Supplementary Data

1. **Trace Element Melting Model**

We found that batch melting of a mixture of 80:20 depleted:metasomatized subcontinental lithospheric mantle (SCLM) peridotite closely reproduces the trace element pattern of HIMU basalts (Fig. 2). We assumed simple mixing between the two lithologies and used average depleted MORB mantle (DMM) and average and median post-Archean SCLM compositions as representing the depleted and metasomatized rocks, respectively, to produce a mixed SCLM composition. The melt composition (with a partial melt fraction F=1%) was calculated assuming equilibrium with the mixed SCLM having a residual modal mineralogy of 72% olivine, 20% orthopyroxene, 2% clinopyroxene, 5% garnet and 1% carbonate. Calculations used partition coefficients for silicates/basaltic-melt from alphaMELTS, except for Pb, which is not controlled by silicate melting and was set to be equal to Ce partitioning values; carbonate partitioning values are from ref.

2. **Os Evolution Model of Old Metasomatized SCLM**

In Re-Os isotopic studies of lithospheric mantle rocks, ‘formation ages’ or ‘depletion ages’ of the subcontinental lithosphere correspond to the timing of melt extraction from ‘fertile’ peridotite (containing components that can be easily melted), leaving a ‘refractory’ (difficult to melt) residue. The approach works because Re is partitioned into melts during partial melting, while Os remains in the solid residue. To a first approximation this results in a Re/Os ratio of zero in SCLM formed by melt extraction, thus preserving the Os/Os ratio at the time of SCLM formation. However, there are complications that should be considered when applying and interpreting Os data in samples from the SCLM. Among those, metasomatic
refertilization has shown to introduce significant Re, and occasionally Os, into peridotites\textsuperscript{51,56-60}. The contrast between low $^{187}\text{Os}/^{188}\text{Os}$ ratios in old (e.g. Archean and Proterozoic) subcontinental mantle peridotite and the high ratios in OIBs has led to the conclusion that recycled SCLM is not an important component in OIB sources, and particularly HIMU\textsuperscript{26,61}. However, one must consider that studies of SCLM ‘formation ages’ exclude metasomatised peridotites, effectively biasing the available data on xenoliths towards those with low $^{187}\text{Os}/^{188}\text{Os}$ ratios. Indeed, many metasomatised samples show high Re/Os ratios (main text Fig. 3e) and even high $^{187}\text{Os}/^{188}\text{Os}$ ratios (main text Fig. 3f).

We evaluate here whether we can expect carbonatite metasomatized SCLM to develop the high $^{187}\text{Os}/^{188}\text{Os}$ ratios observed in HIMU lavas. The ingrowth of $^{187}\text{Os}/^{188}\text{Os}$ can be evaluated using the basic radioactive decay equation:

\[
(\frac{^{187}\text{Os}}{^{188}\text{Os}})_{\text{today}} = (\frac{^{187}\text{Os}}{^{188}\text{Os}})_{\text{initial}} + (\frac{^{187}\text{Re}}{^{188}\text{Os}})_{\text{today}} \times (e^{\lambda t} - 1)
\]

where $\lambda = 1.67 \times 10^{-11}$ yr$^{-1}$ is the decay constant and $t$ is the age of the metasomatism. We use the following considerations. The presence of sulfur showing mass independent fractionation (MIF) in Mangaia lavas\textsuperscript{8} is evidence that the HIMU mantle source contains subducted surface material that formed in the Archean or earliest Proterozoic. We treat the HIMU source as a mixture of ‘normal’ melt-depleted SCLM plus SCLM that was metasomatized by the subducted material, as described above. By analogy to present-day oceanic crust, we assume that only a short amount of time passed (<200 Ma) between its formation and subduction. Thus the sequence of events from the formation of ‘normal’ SCLM melt to the metasomatism of SCLM to form the HIMU mantle source (events 1 and 2 in main text Fig. 4), would have occurred during the Archean or early Proterozoic.
In order to evaluate the Os isotope evolution, we illustrate the effects of a metasomatic event at 2.7 Ga, realizing that it might have occurred earlier or later. For simplicity, we assume that the $^{187}\text{Os}^{188}\text{Os}$ ratio of the SCLM at the time of the metasomatic event was the same as primitive upper mantle (PUM), which can be calculated using the present-day PUM values of $^{187}\text{Os}^{188}\text{Os} = 0.129$ and $^{187}\text{Re}^{188}\text{Os} = 0.43$ as equal to 0.109 at 2.7 Ga. In order to estimate the Re/Os ratios of ‘normal’ and ‘metasomatized’ SCLM, we use the averages of 143 cratonic lherzolite xenoliths (Os= 1.29 ±1.93 ppb, Re= 0.08 ±0.19 ppb) and 31 metasomatized harzburgite xenoliths (Os= 1.22 ±1.88 ppb, Re= 0.22 ±0.4 ppb), respectively, from the mantle xenolith database in PetDB (Source Data Table 1, www.earthchem.org/petdb), all with Mg# between 0.910-0.935. Samples that were not defined as harzburgite or lherzolite in the original papers were not included in the averages. We calculate $(^{187}\text{Os}^{188}\text{Os})_{\text{today}}$ for mixtures of different proportions of lherzolite ($^{187}\text{Re}^{188}\text{Os}=0.4$) and metasomatized harzburgite ($^{187}\text{Re}^{188}\text{Os}=2.44$) (Extended Data Fig. 5), that evolved from the PUM value $(^{187}\text{Os}^{188}\text{Os} =0.109)$ at 2.7 Ga.

Extended Data Fig. 5 shows that only 18-30% metasomatized harzburgite is required in the SCLM mixture in order to reproduce the range of $^{187}\text{Os}^{188}\text{Os}$ observed in HIMU lavas for a metasomatic event at 2.7 Ga (corresponding to $^{187}\text{Re}^{188}\text{Os}$ ratios between 0.7672 and 1.012). A lower proportion of metasomatized harzburgite would allow for an earlier metasomatic event, and higher proportions would imply a later event. Thus the example shows that SCLM that experienced carbonatite metasomatism during the Archean to early Proterozoic is a reasonable source to explain the high Os ratios observed in HIMU basalts.
Supplementary Data References


