

possible to assess whether the observed changes in the WTP reflect a larger, basin-scale change in the isotopic composition of the ocean. However, numerical model simulations have suggested that sustained shifts in the location of the Intertropical Convergence Zone (ITCZ) over the tropical Atlantic Ocean would probably affect the vapour flux to the Pacific, and change the fresh water as well as the isotopic balance over the oceans¹⁵. A persistent displacement of the ITCZ to more northerly latitudes in summer would act to trap isotopically light vapour within the Atlantic basin and decrease the vapour gain in the Pacific. The salinity and $\delta^{18}\text{O}$ changes we document from the WTP occurred in close association with the precessional cycle and with enhanced solar heating in the northern tropics during the early Holocene, which would have tended to pull the ITCZ north off its present summer latitude¹⁴. Over the course of millennia a northerly bias in the latitude of the ITCZ and reduced vapour transport between the oceans could have affected the isotopic composition of Pacific surface waters. At present there are no continuous SSS records from the tropical Atlantic and eastern Pacific that span the entire Holocene and provide the same temporal resolution that is available for the WTP. Nonetheless, previous studies have documented an early Holocene pluvial over North Africa and a stronger Indian Ocean summer monsoon in response to Earth's precessional cycle^{16,17}. Cariaco Basin sediments also contain evidence of higher rainfall in northern South America during the early Holocene, with increasingly arid conditions developing during the past 5,000 yr (ref. 18). These data all point to tropic-wide changes in the hydrological cycle that have been attributed to a more northerly position of the ITCZ during the early Holocene in response to changes in solar radiation associated with the precessional cycle. Data from other parts of the Pacific and Atlantic will now be required for an assessment of whether the changes in the hydrologic cycle affected the salinity gradient between the Pacific and Atlantic Oceans. If so, millennial to centennial scale changes in Holocene ocean thermohaline circulation would be directly affected by ocean-atmosphere processes that have occurred in the tropics. □

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1. Levitus, S. & Boyer, T. P. *World Ocean Atlas 1994* Vol. 3, *Salinity* (NOAA Atlas NESDIS, US Department of Commerce, Washington DC, 1994).
2. Cronin, M. F. & McPhaden, M. J. Upper ocean salinity balance in the western equatorial Pacific. *J. Geophys. Res.* **103**, 27567–27587 (1998).
3. Sun, D.-Z. & Trenberth, K. E. Coordinated heat removal from the equatorial Pacific during the 1986–87 El Niño. *Geophys. Res. Lett.* **25**, 2659–2662 (1998).
4. McPhaden, M. J. Genesis and evolution of the 1997–98 El Niño. *Science* **283**, 950–954 (1999).
5. Aggarwal, P. K., Fröhlich, K., Kulkarni, K. M. & Gourcy, L. L. Stable isotope evidence for moisture sources in the Asian summer monsoon under present and past climate regimes. *Geophys. Res. Lett.* **31**, doi:10.1029/2004GL019911 (2004).
6. Fairbanks, R. G. *et al.* Evaluating climate indices and their geochemical proxies measured in corals. *Coral Reefs* **16**, S93–S100 (1997).
7. Morimoto, M. *et al.* Salinity records for the 1997–98 El Niño from Western Pacific corals. *Geophys. Res. Lett.* **29**, doi:10.1029/2001GL013521 (2002).
8. Nürnberg, D., Bijma, J. & Hemleben, C. Assessing the reliability of magnesium in foraminiferal calcite as a proxy of water mass temperature. *Geochim. Cosmochim. Acta* **60**, 803–814 (1996).
9. Lea, D. W., Pak, D. K. & Spero, H. J. Climate impact of late Quaternary equatorial Pacific sea surface temperature variations. *Science* **289**, 1719–1724 (2000).
10. Oppo, D. W., Linsley, B. K., Rosenthal, Y., Dannenmann, S. & Beaufort, L. Orbital and suborbital climate variability in the Sulu Sea, western tropical Pacific. *Geochim. Geophys. Geosyst.* **4**, doi:10.1029/2001GC000260 (2003).
11. Fairbanks, R. A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature* **342**, 637–642 (1989).
12. Clement, A. C., Seager, R. & Cane, M. A. Orbital controls on the El Niño/Southern Oscillation and the tropical climate. *Paleoceanography* **14**, 441–456 (1999).
13. Gagan, M. K. *et al.* Temperature and surface-ocean water balance of the mid-Holocene tropical western Pacific. *Science* **279**, 1014–1018 (1998).
14. Liu, Z., Kutzbach, J. & Wu, L. Modeling climate shift of El Niño variability in the Holocene. *Geophys. Res. Lett.* **27**, 2265–2268 (2000).
15. Schmittner, A., Appenzeller, Z. & Stocker, T. F. Enhanced Atlantic freshwater export during El Niño. *Geophys. Res. Lett.* **27**, 1163–1166 (2000).
16. Prell, W. L. & Van Campo, E. Coherent response of Arabian Sea upwelling and pollen transport to late Quaternary monsoonal winds. *Nature* **323**, 526–528 (1986).
17. DeMenocal, P., Ortiz, J., Guilderson, T. & Sarnthein, M. Coherent high- and low-latitude climate variability during the Holocene warm period. *Science* **288**, 2198–2202 (2000).
18. Haug, G. H. *et al.* Southward migration of the Intertropical Convergence Zone through the Holocene. *Science* **293**, 1304–1308 (2001).

19. Waelbroeck, C. *et al.* Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records. *Quat. Sci. Rev.* **21**, 295–305 (2002).

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Osmium isotopic constraints on the nature of the DUPAL anomaly from Indian mid-ocean-ridge basalts

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The isotopic compositions of mid-ocean-ridge basalts (MORB) from the Indian Ocean have led to the identification of a large-scale isotopic anomaly relative to Pacific and Atlantic ocean MORB¹. Constraining the origin of this so-called DUPAL anomaly² may lead to a better understanding of the genesis of upper-mantle heterogeneity. Previous isotopic studies^{3–10} have proposed recycling of ancient subcontinental lithospheric mantle or sediments with oceanic crust to be responsible for the DUPAL signature. Here we report Os, Pb, Sr and Nd isotopic compositions of Indian MORB from the Central Indian ridge, the Rodriguez triple junction and the South West Indian ridge. All measured samples have higher ¹⁸⁷Os/¹⁸⁸Os ratios than the depleted upper-mantle value^{11,12} and Pb, Sr and Nd isotopic compositions that imply the involvement of at least two distinct enriched components in the Indian upper-mantle. Using isotopic and geodynamical arguments, we reject both subcontinental lithospheric mantle and recycled sediments with oceanic crust as the cause of the DUPAL anomaly. Instead, we argue that delamination of lower continental crust may explain the DUPAL isotopic signature of Indian MORB.

In the Pb–Sr–Nd isotopic space, the Indian MORB array differs from the Pacific and Atlantic arrays by a distinct ‘low ²⁰⁶Pb/²⁰⁴Pb’ end-member characterized by lower ²⁰⁶Pb/²⁰⁴Pb, ¹⁴³Nd/¹⁴⁴Nd and higher ²⁰⁷Pb/²⁰⁴Pb, ²⁰⁸Pb/²⁰⁴Pb and ⁸⁷Sr/⁸⁶Sr ratios. These compositions imply the presence in the upper Indian mantle of a component that has undergone a long time-integrated evolution with high Th/U, Rb/Sr ratios and low U/Pb, Sm/Nd ratios relative to the Atlantic–Pacific upper mantle. Previous Sr–Nd–Pb isotopic studies^{3–10} of Indian MORB have related the DUPAL signature to recycled continental lithosphere, either as old subcontinental lithosphere or as sediments associated with oceanic crust. Subcontinental lithosphere requires the presence in the upper mantle of another recycled component having HIMU-like isotopic compositions (that is, high $\mu = ^{238}\text{U}/^{204}\text{Pb}$) whereas recycled oceanic crust associated with variable amounts of sediments may produce both the HIMU

and DUPAL signatures and account for all the Indian MORB isotopic variations. Solving the origin of the DUPAL anomaly remains a major goal of chemical geodynamics, essential for understanding the genesis of mantle heterogeneity.

The Re–Os isotopic system differs from other long-lived isotopic systems because the melting process strongly fractionates Re and Os; Re behaves as a moderately incompatible element and is thus enriched in melts whereas Os is strongly compatible and remains in the residue. Owing to their high Re/Os ratios, the oceanic and continental crusts develop radiogenic $^{187}\text{Os}/^{188}\text{Os}$ ratios. The radiogenic $^{187}\text{Os}/^{188}\text{Os}$ ratios measured in oceanic island basalts (OIB) are generally thought to reflect the recycling of such crustal materials in the Earth's mantle—more specifically, oceanic crust with or without sediment^{13–17}. The Re–Os system appears to be relatively insensitive to large-scale mantle metasomatism compared to the other isotopic systems, with an elevation of the mantle's $^{187}\text{Os}/^{188}\text{Os}$ ratio limited to 0.15 (ref. 18 and references therein). Indeed, the negative correlation between the Re/Os ratio and the Os content defined by metasomatized xenoliths and metasomatic minerals implies that the more Os-rich a metasomatic agent is, the less radiogenic it becomes through ^{187}Re decay and the less it affects the mantle Os isotopic evolution¹⁸. Even metasomatized, mantle fragments that have encountered significant melt extraction—that is, old continental and oceanic lithosphere—display a relative Re depletion and preserve subchondritic Os evolution. Particularly unradiogenic Os compositions of oceanic basalts, lower than the depleted MORB mantle (DMM) value, have been interpreted to reflect the presence of such an old recycled lithosphere in their mantle sources¹⁹. Thus, the Os isotopic ratios should enable us to determine which part of the continental lithosphere—that is, subcontinental mantle or continental crust-related material—is the origin of the DUPAL anomaly. The first Os isotopic analyses of MORB^{11,13,20} revealed significantly higher $^{187}\text{Os}/^{188}\text{Os}$ ratios than the estimated DMM composition^{11,12}. This difference has been attributed either to the melting of a heterogeneous mantle source^{11,20} or to sea-water-related contamination^{11,13}. Here we present evidence that, for samples with Os > 2 p.p.t., the Os isotopic compositions we measured in Indian MORB (that is, 13 samples from the Central Indian ridge (CIR), two samples from the

Rodriguez triple junction (RTJ) and one from the 39–41° E segment of the South West Indian ridge (SWIR), reported in Table 1) reflect the Indian upper-mantle composition. The ultralow Os contents of our analytical blanks allow us to interpret the measured ratios as representative of the samples we analysed. Moreover, because these Os isotopic compositions do not correlate with the Os (Fig. 1) or with MgO content, contamination by sea water ($^{187}\text{Os}/^{188}\text{Os} \approx 1.06^{21}$) and assimilation-fractional crystallization can be rejected as the origin of the high Os isotopic ratios measured. MORB from the CIR and RTJ display very homogeneous $^{187}\text{Os}/^{188}\text{Os}$ ratios (0.1356–0.1400) along the ridge, with the exception of four samples (Fig. 2). The significantly higher $^{187}\text{Os}/^{188}\text{Os}$ ratios of two CIR samples having Os contents higher than 2 p.p.t., located south of the Marie Céleste fracture zone (MCFZ), are in agreement with their significantly higher $^{87}\text{Sr}/^{86}\text{Sr}$, $^{206}\text{Pb}/^{204}\text{Pb}$ and lower $^{143}\text{Nd}/^{144}\text{Nd}$ and can be attributed to the interaction with a Réunion-type mantle flow⁸ (Fig. 2). The two other Os radiogenic CIR samples have the lowest Os contents of this study (below 2 p.p.t.) and irreproducible $^{187}\text{Os}/^{188}\text{Os}$ ratios. Their Os isotopic compositions also contrast with their other isotopic ratios, suggesting syn- or post-eruption contamination. The sample from the extreme DUPAL segment of the SWIR has the highest $^{187}\text{Os}/^{188}\text{Os}$ ratio we measured, among the most radiogenic compositions measured in MORB, and 6 p.p.t. Os. Such an extreme composition is consistent with the extreme Pb, Sr and Nd isotopic compositions of this sample. Taken as a whole, this evidence suggests that, for our data, the Os isotopic compositions of MORB with Os > 2 p.p.t. can be interpreted as reflecting the Indian upper-mantle composition and used to constrain the nature of the DUPAL anomaly.

Our Os systematics in Indian MORB confirm the radiogenic $^{187}\text{Os}/^{188}\text{Os}$ ratio of the DUPAL component²⁰ and preclude delaminated subcontinental lithospheric mantle with its low $^{187}\text{Os}/^{188}\text{Os}$ ratio as the DUPAL component. The high $^{187}\text{Os}/^{188}\text{Os}$ ratios of the extreme Indian MORB can hardly be produced by mantle metasomatism¹⁸ and instead support the recycling of a continental-crust-related component into the Indian mantle, as proposed on the basis of the Nb/U and $^{87}\text{Sr}/^{86}\text{Sr}$ correlation defined by central Indian MORB¹⁰. While sediments

Table 1 Os, Re and MgO concentrations and isotopic compositions of MORB from CIR, RTJ and 39–41° E SWIR

	Latitude	Longitude	MgO (wt%)	Re (p.p.t.)	Os (p.p.t.)	^{188}Os (p.p.t.)	$^{187}\text{Os}/^{188}\text{Os}$	$^{187}\text{Re}/^{188}\text{Os}$	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
Central Indian ridge													
MD57 D14-1	-1.71	67.97	8.05	918	4.93	0.65	0.1381 (33)	899	0.702936 (06)	0.513095 (07)	18.068	15.498	37.767
MD57 D14-4	-1.71	67.97	7.82	930	17.40	2.28	0.1400 (20)	258	0.702956 (20)	0.513117 (13)	17.983	15.450	37.772
MD57 D13-m	-1.47	67.64	7.27	1148	13.39	1.75	0.1356 (15)	414	0.702983 (07)	0.513063 (07)	18.040	15.469	37.860
MD57 D11-1	-4.17	68.33	8.10	766	1.50	0.20	0.1451 (30)	2474	0.702839 (21)	0.513106 (04)	18.170	15.475	37.765
MD57 D10 ⁻ -1	-6.22	68.25	7.01	963	3.16	0.41	0.1397 (15)	1470	0.703018 ^a	0.513022 ^a	18.318 ^a	15.499 ^a	38.244 ^a
MD57 D9-6	-8.00	68.08	8.97		110.93	14.53	0.1366 (06)		0.702789 (06)	0.513131 (06)	18.166	15.495	37.876
MD57 D9-1	-8.00	68.08	8.88	860	92.71	12.14	0.1400 (06)	45	0.702771 (20)	0.513108 (08)	18.210	15.536	37.946
MD57 D7-2	-12.86	66.41	8.09	865	6.41	0.84	0.1371 (24)	652	0.702847 (21)	0.513129 (42)	18.085	15.473	37.876
MD57 D7-5	-12.86	66.41	8.12	786	5.46	0.71	0.1389 (20)	701	0.702782 (16)	0.513117 (25)	18.271	15.493	37.885
MD57 D6-6	-15.86	67.28	7.94	1508	1.61	0.21	0.1479 (18)	4539	0.702907 (13)	0.513133 (06)	17.872	15.450	37.664
				604	1.34	0.18	0.1530 (19)	2175					
MD57 D5-1	-19.48	65.81	8.37	966	14.72	1.92	0.1628 (14)	318	0.703410 (18)	0.513013 (44)	18.418	15.529	38.345
				938	6.39	0.83	0.1572 (87)	711					
MD57 D3-8	-20.15	66.83	8.30	1008	9.99	1.31	0.1388 (20)	270	0.702985 (19)	0.513045 (35)	18.152	15.514	37.971
MD57 D4-3	-20.27	67.67	8.12	946	13.70	1.79	0.1468 (14)	334	0.702940 (06)	0.513106 (14)	18.294	15.495	37.946
					8.41	1.10	0.1475 (18)						
Rodriguez triple junction													
JC 3-07/3 D1	-25.57	70.03	7.87	713	10.20	1.34	0.1357 (12)	336	0.703113 ^b	0.513048 ^b	17.488 ^b	15.455 ^b	37.500 ^b
JC 2-17/2 D1	-25.61	69.94	8.24	1014	6.67	0.88	0.1388 (12)	725	0.703050 ^b	0.513027 ^b	17.477 ^b	15.455 ^b	37.470 ^b
39–41° E SWIR													
MD34 D5	-43.89	40.65	8.08 ^c	476	6.11	0.78	0.3349 (68)	385	0.704870 ^d	0.512437 ^d	16.877 ^d	15.475 ^d	37.245 ^d

Errors shown in parentheses represent 2σ and correspond to the last two digits. Analytical blanks range from 2 to 12 pg g⁻¹ for Re, from 40 to 70 fg g⁻¹ for Os and 0.25 to 0.45 for $^{187}\text{Os}/^{188}\text{Os}$. All samples have been blank-corrected. $^{143}\text{Nd}/^{144}\text{Nd}$ ratios are corrected for mass-discrimination using $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ and reported to $^{145}\text{Nd}/^{144}\text{Nd} = 0.511960$ for the AMES standard. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are corrected for mass-fractionation using $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and normalized to $^{87}\text{Sr}/^{86}\text{Sr} = 0.71025$ for the NIST SRM987 standard. Mass fractionation for lead was 0.1‰ per atomic mass unit (a.m.u.). Typical uncertainties (1 σ) for lead ratios are 0.012 for $^{206}\text{Pb}/^{204}\text{Pb}$, 0.014 for $^{207}\text{Pb}/^{204}\text{Pb}$ and 0.031 for $^{208}\text{Pb}/^{204}\text{Pb}$. MgO contents have been determined by ICP-AES. ^{a,b,c,d} see Supplementary Information.

subducted with oceanic crust are commonly proposed to be the continental crust material recycled into the upper mantle, we develop arguments against recycled sediments as the DUPAL component and show that delamination of lower continental crust represents a better candidate.

With the aim of explaining the central Indian MORB isotopic variations, Rehkämper and Hofmann¹⁰ have related the DUPAL signature to the contamination of the Indian upper mantle with a recycled component including a 1.5-Gyr-old oceanic crust and variable proportions of pelagic sediments. To reproduce the isotopic variations of the CIR, the RTJ and the 39–41° E SWIR segment basalts, the proportion of sediments in the recycled component has to vary as a function of the degree of upper-mantle contamination. As an example, to explain the Central Indian MORB isotopic variations, the sediment contribution in the recycled component has to increase from 0.5% to 10% as the proportion of recycled component decreases (see Fig. 4 in ref. 10), which requires special pleading. Moreover, the high proportion of recycled component required in the CIR basaltic source, 100% in some cases, would imply that the Indian

upper mantle is mainly composed of recycled material. Turning to the most extreme DUPAL compositions, from the 39–41° E SWIR segment and the lavas of Afanasy Nikitin (AFN)²², even 100% of recycled component with 10% of sediments does not fully account for the data. Furthermore, the DUPAL anomaly is geographically restricted to the Indian and South Atlantic upper mantle, although recycling of oceanic crust and sediments has not been limited to this particular area. All these features argue against recycled sediments as the DUPAL component.

The CIR, the RTJ and the 39–41° E SWIR segment basalts define isotopic trends from an end-member having high ²⁰⁶Pb/²⁰⁴Pb and ¹⁸⁷Os/¹⁸⁸Os and moderate ⁸⁷Sr/⁸⁶Sr and ¹⁴³Nd/¹⁴⁴Nd ratios, close in the Pb–Sr–Nd isotopic space to the convergence zone of the Atlantic, Pacific and Indian MORB trends²³, towards different

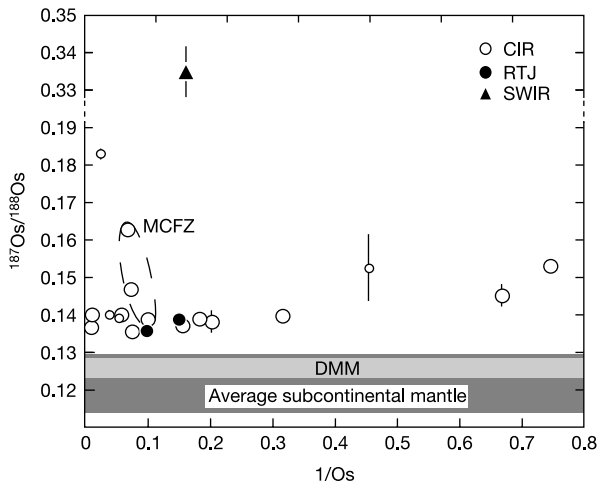


Figure 1 $1/Os$ versus $^{187}Os/^{188}Os$ ratios of MORB from CIR, RTJ and 39–41° E SWIR segment. Data from the Central Indian ridge from^{11,20} are represented as smaller symbols. The $^{187}Os/^{188}Os$ ratios of the two samples with $[Os] < 2$ p.p.t. are non-reproducible and contrast with the Pb–Sr–Nd latitudinal variation (see Fig. 2) which led us to relate these Os isotopic compositions to contamination processes. The lack of correlation between $^{187}Os/^{188}Os$ ratios and $1/Os$ or MgO content supports the absence of significant contamination of samples with $[Os] > 2$ p.p.t. by seawater interaction or assimilation-fractional crystallization. Samples located just south of the MCFZ show relatively high Os content associated with high and reproducible $^{187}Os/^{188}Os$ ratios, consistent with their Pb–Sr–Nd compositions. With the exception of these samples, MORB with $[Os] > 2$ p.p.t. from CIR and RTJ display homogeneous isotopic composition, significantly higher than the DMM value^{11,12} and higher than the average composition of subcontinental lithosphere (average $^{187}Os/^{188}Os \approx 0.1214 \pm 0.0078$ (1 σ), see the Supplementary Information for references used). Sample MD34 D5 from the 39–41° E SWIR segment presents an Os isotopic composition among the highest measured in MORB together with extreme Pb, Sr, Nd isotopic ratios. This result confirms the radiogenic Os composition of the DUPAL component. Two of our samples (MD57 D9-6 and MD57 D'10-1) have already been analysed and the compositions we measured are significantly less radiogenic than those obtained in refs 11 and 20, respectively. Such a difference may be related either to the existence of isotopic heterogeneity within MORB or to the higher Os blanks of previous Os studies. The ratios we measured in this study are consistent with the Os isotopic range of samples with $[Os] > 2$ p.p.t. and with their Pb, Sr and Nd isotopic compositions. All these features together strongly support the idea that the Os isotopic ratios for samples with $[Os] > 2$ p.p.t. reflect the MORB source composition.

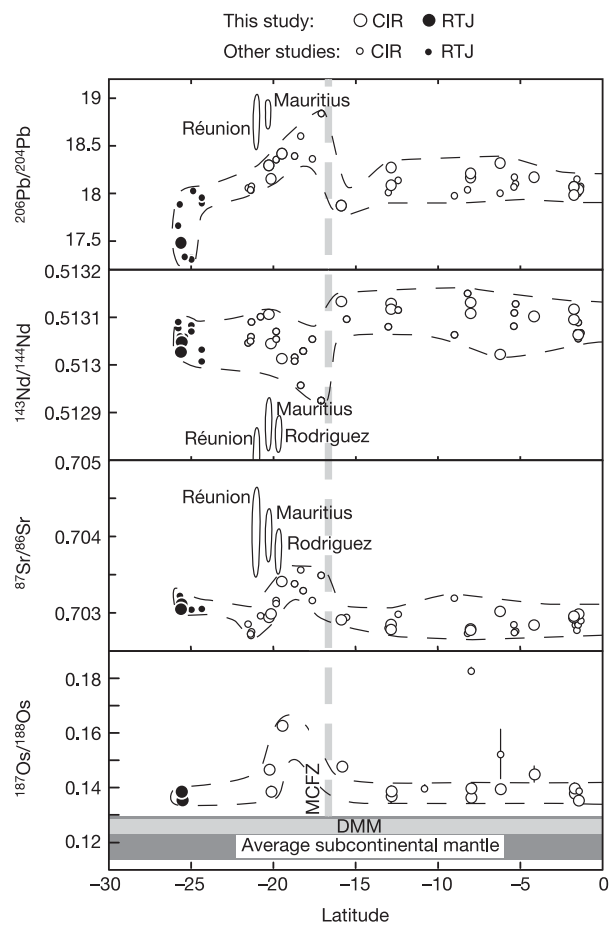


Figure 2 Latitudinal isotopic variation of CIR and RTJ basalts. The larger circles represent samples analysed for Os in this study. Smaller circles are data from previous studies (see Supplementary Information for references used). Os isotopic compositions of DMM^{11,12} and subcontinental lithosphere ($^{187}Os/^{188}Os \approx 0.1214 \pm 0.0078$ (1 σ), see Supplementary Information for references used) are also reported. Dashed curves illustrate the latitudinal isotopic variations. The ratios measured for two of our samples in previous studies and the two Os isotopic ratios of our data set thought to reflect contamination (see Fig. 1) are excluded from the Os dashed field. Os isotopic variation appears similar to those of other isotopes. Indian MORB display limited isotopic variations with latitude, except in the RTJ area and south of the MCFZ. Samples located just south of the MCFZ tend towards the isotopic fields of the Mascarene Islands (data from the GEOROC database, <http://georoc.mpch-mainz.gwdg.de/>), which supports an interaction with Mascarene-type mantle material⁶. The asymmetry of this isotopic anomaly reflects the effect of MCFZ on the mantle flow at the base of the lithosphere.

'low $^{206}\text{Pb}/^{204}\text{Pb}$ ' end-members (Fig. 3). Our data set does not provide any new constraints on the nature of the high $^{206}\text{Pb}/^{204}\text{Pb}$ component, so we focus the following discussion on the other end-members, which are responsible for the DUPAL signature. The alignment of these DUPAL end-members and the AFN (Fig. 3) supports a binary mixing between a depleted mantle source and an extreme DUPAL component.

To reconcile the continental origin of the DUPAL signature with geodynamical aspects, we favour an Indian upper-mantle contamination by delamination of lower continental crust, which represents an alternative mechanism for recycling continental material into the convecting upper mantle. The presence of lower continental crust in the MORB source has already been proposed to explain the extreme composition of one South Atlantic MORB²⁴. In a recent study²⁵, Jull and Kelemen have shown that, owing to the high temperature required for lower continental crust delamination, this delamination process is restricted to arcs, volcanic rifted margins and continental areas that are undergoing extension or removal of the underlying upper mantle. The extension associated with the Gondwana break-up has probably fulfilled the conditions required for lower continental crust delamination and such a contamination would explain the geographical distribution of the DUPAL anomaly. Lower continental crust has the advantage of long-time evolution isolated from mantle convection with high $\text{Re}/$

Os , Th/U , Rb/Sr and low U/Pb , Sm/Nd ratios in agreement with the isotopic features of the DUPAL end-member. Lower continental crust displays radiogenic $^{187}\text{Os}/^{188}\text{Os}$ (ref. 26) as well as low Nb/U associated with radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ (refs 27, 28), consistent with the continental signature identified in the central Indian MORB¹⁰. Mafic xenoliths sampling the African lower continental crust, located between the South Atlantic and Indian oceans, display Pb , Sr and Nd isotopic compositions^{29–31} consistent with the DUPAL signature.

Recycled lower continental crust heterogeneously distributed in the Indian upper mantle explains the different DUPAL end-member isotopic compositions. As shown in Fig. 3, each end-member could be produced by mixing in different proportions of depleted MORB-like melt and lower-continental-crust-derived melt. To maximize the contribution of the lower continental crust, the latter melt is chosen as being produced by 100% of melting of delaminated lower continental crust. Our model shows that only 10% of the melt need be derived from lower continental crust to produce the extreme compositions of RTJ basalts and 50% for the 39–41°E SWIR segment. During the melting process, mafic rocks are expected to be more fertile than the peridotitic mantle and thus to melt to a higher degree, so their contribution in the liquid is increased by a factor of three to four compared to the pristine solid mafic-ultramafic proportions³². A maximum of 4% of recycled lower

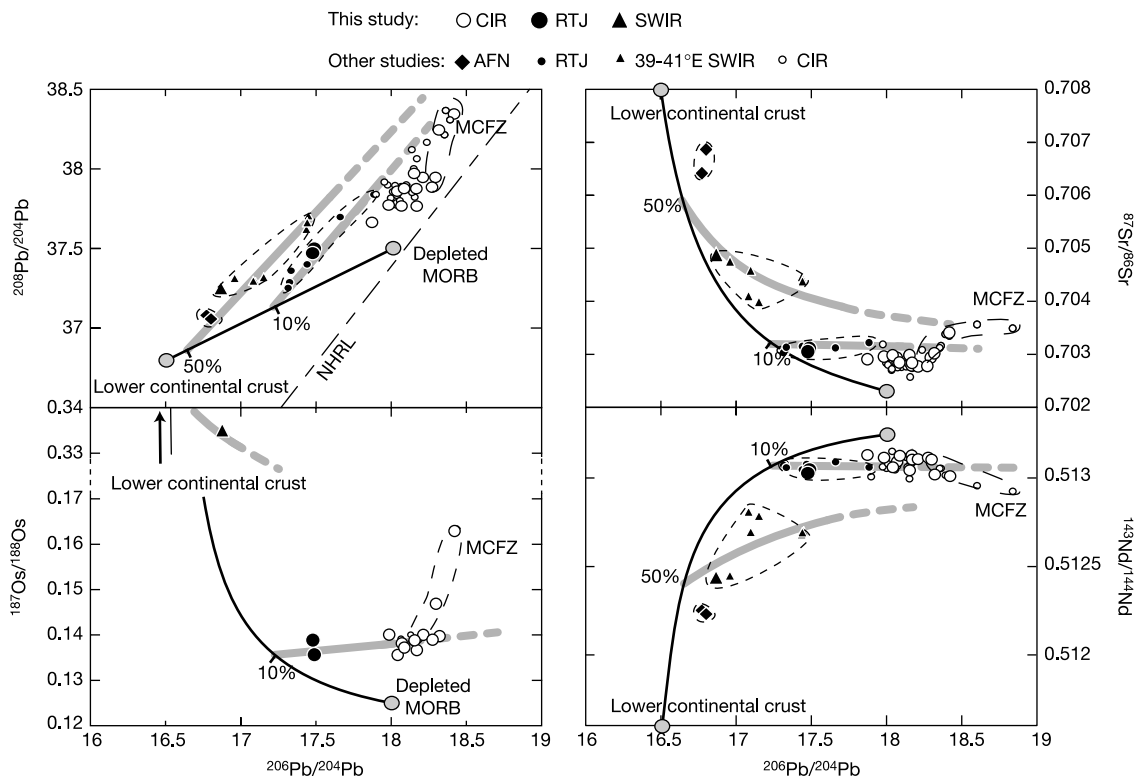


Figure 3 Pb , Sr , Nd and Os isotopic variations of the CIR, the RTJ, the 39–41°E SWIR and the AFN. NHRL, Northern Hemisphere reference line of Hart². The different groups of Indian basalts reported in the Pb – Sr – Nd isotopic diagrams define trends towards different DUPAL end-members that can be produced by mixing recycled lower continental crust and depleted upper mantle. As illustrated by the thick grey curves, the isotopic variations of basalts from the Rodriguez triple junction and the 39–41°E SWIR segment are reproduced by mixing DUPAL end-members produced by different proportions (10% and 50%) of lower continental crust with an end-member close in composition to the convergence zone of the Atlantic, Pacific and Indian MORB trends ($^{206}\text{Pb}/^{204}\text{Pb} = 19.2$ – 19.8 , $^{208}\text{Pb}/^{204}\text{Pb} = 38.8$ – 39.6 ; $^{87}\text{Sr}/^{86}\text{Sr} = 0.703$ – 0.704)²³. Black curves represent

binary mixing between a MORB melt and material from the lower continental crust that is assumed to be entirely melted. Data used for mixing calculation is as follows. MORB: $^{206}\text{Pb}/^{204}\text{Pb} = 18.00$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.45$, $^{208}\text{Pb}/^{204}\text{Pb} = 37.50$, $^{87}\text{Sr}/^{86}\text{Sr} = 0.7023$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.51325$, $^{187}\text{Os}/^{188}\text{Os} = 0.125$, $\text{Pb} = 0.45$ p.p.m., $\text{Sr} = 200$ p.p.m., $\text{Nd} = 10$ p.p.m., $\text{Os} = 0.15$ p.p.b. Lower continental crust: $^{206}\text{Pb}/^{204}\text{Pb} = 16.50$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.35$, $^{208}\text{Pb}/^{204}\text{Pb} = 36.80$, $^{87}\text{Sr}/^{86}\text{Sr} = 0.7080$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.51160$, $^{187}\text{Os}/^{188}\text{Os} = 0.5$, $\text{Pb} = 4.2$ p.p.m.²⁸, $\text{Sr} = 350$ p.p.m.²⁸, $\text{Nd} = 11$ p.p.m.²⁸, $\text{Os} = 0.04$ p.p.b. The lower-continental-crust isotopic composition has been chosen within the African mafic xenoliths' isotopic range^{29–31}.

continental crust is thus sufficient to reproduce the extreme DUPAL compositions of RTJ MORB and 15% for the 39–41° E SWIR segment. Most of the MORB from the central, southeast and southwest Indian ridges has a less marked DUPAL signature that requires less than 4% of lower continental crust to be recycled into its source. The fact that recycled lower continental crust probably does not melt entirely decreases significantly the quantity of lower-continental-crust-derived melt required for a given contribution on the isotopic compositions. Indeed, incompatible elements such as Pb, Sr and Nd would be enriched in the melt derived from the lower continental crust and, because the melting degree remains high, mantle sulphides may be removed from the residue and platinum-group elements such as Os would also be enriched³³.

All of these features support the idea that delaminating of continental lithosphere, including the mafic lower continental crust, is responsible for the Indian upper-mantle isotopic anomaly. Some fragments may have sunk down to the OIB reservoir material and mixed with other recycled components, which would explain the particular compositions of Indian and South Atlantic OIB. Finally, recycling significant amounts of lower continental crust may help to explain the relatively andesitic composition of the continental crust²⁸. □

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1. Dupré, B. & Allègre, C. J. Pb–Sr isotope variation in Indian Ocean basalts and mixing phenomena. *Nature* **303**, 142–146 (1983).
2. Hart, S. R. A large-scale isotope anomaly in the southern hemisphere mantle. *Nature* **309**, 753–757 (1984).
3. Hamelin, B. & Allègre, C. J. Large-scale units in the depleted upper mantle revealed by an isotope study of the Southwest Indian Ridge. *Nature* **315**, 196–199 (1985).
4. Hamelin, B., Dupré, B. & Allègre, C. J. Pb–Sr–Nd isotopic data of Indian Ocean ridges: new evidence of large-scale mapping of mantle heterogeneities. *Earth Planet. Sci. Lett.* **76**, 288–298 (1985/86).
5. Michard, A., Montigny, R. & Schlich, R. Geochemistry of the mantle beneath the Rodriguez Triple Junction and the South-East Indian Ridge. *Earth Planet. Sci. Lett.* **78**, 104–114 (1986).
6. Price, R. C., Kennedy, A. K., Riggs-Sneeringer, M. & Frey, F. A. Geochemistry of basalts from the Indian Ocean triple junction: implications for the generation and evolution of Indian Ocean ridge basalts. *Earth Planet. Sci. Lett.* **78**, 379–396 (1986).
7. Dosso, L., Bougault, H., Beuzart, P., Calvez, J. Y. & Joron, J.-L. The geochemical structure of the South-East Indian ridge. *Earth Planet. Sci. Lett.* **88**, 47–59 (1988).
8. Mahoney, J. J. *et al.* Isotopic and geochemical provinces of the Western Indian Ocean spreading centers. *J. Geophys. Res.* **94**, 4033–4052 (1989).
9. Mahoney, J. J., LeRoex, A. P., Peng, Z., Fisher, R. L. & Natland, J. H. Southwestern limits of Indian Ocean ridge mantle and the origin of low ²⁰⁶Pb/²⁰⁴Pb mid-ocean ridge basalt: isotope systematics of the central Southwest Indian Ridge (17°–50°E). *J. Geophys. Res.* **97**, 19771–19790 (1992).
10. Rehkämper, M. & Hofmann, A. W. Recycled ocean crust and sediment in Indian Ocean MORB. *Earth Planet. Sci. Lett.* **147**, 93–106 (1997).
11. Roy-Barman, M. & Allègre, C. J. ¹⁸⁷Os/¹⁸⁶Os ratios in mid-ocean ridge basalts and abyssal peridotites. *Geochim. Cosmochim. Acta* **58**, 5043–5054 (1994).
12. Snow, J. E. & Reisberg, L. Os isotopic systematics of the MORB mantle: results from altered abyssal peridotites. *Earth Planet. Sci. Lett.* **133**, 411–421 (1995).
13. Martin, C. E. Osmium isotopic characteristics of mantle-derived rocks. *Geochim. Cosmochim. Acta* **55**, 1421–1434 (1991).
14. Pegram, W. J. & Allègre, C. J. Osmium isotopic composition from oceanic basalts. *Earth Planet. Sci. Lett.* **111**, 59–68 (1992).
15. Hauri, E. H. & Hart, S. R. Re–Os isotope systematics of HIMU and EMII oceanic island basalts from the south Pacific Ocean. *Earth Planet. Sci. Lett.* **114**, 353–371 (1993).
16. Reisberg, L. *et al.* Os isotope systematics in ocean island basalts. *Earth Planet. Sci. Lett.* **120**, 149–167 (1993).
17. Roy-Barman, M. & Allègre, C. J. ¹⁸⁷Os/¹⁸⁶Os in Oceanic Island Basalt: Tracing oceanic crust recycling in the mantle. *Earth Planet. Sci. Lett.* **129**, 145–161 (1995).
18. Chesley, J., Righter, K. & Ruiz, J. Large-scale mantle metasomatism: a Re–Os perspective. *Earth Planet. Sci. Lett.* **219**, 49–60 (2004).
19. Schaefer, B. F., Turner, S., Parkinson, I., Rogers, N. & Hawkesworth, C. Evidence for recycled Archaean oceanic mantle lithosphere in the Azores plume. *Nature* **420**, 304–307 (2002).
20. Schiano, P., Birck, J. L. & Allègre, C. J. Osmium–strontium–neodymium–lead isotopic covariations in mid-ocean ridge basalt glasses and heterogeneity of the upper mantle. *Earth Planet. Sci. Lett.* **150**, 363–379 (1997).
21. Levasseur, S., Birck, J.-L. & Allègre, C. J. Direct measurement of femtomoles of osmium and the ¹⁸⁷Os/¹⁸⁶Os ratio in seawater. *Science* **282**, 272–274 (1998).
22. Mahoney, J. J., White, W. M., Upton, B. G. J., Neal, C. R. & Scrutton, R. A. Beyond EM-1: Lavas from Afanasy-Nikitin Rise and the Crozet Archipelago, Indian Ocean. *Geology* **24**, 615–618 (1996).
23. Hanan, B. B. & Graham, D. W. Lead and helium isotope evidence from oceanic basalts for a common deep source of mantle plumes. *Science* **272**, 991–995 (1996).
24. Kamenetsky, V. S. *et al.* Remnants of Gondwanan continental lithosphere in oceanic upper mantle: Evidence from the South Atlantic Ridge. *Geology* **29**, 243–246 (2001).

25. Jull, M. & Kelemen, P. B. On the condition for lower crust convective instability. *J. Geophys. Res.* **106**, 6423–6446 (2001).
26. Saal, A. E., Rudnick, R. L., Ravizza, G. E. & Hart, S. R. Re–Os isotope evidence for the composition, formation and age of the lower continental crust. *Nature* **393**, 58–61 (1998).
27. Rudnick, R. L. in *The Continental Lower Crust* (eds Fountain, D. M., Arculus, R. & Kay, R.) 269–316 (Elsevier, Amsterdam, 1992).
28. Rudnick, R. L. & Fountain, D. M. Nature and composition of the continental crust: a lower crustal perspective. *Rev. Geophys.* **33**, 267–309 (1995).
29. Rogers, N. W. & Hawkesworth, C. J. Proterozoic age and cumulate origin for granulite xenoliths, Lesotho. *Nature* **299**, 409–413 (1982).
30. Cohen, R. S., O’Nions, R. K. & Dawson, J. B. Isotope geochemistry of xenoliths from East Africa: implications for development of mantle reservoirs and their interaction. *Earth Planet. Sci. Lett.* **68**, 209–220 (1984).
31. Huang, Y.-M., Van Calsteren, P. W. & Hawkesworth, C. J. The evolution of the lithosphere in southern Africa: a perspective on the basic granulite xenoliths from kimberlites in south Africa. *Geochim. Cosmochim. Acta* **59**, 4905–4920 (1995).
32. Hirschmann, M. M. & Stolper, E. M. A possible role for garnet pyroxenite in the origin of the “garnet signature” in MORB. *Contrib. Mineral. Petrol.* **124**, 185–208 (1996).
33. Rehkämper, M. *et al.* Ir, Ru, Pt, and Pd in basalts and komatiites: New constraints for the geochemical behavior of the platinum-group elements in the mantle. *Geochim. Cosmochim. Acta* **63**, 3915–3934 (1999).

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The evolution of müllerian mimicry in multispecies communities

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Prey species that are unprofitable to attack often share conspicuous colours and patterns with other coexisting defended species^{1–6}. This phenomenon, termed müllerian mimicry^{2,3}, has long been explained as a consequence of selection on defended prey to adopt a common way of advertising their unprofitability^{7,8}. However, studies using two unpalatable prey types have not always supported this theory^{9–12}. Here we show, using a system of humans hunting for computer-generated prey, that predators do not always generate strong selection for mimicry when there are two unprofitable prey types. By contrast, we demonstrate that when predators are faced with a range of different prey species, selection on unprofitable prey to resemble one another can be intense. Here the primary selective force is not one in which predators evaluate the profitabilities of distinct prey types independently, but one in which predators learn better to avoid unprofitable phenotypes that share traits distinguishing them from profitable prey^{13,14}. This need to simplify decision making readily facilitates the spread of imperfect mimetic forms from rarity, and suggests that müllerian mimicry is more likely to arise in multispecies communities.

If a predator community needs to attack a fixed number of each distinct form of defended prey (such as those with stings or toxins) before it learns to avoid them, and if this pressure is significant, then there will be selection on unprofitable prey to resemble one another^{2,3,7}. Although field experiments have lent support to the idea that common forms of unpalatable prey are at a selective