HOW THICK IS THE EARTH'S CRUST?

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ABSTRACT

Thorough knowledge of the Earth's crustal structure is necessary for monitoring the Comprehensive Nuclear-Test-Ban Treaty. We present an updated contour map of the thickness of the Earth's crust using a 10-km contour interval, and the 45-km contour. This contour map was created from a 5° by 5° gridded crustal model (CRUST 5. 1, Mooney et al., 1998) and recently obtained information from Russia and China. The contour map honors all available seismic refraction measurements for features with a dimension greater than 2 degrees. Crustal thickness in Eurasia, North America, and Australia is well constrained by seismic refraction data, whereas Antarctica, South America, Africa, and Greenland are less well constrained. To a first approximation, the continents and their margins are outlined by the 30-km contour. The part of the continental interior enclosed by the 40-km contour and regions with crustal thickness of 45 to 50 km are found on all well-surveyed continents. Continental crust with thickness in excess of 50 km is exceedingly rare and accounts for less than 10% of surveyed continental crust. These observations, now available on a global basis, provide important information to be used for seismic monitoring.

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http://quake.wr.usgs.gov/study/CrustalStructure

Key Words: crustal thickness, global, seismic refraction

OBJECTIVE

Monitoring under the Comprehensive Nuclear-Test-Ban Treaty (CTBT) requires accurate locations of questionable events. In order to constrain the area in which an event has occurred, it is necessary to have a good model of the crustal structure. 'Me work summarized in this paper provides one of the most accurate and complete models of the crustal structure of the world.

RESEARCH ACCOMPLISHED

Introduction

Previous global crustal models have provided various levels of detail. Soller et al. (1982) presented a crustal thickness map but did not specify seismic velocities or densities. Hahn et al. (1984) presented a model wherein the crustal structure was described in terms of irregularly shaped regions, each with a uniform structure. More recently, Tanimoto (1995) reviewed the crustal structure of the Earth using a wide range of seismic data, and Nataf and Ricard (1996) presented a model for the crust and upper mantle on a 2° x 2° scale (3SMAC). This latter model was derived using both seismological data and non-seismological constraints such as chemical composition, heat flow and hotspot distribution, from which estimates of seismic velocities and the density in each layer were made.

In this paper, we present a recently published (Mooney et al., 1998) global crustal model (CRUST 5.1) that is based on significantly more data than previous models, and we discuss the model's application as a "crustal correction". Compiling a new global crustal model is timely because of the availability of a large body of new data. Our new global model for the Earth's crust (CRUST 5.1) is based on an extensive compilation of information through the year 1995 (Fig. 1). Published interpretations of the seismic velocity structure of the crust are now numerous enough and cover sufficiently diverse geological settings that it is possible to calculate statistical averages for various geological settings such as Precambrian shields, extended continental crust, and passive margins. These statistical averages define a set of standard crustal sections (referred to here as crustal types). For the vast continental regions where, as yet, no seismic measurements are available, such as large portions of Africa, South America, and Greenland, we predict the crustal structure using the standard crustal types, and present the statistical basis for these predictions.

Our purpose is to create a model for the seismic velocity (Vp and Vs) and density structure of the crust and uppermost mantle that is at a large enough scale to be commensurate with the (non-uniform) global distribution of seismic field observations but that is also at a small enough scale to resolve significant lateral variations in crustal properties. In order to meet these competing goals, we have constructed our model using 5° x 5° tiles that measure 550 km by 550 km at the Equator. In each tile, crustal properties are described by seven layers: (1) ice, (2) water, (3) soft sediments, (4) hard sediments, (5) crystalline upper, (6) middle, and (7) lower crust. An eighth layer is included to describe the elastic properties and density immediately below the Moho since this information is readily obtained from the seismic refraction profiles compiled here. Topography and bathymetry are provided as a separate file. Compressional wave velocity in each layer is based on field measurements, and shear wave velocity and density are estimated using empirical Vp-Vs and Vp-density relationships, as discussed below.

Global Crustal Thickness

The crustal thickness of our model is shown in Fig. 2. In areas with good data coverage, crustal thickness is very similar to existing continental-scale models (e.g., compare Eurasia with Meissner, 1986, and North America with Mooney and Braile, 1989). There is also generally good agreement with the crustal thickness from the model 3SMAC of Nataf and Ricard (1996), who used different data sources for their compilation. The largest differences between their model and ours occur where constraints from seismic refraction data are sparse (e.g. Africa, Greenland, and Antarctica).

The mean Moho depths (with respect to sea level) are 21.8 km (global), 38.0 km (continents) and 12.6 km (oceans, including the water layer of 4.0 km average thickness). The total crustal thickness is clearly bimodal and, in comparison to the crustal thickness our model has substantially higher values for continental regions. The Moho in our model is located at greater depth in some areas than in the model of Soller et al. (1982), especially those areas with poor data coverage such as Africa and South America. Our crustal thickness (40 km) for the vast shield areas of Africa and South America is in excellent agreement with the global average for shield areas, whereas the thin (30 km) crust in the model of Soller et al. (1982) is clearly inconsistent with these statistics. The data coverage in Australia has increased tremendously since the publication of Soller et al. (1982), and our model displays a slightly deeper (by approx. 5 km) Moho. In northeastern Eurasia, the Moho lies substantially deeper in CRUST 5.1 (as it does in 3SMAC of Nataf and Ricard, 1996) than in the model of Soller et al. (1982). In this part of the continent, the Moho depth is constrained quite well by recently released data so that, again, we have more confidence in our model. On the other hand, based on much new data, the Moho in all of southern Eurasia is shallower in our model than in that of Soller et al., sometimes by over 10 km. Again, our model agrees quite well with 3SMAC, especially in Southeast Asia. The crust in our model is also slightly thinner in North America, where our map is in close agreement with Mooney and Braile (1989).

Large local differences in the oceans are found in the Coral Sea (northeast of Australia) and along the Tonga-Kermadec trench. For the Coral Sea, Soller et al. (1982) refer to results reported by Shor (1967) and Ewing et al. (1970). Shor (1967) reports the Moho at 19 km depth along a profile lying immediately south of the Coral Sea Basin, which has normal oceanic crust (Ewing et al., 1970). North of the Queensland plateau, Shor (1967) also report a significantly thicker crust. However, the contour lines in this area are rather uncertain and are probably overestimated by Soller et al. (1982) who specified 25 km as the crustal thickness. Shor et al. (I 97 1) report crustal thicknesses between I 1 and 15 km along portions of the Tonga Kermadec trench, which may indicate a significant crustal thickening on a 5° x 5° scale. The regional extent of this area of thicker oceanic crust is unknown, and thus has not been included in our model.

The Crustal Model and Mantle Tomography

Seismic tomography has been extensively used in various forms to determine the deviations from a purely radial dependence of seismic velocities within the Earth's mantle. Surface wave and free oscillation data have been used to determine the upper mantle shear wave velocity structure (e.g., Masters et al., 1982; Woodhouse and Dziewonski, 1984; Montagner and Tanimoto, 1991; Trampert and Woodhouse, 1995). Body wave arrivals reported to the International Seismological Center (ISC), or specially picked from seismic records, have been used to determine the P-wave and S-wave structure both on global and regional scales (e.g, Dziewonski, 1984; Inoue et al., 1990; Woodward and Masters, 1991; Pulliam et al., 1993; Zielhuis and Nolet, 1994, Grand, 1994; Vasco et al., 1995; Masters et al., 1996; Alsina et al., 1996). For the majority of these studies, the crust has a significant effect on the observed seismic data but, at the same time, it is too thin to be resolved by these studies. Most authors handle this by applying an assumed "crustal correction" to the data before inverting for mantle structure. Since the inversion techniques can erroneously map crustal structure down to great depth, the application of accurate crustal corrections to the data sets is extremely important.

We will concentrate on effects on phase velocity (not group velocity) in the following. Since surface waves are sensitive to Vp, Vs, and density, a model prescribing all these parameters is essential. When calculating the crustal corrections for global maps of phase velocity we ignore the lateral variations of Vp, Vs and density as specified in layer 8 (uppermost mantle) of CRUST 5.1 so that anomalies displayed in the maps are caused only by variations within the crust itself. For the mantle, we use the reference ID-model PREM (Dziewonski and Anderson, 1981). Global surface wave phase velocity maps are commonly expanded in surface spherical harmonics. We adopt this parameterization and truncate the harmonic expansions as specified in the individual figure captions. For plotting purposes, the spherical averages of the maps have been removed. Crustal structure has the greatest effect on short-period surface waves. The peak-to-peak amplitude in phase velocity anomaly for Rayleigh waves at 40 s is about twice as large as that at 167 s. For Love waves, the crustal effect is more than twice that of Rayleigh waves at the same period. Love waves at 40 s are most sensitive to the S-wave velocity structure in the uppermost 60 km (they are also sensitive to density in the same depth range, although to a much lesser extent). Rayleigh waves at these periods are primarily sensitive to uppermost mantle structure. The sensitivity kernel for S-wave velocity peaks at about 60 km and has a minimum at 20 km depth. However, Rayleigh waves at 40 s are also quite sensitive to variations of P-wave velocity within the shallow most layers of the crust. Hence the large thick sedimentary basins (e.g., in the Arctic ocean or the Gulf of Mexico) cause significant phase velocity anomalies which are not seen in the maps for Love waves at the same period.

When expanded in surface spherical harmonics, continent-ocean-type functions (such as our crustal model) are dominated by harmonic degrees l=1 through 5, but the amplitude is greatest at the first harmonic degree. Surface wave phase velocity maps that have had the crustal signal removed are dominated by contributions from the first harmonic degree in a wide range of periods. Hence, it is very important to obtain an accurate estimate of the structural contrast between continental and oceanic crust in order to ultimately avoid erroneous mapping of the continent-ocean function into greater depth in the upper mantle.

At higher harmonic degrees, the spectra of the crustal corrections roll off roughly as l^a, where a is a negative number between minus one and minus 2. The roll-off of the amplitude spectra plotted on a double-logarithmic scale can then be fit by straight lines where the slope of the lines is a. We find that this parameter is fairly uniform (a=-1.35) for both Love and Rayleigh in the period range between 167 s and 40 s. For Rayleigh waves at 40 s, the roll-off is slightly less (a=-1.19), probably due to the increased sensitivity to the small-scale variations of the P-wave velocity in the thick sedimentary basins.

Figures 3 and 4 show examples of the global phase velocity maps of Laske and Masters (1996) and Ekström et al. (1997) before and after removal of the perturbations due to the crust. For long-period surface waves, lateral phase velocity variations caused by crustal heterogeneities are relatively small. Nevertheless, the crustal correction actually increases the variance of the observed phase velocity. The peak-to-peak amplitude for Rayleigh waves at 167 s is larger after the correction by a factor of roughly 1.3 (Fig. 3a and 3b). The increase in variance is caused by the fact that the signals from the crust and the uppermost mantle are often anticorrelated, e.g., shields have large crustal thickness and low crustal velocities (as compared to the oceans at the same depth) but high velocities in the upper mantle. Obviously, the application of a crustal correction is important for interpreting these long-period surface wave data. However, the fine details of the crustal model used do not appear to be crucial.

The situation is quite different for short period surface waves. In this case, for continental paths, Love waves with a period of 40 s are dominantly sensitive to crustal structure. In fact, Love wave phase velocities at shorter periods (e.g., Ekstr6m et al., 1997) could be used in the future to further refine crustal models where no refraction seismic data are available. The signal in the map (Fig. 4a) is greatly (by a factor of 1.7) by the crustal correction (Fig. 4c). The remaining signal is primarily produced by an age-dependent cooling of the oceanic lithosphere, which is not included in the crustal model. For comparison, we also show the crustal correction for a model (Smith, 1989) used in earlier studies (Fig. 4d). This model includes the Moho variation of Soller et al. (1982) and estimated average seismic velocities and densities for continents and oceans (Smith, 1989) (referred to as the "Soller model" hereafter). It is interesting to note that the resulting map (Fig. 4d) does not display the pronounced high velocity regions beneath the shields that CRUST 5.1 produces, and there are many other regional differences. Since 40 s Love waves are sensitive to upper mantle structure below 60 km, it is to be expected that the high-velocity mantle beneath shields will be clearly evident in the corrected maps. Based on this comparison, we are confident that the crustal corrections from CRUST 5.1 are more accurate than the corrections derived from the Soller model. It is also worth noting that the spectra of the crustal corrections of CRUST 5.1 and the Soller model are similar in shape but that the corrections of CRUST 5.1 have significantly larger amplitudes at harmonic degrees less than l=5 (not shown here). The largest discrepancy is at l=1 where the amplitude of CRUST 5.1 is roughly 1.5 times that of the Soller model. This discrepancy is due to the difference between the average parameters for continents and oceans in the two models. This comparison further stresses the need for accurately estimating seismic velocities and densities at even the longest-wavelength scale (i.e. the contrast in physical properties between continents and oceans).

Rayleigh waves at 40 s sample the Earth quite differently than Love waves at 40 s. As mentioned above, these waves primarily sample the S-wave velocity in the upper mantle, but they are also sensitive to the shallow P-wave velocity and density structure. The overall effect is that crustal corrections for 40 s Rayleigh waves (Fig. 3c) do not change the variance of the anomalies in the maps but redistributes the phase velocity anomalies significantly. High velocities in the mantle beneath shields are much more pronounced after the correction, while the low-velocity anomaly extending from the Afar Triangle through China is decreased significantly (Fig. 3d.). After crustal correction, the previously large low velocity anomaly around the Afar Triangle/Red Sea area is much smaller and concentrates along the Red Sea. This same behavior occurs for both Love and Rayleigh wave phase velocity maps in a large range of frequencies (down to 167 s) and indicates that the Afar Triangle/Red Sea low velocity anomaly is mostly produced by shallow structure.

CONCLUSIONS AND RECOMMENDATIONS

A contour map based on CRUST 5.1 shows the global variation of crustal thickness (Fig. 2). Because of the 5° x 5° cell size, many interesting but narrow (less then about 250 km wide) features are not evident on this map. The thickest crust (more than 50 kin) is found beneath the Tibetan Plateau, the Andes of South America, and southern Finland. Continental crust (including shelf regions) typically has a crustal thickness of 30-45 km, with a global average of 38 km. Vast regions of oceanic crust have an average thickness of 6-7 km (not including the water layer). A comparison with Figure 1 indicates where crustal thickness has been measured, and where it has been estimated based on tectonic province and crustal age.

We have evaluated the seismological effects of this model by comparing observed short period (40s) Love and Rayleigh wave phase velocities with those predicted by the crustal model. Such a comparison must be approached with caution since these phase velocities are also sensitive to mantle structure. With the global surface wave data currently available, it is not possible to completely isolate the crustal signal. However, this comparison indicates that our model provides a good match to the amplitude and areal extent of phase velocity anomalies that are associated with variations in the thickness of the continental crust and large sedimentary basins. We have applied the crustal correction to observed surface wave phase velocity maps to isolate those features that are due to variations in upper mantle structure. The most obvious features in these corrected maps are the age dependence of oceanic lithosphere and enhanced high velocity anomalies under shields. We also show that an important factor in mapping these features (especially at long periods) is an accurate knowledge of the contrast between continental and oceanic crustal structure.

There are two primary limitations to the CRUST 5.1 model. The first is the cell size (5° x 5°), which measures 550 km by 550 km at the Equator. This cell size is too coarse to permit an accurate model of many important crustal features (e.g., narrow mountain belts or rifts) other than by using a weighted average to account for lateral variations within a cell. A smaller cell size, such as 2° x 2°, would provide approximately six times the resolution of the present model; such a cell size may be needed for many regional studies. However, we feel that the construction and thorough evaluation of a model with a cell size of 5° x 5° is a necessary first step to finer scale models. A second limitation is the means by which we have parameterized the model. This consisted of assigning one of 139 crustal models to each of the 2,592 cells. We found that this parameterization was well suited for the crystalline crust and uppermost mantle but did not provide the desired flexibility for parameterizing the thickness and physical properties of sedimentary accumulations. An alternative approach would be to parameterize the upper layers (ice, water, and sediments) by a grid, and the lower layers (crystalline crust and upper mantle) by crustal types.

As global datasets become more complete and processing techniques evolve, it will be possible to better constrain a crustal model by using observations of short period surface wave dispersion (Ekstr6m et a]., 1997). Such observations will be particularly valuable to constrain those parts of the Earth's crust where the data coverage from seismic refraction studies is likely to remain poor, such as regions at high latitude. For the present, our new model, CRUST 5.1, provides the most accurate mapping of the physical properties of the crust and uppermost mantle available at a 5° x 5° scale. Further refinement will be possible as additional data become available and as additional checks are made by those who apply it to seismological and non-seismological problems.

REFERENCES

Alsina, D., R.L. Woodward, and R.K. Snieder, Shear wave velocity structure in North America from large-scale waveform inversions of surface waves, *J. Geophys. Res., 101*, 15,969-15,986, 1996.

Dziewonski, A.M., Mapping the lower mantle: determination of lateral heterogeneity in P-velocity up to degree and order 6, *J. Geophys. Res., 89*, 5929-5952, 1984.

Dziewonski, A.M., and D.L. Anderson, Preliminary reference Earth model (PREM), *Phys. Earth Planet. Inter., 25*, 289-325, 1981.

Ekström, G., J. Tromp, and E.W. Larson, Measurements and global models of surface wave propagation, *J. Geophys. Res., 102*, 8137-8157, 1997.

Ewing, M., L.V. Hawkins, and W.J. Ludwig, Crustal structure of the Coral Sea, *J. Geophys. Res., 75*, 1953-1962, 1970.

Grand, S.P., Mantle shear structure beneath the Americas and surrounding oceans, *Journ. Geophys. Res.*, *99*, 11.591-11.621, 1994.

Hahn, A., H. Ahrendt, J. Meyer, and J.-H. Hufen, A model of magnetic sources within the Earth's crust compatible with the field measured by the satellite magsat, *Geologisches Jahrbuch, A75*, 125--156, 1984.

Inoue, H., Y. Fukao, K. Tanabe, and Y. Ogata, Whole mantle P-wave travel time tomography, *Phys. Earth Planet. Inter., 59*, 294-328, 1990.

Laske, G., and G. Masters, Constraints on global phase velocity maps by long-period polarization data, *J. Geophys. Res., 101*, 16,059-16,075, 1996.

Masters, G., T.H. Jordan, P.G. Silver, and F. Gilbert, Aspherical earth structure from fundamental spheroidal-mode data, *Nature, 298*, 609-613, 1982.

Masters, G., S. Johnson, G. Laske, and H. Bolton, A shear-velocity model of the mantle, *Phil. Trans. R. Soc. Lond. A, 354*, 1285-1411, 1996.

Meissner, R., The Continental Crust; A Geophysical Approach, 426 pp., Academic Press, San Diego, 1986.

Montagner, J.-P., and T. Tanimoto, Global upper mantle tomography of seismic velocities and anisotropies, *J. Geophys. Res., 96*, 20,337-20,351, 1991.

Mooney, W.D., and L.W. Braile, The seismic structure of the continental crust and upper mantle of North America, in *The Geology of North America, Vol. A, Overview*, edited by A.W. Bally, and A.R. Palmer, pp. 39-52, Decade of North Am. Geol. Project, Geol. Soc. Am., Boulder, Colo., 1989.

Mooney, W.D., G. Laske and T.G. Masters, CRUST 5. I. A global crustal model at 5° X 5°, *J. Geophys. Res., 89*, 727-747, 1998.

Nataf, H.-C., and Y. Ricard, 3SMAC: An a priori tomographic model of the upper mantle based on geophysical modeling, *Phys. Earth Planet. Int., 95*, 101-122, 1996.

Pulliam, R.J., D.W. Vasco, and L.R. Johnson, Tomographic inversions for mantle P wave velocity structure based on the minimization of 1^2 and 1^1 norms of International Seismological Centre travel time residuals, *J. Geophys. Res., 98*, 699--734, 1993.

Shor, G.G. Jr., Seismic refraction profile in Coral Sea Basin, Science, 158, 911-913, 1967. Smith, M.F., *Imaging the Earth's aspherical structure with free oscillation frequency and attenuation measurements*, Ph.D Thesis, Univ. Cal. San Diego, La Jolla, CA, 97 pp., 1989.

Soller, D.R., R.D. Ray, and R.D. Brown, A new global crustal thickness model, *Tectonics, 1*, 125- 149, 1982.

Tanimoto, T., Crustal structure of the Earth, *A Handbook of Physical Constants, Global Earth Physics*, edited by T.J. Ahrens, pp. 214-224, AGU, Washington, D.C., 1995.

Trampert, J., and J.H. Woodhouse, Global phase velocity maps of Love and Rayleigh waves between 40 and 150 seconds, *Geophys. J. Int., 122*, 675-690, 1995.

Vasco, D.W., L.R. Johnson, and J. Pulliam, Lateral variations in mantle velocity structure and discontinuities determined from P, PP, S, SS, and SS-S_dS travel times residuals, *J. Geophys. Res., 100*, 24,037-24,059, 1995.

Woodhouse, J.H., and A.M. Dziewonski, Mapping of the upper mantle: three-dimensional modeling of earth structure by inversion of seismic waveforms, *J. Geophys. Res., 89*, 5953-5986, 1984.

Woodward, R.L., and G. Masters, Global upper mantle structure from long-period differential travel times, *J. Geophys. Res., 96*, 6351-6377, 1991.

Zielhuis, A., and G. Nolet, Shear-wave velocity variations in the upper mantle beneath central Europe, *Geophys. J. Int., 117*, 695-715, 1994.

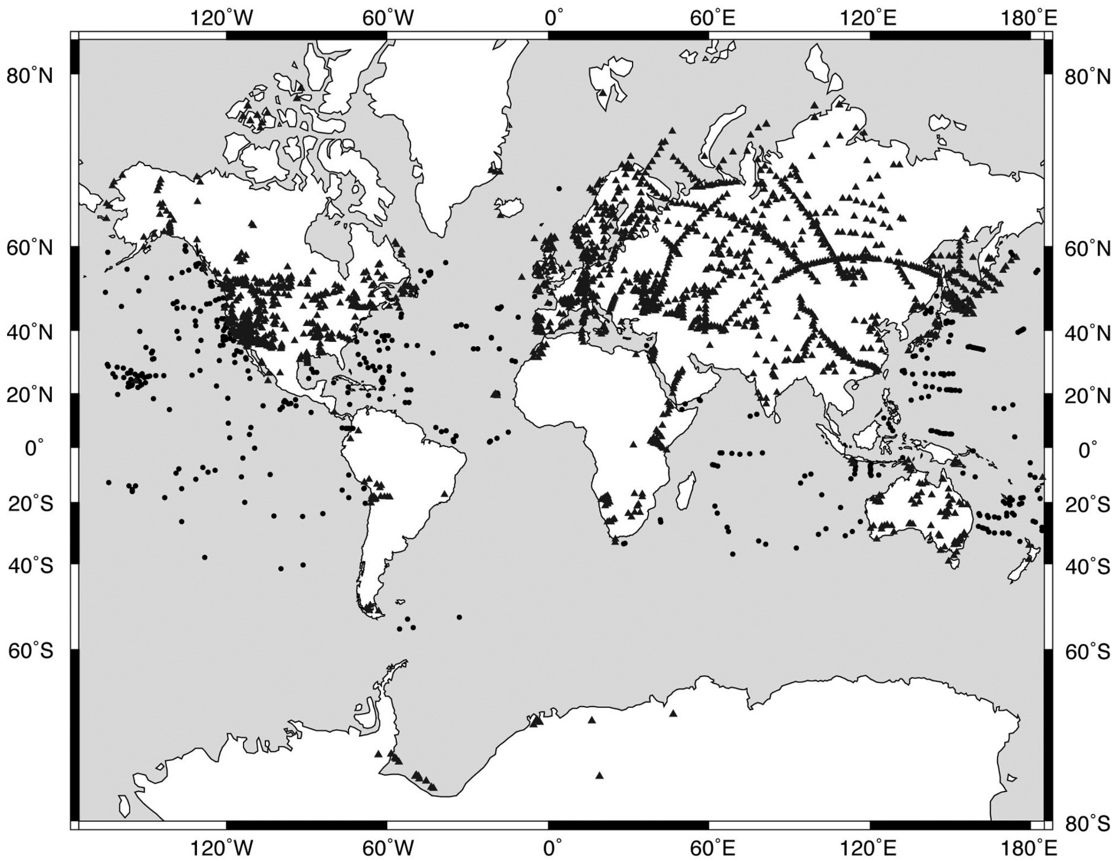

Figure 1. Location of seismic refraction profiles used in this study. Triangles correspond to locations within continents and on margins where a velocity-depth function has been extracted from a published crustal interpretation. These locations are generally at the midpoint between shot points along each profile. These data provide details on the compressional-wave seismic velocity structure and, in about 10% of the cases, also the shear-wave structure of the crust in a wide range of tectonic settings. Sources are cited in Christensen and Mooney (1995). Solid circles are locations of oceanic refraction profiles (Christensen, 1982). A standard crustal model is used for normal oceanic crust, and appropriate models are used for oceanic plateaus and other features. Data selection and interpretation uncertainties are discussed in the text.

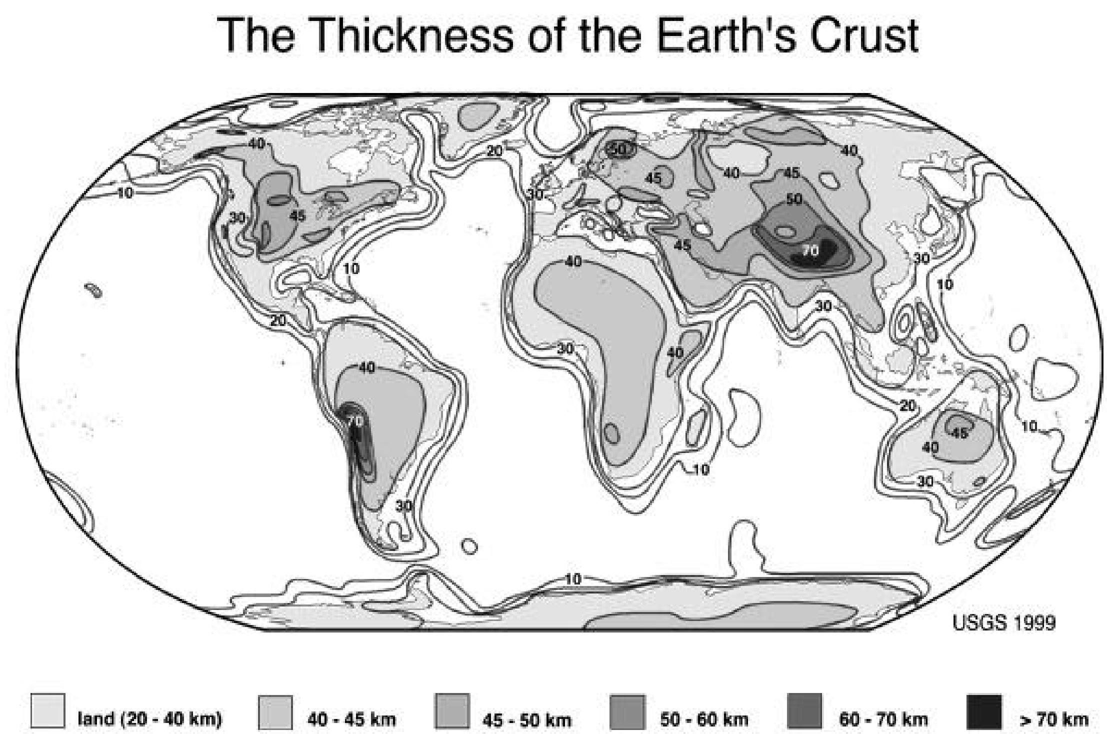

Figure 2. Robinson projection of crustal thickness from CRUST 5.1 (85° N to 80° S latitudes). The normal ocean crust is 6-7 km thick (excluding an average water depth of 4 km). Thin crust at mid-ocean ridges and oceanic fracture zones is not visible, as these and other narrow features (such as the East African Rift) are not resolved by a map based on a 5° X 5° cell size. Stable continental regions typically have crustal thicknesses of 35-45 km, and there are few regions (at the broad scale of this map) with a crustal thickness in excess of 50 km. A comparison with Figure 1 indicates where crustal thickness has been estimated based on tectonic province and crustal age.

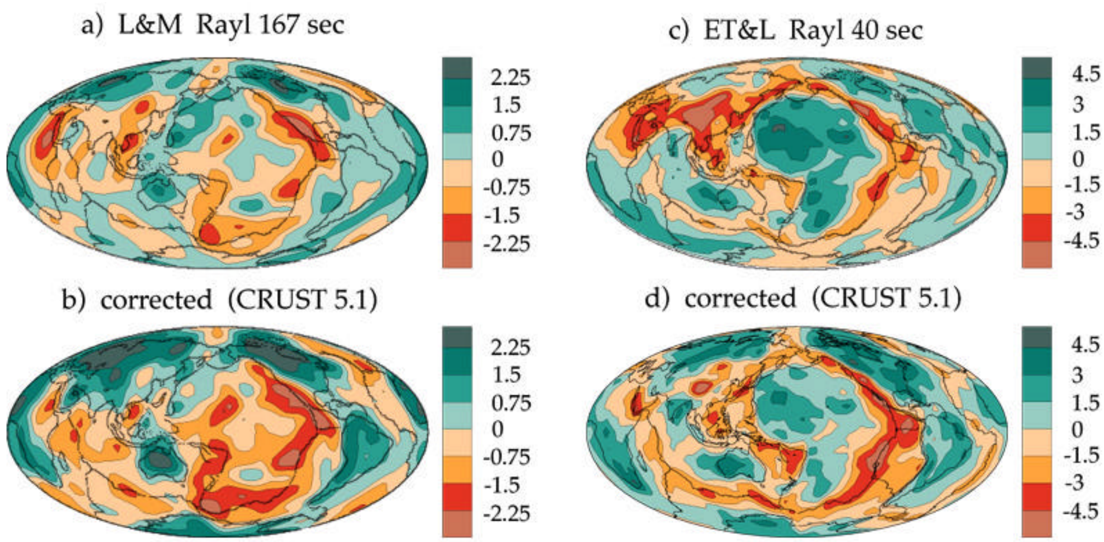

Figure 3. a) Observed phase velocity map for Rayleigh waves at 167 s (Laske and Masters, 1996; "L&M"). The phase velocity perturbation typically varies between -1.5% and 1.5%. b) After the correction for crustal signal, these variations are substantially larger. c) Observed phase velocity map for Rayleigh waves at 40 s (Ekstr6m et al., 1997; "ET&L"). d) Map corrected for crustal signal. The crust correction at this period does not increase the variance but redistributes the anomalies.

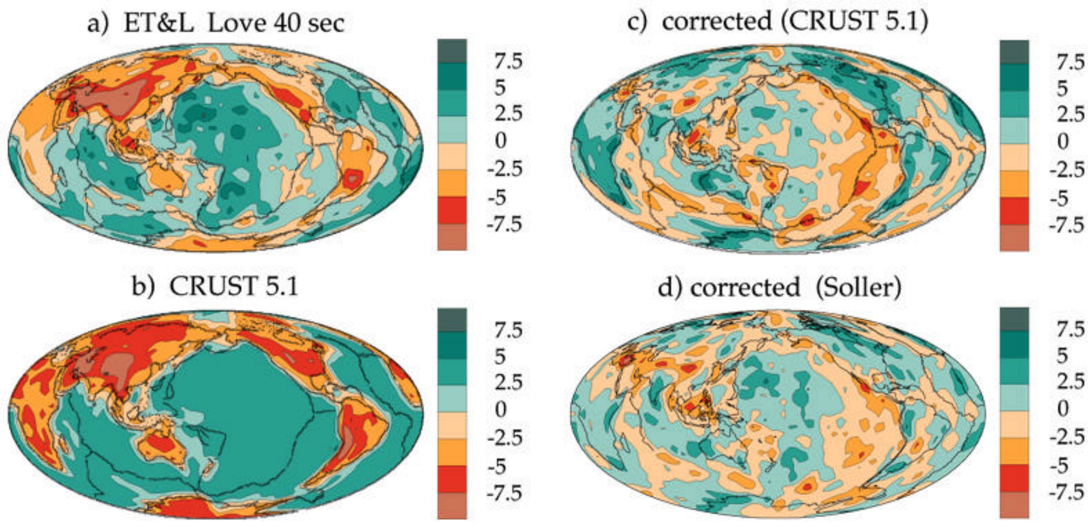

Figure 4. a) Observed phase velocity map for Love waves at 40 s (Ekström et al., 1997). b) Calculated crustal signal in the phase velocity map as predicted by our crustal model CRUST 5.1. c) Observed phase velocity map (a) corrected for crustal signal for the model CRUST 5.1 (b). d) Observed phase velocity map (a) corrected for the crustal signal using Soller's et al. (1982) crustal thickness (see text for details). Note that, while map (c) displays pronounced high velocity anomalies under shields, these anomalies are much smaller in (d).