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Worldwide distribution of ages of the continental lithosphere derived from a global seismic tomographic model

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ABSTRACT

It has long been known that continental regions of different age have different seismic properties: the older the lithosphere, the greater the velocity. Here we ask whether we can obtain a more formal relationship between seismological observations and the age of continents. The deep structure of continents has been seismically mapped for the entire Earth. S-vertical travel time delay maps were computed from velocity maps. S-delay maps (using [Shapiro, N.M., Ritzwoller, M.H., 2002. Monte-Carlo inversion of broad-band surface wave dispersion for a global shear wave velocity model of the crust and upper mantle. *Geophys. J. Int.* 151, 88–105]) correlate with maps show a broad correlation with the ages of surface rocks but when studied in detail, the correlation is not good. The histogram of the S delays for continents is not Gaussian but contains two maxima. From a study in North American stations, Romanowicz and Cara [Romanowicz, B.A., Cara, M., 1980. Reconsideration of the relationship between S and P station anomalies in North America. *Geophys. Res. Lett.* 7, 417–420] found that the ratio of S- to P-delay does not fit a linear relationship: different intercept times have to be used for positive and for negative S to P ratios. They explained this by the presence of low-velocity mantle beneath tectonically active regions but not beneath stable cratons. By imposing that the negative peak of the S-delay histogram corresponds to a major period of continent growth, a relationship between S delay and age is obtained. Using this relationship, a “seismic continental growth curve” is derived. This growth curve is similar to curves published by geochronologists in that it shows strong growth between 3 and 1 Ga. Many uncertainties remain, particularly on the exact meaning of the age of a continental region.

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1. Introduction

Plate tectonics explains the formation and evolution of oceanic plates, born as oceanic ridges and consumed in subduction zones. Relatively young (<200 My) oceanic plates subduct in the deep mantle and participate to the global convection cycle. Due to thermal cooling, their thickness is a function of their age, with some complexities for older plates (e.g., Parsons and Sclater, 1977; Stein and Stein, 1992; Ritzwoller et al., 2004). Continental plates do not subduct but float on the asthenosphere and drift on the surface of the Earth. The formation of continents is not as easy to understand as the formation of oceanic plates and extensive analysis has been necessary to unravel the main properties of the continental lithosphere (e.g., Shapiro et al., 2004). Here we summarize some key observations that indicate the properties and structure of continental plates depends on their age.

1.1. Geochemical and petrological constraints

An important difference between oceanic and continental lithosphere is the existence of thick silicic continental crust. Some differentiation process extracts granitic continental crust from peridotitic mantle. The light continental crust contributes to the buoyancy of continents and largely prevents them from subducting. Boyd (1989) found in addition that the composition of xenoliths from subcontinental lithosphere is different from that of oceanic lithosphere and he illustrated this difference in a diagram giving the forsterite content of olivine as a function of the proportion of olivine. More recent geochemical analyses of rocks and minerals from the lithospheric mantle – xenoliths or xenocrysts – show that there is a systematic difference in composition between the subcrustal lithosphere beneath Archean cratons and that beneath younger, Proterozoic and Cenozoic terranes (Griffin et al., 2003; O'Reilly and Griffin, 2006). Griffin et al. (2003) compiled a very large set of data on the composition of xenoliths and by plotting the percentage of CaO as a function of Al₂O₃, they demonstrated that the composition and the physical properties of the subcrustal continental lithosphere vary as a

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function of age. O'Reilly and Griffin (2006) showed that Archean subcrustal lithosphere is rich in MgO and has a low geotherm whereas young subcrustal lithosphere is rich in Fe and has a steep geotherm. Jordan (1975, 1981) introduced the notion of tectosphere – a deep root beneath cratons. Jordan (1979) argued that magma extraction plays a key role in the secular evolution of the continental lithosphere; he computed the decrease in density that results from the extraction of basalt from a fertile (basalt rich) mantle and showed that this deficit is sufficient to prevent cratons from sinking. The subcrustal lithosphere of cratons is depleted and less dense than the primitive mantle, even though the root probably does not extend as deep as postulated in the tectosphere hypothesis. The different extents of depletion of primitive mantle in basalt provide a first-order explanation of the main chemical variations in lithosphere. It seems possible to reconcile available geophysical, geochemical and petrological observations through a combination of thermal effects and progressive basalt depletion, all as a function of the age of the lithosphere.

1.2. Crustal growth patterns inferred from geochronological data

Geochemistry and geochronology are the main tools for understanding the formation and growth of the Earth's crust (Albarède, 1998). The first compilations showed that geochronological ages tend to cluster around major growth periods (Gastil, 1960). More recent compilations (Condie, 1998; McCulloch and Bennett, 1994; Hawkesworth and Kemp, 2006) have confirmed that ages of 3.6–3.5, 2.7–2.6, 2.0–1.8, 1.2–1.0 and 0.5–0.3 Ga were periods of rapid continental growth. On many continents, old Precambrian nuclei are surrounded by provinces whose age decreases as a function of distance to the central nucleus; the classical example is North America with its centrifugal pattern around the centre of the Canadian shield (Hoffman, 1978). Crustal growth curves published by Hurley and Rand (1969) initiated a debate on the extent of recycling of crust in the mantle (Armstrong, 1968). Recycling of crust back into the mantle complicates the direct construction of crustal growth curves using a histogram of geological ages and many authors have presented their own crustal growth curves from different sets of geochronological data. Such curves show a large variety of forms that probably reflects a-priori hypotheses on the model of crustal growth. For our analysis, the basic geochronological histogram (Fig. 1) is extracted from Condie (1998).

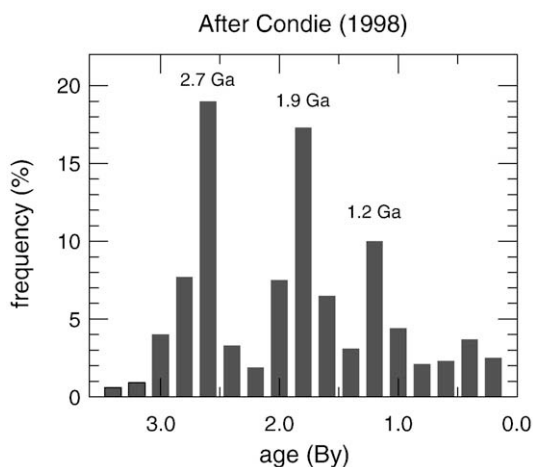


Fig. 1. Histogram of the ages of continental rocks compiled by Condie (1998). Such a histogram results from the compilation of dates all over the continents performed by large number of geochronologists. Each peak corresponds to a major period of formation of continental crust. A compilation by McCulloch and Bennett (1994) finds also another small peak at ~3.6 Ga but the larger peaks are similar.

1.3. Heat flow

A relationship between surface heat flow and age at a global scale was proposed by Polyak and Smirnov (1968) and by Pollack and Chapman (1977). Assuming a linear relationship between surface heat flow and radiogenic heat production in the crust, Chapman and Pollack (1977) derived a simple model according to which the continental plate thickens as a function of age. In recent years, the global thermal model of the continents has been used by Artemieva and Mooney (2001) and Artemieva (2006) to explain their extensive compilation of geophysical and geological data. Pollack (1986) considered that the extraction of volatiles from the lithosphere had an essential role in the stabilization of cratons by increasing the solidus and increasing the stiffness of the residual mantle. Pollack (1986) and Artemieva (2006) presented crustal growth curves derived from geothermal observations. At a regional scale, Jaupart and Mareschal (1999) and Mareschal and Jaupart (2004) conducted detailed measurements on the Canadian Shield and found large changes in surface heat flow that they attributed to variations in crustal heat production. They claimed that surface heat flow measurements do not constrain the temporal evolution of temperature within lithospheric plates. Therefore, the trend exhibited by heat flow data – lower temperatures in the lithosphere correlates with greater age – seems to be valid only at a global scale and only when effects of regional-scale processes are averaged.

1.4. P-wave seismic tomography

Two kinds of data are used for producing a global seismic tomography of the Earth. High frequency (~1 Hz) P-waves generated by earthquakes are recorded in seismic observatories. The locations of the earthquakes are obtained by inverting the arrival times: a P-travel time delay is computed for each event in every station that recorded it. The International Centre for Seismology (ISC) collects arrival times worldwide and computes definitive locations. ISC distributes the hypocenters, the arrival times and the delays on CR-ROMs or on the web. Global P-wave tomographies of the Earth (e.g., van der Hilst et al., 1997), computed from these large sets of P-delays (e.g., Engdahl et al., 1998), describe heterogeneities at all depths inside the Earth. Their resolution close to the surface is limited to non-seismic regions but the average lithospheric structure beneath stations can be obtained by P-station delays which are a weighted mean of P-delays. From Herrin and Taggart (1968), we know that P-station delays are loosely correlated to the age of surface rocks: the “fastest” stations, identified by negative P-delays, are usually on the oldest regions (but also on subduction zones) and the “slowest” stations, identified by positive residuals, are on the youngest platforms. Poupinet (1979) and Poupinet et al. (2003) proposed an approximate relationship between P-delays and age. This relationship is found for old stable cratons but not for tectonic regions. When we compare P-delays to heat flow data, we find that in general a negative delay corresponds to a low geotherm inside a thick lithosphere and a positive delay to a high geotherm inside a thin lithosphere. This simple rule does not apply to regions of anomalous asthenosphere, such as mantle plumes. Unfortunately, the spatial coverage in P-delays is not uniform over the Earth's surface and does not allow us to calculate a crustal growth curve.

1.5. S-wave seismic tomography

Global surface wave tomography is well adapted for the mapping of the lithosphere worldwide. Using this technique, large-magnitude earthquakes are recorded by broadband seismic stations, the dispersion of Rayleigh and Love waves is measured on many paths and group and/or phase velocities are measured as a function of period. Some techniques deal directly with waveforms and invert them without the step of the dispersion curve: their information content is slightly richer than that yielded by a fundamental mode study. The depth

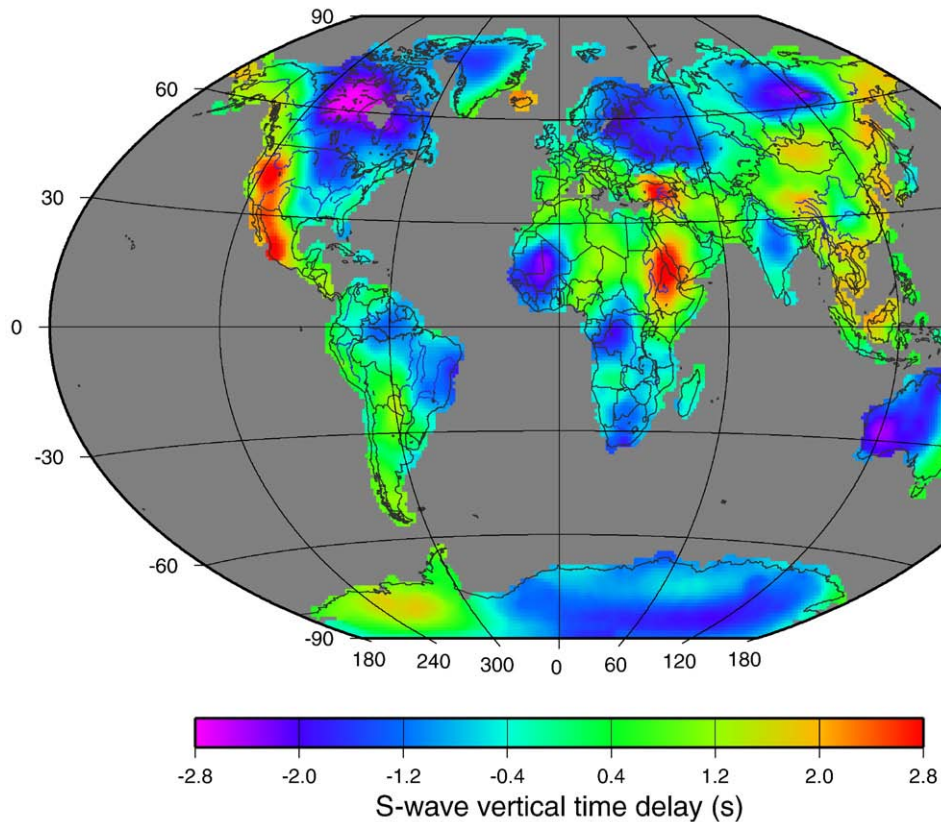


Fig. 2. Map of S vertical travel time delays to a depth 250 km computed from the CUB2.0 global tomographic model using the Voigt average S-wave velocity at every depth. The blue colors correspond to fast regions and the red colors to slow regions.

resolution of a fundamental Rayleigh mode is about one third the wavelength and its spatial resolution depends on the distribution of seismic stations and on the wavelength. The best surface wave based models of the upper mantle have a spatial resolution of a few hundred km in densely monitored regions and around 1000 km elsewhere.

We use here a radially anisotropic 3-D tomographic model of shear-wave velocities in the crust and the upper mantle (CUB2.0) obtained from a large data set of broad-band Rayleigh and Love wave phase and group velocity measurements (Trampert and Wodtke, 1995; Ekström et al., 1997; Ritzwoller and Levshin, 1998; Ritzwoller et al., 2002). The model is derived in two steps. In the first step, we obtained worldwide group velocity maps from 18 to 200 s periods for Rayleigh waves and from 20 to 150 s for Love waves. Phase velocity maps from 40 to 150 s period for both Rayleigh and Love were produced on a $2^\circ \times 2^\circ$ geographical grid from more than 200,000 measurement paths (Ritzwoller et al., 2002). In the second step, the dispersion maps are inverted with a Monte-Carlo algorithm (Shapiro and Ritzwoller, 2002) to construct a 3-D model on a $2^\circ \times 2^\circ$ grid to 400 km depth.

2. Data processing

2.1. Maps of S-vertical travel time computed from surface wave tomography

We use “Voigt” average S-wave velocity $((2V_{sv} + V_{sh})/3)$ from the CUB2.0 model as a function of depth to compute S vertical travel times on a worldwide $2^\circ \times 2^\circ$ geographical grid. To compare regions, we have to compute a travel time from the surface to a depth at least equal to the thickest lithosphere. This maximum thickness is difficult to measure, but most geophysicists agree that the seismic lithospheric thickness is no larger than 250 km (e.g., Gung et al., 2003). Thus, S vertical travel times were computed between this depth and the surface. S-delays

were obtained by subtracting the global average value from these vertical travel times. Fig. 2 shows our S vertical delay map. It is similar to the original S-wave velocity maps at different depths published by Shapiro and Ritzwoller (2002). Fast travel times are found below Precambrian shields because velocity is elevated at all depths inside the lithosphere. In Fig. 3, S vertical travel time residuals are plotted as

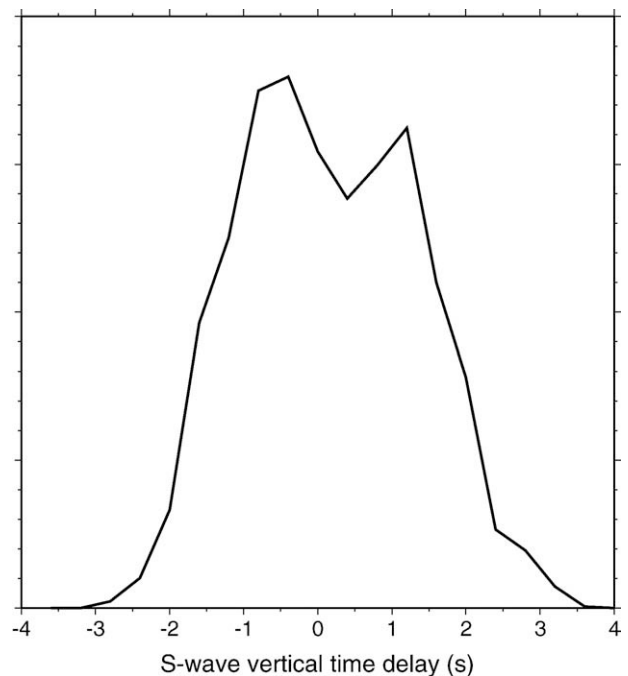


Fig. 3. Histograms of S vertical travel time delays for continents for depths of 250 km.

histograms that are clearly non Gaussian and exhibit two maxima. How are these explained? Romanowicz and Cara (1980) studied the ratios of S- to P-delays in North America and found that the relationship is not linear. They introduced an offset between positive S-delays and negative S-delays in order to obtain a meaningful slope of the ratio between the two parameters. To explain the offset they proposed that a layer with very low velocity exists in the upper mantle beneath tectonic regions but not beneath stable regions. The first maximum of our histogram, at -0.5 s, corresponds to an average stable region and the second maximum, at $+1$, is related to the average upper mantle in “tectonic” regions. In fact an S-delay is the sum of two individual delays, one in the lithosphere and the other in the asthenosphere. The average delays are separated by ~ 1.5 s. The global S-delay histogram is therefore the sum of two shifted histograms as illustrated by a schematic synthetic example in Fig. 4.

2.2. A relationship between S vertical travel time and “lithospheric age”

Simons and van der Hilst (2002) concluded that in Australia the older cratons are not systematically underlain by thicker lithosphere. Nevertheless, our assumption is that there is a relationship between S vertical travel time and age on a global scale. The most obvious way to refine this relationship would be to correlate each station delay with the surface age at this location. Artemieva (2006) compiled numerous geochronological ages and published a detailed map of surface ages. Using this map, an age can be attributed to each point of our S-delay map. The correlation of the two maps results in a very large dispersion and favors Simons and van der Hilst (2002) observation; when considered in detail the correlation is poor.

Let us consider instead the S-delay distribution in order to investigate a global relationship between S-delay and age, the latter covering the entire range from the age of the Earth to the present. The fastest regions are found inside major cratons and have a S-delay of -3 s; their age cannot be older than the earth and must be less than 4.5 Ga. The slowest regions have a S-delay of $+3.22$ s and their age is ~ -0.1 to 0.0 Ga (for example in the Afar). These points correspond to the two squares plotted in Fig. 5 which define the limits of the age spectrum. We postulate that the maximum at -0.5 s. corresponds to one of the major geochronological peaks in the histogram of Condie

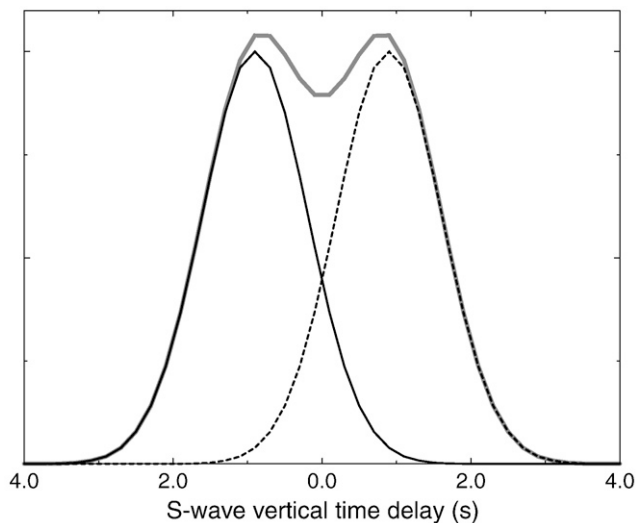


Fig. 4. Illustration of the histogram resulting from the addition of two synthetic histograms shifted by 1.8 s. This plot illustrates the fact that the upper mantle beneath tectonic zones is very slow compared to stable platforms. Therefore in a very simplified model, a S-vertical delay is the sum of two independent components, one in the lithosphere and one in the “asthenosphere” (see Romanowicz and Cara, 1980). Such a scheme is the simplest explanation of the non Gaussian nature of the histograms in Fig. 3.

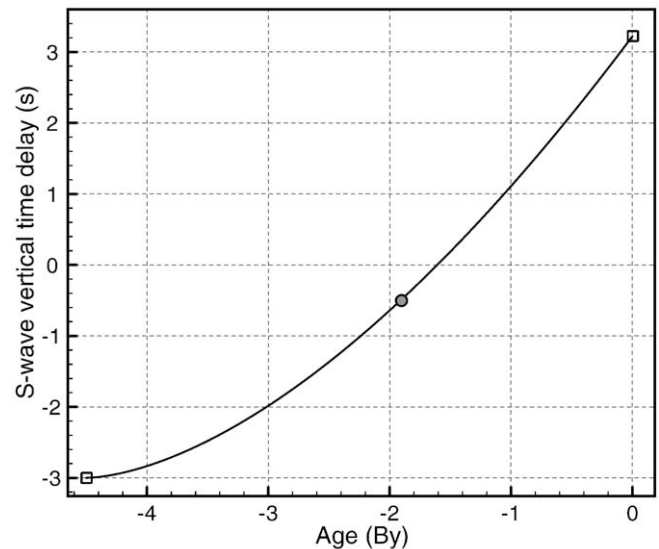


Fig. 5. Approximate relationship between the age of the lithosphere and the S vertical traveltime delay (computed in top 250 km). Extremities of the curve are fixed by the age range of the Earth. Black circle corresponds to the peak of continental growth in Fig. 1 found by geochronology.

(1998) or McCulloch and Bennett (1994). If we associate the -0.5 s. peak with an age of -2.7 Ga, the point 2.7 Ga/ -0.5 s lies approximately on the line joining the open squares in Fig. 5. With this choice, the S-delay is linearly related to age and has a value of ~ 1.4 s. per Ga. This value has to be compatible with the P-delay dependency on age, which is close to ~ 4 s per Ga (Poupinet et al., 2003). The two slopes are obviously not compatible; we would expect a ratio of S- to P-delay of the order of 1.5 or 1.7 (Romanowicz and Cara, 1980) and not 4. The age of -1.9 Ga is the other choice and seems more satisfactory. The S-delay versus age relationship corresponding to this choice is not linear, as seen in Fig. 6. The dependency is larger for recent ages, particularly in

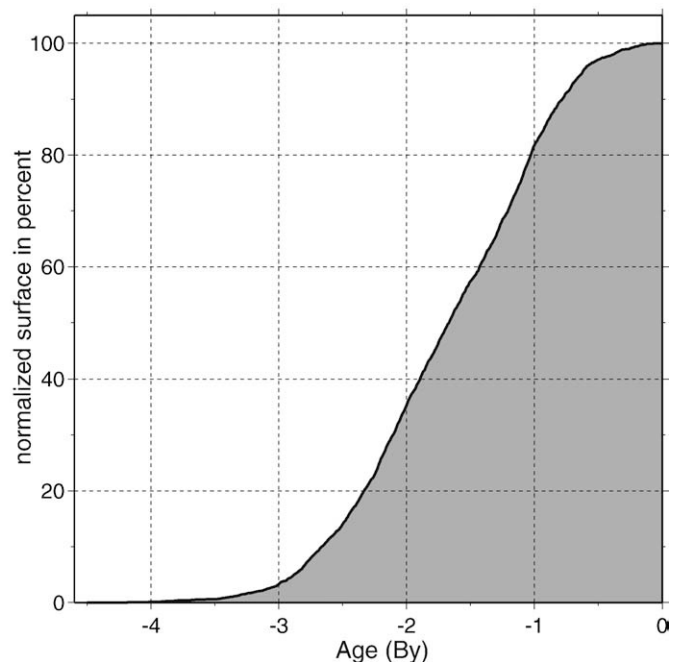


Fig. 6. Seismic continental growth curves deduced from the CUB2.0 tomographic model and the relationship between the age of the lithosphere and the S vertical traveltime delay shown in Fig. 5.

regions where the upper mantle is very anomalous. An approximate formula for this curve is

$$\delta T_s = -3. + 0.52(A + 4.5)^{1.65}$$

where S is the vertical travel time, residual δT_s is expressed in seconds, and A is the lithospheric age in Ga.

2.3. A “seismic continental growth curve”

Applying this S -delay versus age relationship to the global maps of Fig. 2, we obtain a histogram that relates surface of continents with a given lithospheric age. A cumulative representation of this distribution may be interpreted as a “continental growth curve”. The curve obtained from the 250 km S vertical travel times, plotted in Fig. 6, is very similar to the average of a large collection of the curves published by geochronologists (for a recent compilation see Fig. 1 of Rino et al., 2004). In both sets of curves, the largest increase in the growth rate of continents occurs between 3 and 1 Ga. The growth curve derived from seismology is also reminiscent of the curves obtained from heat flow interpretations (Pollack, 1986; Artemieva, 2006) but Pollack’s curve is shifted towards older ages. Despite the better constraint provided by seismological measurements on the deep structure of the lithosphere, the trend of secular evolution of the continents is similar that from other disciplines. The growth curve of Fig. 6 depends strongly on the validity of the S delay versus age relationship. Use of a more “linear” relationship would shift the growth curve toward older ages. The initial S delay histograms do not contain very large peaks and this may indicate continuity in the rate of continental growth. Alternatively, it could reflect the lack of lateral resolution of surface wave tomography. The inversion smoothes velocity variations and does not preserve the discontinuous nature of the velocity histogram.

2.4. A global map of “lithospheric ages” derived from seismology

The map in Fig. 7 is a direct conversion of the S delay map into a map showing the ages of the continental lithosphere. It is similar in many ways to a map of tectonothermal ages. The smoothness of the initial S delay map is transferred to the lithospheric age map. The map clearly shows the principal cratons and indicates a significant variation in their tectonothermal ages. A relatively young age (<2.5 Ga) for some cratons could be caused by thermal and/or tectonic perturbations resulted in rejuvenation of their lithosphere.

3. Conclusions

Knowing the age of the continental lithosphere is necessary if we are to understand its origin and its tectonic and thermal evolution. This parameter, however, is difficult to determine. Geological ages of exposed crustal rocks are commonly used as proxies for lithospheric ages but this approximation only works if the crust and the upper mantle formed at the same time; it breaks down when thermal process in the crust and the mantle lithosphere are decoupled. Moreover, in many regions, the ages of crustal rocks are poorly constrained or totally unknown. Therefore, it could be useful to find alternative methods to establish the age of the continental lithosphere.

Many seismological studies demonstrated a clear correlation between the age of the continental lithosphere and its seismic properties. We have attempted to use this correlation to establish a simple quantitative relationship between seismic travel times and lithospheric age. A similar approach has been recently applied by Ritzwoller et al. (2004) to study oceanic lithosphere across the Pacific. Based on inversion of surface wave dispersion data and a simple cooling model they mapped the “thermal age” of the oceanic lithosphere. At young ages (<70 My) this parameter was found to be in excellent agreement with the sea floor age as determined from magnetic anomalies

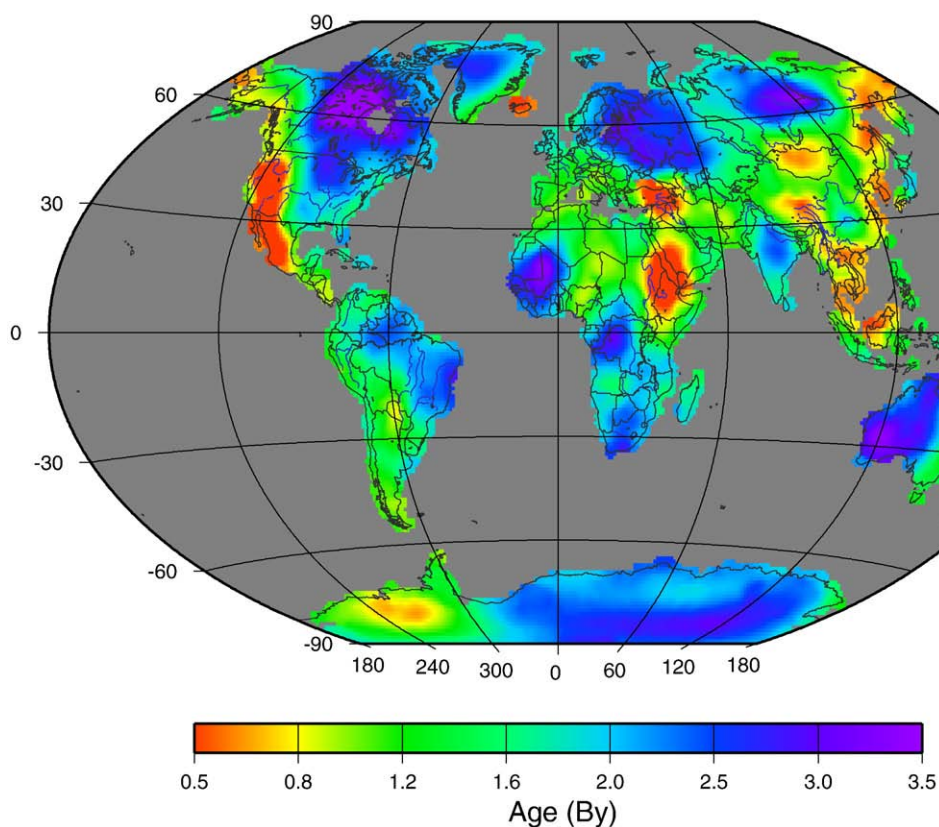


Fig. 7. Map of the age of the lithosphere computed from the CUB2.0 tomographic model and the relationship between the age of the lithosphere and the S vertical travelttime delay shown in Fig. 5.

(e.g., Müller et al., 1997) and its deviation from sea-floor age for older lithosphere has been interpreted as manifestation of existence small-scale sub-lithospheric instabilities (van Hunen et al., 2005; Zhong et al., 2007). Establishing a relationship between seismic properties and tectonothermal age is more difficult for the continental lithosphere than for the oceanic lithosphere because of complications caused by the compositional and structural heterogeneity of the continental crust and underlying lithosphere. Moreover, a simple cooling model, as applies to the oceanic lithosphere, cannot describe the thermal evolution of the continental lithosphere. Therefore, in this study we tried only to establish a simple empirical relation that is valid only for global-scale variations of the lithospheric age and its seismic properties.

We used a global *S*-wave velocity of the crust and the uppermost mantle (CUB2.0) to compute vertical *S*-wave travel times in uppermost 250 km beneath continents. We then imposed the negative peak of the *S*-delay histogram to correspond to a major period of continental growth to constraint a simple non-linear relationship between *S*-delay and lithospheric age. Using this relationship, we derived a “seismic continental growth curve” which shows strong growth between 3 and 1 Ga as in curves published by geochronologists. Finally, we computed a worldwide geographical distribution of “lithospheric age” derived from seismology across continents. Because of uncertainties in relationship between seismic travel times and lithospheric age and inherent smoothness of the used surface-wave seismic tomographic model, this map only reflects very large scale global trends and should not be used to understand small-scale regional variability of lithospheric properties. For such small scale studies, detailed regional geological observations and seismic tomographic models should be used. However, the map shown in Fig. 7 is based on more direct measurements of properties of the mantle lithosphere than maps derived from surface geological determinations. Therefore the results obtained in this study may give a more appropriate representation of global distribution of continental lithosphere of different age and, therefore, may be more useful for studies of global-scale lithospheric dynamics.

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