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The differentiation and rates of generation of the continental crust

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Abstract

A new approach is developed to evaluate the rates of crust generation and hence the quantities of incompatible elements processed through the continental crust over the last 4 Ga. This relies more on minor and trace elements, and residence times in the upper crust and less on radiogenic isotopes since the latter constrain the stabilisation of continental crust rather than the rates of crust generation. In this model, the composition of new material added to the continental crust is similar to estimates of the average lower continental crust. The median composition of granitic magmas with Eu/Eu* = 0.7 is strikingly similar to that of the average upper crust and, in the simplest model, this represents ~14% melting or 86% fractional crystallisation of new crust. For an upper crust of 12.5 km thickness, there would be 77 km of complementary residue, for which there is scant geological evidence. It is therefore inferred that the residence times of elements in the lower crust is much less than in the upper crust. The annual flux of material into the upper crust can be inferred from its volume and the residence times of elements in the upper crust. A maximum value of the latter is provided by the model Nd age of the upper crust of 2 Ga, indicating that the average rates of crust generation are in excess of six times those in the recent geologic past and two to three times greater than the rates inferred from radiogenic isotopes. Over 4 Ga more than half the K, and one quarter of the Li, in the silicate Earth may therefore have been processed through the continental crust.
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Keywords: Continental crust; Formation of upper crust; Crustal residence times; Annual fluxes

1. Introduction

When the continental crust formed, the rates at which it was generated are fundamental questions in the evolution of the Earth. Radiogenic isotopes are the basis for exploring the age of the continental crust, and they are widely used to investigate the extent to which its volume has increased over time (O'Nions et al., 1979; Jacobsen and Wasserburg, 1979; Armstrong, 1981). Such information in turn constrains models for the compositional evolution of the mantle residue after the continental crust was extracted (Allègre, 1982, 1986; Hofmann et al., 1986: Hofmann, 1997), and for the changes in radiogenic isotopes with time in the different reservoirs in the Earth that have disparate parent–radiogenic daughter ratios (Hart, 1988). This approach requires that these chemical reservoirs, such as the continental crust, remained stable for long enough to result in significant changes in Sr, Nd, Hf and/or Pb isotope ratios, typically for more than several hundred million years. However, significant volumes of continental crust are likely to have been formed and destroyed relatively rapidly, whereupon they will have left no isotope signature. Thus, we seek to constrain the rates of *generation* of the continental crust as far as

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possible without recourse to radiogenic isotopes. The average rates of generation, and hence of destruction, of the continental crust inform models for the degree of crustal recycling involved in the evolution of the mantle (Kramers and Tolstikhin, 1997), and the various basaltic components of the oceanic crust derived therefrom. There are also implications for atmospheric evolution and thus climate, given changes in weathering regimes and CO_2 draw down attending formation of continental crust (Lowe and Tice, 2004).

Due to the large-scale averaging processes of erosion and sedimentation, coupled with regional geochemical studies, the overall composition of the upper continental crust is reasonably well constrained. Our approach is to assess the degree of differentiation required to generate this chemically evolved reservoir by deriving an estimate of the composition of new continental crust. Estimates of element residence times in the upper crust are then used to investigate the rates of crust generation, and hence the proportions of different elements in the silicate Earth that may have been processed through the continental crust in the last 4 Ga. The composition of the bulk continental crust and the different crustal reservoirs are taken from Rudnick and Gao (2003), and the reader is referred there for a comprehensive discussion of the strengths and weaknesses of these estimates.

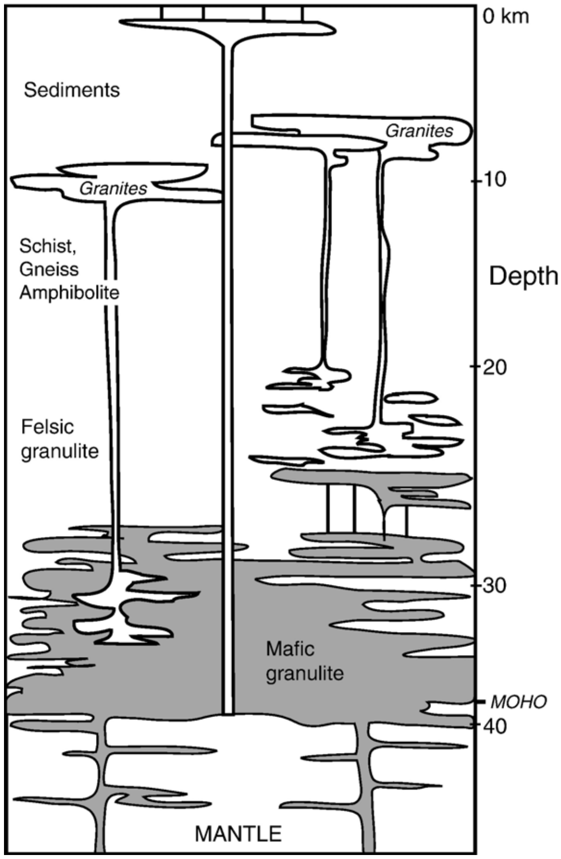

Fig. 1. A schematic geological cross section through the continental crust.

2. Composition of new continental crust

The dominant rock types at different levels in the continental crust are summarised in Fig. 1. Schematic models for the crust have a felsic upper crust (31.7%) of sedimentary and granitic compositions, a middle crust (29.6%) of amphibolite facies metamorphic rocks and a mafic lower crust (38.8%) comprising granulite facies country rocks and basic intrusives and/or cumulates (see reviews in Rudnick and Gao, 2003; Rudnick and Fountain, 1995). The lower crust has traditionally been regarded as the residue from the generation of the differentiated upper crust (e.g. Taylor and McLennan, 1995). However, in an overall sense, this is not consistent with the moderately high (basalt-like) content of incompatible elements, such as K (0.61%) and Rb (11 ppm), in the average lower crust (Rudnick and Gao, 2003), the lack of sufficient europium enrichment to balance the characteristic depletion of this element in the upper crust (Taylor and McLennan, 1995) and its elevated Th/La ratio (Plank, 2005). The lower crust estimates are not sufficiently mafic, or depleted in incompatible elements, or sufficiently voluminous to comprise the complementary residual reservoir to the granodioritic upper crust. Rather, for reasons outlined below, the composition of the lower crust is closer to that of magmas that may be similar to that of new continental crust.

The structure of the continental crust requires two stages of formation, involving the extraction of mafic magmas from the mantle and their differentiation within the crust. The latter involves either remelting or fractional crystallisation of the mantle-derived materials, augmented by weathering and erosion (Taylor and McLennan, 1995; Anderson, 1987; Rudnick, 1995). The starting point for models of crustal evolution is the composition of the material added to the crust from the mantle. As basalt is by far the dominant magma type generated by peridotite melting, a corollary is that newly formed crust should be basaltic. There may also be a small contribution from high-Mg andesite (Kelemen, 1995), a relatively minor constituent of some magmatic arcs.

Previous studies have used element ratios that reflected the distinctive negative mantle-normalised Nb and Ta anomaly of the continental crust, for example, La/Nb (e.g. Rudnick, 1995; Barth et al., 2000). The average composition of new crustal material is likely to include contributions from intraplate magmas and subduction related magmas that may contain variable amounts of recycled sediment. Currently, basaltic magmas are generated in both intraplate and subduction-related tectonic settings, and to assess the compositional balance of these it is necessary to make some general assumptions about the end-members. The former is reasonably represented by ocean island basalts (OIB), irrespective of whether such magmas are associated with mantle plumes and/or tectonic rifting. The time-integrated composition of the subduction end-member is harder to constrain, given the number and potential diversity of source components involved in the formation of arc magmas. An important consideration is whether this end-member is best represented by primitive oceanic arc basalts, or by mafic magmas that may be more representative of continental arcs but which contain a greater contribution of recycled continental crust from subducted sediment. Contributions from the latter can be quantified from Th/Ce ratios, since these are typically high in marine sediments (Plank and Langmuir, 1998) and partial melts derived therefrom (Hawkesworth et al., 1997). Given that the discussion is about the generation of new crust, our preferred average island arc basalt (IAB) composition has relatively little contribution from subducted sediment (Table 1). It has a Th/Ce ratio of 0.09, and from the observed correlations between Th/Ce and Nd isotopes (e.g. Hawkesworth et al., 1997), and Nd and Sr isotopes in oceanic basalts (Hart, 1988), that corresponds to $^{143}Nd/^{144}Nd = \sim 0.5129–30$ and $^{87}Sr/^{86}Sr$ of ~0.7030–35. Relative to present day values of ~0.5132 and ~0.7025, respectively, for the depleted upper mantle (Rehkamper and Hofmann, 1997), this island arc end-member either derives from a less depleted reservoir and/or it contains a small contribution from recycled Nd and Sr.

The two distinctive features of the present-day bulk continental crust (Hofmann, 1997; Rudnick and Gao, 2003) are its negative mantle-normalised anomalies for niobium and tantalum (i.e. low Nb/La), and high lead contents. These are the hallmark signatures of arc lavas and they underpin arguments for the dominance of subduction processes in continental crust formation (e.g. Arculus, 1999). Aspects of this are shown on Fig. 2. The plot of Nb/La–Sr/Nd contrasts rocks with different Nb anomalies, as in OIB and IAB, and utilises Sr/Nd ratios because they are high in primitive arc basalts and fractionate during crustal differentiation. The latter reflects the control of residual plagioclase feldspar, in which Sr is strongly compatible relative to Nd. This is also illustrated by Rb/Sr ratios, since the time integrated fractionation of Rb/Sr can be inferred from variations in Sr isotopes in igneous rocks whose

Table 1
Composition of the average magmatic flux into the upper crust and its corresponding residue, assuming 14% batch melting (or 86% equilibrium crystallisation) of newly added crust (itself a mixture of 92% average arc and 8% OIB)

	Magmatic flux	Residue	Average arc	New crust (OIB-arc mix)	*D* value
wt.%					
SiO_2	68.0				
TiO_2	0.48	0.95	0.71	0.89	2.00
Al_2O_3	15.4				
FeOt	3.30				
MnO	0.07				
Mg0	1.63				
CaO	3.62				
Na_2O	3.60				
K_2O	2.76	0.27	0.54	0.61	0.09
P_2O_5	0.14	0.16	0.11	0.15	1.12
ppm					
Rb	80	0.1	9.2	10.9	0.00
Ba	568	156	200	212	0.27
Sr	301	354	320	347	1.20
Nb	10.3	3.9	1.0	4.8	0.40
Y	21	17.6	17.1	18.0	0.86
Zr	157	42.8	39.1	58.4	0.27
Hf	–	–	1.1	1.6	
La	34	3.7	5.3	7.8	0.11
Ce	64	10.6	12.5	17.9	0.20
Nd	26	8.6	8.6	11.0	0.33
Sm	5.0	2.5	2.2	2.9	0.51
Eu	1.0	1.0	0.8	1.0	1.00
Gd	4.1	2.6	2.4	2.8	0.64
Tb	–	–	0.4	0.5	
Dy	–	–	2.7	3.0	
Er	–	–	1.8	1.8	
Yb	1.9	1.7	1.7	1.7	0.88
Lu	–	–	0.3	0.3	
Pb	12	1.3	2.7	2.7	0.11
Th	9.3	0.2	1.2	1.5	0.02
U	2.1	0.1	0.3	0.4	0.04
Eu/Eu*	0.70	1.18	1.06	1.06	
Mg#	0.47	–	–	–	

The average arc basalt composition used to calculate the new crust is also listed. The *D* values represent the calculated bulk partition coefficient of each element in the residue relative to $D \sim 0$ for Rb during differentiation of the new crust. For the calculation of heat production, the crustal proportions were taken to be 31.7% upper crust, 29.6% middle crust and 38.8% lower crust, from Rudnick and Fountain (1995). The U, Th and K contents of the upper crust were from Rudnick and Gao (2003); for the middle crust, they were the same as for bulk new crust, and the lower crust was inferred to be 5/6th bulk new crust and 1/6th residue after melting to form the bulk upper crust composition.

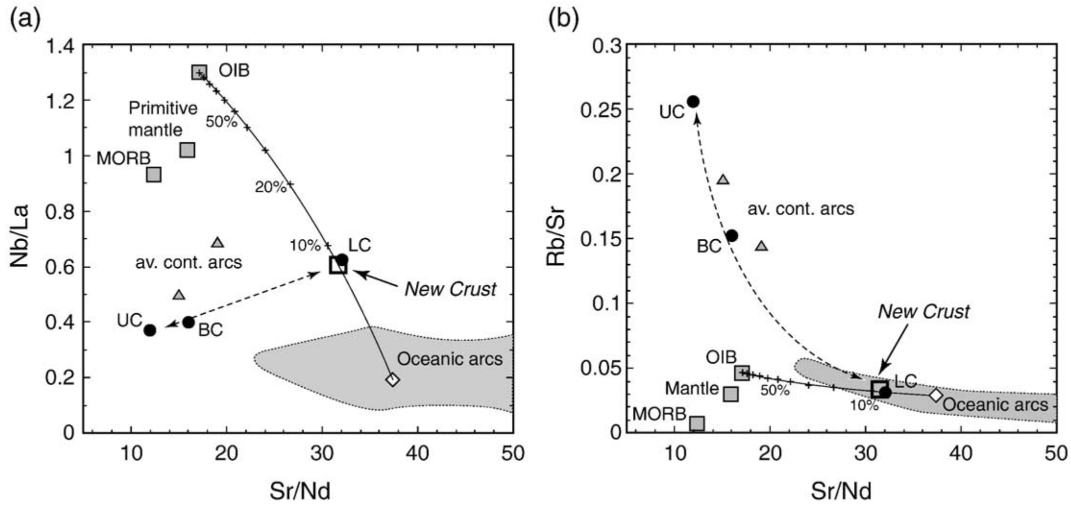

Fig. 2. Plots of (a) Nb/La–Sr/Nd (after Rudnick, 1995) and (b) Rb/Sr–Sr/Nd, illustrating the composition of average oceanic island arc basalts (Table 1), ocean island basalts (OIB) (Sun and McDonough, 1989), selected crustal reservoirs (upper crust, UC; bulk crust, BC; lower crust, LC) and MORB and primitive mantle (Sun and McDonough, 1989). Bulk new crust is inferred to be 92% island arc basalt and 8% OIB, whereupon the average upper crustal composition is consistent with ~14% melting of bulk new crust. Note that, unlike the bulk crust, the average lower crust of Rudnick and Gao (2003) lies on the IAB-OIB mixing line.

crustal precursors were extracted form the mantle at different times (e.g. Kemp and Hawkesworth, 2003).

The striking conclusion from Fig. 2 is that the bulk continental crust of Rudnick and Gao (2003) cannot be modelled as a simple mixture between global average OIB and IAB end-members (e.g. Rudnick, 1995). Furthermore, the bulk crust has an evolved major element composition (60.1% SiO_2 and 4.6% MgO, Rudnick and Gao, 2003) that is analogous to silicic andesite, a composition that cannot derive directly from peridotitic mantle. This paradox has been interpreted to reflect the delamination of residual lower crustal material that initially contained plagioclase (Ellam and Hawkesworth, 1988; Arndt and Goldstein, 1989; Kay and Kay, 1991; Rudnick, 1995), resulting in lower Sr/Nd and elevated Rb/Sr ratios for the bulk crustal composition. Recently, Plank (2005) demonstrated that Th/La ratios are principally fractionated by melting processes within the crust, and so the relatively high Th/La ratio of the bulk continental crust also requires the delamination of residual low Th/La crustal material. It follows that element ratios that are primarily fractionated by intracrustal processes cannot be simply used to estimate the proportions of different materials being added to the crust. Plank (2005) therefore cautioned that there may be risks in using Nb/La ratios to estimate the proportion of intraplate and subduction related magmatism involved in the generation of new crust. This has been assessed by examining geochemical variations in granitic suites, since these represent the products of intracrustal differentiation. In granitic rocks from, for example, the Lachlan Fold Belt (Kemp and Hawkesworth, 2003; Hawkesworth and Kemp, 2006-this volume) and a global compilation that includes Archaean tonalites (Kemp and Hawkesworth, 2003), Th/La increases with indices of differentiation, whereas Nb/La changes little except in highly evolved rocks, where the ratio increases rather than decreases. On this basis, it appears that Nb/La is not fractionated significantly by the dominant processes of intracrustal differentiation, and so offers more insight into the composition of magmas emplaced into the continental crust, i.e. of new crust. However, we are principally concerned here with the composition of those magmas, rather than the specific proportions of intraplate and subduction-related components they represent.

In this light, Fig. 2 can still be used to estimate the time-averaged composition of new crust, since it is reasonable to surmise that it lies at the intersection of the OIB-IAB mixing line with the intracrustal differentiation trend inferred from the compositions of upper, bulk and lower crust from Rudnick and Gao (2003). We note that the intracrustal differentiation trend includes material with very different crustal residence times (see below). Nonetheless, with this approach, the composition of average new crust is best represented by a mixture of ~8% OIB and ~92% island arc basalt. This agrees with previous estimates based solely on the La/Nb ratio of the bulk crust (Barth et al., 2000)

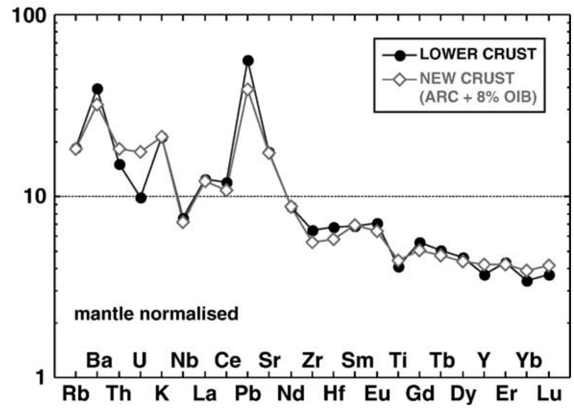

Fig. 3. The mantle normalised trace element pattern of the mixture of 92% IAB and 8% OIB (data from Sun and McDonough, 1989), representing bulk new continental crust (see Table 1), and that of the average lower crust (Rudnick and Gao, 2003). The main difference is in the higher U and Th contents of the new crust composition.

and reinforces the importance of convergent margin processes in the generation of continental crust.

It is also significant that the composition of model new crust on Fig. 2 coincides with the estimate of average lower continental crust, and Fig. 3 shows that the full trace element patterns of these are remarkably similar (Table 1). Notable exceptions are the U and Th contents, which are higher in the model new crust than in average lower crust. Nevertheless, the total heat production of new crust (0.67 μW m^{-3}, see caption to Table 1) is closer to the range (0.79–0.95 μW m^{-3}) inferred from continental heat flow data (Jaupart and Mareschal, 2003). In general, Fig. 3 emphasises that the average lower crust composition of Rudnick and Gao (2003) is not significantly influenced by the presence of rocks that are cumulates or residues after melt extraction. While recognising its geological heterogeneity, we therefore infer that the average lower crust is broadly representative of the protolith to the continents.

3. Crustal differentiation

The model composition of new crust established above provides a platform for assessing models of crust differentiation. In detail the composition of the calculated new crust, or the average composition of the lower crust, are sufficiently similar that either could be used in this discussion, but we have chosen to use the former. A convenient chemical index is the europium anomaly (Eu/Eu*), a measure of the depletion or enrichment of Eu in chondrite-normalised rare earth element (REE) patterns relative to neighbouring elements Sm and Gd. Eu/Eu* is little affected by sedimentary recycling (Taylor and McLennan, 1985; McLennan, 1989), but it is sensitive to magmatic differentiation processes involving plagioclase, since this phase preferentially incorporates divalent europium. The distinctive negative Eu anomaly (Eu/Eu* = 0.7, Rudnick and Gao, 2003) of the upper continental crust must therefore reflect the input of differentiated magmas into this reservoir through time. To determine the average composition of this material, we assessed the major and trace element patterns of silicic igneous rocks with Eu/Eu* = 0.7 (Fig. 4). The granitic suites used are those that show no evidence for a significant contribution from sedimentary sources and they were compiled from global igneous rock datasets of all ages (references in Frost et al., 2001; Kemp and Hawkesworth, 2003). The data were plotted against Eu/Eu* and the medians and standard deviations for the different elements at Eu/Eu* = 0.7 were calculated. The latter are typically < 10% 10% at the 95% confidence level.

The median element abundances are summarised in Table 1 and Fig. 5a. This reveals that the overall composition of the granitic magmas with Eu/Eu* = 0.7 is strikingly similar to that of the average upper continental crust for most major and trace elements (Fig. 5). One implication is that the effects of crustal differentiation by erosion and sedimentation have been swamped

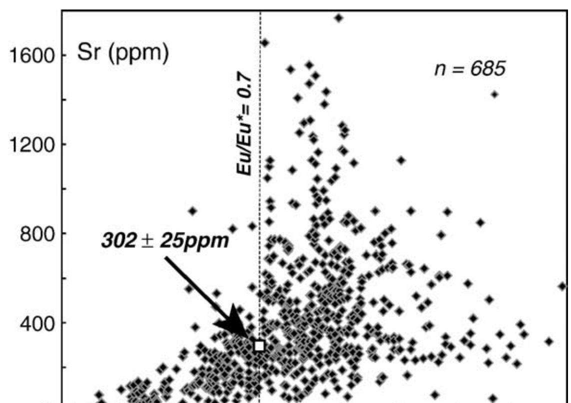

Fig. 4. A plot of Sr versus Eu/Eu* for Archaean, Proterozoic and Phanerozoic igneous rock suites of all tectonic settings, but excluding peraluminous to strongly peraluminous leucogranites and S-type granitic rocks with demonstrably sedimentary sources, or those showing trace element and/or isotopic evidence for a significant recycled sedimentary component. The data (over one thousand analyses) were taken from the sources quoted by Frost et al. (2001) and Kemp and Hawkesworth (2003) and screened for analytical quality. The standard deviation on the median value quoted in Table 1 is typically < 10% at the 95% confidence level.

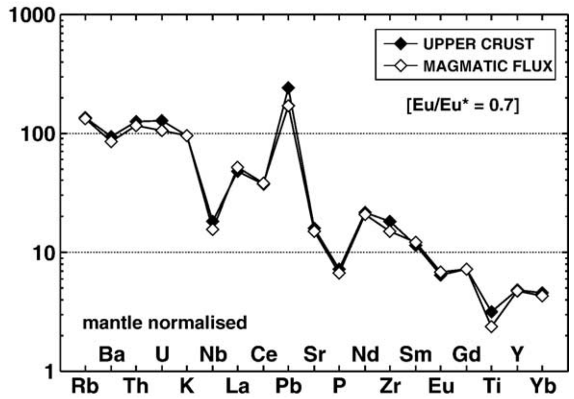

Fig. 5. The mantle normalized trace element pattern of the median values of the granitic rocks with Eu/Eu* = 0.7 (the 'magmatic flux' in Table 1), compared with that for the average upper crust (Rudnick and Gao, 2003).

by those from magmatic processes. A second is that we can use this granite composition, together with that of average new crust, to explore the processes of intracrustal differentiation, and the magmatic flux into the upper crust.

Assuming that the bulk distribution coefficients (*D*) for highly incompatible elements such as Rb approach zero, the degree of melting required to generate a magma with 80 ppm Rb and a Eu/Eu* of 0.7 from the average new mafic crust is ~14% (see Table 1). An analogous argument can be made if the upper crustal magma composition was generated by fractional (equilibrium) crystallisation of a mantle-derived magma similar to that of average new crust. The residual lower crustal composition (RLC) is derived by a mass balance involving the granitic upper crust and average new crust, and is illustrated in Fig. 6. As illustrated in Fig. 6b, or by comparing Figs. 3 and 6a, the RLC is very different from the existing lower crust in having strongly depleted incompatible element abundances (e.g. U, Th, Pb, La, Zr) and relatively high Ti contents; in other words, it is more refractory and genuinely residual. The Eu anomaly and Sr contents of RLC and average lower crust are similar, although the former has much higher Sr/Nd (Fig. 6b) and lower Rb/Sr (Fig. 6a, Table 1), as would be imparted by the retention of plagioclase in the RLC during crustal differentiation. In contrast, the lack of Y and Yb enrichment highlights a relatively minor time-integrated role for residual garnet. The calculated *D* values for different elements during crustal differentiation are summarised in Table 1, and these reflect the principal mineralogical controls in the differentiation of the continental crust.

A second implication of this model concerns the relative proportions of the differentiated upper crust and its complementary mafic residue. The upper crust with Eu/Eu* = 0.7 is ~12.5 km thick in crust with an average thickness of 40 km (Rudnick and Gao, 2003). If the upper crust represents the product of 14% melting, the corresponding RLC would be 77 km thick, resulting in a total crustal thickness of ~100 km, including the middle crust. However, there is scant geophysical evidence for a contemporary mafic lower crust of this thickness (Rudnick and Gao, 2003), and the appropriate melt-depleted compositions are uncommon in the spectrum of exposed lower crustal lithologies

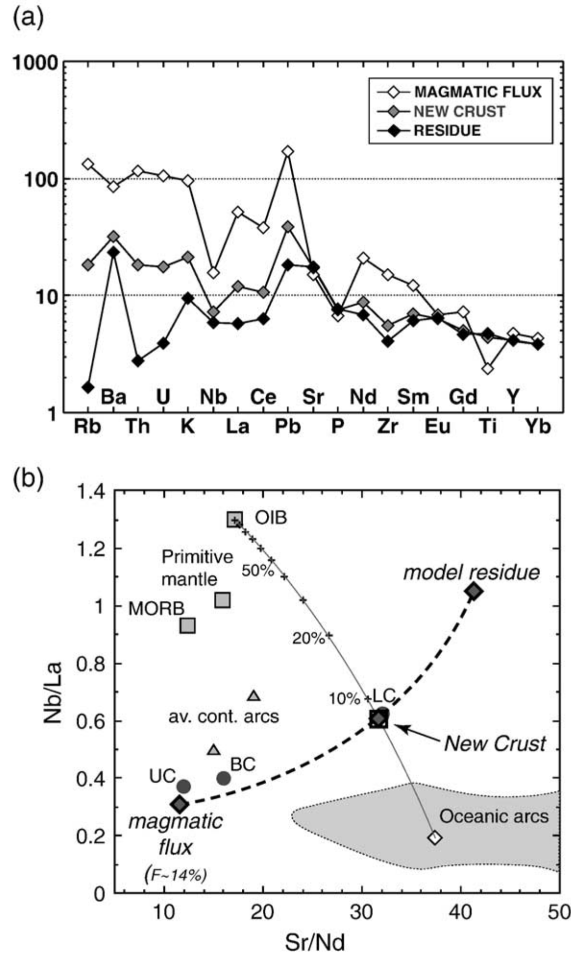

Fig. 6. (a) The compositions of the 'magmatic flux' (Table 1), the inferred bulk composition for new continental crust (Fig. 3), and the residue after 14% melting to generate the magmatic flux into the upper continental crust. (b) Plot of Nb/La–Sr/Nd, as in Fig. 2, illustrating the crust differentiation model for 14% partial melting. The model residue after 14% melting is also plotted and it is clearly displaced from the average lower crust of Rudnick and Gao (2003).

(Rudnick and Fountain, 1995). These observations agree with predictions that such a thick residual layer would be gravitationally unstable under most geothermal conditions, owing to phase transformations that produce dense minerals like garnet (Kay and Kay, 1991, 1993; Jull and Kelemen, 2001). Thus, the volumetrically dominant residue of upper crust formation has largely been returned to the mantle, with the consequence that the residence time of material in the lower crust is far shorter than in the upper crust. Crustal differentiation is a logical thermal consequence of crust generation, as seen for example in the Andes (Petford and Atherton, 1996) and the Lachlan Fold Belt (Kemp and Hawkesworth, 2003; Hawkesworth and Kemp, 2006-this volume), particularly where crustal melting is driven by basaltic under-/intraplating (e.g. Voshage et al., 1990; Bergantz and Dawes, 1994; Annen and Sparks, 2002). The inferred rapid processing of lower crustal material, and delamination of the residues, therefore tend to happen at the sites of active crustal growth (e.g. Kay and Kay, 1993; Jull and Kelemen, 2001; Zandt et al., 2004), facilitated by both density foundering (Petford and Atherton, 1996) and tectonic erosion of the over-riding plate at subduction zones (von Huene and Scholl, 1991; Clift and Vannuchi, 2004).

4. Rates of generation and recycling of continental crust

Understanding the rates at which new crust was formed, and subsequently recycled into the mantle, requires quantification of the various mass fluxes into and out of the continental reservoir. One approach entails the direct measurement of magmatic addition rates to the continental crust at modern or relatively recent volcanic arcs and intraplate hot spots, first attempted by Reymer and Schubert (1984). These workers estimated a global average of 1.65 km^3/year for the addition of new continental crust, with destructive plate margin settings being dominant (1.1 km^3/year). This figure can be revised upwards slightly to 1.84 km^3/year, using more robust seismic refraction data to assess oceanic arc magma productivity (Kelemen et al., 2003; Holbrook et al., 1999; Suyehiro et al., 1996). Nevertheless, these estimates must be viewed as minimum growth rates or survival rates, since they neglect the destruction of continental crust by forearc erosion and sediment subduction (von Huene and Scholl, 1991). According to Clift and Vannuchi (2004), the latter amounts to about 3.6 km^3/year globally. Given that a small annual increase in continental crustal volume is needed to maintain constancy of freeboard since the Archaean (Schubert and Reymer, 1985), the true global magma emplacement rates would then be slightly higher than this, viz. 3.7 km^3/year (Clift and Vannuchi, 2004). The envisaged higher melt emplacement rates above subduction zones means that the ratio of new crust generated in modern arcs and intraplate settings (8:1) approaches that inferred for the continental protolith using the independent geochemical arguments summarised in Fig. 2.

A second approach relies on the residence time of key elements in the crustal column and this tends to yield higher crust generation rates. The rare earth elements Sm and Nd are perhaps the most useful, since they form a long-lived radiogenic isotope system and the Sm/Nd (parent–daughter) ratio of mantle-derived rocks is not readily fractionated during intracrustal differentiation. As such, the average or ‘model’ age for when Nd in the rocks of the continental crust was extracted from the mantle can be calculated. The mean Nd isotope model age of the global sedimentary mass is 2.0 ± 0.2 Ga (Allègre and Rousseau, 1984), which, by extension, approximates the average residence time for the upper continental crust and the elements therein.

Fig. 7 illustrates the relationship between the annual flux into the upper continental crust and the residence

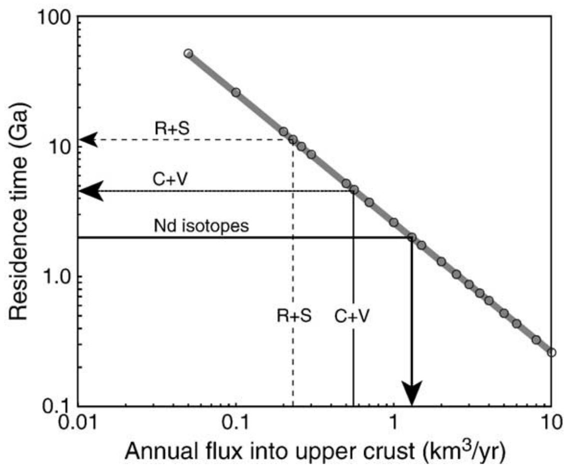

Fig. 7. Plot of residence time in the continental crust (in Ga) versus the annual flux of differentiated material into the upper crust. For the sake of discussion, we have assumed that the volume of the upper crust has remained approximately constant. The residence times corresponding to the magmatic flux rates of Reymer and Schubert (1984) (R+S, 0.23 km^3/year) and that calculated from Clift and Vannuchi (2004) (C+V, 0.56 km^3/year) are indicated. In contrast, the solid line shows the much higher rate of upper crustal addition (1.3 km^3/year) necessary to satisfy the 2 Ga upper crustal residence time indicated by Nd isotope studies (Allègre and Rousseau, 1984).

times therein for a simple box model in which the volume of the upper crust is kept constant at 2.61×10^9 km^3. The annual flux into the upper continental crust is taken to be 14% of the total amount of bulk continental crust generated each year for the reasons outlined in the model summarized in Table 1 and Fig. 6. Thus, the various estimates for the rate of magma addition to the crust (1.65, 1.84 and 3.7 km^3/year) are equivalent to values of 0.23, 0.26 and 0.56 km^3/year for the rate of formation of new upper crust. These correspond in turn to upper crustal residence times of 11 Ga, 10 Ga and 4.7 Ga, respectively; all of which greatly exceed the average Nd model age for the continental crust and indeed the age of the Earth. We interpret this difference as evidence that the rate of continental crustal generation, and of the flux of differentiated magma into the upper crust, was far greater earlier in Earth history than in the relatively recent geologic past. In contrast a residence of 2 Ga for elements in the upper crust converts to an average rate of generation of 1.3 km^3/year for the upper crust (Fig. 7) and of 9.3 km^3/year for the bulk continental crust. This finding is consistent with the relatively rapid increase in the volumes of stable continental crust in the Late Archaean and Early Proterozoic inferred from Nd isotopes (Allègre and Rousseau, 1984), the distribution of U–Pb ages of juvenile igneous rocks (Condie, 1998) and models of a hotter early Earth (Davies, 1995). The rate of 9.3 km^3/year is significantly higher than the average rate of crustal growth if the present volume has been generated since 3.5 Ga, which is 2.2 km^3/year. But given that crustal material is recycled into the mantle, the true rate of crust generation is inevitably higher than the rates at which volumes of continental crust were *stabilised*, as constrained from long-lived radioactive isotopes. Finally, we note that, since the residence times of elements in the upper crust was inferred from long-lived isotopes, this is likely to be a maximum value and hence the calculated rate of crust generation will be a minimum.

5. Wider implications

The model outlined here for the differentiation of the continental crust indicates that it is dominated by magmatic processes, and that the residence times for elements in the upper and the lower crust are likely to be very different. The residence time of the upper crust inferred from the model Nd age suggests that the annual fluxes of material into this reservoir, and hence of new continental crust, are at least three to six times higher than previous estimates. These are the inferred rates at which new crust was generated, and they are therefore higher than the rates at which the continental crust stabilised for long enough to be reflected in changes in Nd isotope ratios. A consequence of the higher rates of crust generation, and hence of destruction, is that more of the Earth's mantle has potentially been processed through the continental crust. For example, using a crust generation rate of 9.3 km^3/year and concentrations of K and Li of 1.6 and 250 ppm for the primitive mantle (from Elliott et al., 2004) and 15,000 and 8 ppm for new continental crust, 47% of the K and 25% of the Li in the silicate Earth could have been processed through the continental crust over the last 4 Ga. This has clear implications for, for example, the Li isotope geochemistry of oceanic basalts and thus mantle convection processes (Elliott et al., 2004). In practice, these may be minimum estimates since (a) the model Nd age for the upper crust is a maximum value and (b) the rates of crust generation will have been higher than average in the Archaean and continental crustal rocks are known to have been present at 4.4 Ga (Wilde et al., 2001).

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