Re–Os isotope evidence for the composition, formation and age of the lower continental crust

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Knowledge of the composition of the lower continental crust is important for understanding the formation and evolution of the crust as a whole, and the petrogenesis of continental basalts. Here we present rhenium–osmium isotope data for two well characterized suites of lower-crustal xenoliths from North Queensland, Australia[1–7], which have average major- and trace-element compositions similar to estimates of the bulk lower continental crust[8–9]. Our data indicate that the lower crust has 1 to 2 times as much osmium, about half as much rhenium, and is less radiogenic than the upper continental crust[10]. We interpret the rhenium–osmium isotope systematics to indicate that assimilation and fractional crystallization are important processes in the formation of the lower crust, and lead to dramatic changes in the osmium isotopic composition of basalts that pond and fractionate there. A consequence of this is that the rhenium–osmium isotopic system should not be relied on to yield accurate mantle extraction ages for continental rocks.

Re–Os differs from other isotopic systems (Pb, Sr and Nd) because Re and Os are siderophile and chalcophile (rather than lithophile) elements, and because Os is a compatible element (Os is retained in the crystals) during partial melting or fractional crystallization[11]. The fact that Os is a compatible element leads to high Re/Os ratios and radiogenic Os isotopic compositions in the continental crust[12] and makes $^{187}Os/^{188}Os$ ratios in fractionating mantle-derived magmas susceptible to change by crustal contamination[13–18].

The Os isotopic composition and Re and Os concentrations of 16 samples from two well characterized lower-crustal xenolith suites from North Queensland, Australia[1–7], are reported in Table 1. These xenoliths have average major- and trace-element compositions similar to estimates of the bulk lower continental crust[8,9] (Fig. 1a), and can therefore be used to place broad constraints on its Re–Os concentration and Os isotopic composition. The xenoliths have average Os and Re concentrations of respectively 102 and 276 parts per 10^{12} (p.p.t; Re/Os = 2.71), with median values of 49 and 184 p.p.t. (Re/Os = 3.75), respectively (Table 1, Fig. 1b). The differences between the average and the median are produced by one outlier (sample 85–100) with high Os (~1,000 p.p.t.) and Re (~800 p.p.t.) concentrations. The median values are probably more representative of the bulk lower crust, but more data are clearly desirable. The mean, concentration-weighted, $^{187}Os/^{188}Os$ ratio for the lower crust in north Queensland is 0.4 or 0.8, including and excluding the outlier, respectively. Recent analysis of eclogitic and granulite facies xenoliths from central Arizona give similar results (Table 1, Fig. 1b and c)[19], although these have somewhat lower Os contents which translate into a slightly higher mean Re/Os ratio. We infer from these data that, relative to the upper crust[10], the lower crust has one to two times as much Os, about half of the Re, and is probably less radiogenic (having one-half to one-third the $^{187}Os/^{188}Os$ of the upper crust). However, the Os isotopic composition of the lower
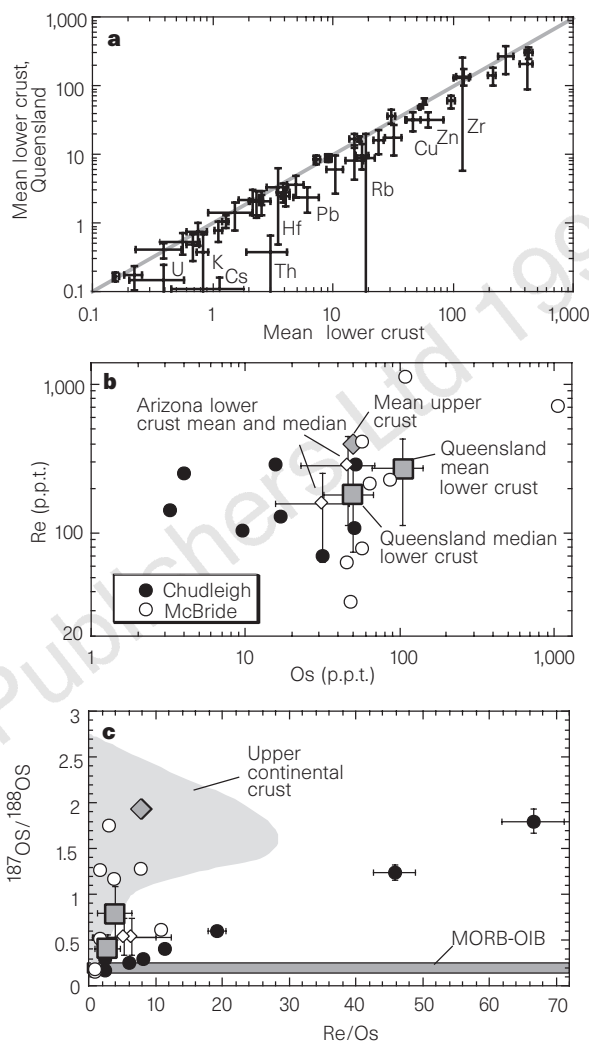

Figure 1 Representativeness and Re-Os composition of Queensland lower-crustal xenoliths. **a**, Comparison between the mean major- and trace-element composition of global lower-crustal xenoliths with those from the Queensland xenoliths. The global dataset (available on http://www-ep.es.llnl.gov/germ/) includes 450 analyses of major elements and 150 analyses of trace elements, excluding the Queensland data. Both means agree within the standard errors of the compilations, with the exception of Cs, Th, U, Pb, Cu and Zn, which we attribute to the mobility of these elements during secondary processes and the difficulty in their accurate measurement. The fact that many lower-crustal xenoliths are demonstrably older than the magmatic episode that carried them to the surface[8] suggests that the global average is a reasonable estimate of lower-crust composition. **b**, Os versus Re concentrations, and **c**, Re/Os versus $^{187}Os/^{188}Os$ ratios for lower-crustal xenoliths from Queensland, Australia. The two mean lower-crustal isotopic compositions shown in **c** are weighted according to Os concentrations (filled squares). The lower one includes an anomalously high Os point, the upper one excludes this point. Fields for upper continental crust (without organic and carbonate-shelf sediments) (filled diamond) and oceanic basalts (mid-ocean ridge basalts and oceanic island basalts) were compiled by B. Peucker-Ehrenbrink. The mean and median Re and Os concentration, Re/Os ratios and isotopic composition weighted by Os concentration for Arizona xenoliths[19] (open diamonds) are plotted for comparison. The McBride xenoliths (open circles) show chemical characteristics indicative of a lithologically and genetically diverse suite, and plot in the field defined by upper-crustal material. The Chudleigh suite (filled circles) shows characteristics of genetically related cumulates from basaltic magma undergoing crustal contamination (see text).
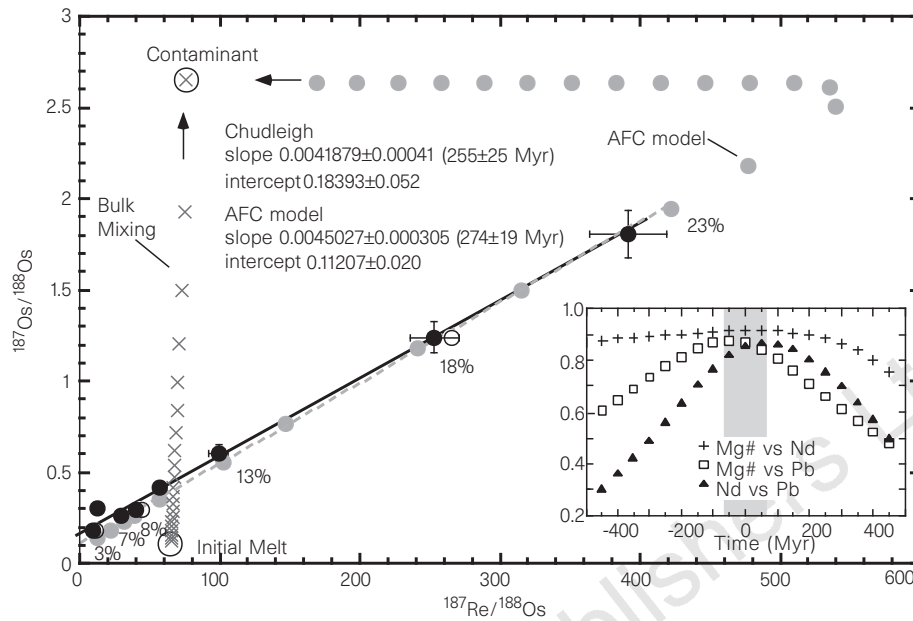
Figure 2 Re–Os isochron diagram for the Chudleigh suite showing bulk mixing and AFC trends. The data define a linear tend (filled circles), defining an apparent age of ~260 Myr. Inset shows correlation coefficients (for linear correlations) between Mg#, Nd (^{143}Nd/^{144}Nd) and Pb (^{206}Pb/^{204}Pb). In contrast to the Re–Os age, the best correlations exist at < 100 Myr, suggesting that the crystallization age of these xenoliths was <100 Myr. The AFC model (using the parameters listed in Fig. 3 legend) generates a linear trend in the Re–Os diagram (shown by grey circles), which has no age significance. Open circles are duplicate analyses, not included in the isochron regression. X's show the bulk mixing trend between the initial melt and the assimilant used in the AFC model. Each grey circle and X corresponds to 5% AFC or bulk mixing, respectively. The York regression for the AFC model was calculated using the same number of points and same distribution in the isochron as the Chudleigh suite to make the results comparable (the points used are labelled; for example 3%). We note that the Chudleigh xenoliths are cumulates, producing low Re/Os during the initial stages of AFC. Figs 2 and 3 indicate that careful evaluation of AFC is necessary before age significance is attributed to Re–Os isochrons for lower-crustal xenoliths or for basalts (or their cumulates) that may have differentiated in the lower continental crust.

Table 1 Re and Os concentrations and Os isotopic compositions of granulite-facies lower-crustal xenolith suites from Northern Queensland, Australia

Sample	Lithology	Re (p.p.t.)	Os (p.p.t.)	^{187}Re/^{188}Os	^{187}Os/^{188}Os	$T_{Os,CH}$ (Myr)
Chudleigh suite						
83-107	Pl-rich cumulate	153.2	3.20	265	1.2492	258
		146		252		271
83-114*	Pl-rich cumulate	109.6	49.7	10.66	0.18750	349
		89.8	53.8	8.08	0.18895	478
83-127	Pl-rich cumulate	132.2	16.5	39.5	0.30557	275
		146.6		43.9		248
83-131	Pl-rich cumulate	104.7	9.39	56	0.4251	324
83-140	Pl-rich cumulate	259	3.85	391	1.8138	263
83-110	Px-rich cumulate	70.8	31.3	11.27	0.31038	1,013
83-115	Px-rich cumulate	292	15.3	97.9	0.6132	302
BC	Transitional cum.	297	51	28.7	0.27030	305
McBride suite						
83-160	Felsic granulite	219	61.9	19.33	1.1799	3,299
83-162	Felsic granulite	80.1	56.2	7.23	0.5013	3,250
85-100*	Mafic granulite	734	1,043	3.41	0.1794	897
		808	931	4.21	0.16524	586
85-108*	Mafic granulite	1,141	106.5	55.0	0.6230	550
		1,210	104.5	59.3	0.6079	494
85-106	Mafic cumulate	50.8	47.4	5.26	0.19930	884
		34.5		3.58		1,349
83-159	Mafic residue	422	55.9	41.9	1.2959	1,692
85-114*	Mafic residue	234	84	16.28	1.7597	5,970
		230	86	15.46	1.6590	5,910
83-157	Metasediment	64.1	44.5	8.00	1.2832	8,649
Crustal averages						
North Queensland mean		276	102	13.54	0.418	1,330
North Queensland median		**184**	**49**	**19.70**	**0.804**	**2,100**
Central Arizona mean[19]		286	45	32.33	0.548	2,278
Central Arizona median[14]		161	31	26.42		796
Average upper crust[10]		400	50	47.62	1.9256	976

$T_{Os,CH}$ are Os model ages calculated with respect to 'bulk earth' ^{187}Re/^{188}Os = 0.4243 and ^{187}Os/^{188}Os = 0.1287 (ref. 21) and a decay constant of 1.64×10^{-11}; Pl, plagioclase; Px, pyroxene. Analytical techniques are described in ref. 22. Run precision in all measurements is $2\sigma < 0.35\%$ for ^{187}Os/^{188}Os, $2\sigma < 1\%$ for Os and $2\sigma < 2\%$ for Re contents (samples 83-107 and 83-140 have $2\sigma < 10\%$ and <7% for Os concentration and isotopic composition, respectively, due to blank correction). The analytical blanks ranged from 4 to 4.7 for ^{187}Os/^{188}Os, 0.4 to 0.5 pg g^{-1} for Os and 5 to 24 pg g^{-1} for Re. All samples were corrected for blank contribution. Re and Os were determined on separate powder splits subjected to acid digestion (Re) or fusion (Os). Repeat Re and Os concentration and ^{187}Os/^{188}Os were made on separate powder splits. Os and Re replicates range from 2% to 11% and 1% to 18%, respectively (excluding 85-106 with 32% difference in the Re replicate). ^{187}Os/^{188}Os ratios for replicates for the Chudleigh xenoliths are <0.6%, but for the McBride suite, the replicates range from 2% to 5%. The style of the poor reproducibility in replicates in the McBride suite (that is, large variation in ^{187}Os/^{188}Os ratios and Re contents, at similar Os concentrations) is suggestive of a Re 'nugget' effect–that is, domains or minerals having higher Re/Os are heterogeneously distributed within the rock, and have been out of diffusive equilibrium with the rest of the rock for reasonably long time spans (in this case ~300 Myr, the age of the suite[3]).
* Indicates sample and replicate that were rerun on the same day.

continental crust will vary with the age of the crust. Given a mean age of 2.3 Gyr for the continental crust[20], the Re–Os composition of the mantle[21] and our average Re/Os estimates including and excluding the data for the Arizona xenoliths[19] (^{187}Re/^{188}Os ≈ 20 and 16, respectively), we calculate the mean ^{187}Os/^{188}Os of the bulk lower crust to be between 0.7 and 0.9 (Fig. 1c), a range that encompasses the median Os isotopic composition derived from the Queensland xenoliths (Table 1). Importantly, our data establish the presence of material with relatively high Os contents and radiogenic Os isotopic compositions in the lower crust. The variation in Os isotopic composition and Re–Os concentrations in all three xenolith suites illustrates the heterogeneity of the present

lower crust and shows that isotopic homogenization through fluid flow or melting has not been important.

The two suites of xenoliths from Queensland show differences in Re and Os concentration and Re/Os ratios, but have a similar, and large, range in ^{187}Os/^{188}Os ratios (from 0.1721 and 1.759 versus 0.1889 to 1.814) (Fig. 1a and b). McBride xenoliths have a larger range of Re (two orders of magnitude), and a smaller range of Os contents and Re/Os ratios than Chudleigh xenoliths (a factor of less than two, excluding the outlier). These characteristics are consistent with the extreme lithologic and genetic diversity of McBride xenoliths, which range from paragneisses to mafic and felsic orthogneisses formed during large-scale mixing between Protero-
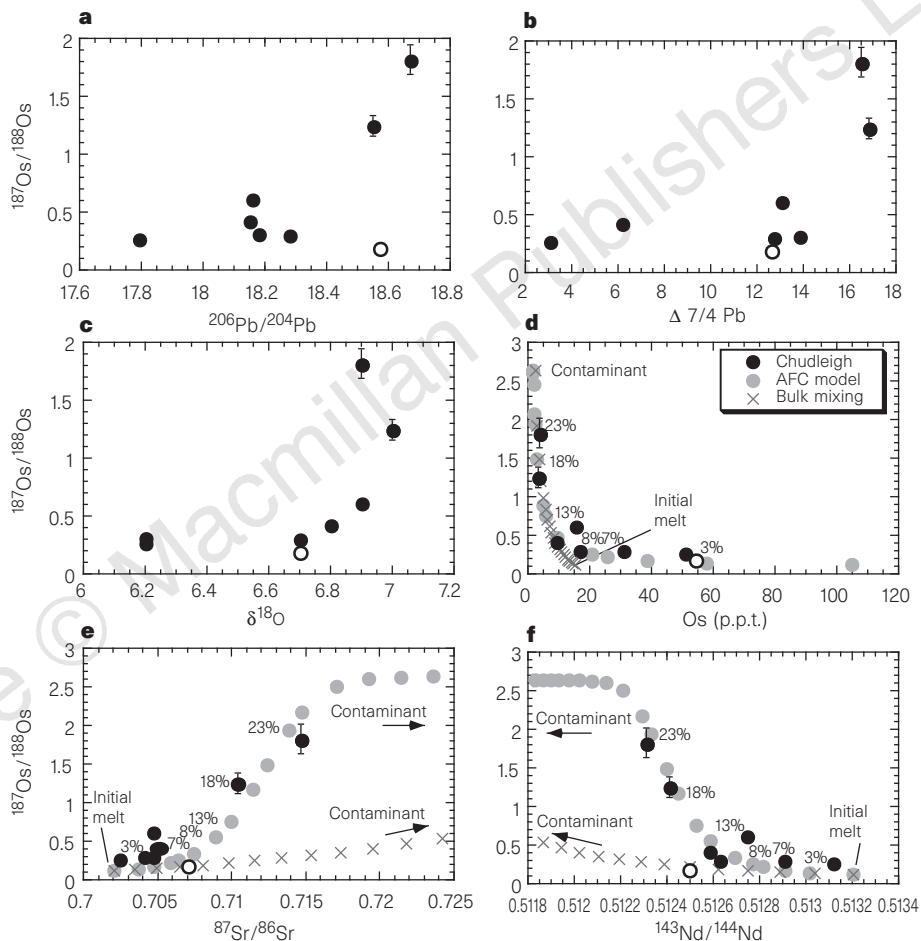

Figure 3 Isotopic correlations and AFC model for Chudleigh xenoliths. ^{187}Os/^{188}Os versus ^{206}Pb/^{204}Pb (**a**), Δ 7/4 Pb (see ref. 23) (**b**), δ^{18}O (**c**), Os concentration (**d**), ^{143}Nd/^{144}Nd (**e**) and ^{87}Sr/^{86}Sr (**f**) for the Chudleigh suite. Relatively good correlations exist between ^{187}Os/^{188}Os, Os concentration and Pb, Sr, Nd, Pb, O isotopic systems, with the exception of one sample. The aberrant sample (83-114, open circle) is probably showing the 'nugget' effect (see Table 1); this explanation is consistent with this sample having the lowest Os isotopic ratios and the highest Os concentration, and plotting outside the correlation defined by the other samples in Os-Ni and Os-Mg# plots (not shown). The AFC curves are marked in 5% increments (except the labelled points), where the ratio of mass assimilated to mass fractionated is ≈0.67. The contaminant has intermediate Sr and Nd isotopic compositions (^{87}Sr/^{86}Sr ≈ 0.75 and ^{143}Nd/^{144}Nd ≈ 0.5114) and elemental concentrations (Sr ≈ 200 p.p.m., Nd ≈ 27 p.p.m.), based on published data for Tasman fold belt crust[1]. It is assumed to have very low Os (~2 p.p.t.) to test the sensitivity of Os to crustal contamination, and Re concentrations (~24 p.p.t.), and ^{87}Os/^{188}Os ≈ 2.6477 (T_{OsCH} ≈ 2 Gyr; see Table 1 for definition), similar to Proterozoic upper continental

crust. All isotope systems (for example, Sr, Nd, Pb, O and Os) require a contaminant that is more evolved than any sample seen in either the Chudleigh or McBride xenolith suites and suggests the presence in the lower crust of (unsampled) old material with high δ^{18}O and time-integrated high Rb/Sr, U/Pb and Re/Os, and low Sm/Nd. For the parental basaltic melt we used the most primitive isotopic composition seen in the xenoliths (^{87}Sr/^{86}Sr ≈ 0.702, ^{143}Nd/^{144}Nd ≈ 0.5131) and inferred ^{187}Os/^{188}Os ≈ 0.1276. We assumed that this melt has Sr ≈ 350 p.p.m., Nd ≈ 14 p.p.m., and has Re ≈ 250 p.p.t., and 7.5 times the Os concentration of the contaminant (~15 p.p.t.). Bulk partition coefficients for Sr and Nd were estimated assuming cumulates of plagioclase + clinopyroxene + olivine (D^{Sr} ≈ 0.5, D^{Nd} ≈ 0.1). The bulk partition coefficient for Os (D^{Os} ≈ 7), was estimated from the correlation of Os-Ni (bulk D^{Ni} ≈ 7.4)[11]; Re was assumed to be moderately incompatible (D^{Re} ≈ 0.6). The AFC model presented here is not unique, but serves to illustrate that the trends observed in the data are explained by an AFC process; the same is not true for bulk mixing, which is shown for comparison. D is the bulk partition coefficient of an element between the solid crystals and the residual melt.

zoic crust and basalts during late Palaeozoic (~300 Myr age) convergent margin magmatism[2–7]. Chudleigh xenoliths are mafic in composition ($SiO_2 < 51.2$ wt%), showing good correlations between Sr, Nd, Pb and O isotopic composition, trace-element contents and Mg# (molar Mg/(Mg + Fe) ratios)[1,4,6,7]. These correlations reflect a genetically related suite of cumulates from mafic magma(s) that underwent simultaneous assimilation and fractionation in the deep crust[1]. It is very unusual to find such simple chemical and isotopic systematics in lower-crustal xenolith suites. The Chudleigh suite thus provides a unique natural laboratory with which to investigate the chemical changes occurring to mafic magmas that pond and fractionate within the deep continental crust.

Although the Chudleigh xenoliths cannot be dated directly, the chemical systematics described above provide some constraints on their magmatic crystallization age. Because the xenoliths are cumulates, and not crystallized magmas, they have a large range in Sm/Nd ratio, depending upon whether plagioclase or clinopyroxene is the main cumulate phase. Thus the excellent correlations between Nd isotopic composition (which ranges from ϵ_{Nd} of +9.6 to −6.1), Mg# (63–79) and Pb ($^{206}Pb/^{204}Pb$ = 17.8–18.7), Sr (0.70239–0.71467) and O ($\delta^{18}O$ = +6.2 to +7.0) isotopes seen today degrade as the isotopic compositions are calculated at earlier times[1,4] (Fig. 2, inset). These features led to the conclusion that the cumulates crystallized relatively recently (<100 Myr ago), and that they are probably related to Cenozoic igneous activity that occurs throughout eastern Australia[1].

The Re–Os results for the Chudleigh xenoliths show a strikingly good linear correlation on a Re–Os isochron diagram, defining an apparent age of ~260 Myr (Fig. 2). There are two possible interpretations of this correlation: (1) it accurately reflects the igneous crystallization age of the xenoliths, and (2) it reflects recent mixing between a mantle-like endmember and a radiogenic crustal endmember. We prefer the second interpretation for the reasons outlined below.

Parental magmas to the xenoliths underwent both crystallization (as evidenced by the cumulate xenoliths) and crustal assimilation (as seen in the Nd, Sr, Pb, O isotopic systems, trace-element and Mg# systematics)[1,4,7]. If interpretation (1) is correct, at ~260 Myr ago either Os isotopes were completely immune to crustal assimilation, and the samples should all have the same initial $^{187}Os/^{188}Os$, or Os was affected and should therefore correlate with other indicators of contamination (for example, O isotopes). Neither is true. The ($^{187}Os/^{188}Os)_{260 Myr}$ ratios of these xenoliths have a large range, between 0.12 and 0.26 (compare with 0.1276 to 0.1565 for modern mantle-derived basalts), and do not correlate with any of the other isotopic systems at ~260 Myr. In contrast, relatively good positive correlations are seen for present-day $^{187}Os/^{188}Os$ and O, Pb and Sr isotopic compositions and negative correlations between $^{187}Os/^{188}Os$ and Nd isotopic ratios (Fig. 3). The inset to Fig. 2 shows that the correlations between different isotope systems, as measured by their correlation coefficient, are best within 50–100 Ma of the present. The general lack of correlations between Mg# and Nd, Pb isotopes at 260 Myr (refs 1, 4; Fig. 2, inset), coupled with the relatively good present-day correlations[1,4] (Fig. 3), strongly suggests that these cumulates did not crystallize at 260 Myr. We conclude that the positive trend in the Re–Os isochron diagram was produced by assimilation and fractional crystallization (AFC) processes at a later date.

We model the Chudleigh xenoliths as cumulates resulting from simultaneous AFC of a basaltic melt in the deep continental crust (Fig. 3d–f; modelling parameters are given in Fig. 3 legend). The sigmoidal shape of the curves shows that during the first stages of AFC the Os isotopic composition is buffered by the Os content in the basaltic magma, whereas during the later stages it is buffered by the Os content and isotopic composition of the assimilate (old continental crust). The fractionation of olivine and/or sulphide

decreases the concentration of Os in the magma[11], making it susceptible to contamination with crustal material having low Os concentration (2 p.p.t., in our model). We note that in the initial and final stages there is decoupling between $^{187}Os/^{188}Os$ and the other isotopic systems. The compatible behaviour of Os relative to Nd, Sr and Pb, and the differences in Os concentration and isotopic composition between mantle melts and evolved crustal materials, accounts for the buffering of Os in the melt; such effects are generally not observed in the other isotopic systems. Moreover, the compatible character of Os explains the large difference between the trends produced by AFC and bulk mixing (Figs 2 and 3) and makes AFC a far more effective process for changing the isotopic composition of the basalt than bulk mixing, especially when the contaminant has a low Os concentration. Not only does the AFC model explain the correlation between $^{187}Os/^{188}Os$ and the other isotopic ratios observed in the Chudleigh xenoliths (Fig. 3d–f), it also reproduces the near-linear trend in the Re–Os isochron diagram (Fig. 2). Our data show that apparent whole-rock Re–Os isochrons with no age significance may be produced during AFC processes by depletion of Os through olivine-sulphide fractionation, coupled with assimilation of radiogenic crust. Moreover, small amounts (<20%) of AFC during basalt/lower-crust interaction can produce isotopic variations in the melt that could be erroneously interpreted as evidence for mantle heterogeneity. □

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