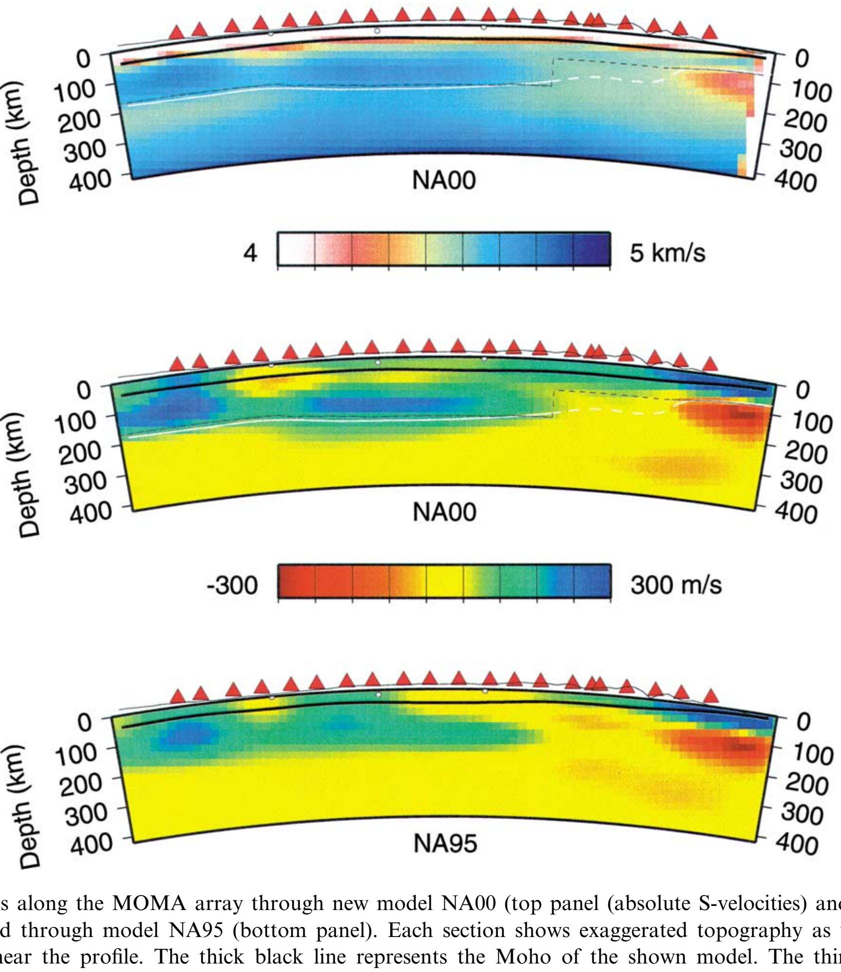

Fig. 2. Cross-sections along the MOMA array through new model NA00 (top panel (absolute S-velocities) and center panel (relative S-velocities)) and through model NA95 (bottom panel). Each section shows exaggerated topography as well as the MOMA and other stations near the profile. The thick black line represents the Moho of the shown model. The thin black line for the NA00 panels represents the seismic thickness of the lithosphere, as defined in the text, and the thick white line represents the thermal thickness of the lithosphere, as computed from the temperatures of [9]. No lithospheric thickness can be defined where the lines are dashed.

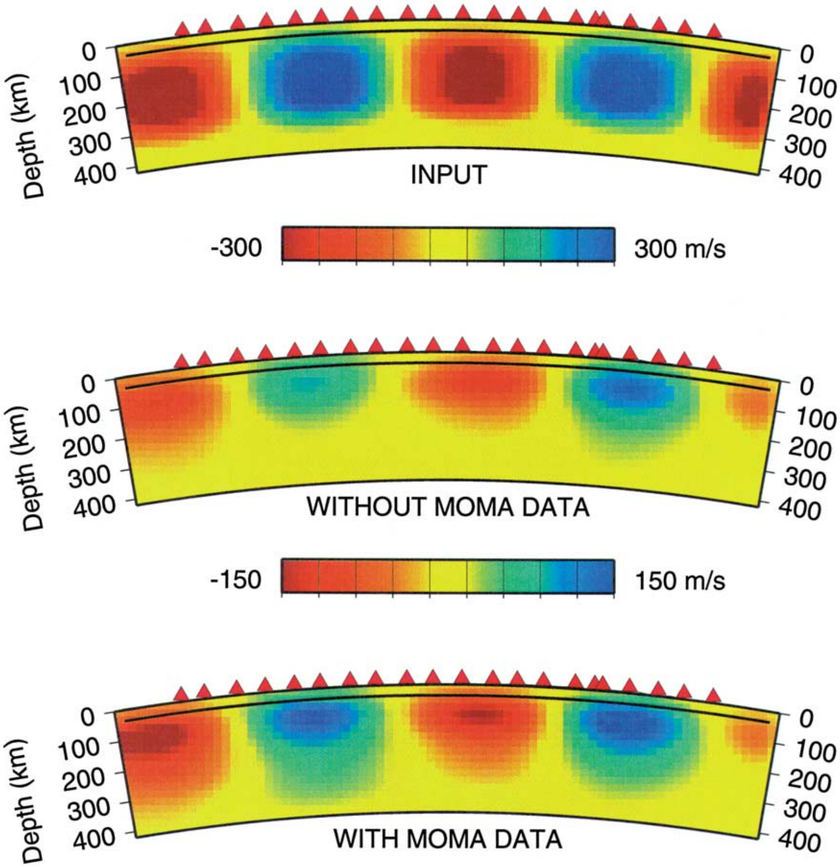

Fig. 3. Resolution test for an alternating pattern of high- and low-velocity anomalies (top panel). The middle panel shows how this pattern would be imaged with the NA95 data set and the bottom panel shows how this pattern would be imaged with the NA00 data set. The bottom color bar applies to both the central and the bottom panel.

nuity (Moho) from a thorough receiver function analysis by Li et al. [13] and from the extensive data set assembled by Chulick and Mooney [5]. A damped least squares inversion, using smooth estimates for the a priori model covariance matrix, was applied to this combined data set, which produced 3-D S-velocity model NA00. The same procedure has been applied to derive model NA95 and is explained in detail in [19]. Despite the larger amount of data used, model NA00 (Fig. 1) is not greatly different from NA95 [19], where the largest differences appear near the MOMA profile (Fig. 2). However, the resolution of NA00 has improved with respect to NA95, particularly in the upper mantle along the MOMA array (Figs. 3 and 4). For structures of lateral extent around 350 km, the resolution is significantly improved, in particular the power to resolve the amplitude of the anomalies over a large depth range (Fig. 3). Amplitude resolution is even better (including for depth >150 km) for structures of larger lateral extent, such as a laterally continuous high-velocity lithosphere (Fig. 4A). The high-velocity anomaly for which the resolution is tested in Fig. 4A is designed to have no negative gradients of velocity with depth anywhere, verified in Fig. 4B. The anomaly resolved with the new data set is very similar to the designed anomaly (Fig. 4A), demonstrating that the resolution for thick lithospheric structures is excellent. A lateral average of the recovered high-velocity anomaly is shown in Fig. 4B. This resolution test shows that no artificial zones of relatively low velocities nor artificial negative gradients of velocity with depth are created while using the new data set.

NA00 shows a more pronounced high-velocity anomaly below about 100 km than NA95 (Fig. 2), and higher velocities in the uppermost mantle below the Grenvillian and Appalachian part of the MOMA profile. Both differences between the models are due to improved resolution for NA00 (Figs. 3 and 4). Similarities between the models include the lateral extent of the thick high-velocity region underlying the Proterozoic part of the MOMA profile, the lateral extent of the sub-Atlantic low-velocity layer below the eastern margin of the North American continent, and the deeper, weakly low-velocity region below the Appalachians. We interpret the high-velocity region as lithosphere. We define the bottom of this high-velocity lithospheric region in a following section. While previous studies did not account for 3-D structure [18] or suffered from a resolving power that was decreasing with depth in this region [19], the new data set provides sufficient resolution (Figs. 3 and 4) to quantitatively study the bottom of the lithosphere and sublithospheric mantle structure.

3. 3-D S-velocity model NA00

Away from the MOMA profile, NA00 does not differ sufficiently from NA95 to warrant a separate discussion. The reader is referred to [19] for a discussion of the S-velocity anomalies imaged in NA95, and to [9] for a discussion of implications of NA00 for the thermal and compositional state of the North American upper mantle. Here, features of model NA00 along the MOMA profile are discussed.

In NA00, the high velocities of the lithosphere beneath the MOMA array reach a maximum of 4.73 km/s (Fig. 2). However, in the top 20 km below the crust the lithospheric velocities are not significantly higher than those (4.5 km/s) of the reference model. Resolution tests suggest that this subcrustal velocity increase with depth can be resolved. However, we cannot be certain that there is no effect of (currently unmodeled) crustal velocity heterogeneity and therefore defer interpretation of this thin, subcrustal neutral-velocity layer to more detailed, future work. Such work could also benefit from the inclusion of Sn arrival times [16].

A more deeply extending zone (to 90 km) of neutral to low velocities in the uppermost mantle is found below central Illinois (most clear in the central frame of Fig. 2). The location and lateral extent of this anomaly approximately coincide with those of the Illinois basin, which has a 5 km thick Proterozoic crustal layer of high seismic reflectivity underlying 7 km of Paleozoic sediments [14]. McBride and Kolata [14] favor the explanation that these Proterozoic strata are a stack of basaltic flows interlayered with clastic sediments. If this interpretation of the high-reflectivity crustal layer is correct, the Illinois basin was already different from the surrounding terrain during the Proterozoic, and the cause of this difference might have also left a lasting signature in the uppermost mantle. This signature could be the result of a strong depletion through the extraction of Al-rich basalts [4] or of an enrichment in volatiles supplied by the source of the Proterozoic event that also produced the crustal strata. However, the predominantly shallow depth of this uppermost mantle anomaly and the unsuitability of our Cartesian model grid to support small-scale strong velocity heterogeneity in the crust (such as found beneath the Illinois basin) do not preclude part or all of this feature being an artifact [19].

The low-velocity anomaly around 300 km beneath the eastern part of the MOMA profile extends at an angle with the MOMA profile along the Appalachian mountain chain. This deep anomaly is also present in model NA95 and has been interpreted by [19] as being related to dehydration of the subducted Iapetus Plate.

4. Thickness of the lithosphere

This section compares the estimates for the seismic thickness of the lithosphere with those for the thermal, compositional, and elastic thickness.

We define the seismic thickness of the lithosphere as the depth of maximum negative velocity gradient. Applying this definition to NA00, we find an average lithospheric thickness of 180–200 km for the Proterozoic part (including the western Grenville) of the MOMA profile west of the Appalachians (Fig. 2). This thickness is somewhat smaller than the 250 km estimated in [19] for the average thickness of North American Precambrian lithosphere. Using the same definition, the seismic thickness of the lithosphere beneath the continental margin and shelf (east of the Appalachians) is 80 km on average. The seismic thickness is more difficult to identify beneath the Appalachian mountains themselves, where the vertical gradient in velocity is very small and changes smoothly with depth. However, the least flat gradient is found near depths of 100 km (Fig. 2).

Thermal thickness of the lithosphere in central and eastern North America has been estimated from surface heat flow measurements by Artemieva and Mooney [1]. They find thermal thicknesses greater than 125 km everywhere along the MOMA profile. Eighty-five percent of the profile runs just 200 km south and parallel to their contour for a 150 km thick thermal lithosphere. Thermal thickness of the lithosphere in this region has also been estimated from the seismic velocities of NA00 [9] using experimental data from the petrology literature. The latter estimate is drawn in Fig.

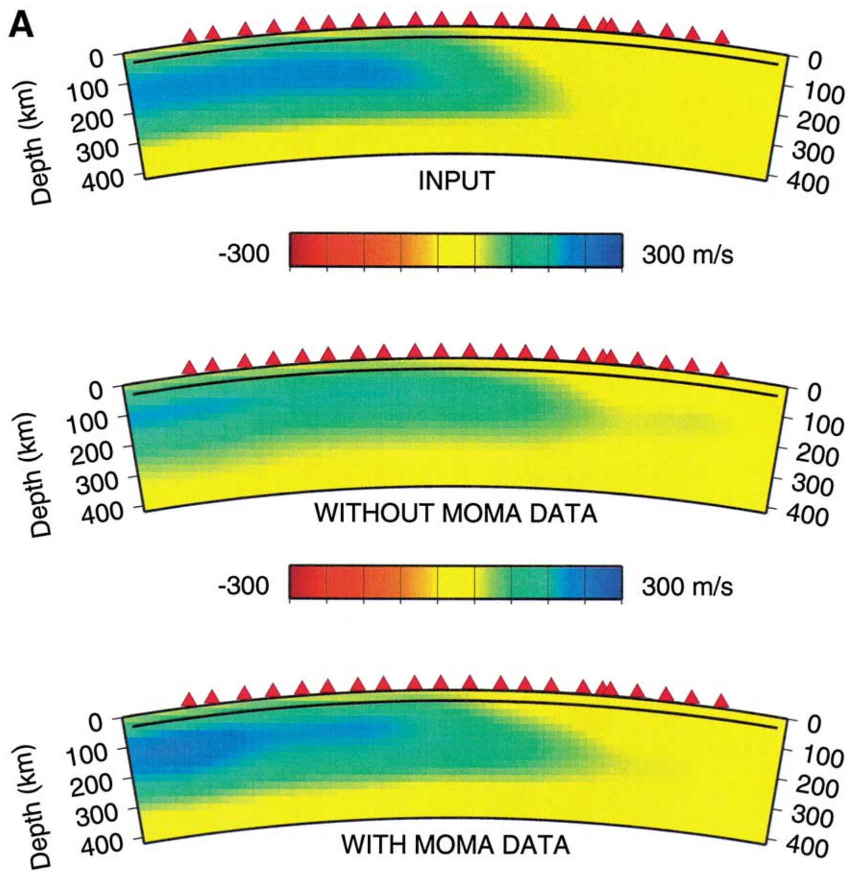

Fig. 4. (A) Resolution test for a high-velocity anomaly that is designed (top panel) to not include a decrease of S-velocity with depth anywhere. The middle panel shows how this anomaly would be imaged by the NA95 data set and the bottom panel shows how this anomaly would be imaged for the NA00 data set. (B) Laterally averaged absolute S-velocities from the input model (red dashed) and the output model (green solid for the NA95 data set and blue dotted for the NA00 data set) of the resolution test in (A). The black solid line represents the reference model used in the tomographic inversion.

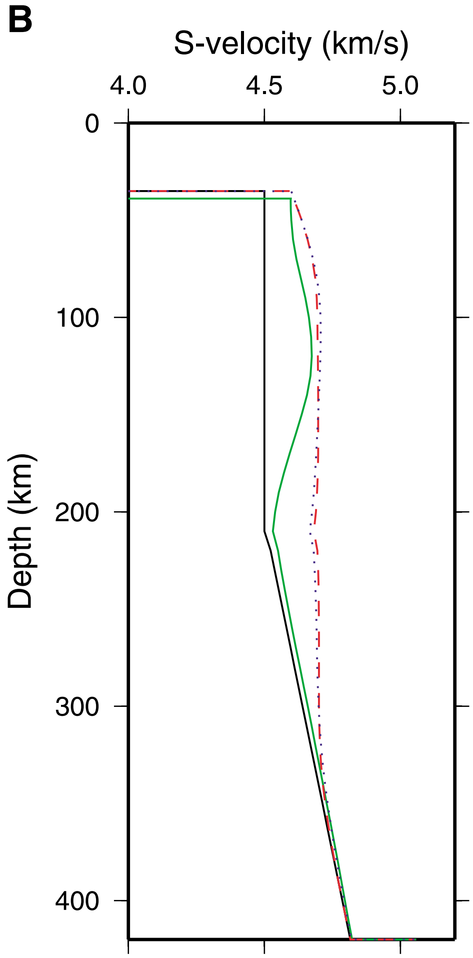

Fig. 4 (*Continued*).

2, and is defined as the depth to the 1200°C isotherm, which corresponds in this depth range to a velocity of roughly 4.6 km/s. This estimate agrees remarkably well with the estimates for seismic thickness of the lithosphere, both west and east of the Appalachians (Fig. 2). Beneath the Appalachians themselves, the derived geotherm is similarly flat as the NA00 velocity profile it is based upon. Given the small vertical gradients in temperature and velocity it is hard to identify a thermal or seismic lithosphere in this region, leaving the question whether a mantle part of the lithosphere exists here at all. West of the Appalachians the thermal thickness derived from NA00 is slightly larger than that derived from surface heat flow. This difference is possibly caused by a lack of heat flow data along and south of the relevant (western) part of the MOMA profile [17].

Compositional thickness of the lithosphere has not been estimated along the MOMA profile because of a lack of rock samples and electrical conductivity measurements. However, Permian kimberlite activity has been recorded in Kentucky, some 200 km south of the western part of the MOMA profile [21]. Thermobarometry on megacrysts and xenoliths from this kimberlite was carried out by Garrison and Taylor [8]. Their temperature estimates are based on a comparison of different geothermometers, which precludes biases introduced by compositional differences between the measured samples and reference data [8]. Their depth estimates are based on samples that contain garnet and orthopyroxene. Compositional variations in the garnets result in depth uncertainties of 15 km [8]. This thermobarometry suggests that the majority of these megacrysts and xenoliths formed at ambient upper-mantle temperatures of at most 1200°C between depths of 140 and 170 km [8]. Such ambient conditions are consistent with those existing in continental lithosphere. Megacrysts from a kimberlite from southwest Pennsylvania equilibrated some 20 km shallower than those from the Kentucky kimberlite [11]. Hirth et al. [12] propose, based on measurements of electrical conductivity of the mantle, that below 150 km cratonic lithosphere is significantly drier and thus more viscous than oceanic mantle. This high viscosity allows stable continental lithosphere to extend to depths greater than 150 km. Although these various compositional constraints on thickness of the lithosphere do geographically not coincide exactly with the estimates for seismic thickness, the compositional and seismic estimates appear to be self-consistent.

Elastic thickness is a proxy for the flexural rigidity of a lithospheric plate and as an actual thickness it is related only to that part of the plate that is mechanically strong on geological time scales. Elastic thickness of the North American lithosphere has been estimated by Bechtel et al. [2] from topography and its degree of coherence with lateral variations in Bouguer gravity. This coherence-based approach yields higher estimates of effective elastic thickness than more traditional admittance-based approaches, which ignored the effects of subsurface loading on topography [2]. For their calculations Bechtel et al. [2] used a Young's modulus that is appropriate for the elasticity of the lithosphere on time scales (seconds) needed to propagate a seismic wave. They find a thickness of 64 km in the center of the MOMA profile. Their estimates of elastic thickness increase to the west, but do not exceed 128 km, and decrease to the east, but remain thicker than 32 km. This trend, showing thinner lithosphere with increasing longitude, is consistent with the trend in the estimates for seismic and thermal thickness. However, the estimated elastic thicknesses are roughly half of those based on seismic, heat flow, and compositional data. This large difference in thickness confirms that large parts of the lithosphere are yielding inelastically to loads applied on geological time scales. Unlike for oceanic lithosphere, elastic thickness of continental lithosphere cannot be directly related to the depth extent of the mechanically strong top half of the plate, nor to the depth of a particular isotherm [3]. However, for lithosphere older than 750 Ma that is not undergoing deformation, the elastic thickness appears to be close to the 700°C isotherm [3]. This isotherm is at roughly half the depth of the 1200°C isotherm used to define the thickness of the thermally conductive lithosphere. This means that the elastic thickness of the lithosphere west of the Appalachians should be roughly half the thickness of the thermally, seismically, and compositionally defined lithospheric thicknesses, which is in good agreement with the observations.

5. Conclusions

The resolution of S-velocities derived from broadband seismograms has been increased greatly along the MOMA profile. This increase is obtained by fitting the waveforms of broadband fundamental and higher mode surface wave trains recorded at MOMA stations and combining the resulting constraints on Earth structure with those that have yielded 3-D S-velocity model NA95 [19]. The accuracy of the uppermost mantle velocities in the new 3-D model is further increased by including constraints on the crustal thickness beneath MOMA derived from receiver function analysis [13] and elsewhere from a compilation of the seismic literature [5].

The new model, NA00, thus allows estimates of lithospheric thickness of unprecedented accuracy. NA00 shows that the lithosphere beneath the Proterozoic basement of the MOMA profile in the central United States is 180–200 km thick. The lithosphere beneath the Massachusetts continental margin and adjacent continental shelf is about 80 km thick. Between this margin and the central USA, no lithosphere can be identified beneath the Appalachians and the eastern part of the Grenville province.

We find that these estimates for seismic thickness of the lithosphere along MOMA are consistent with estimates of thermal and compositional lithospheric thickness in the region. They are roughly consistent with estimates of elastic thickness of the lithosphere if only about half of the lithosphere yields purely elastically to loads applied on geological time scales.

The S-velocities of the thick lithosphere below MOMA reach a maximum of 4.73 km/s. Below the continental lithosphere our new model, NA00, shows a layer of resolved low velocities. The bottom of this layer has also been observed in MOMA receiver functions [13]. However, the velocities in this low-velocity layer are not lower than 4.55 km/s, which is at least 6% and at most 15% higher than the low S-velocities of oceanic asthenosphere [15,19,20] and around 3% higher than those in the 1-D model of [18]. Assuming a monotonically increasing relation between S-velocity and viscosity, this difference between the continental low-velocity zone (LVZ) below MOMA and a typical oceanic LVZ implies that subcontinental mantle flow can not nearly be as vigorous as suboceanic mantle flow. However, the existence of a subcontinental LVZ implies that any strain on plate-tectonic scales will be more strongly concentrated in this zone, lending support to the mantle-flow model of Fouch et al. [7]. Their model explains observations from Missouri to Massachusetts of split shear waves by stronger mantle flow in regions of thinner lithosphere and weaker mantle flow below thicker lithosphere.

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