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LETTERS

A link between large mantle melting events and continent growth seen in osmium isotopes

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Although Earth's continental crust is thought to have been derived from the mantle, the timing and mode of crust formation have proven to be elusive issues. The area of preserved crust diminishes markedly with age[1,2], and this can be interpreted as being the result of either the progressive accumulation of new crust[3] or the tectonic recycling of old crust[4]. However, there is a disproportionate amount of crust of certain ages[1,2], with the main peaks being 1.2, 1.9, 2.7 and 3.3 billion years old; this has led to a third model in which the crust has grown through time in pulses[1,2,5–7], although peaks in continental crust ages could also record preferential preservation. The ^{187}Re–^{187}Os decay system is unique in its ability to track melt depletion events within the mantle and could therefore potentially link the crust and mantle differentiation records. Here we employ a laser ablation technique to analyse large numbers of osmium alloy grains to quantify the distribution of depletion ages in the Earth's upper mantle. Statistical analysis of these data, combined with other samples of the upper mantle, show that depletion ages are not evenly distributed but cluster in distinct periods, around 1.2, 1.9 and 2.7 billion years. These mantle depletion events coincide with peaks in the generation of continental crust and so provide evidence of coupled, global and pulsed mantle–crust differentiation, lending strong support to pulsed models of continental growth by means of large-scale mantle melting events[6].

The detailed timing of continental crust extraction should be recorded in the radiogenic isotope composition of the mantle. A systematically declining distribution of mantle depletion ages would support the steady accumulation model. Peaks in the depletion ages that corresponded to the zircon crustal age peaks would support the pulsed growth model.

The main impediment to seeing the record of crust extraction in the mantle is the disturbance of most radiogenic isotope systems by crustal recycling, metasomatic activity and dilution of the signal by convection. These processes re-enrich parts of the mantle and destroy the signature of melt depletion. Even in continental lithospheric mantle, isolated from convection for billions of years, Sr, Nd and Pb isotope signatures are dominated by enrichment processes[8]. We have therefore been unable to observe clearly the history of crust formation from the mantle.

The Re–Os isotope system has been singularly successful in tracing the depletion history of the subcontinental lithospheric mantle over 3-Gy periods despite equilibration temperatures of more than 1,000 °C (see, for example, refs 8, 9). This is due to its greater robustness to re-enrichment by melts and because osmium resides in dispersed trace phases that are less likely to re-equilibrate by diffusion. These properties also make the system useful for tracing the melt depletion history of the convecting mantle. Two types of sample useful for tracing depletion in the convecting mantle are abyssal peridotites, which increasingly seem to document melting events older than the age of the ridge they are dredged from[10,11], and osmium-rich platinum-group alloy grains (PGAs) derived from ophiolites, which also seem to record melting events older than the oceanic lithosphere in which they are found[12,13]. Here we use published abyssal and cratonic peridotite data along with published and new analyses of PGAs to investigate further the link between crust and mantle differentiation events.

We have made new osmium-isotope analyses of PGAs from the Urals, Tasmania and Tibet. We used a rapid but precise laser ablation ICPMS analytical technique (Supplementary Methods). All PGA grains studied were osmium-rich Os–Ir–Ru alloys[14].

The PGAs studied here form during chromite mineralization events in oceanic lithosphere that subsequently become ophiolites. Silicate-melt, chromite and sulphide inclusions within PGAs clearly indicate their magmatic formation[15]. The parental melts scavenge osmium from the mantle source and hence their osmium isotope compositions reflect source heterogeneities generated from previous melting events. Once formed, the low-Re/Os, osmium-rich PGAs are robust recorders of the source osmium isotope composition.

The four PGA locations studied range in formation age from 95 to 510 Myr. ^{187}Os/^{188}Os values vary widely, from 0.109 to 0.16 (Supplementary Information). The data from each location have probability density distributions indicative of multiple populations, with a main peak and one or more subsidiary peaks. The association of the PGAs with ophiolitic chromites ties the melting regime that transfers their osmium isotope signature from mantle to crust to a back-arc setting. The boninitic character of their trapped melts[15] confirm a previously depleted source and indicate PGAs forming from numerous melt infiltration events into oceanic lithosphere. Depleted ^{187}Os/^{186}Os values have not been not manifested in present-day mid-ocean-ridge and oceanic-island basalts analysed so far because their melt budget is strongly influenced by low-melting-point components such as pyroxenites[16] and high-Re/Os metasomatic sulphides[17]. Only in melting environments where these components have been largely melted out, and where melting of refractory, previously depleted mantle is assisted by the addition of water, can the depleted component dominate the osmium isotopic composition of some melts. Such water-rich melts have been shown to crystallize podiform chromites and hence to provide an environment for PGA formation[18] and the transfer of depleted osmium isotope signatures from the convecting mantle into the lithosphere.

To allow comparison with other records of mantle depletion, the PGA osmium isotope compositions can be recast as model ages, assuming the complete removal of rhenium from the source during melting. The resulting ages are direct functions of the model reservoir selected to simulate upper-mantle osmium isotope evolution. Extreme estimates for upper-mantle osmium isotope evolution models yield an uncertainty in the accuracy of any age of 0.4 Gyr but do not change the relative positions of age peaks (Supplementary Information). We use

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ordinary (O) chondrites[19] as our reference mantle reservoir because this provides age estimates that are intermediate between the extremes produced by carbonaceous chondrites and primitive upper mantle.

Probability density plots of model ages (Fig. 1) show multiple peaks for all suites. The primary age peak for the PGAs and abyssal peridotites, samples of recent convecting upper mantle, is between 200 and 500 Myr, indicating evolution with an average Re/Os ratio slightly less than average O-chondrites. In the PGA suites the most prominent secondary model age peak is at 1.2 Gyr. This peak is also evident in the abyssal peridotite data and is prominent in the age distribution of cratonic peridotites from southern Africa and their sulphides. Given the differences in the physical nature of the PGA and peridotite/sulphide sample sets together with their global distribution, the degree of correspondence between the model age peaks recorded is remarkable. Another, smaller age peak is present in the Urals PGA data, abyssal peridotites and cratonic xenoliths at about 1.9 Gyr, and the Californian PGAs have two grains with ages of 2.7 Gyr. These ancient ages are clear evidence of the ability of the Re–Os isotope system to retain the imprint of ancient melting events, but our currently limited understanding of osmium diffusion in the convecting mantle does not yet permit a complete understanding of how the record is preserved.

To provide an independent estimate of the number and approximate ages of components present in our PGA data sets, we adopted a maximum-likelihood mixture modelling approach[20]. In all two component mixture models (Supplementary Methods), a 1.0–1.2-Gyr component is produced. When additional age components are introduced, the roughly 1.2-Gyr population persists and forms between 10% (California and Tibet) and 43% (Tasmania) of the population. Mixture modelling independently identifies components at about 1.6–1.9 Gyr in the abyssal, Urals and California data and also picks out a population at 2.6 Gyr within the California data in all models with more than two components. The use of a bayesian mixture modelling approach and Markov-chain Monte Carlo methods[21] produces very similar results.

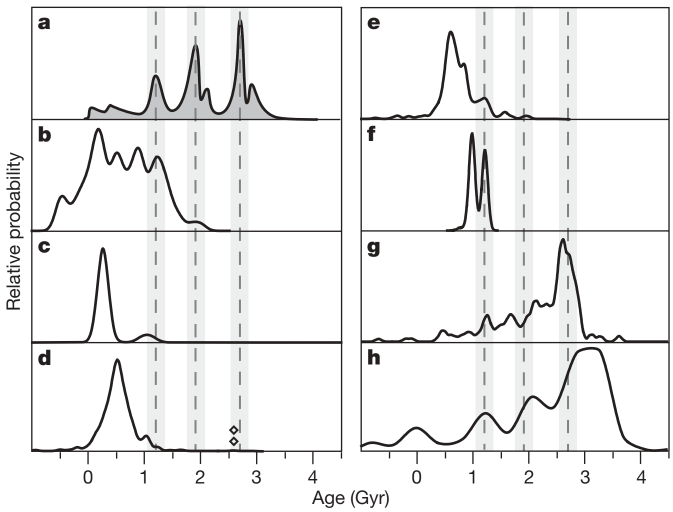

Figure 1 | Continental crust zircon ages compared with ages recorded in mantle samples. Probability density graphs of crustal zircon U-Pb ages[6] (**a**) plus osmium model ages (T_{RD}, Gyr) for mantle samples (**b**–**h**). Mantle samples comprise osmium-rich platinum-group metal alloys[12,13,24–27] (see Supplementary Information) (**c**–**f**), abyssal peridotites[10,11] (**b**), southern African cratonic peridotites[8,9] (**g**) and sulphides from cratonic peridotites[28,29] (**h**). Two stacked diamonds in **d** denote two data points at 2.6–2.7 Gyr. Ages are rhenium depletion ages (T_{RD}) for PGAs and peridotites but are calculated from measured Re/Os ratios (T_{MA}) for sulphides (see ref. 8 for details), to account for their significant Re/Os ratios. Ophiolite emplacement ages for PGAs together with numbers of samples for PGAs, southern African peridotites and their sulfides are as follows: **b**, abyssal, 0–50 Myr, $n = 80$; **c**, Tibet, 95 Myr, $n = 274$; **d**, California, 165 Myr, $n = 721$; **e**, Urals, 400 Myr, $n = 339$; **f**, Tasmania, 518 Myr, $n = 80$; **g**, $n = 228$; **h**, $n = 262$. Data for the Urals, Tasmania and Tibet are from this study and refs 24, 27 (see Supplementary Information). All data and probability density plots of osmium isotope ratios are given in Supplementary Information and were constructed with the program described in ref. 30. Graphs were plotted with uniform internal errors on individual model ages of 0.1 Gyr, to avoid overemphasis on single data points determined to high internal precision. The accuracy of the model ages is illustrated by the shaded zones surrounding the reference lines at 1.2, 1.9 and 2.7 Gyr and is taken from accuracy estimates using the different mantle reference reservoirs (see Supplementary Methods). Parameters for the calculation of model ages relative to the O-chondrite reservoir[19] are $^{187}Os/^{188}Os = 0.1283$ and $^{187}Re/^{188}Os = 0.422$.

It is important to evaluate the statistical significance of the age coincidences and to what extent the age distributions could be explained by heterogeneities in the mantle that have evolved from variable Re/Os and/or $^{187}Os/^{188}Os$ ratios in the original material that accreted to form the Earth. Of the chondritic meteorites analysed for osmium isotopes[19], one has an anomalously low $^{187}Os/^{188}Os$ value, yielding a model age equivalent to 1.2 Gyr. Could the model ages of mantle samples simply reflect original mantle osmium isotope heterogeneity? If so, a convecting mantle reservoir with a relatively low Re/Os ratio should still evolve isotopically through time (Fig. 2) because the anomalous chondrite sample has a Re/Os ratio only 27% lower than average. Any peaks in the isotopic composition of mantle rocks sampling this reservoir should also change position through time to reflect this evolution. This is clearly not true for the PGA and mantle data sets. Although the primary mode of each sample varies back through time, the secondary peak is stationary, at $^{187}Os/^{188}Os \approx 0.120$, equivalent to an age of 1.2 Gyr (Fig. 2). This indicates that the process forming the PGAs samples mantle regions containing additional, non-chondritic components of consistent isotopic composition that must have evolved with a Re/Os ratio close to zero. This almost invariant isotopic evolution will take place only if the source of this signature represents a residue from large degrees of melting, probably in excess of 35%, reducing the Re/Os ratio to very low values. These low-Re/Os sources must have remained in the convecting upper mantle for Gyr timescales, possibly trapped in areas of unusual mantle flow such as subduction zone wedges[22].

Monte Carlo simulations were performed to test the hypothesis that the data are single, normally distributed populations and that the secondary peaks are simply random fluctuations. No secondary 1.2-Gyr age-equivalent peaks were reproduced that were as large as those observed in the real data (Supplementary Information). Furthermore, no simulations produced any data with ages of 2.7 Gyr, indicating the very low probability that such ancient ages are random features. The likelihood of a specific peak's being repeated in different data sets was also tested by Monte Carlo simulation. Using even the widest likely normally distributed PGA data set (Fig. 3, thick lines) and assuming uniform probability, the chance of the California, Urals, Tasmania and Tibet data sets producing coincident age peaks at about 1.2 Gyr, in agreement with the zircon data, is 1 in 10^4. Using our preferred normal distribution, which matches the shapes of the major peaks in all the data sets, gives a probability of 1 in 10^{10} that the age correspondence in PGA data sets is fortuitous. Observing, by chance, only one PGA data set with a 2.7-Gyr age peak coincident with that of crustal zircons has a probability of less than 1 in 10^5. Therefore the coincidences between mantle Re–Os depletion ages and crustal zircon ages are highly significant.

The secondary peaks evident on a global scale seem to be recording large melting events superposed on a general trend of mantle depletion, indicating that an unusually large amount of depleted, low-Re/Os mantle formed at these times. These major melt depletion events, recorded in a diverse array of sample types over a wide geographic area, correspond very well to the crustal zircon age peaks (Fig. 1), so the zircon record must reflect crustal growth during major mantle melting events at these times. It is highly unlikely that such a coincidence could arise from preferential preservation of crust. The crust–mantle age correspondence provides very substantial support

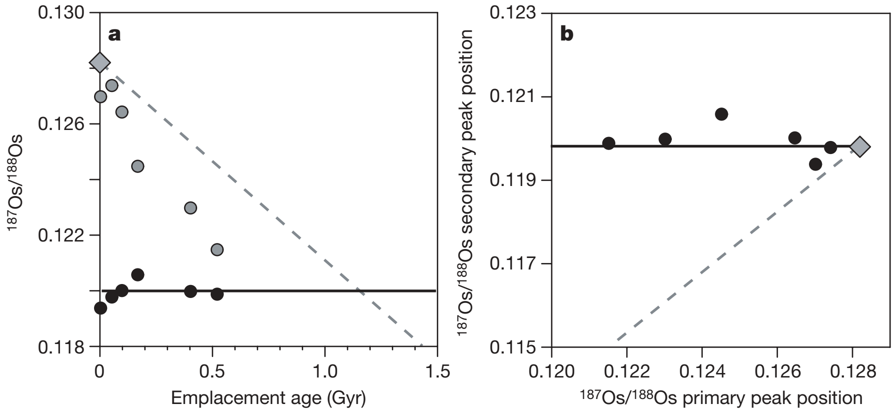

Figure 2 | Assessment of whether age peaks are due to mantle heterogeneity. a, $^{187}Os/^{188}Os$ ratio of the primary and secondary peaks for PGA suites, abyssal peridotites and peridotites from the Izu–Bonin–Mariana trench as a function of emplacement age. Peak positions were taken from probability density graphs and verified by mixture modelling (Supplementary Methods). Dashed line shows the evolution of average ordinary chondrite (parameters given in Fig. 1). Grey circles are $^{187}Os/^{188}Os$ values of the primary peak, which are always sub-chondritic; black circles give the position of the main secondary peaks. Emplacement ages are taken from Fig. 1. **b**, The relative positions of the primary and secondary age peaks. The position of the secondary peak in the PGA and abyssal peridotite data remains constant (horizontal line) as a result of a large-degree melt depletion event at 1.2 Gyr that decreases the Re/Os ratio to close to zero, whereas the position of the primary peak changes. Mantle heterogeneity of the type displayed by chondrites would result in data following the trajectory of the dashed grey line.

for crustal growth models that are punctuated by intense growth periods[5–7]. The periods of enhanced crust generation have been termed 'superevents' and can be can be recognized as pulses of formation of granite–greenstone terranes possibly linked to superplume events[6]. The pulsating nature of mantle depletion and crust formation revealed by osmium isotopes concurs with the picture of crust–mantle differentiation evident from convecting mantle helium-isotope systematics[23], in which peaks in helium isotopic compositions are interpreted to reflect the same major melt extraction events as those identified here.

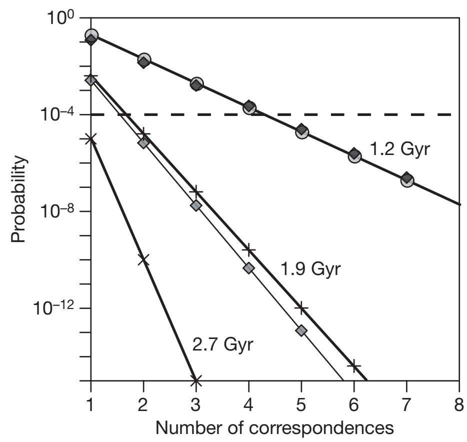

Figure 3 | Probability that the secondary age peaks (Fig. 1) match by random chance as the number of matching localities increases. Grey circles show probabilities calculated assuming the data are uniformly distributed, that is, a data point is equally likely to fall at any location within 99% of the range of the data. As all ages are equally likely, this curve applies to peaks of any age. All probabilities below 10^{-6} were extrapolated from the Monte Carlo modelling (see Supplementary Methods). When the abyssal peridotite data are included, the probability decreases from 1 in 10^4 (see the text) to 1 in 10^5. In fact, the data seem to be quasi-normally distributed (older ages less likely). Thus, the uniform distribution overestimates the probability of these older peaks and provides an upper limit to the probabilities. The use of a best-fit normal curve (primary position = 0.128, variance = 0.003; thick lines) yields very similar probabilities for the 1.2-Gyr peak (black diamonds), but much lower probabilities for the 1.9-Gyr (plus signs) and 2.7-Gyr (crosses) peaks, because data at older ages becomes increasingly unlikely with a normal distribution. Alternatively, the data can be viewed as containing two populations (a primary peak and a secondary peak). In this case, the primary peak represents the distribution of the data (primary position = 0.128, variance = 0.001). This is a much narrower distribution, and older ages are extremely unlikely. In this more realistic case, the chances of four data sets fortuitously giving an age peak correspondence at 1.2 Gyr (grey diamonds) is 1 in 10^{10}.

The zircon record in the continental crust retains abundant evidence of ancient events, whereas the number of ancient osmium model ages from the mantle declines sharply with increasing time (Fig. 1). The declining abundance of ancient depletion ages for PGA grains is a function of the mixing efficiency of mantle convection (Fig. 1). Although it is still possible to see evidence of the roughly 1.9-Gyr and 2.7-Gyr mantle depletion events, their clearer resolution and the detection of even older crust extraction events requires PGAs from older ophiolites than those sampled here.

The roughly 1.2-Gyr 'event' is the most prominent of the old mantle osmium model age peaks. However, this event is the least well defined in the zircon record in the continental crust and has been taken to indicate a less voluminous addition of juvenile material to the crust at 1.2 Gyr (refs 6, 7). However, the signature of major mantle melt extraction at this time is clear and widespread and could suggest unexposed additions to the lower crust that have not yet been documented, or the generation of dominantly zircon-poor basaltic crust at that time. Overall, the striking correlation between the timing of major crustal and mantle melting events is strongly supportive of the punctuated generation of juvenile continental material linked to major melting of the mantle.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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