plied pressure. The fact that this effect is seen for liquids (cyclohexane and OMCTS), whose molecular size differs appreciably from each other as well as from the crystal periodicity of the confining mica surfaces, indicates that epitaxy is not necessary for inducing the transition in such simple liquids.

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25. The configuration of the crossed cylindrical mica surfaces near the region of closest approach is that of a sphere, radius $R \approx 1$ cm, a distance D from a plane. The force $F_{\|}(D)$ required to move a sphere in a liquid medium of Newtonian viscosity η with velocity v_s parallel to a plane wall a distance D away, for $D \ll R$, is given by
$$F_{\|}(D) = (16\pi/5) v_s \eta R \ln(R/D)$$
[A. J. Goldman, R. G. Cox, H. Brenner, *Chem. Eng. Sci.* **22**, 637 (1967)]. Thus, for $D < 100$ nm, the range of the present study, the force on the moving sphere is dominated by its viscous interactions with the wall. In this regime, it can readily be shown that the effective mean viscosity of the liquid confined to a layer of thickness D is given by
$$\eta_{\text{eff}} \approx \frac{[\partial F_{\|}(D)/\partial D]}{2\pi R \dot{\gamma}}$$
where $\dot{\gamma} = (v_s/D)$ is the shear rate at the point of closest approach. In our experiments, $F_{\|}(D)$ is within the noise level $|\delta F_{\|}(D)| \approx 0.5$ μN throughout the range $\Delta D = 116$ to 6.2 nm, as seen from curves a and b of Fig. 2A. Putting $\delta F_{\|}(D)/\Delta D$ as an upper estimate on $\partial F_{\|}(D)/\partial D$ in this range, we find that for $D = 6.2$ nm (that is, seven monolayers of OMCTS) and $v_s = 1600$ nm/s (Fig. 2), this gives an upper estimate on η_{eff} of ~3 P.
26. The area A results from the deformation of the mica surfaces under the known normal and adhesive forces corresponding to point c in Fig. 3C. It is evaluated by means of the Johnson-Kendall-Roberts contact mechanics model [K. L. Johnson, K. Kendall, A. D. Roberts, *Proc. R. Soc. London Ser. A* **324**, 301 (1971)], giving (for point c in Fig. 3C) $A = (1.2 \pm 0.3) \times 10^{-10}$ m^2.
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28. This is in contrast to earlier reports of such a regime in a number of liquids (including OMCTS) (*10*, *20*). These earlier reports were concerned with thinner films under significant compression, where different effects may play a role. Further work will be required to clarify the relation between the different studies.
29. We thank R. Ball, S. Granick, G. Grest, J. Israelachvili, M. Lahav, L. Leiserovicz, and M. Robbins for useful discussions and comments. This work was supported by the Israel Science Foundation, the Commission of the European Community, and the Ministry of Science and Arts (Israel) together with the Kernforschungszentrum (Jülich, Germany).

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Osmium-187 Enrichment in Some Plumes: Evidence for Core-Mantle Interaction?

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Calculations with data for asteroidal cores indicate that Earth's outer core may have a rhenium/osmium ratio at least 20 percent greater than that of the chondritic upper mantle, potentially leading to an outer core with an osmium-187/osmium-188 ratio at least 8 percent greater than that of chondrites. Because of the much greater abundance of osmium in the outer core relative to the mantle, even a small addition of metal to a plume ascending from the D″ layer would transfer the enriched isotopic signature to the mixture. Sources of certain plume-derived systems seem to have osmium-187/osmium-188 ratios 5 to 20 percent greater than that for chondrites, consistent with the ascent of a plume from the core-mantle boundary.

Rhenium and osmium are highly siderophile and chalcophile elements. The two elements form a long-lived radiogenic isotope system based on the β^- transition of ^{187}Re to ^{187}Os, with a decay constant of $\sim 1.64 \times 10^{-11}$ year^{-1} (*1*). The mantle sources for some ocean island basalts (OIBs) (*2–6*) have elevated ^{187}Os/^{188}Os ratios compared with both chondrites and the upper mantle sources of mid-ocean ridge basalts (MORBs) (*2*), signifying a long-term increase in the Re/Os ratio. This long-term Re/Os enrichment is also indicated for the mantle sources of other types of presumably plume-derived rocks (*7*). This enrichment can be attributed to several processes. Here we consider the possibility that in some instances the enrichment is a reflection of chemical interaction between the outer core and lower mantle and the subsequent derivation of plume materials from the core-mantle interface.

Plume-derived melts are generally presumed to come from relatively deep mantle, though whether plumes are ultimately derived from the lower mantle or from mantle above the 670-km seismic discontinuity is still debated (*8–10*). The cause of the long-term enrichment of Re relative to Os in ^{187}Os-enriched rocks derived from plumes is not yet known. Previous researchers (*2*, *3*, *11*) have ascribed the resultant radiogenic Os in these rocks to the ancient incorporation of recycled oceanic crust into their sources. This model for Os evolution in the mantle sources of some plumes is consistent with previous interpretations for certain types of enriched OIB sources, as revealed by Pb, Sr, and Nd isotopes (*10*, *12*). Also, in OIB samples with very low Os concentrations, enriched Os can result from contamination of the basaltic melt with old, radiogenic oceanic crust (*4*).

The enrichment of ^{187}Os in some ocean island sources, however, does not always correlate with enrichments or depletions in other isotopic systems, as would be predicted for the recycling of oceanic crust (*6*, *13*).

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Roy-Barman and Allegre (6) attributed the apparent "decoupling" of the U-Pb and Re-Os isotopic systems to the recycling of a small amount of subducted sediment (having a high Pb concentration, generally an unradiogenic Pb composition, and a low Os concentration). Widom *et al.* (*13*), however, rejected this explanation for results they observed in OIB of the Azores. Such a diversity of opinions argues that other processes should at least be considered.

An alternate hypothesis is that the outer core has an elevated Re/Os ratio, relative to chondrites, and enrichment of ^{187}Os is a direct consequence of core-mantle interaction at the D″ layer (*14*). By capillary action, highly fluid metal may be drawn up into the lower kilometer or so of the D″ layer where it is oxidized. If this mixture is up to 6% denser than the overlying mantle, then it can be carried upward from the D″ layer by a plume (*15*). Thus, material that is perhaps as much as 2 to 5% metal may be drawn from this lowermost D″ layer and incorporated into a rising plume.

Previous studies with isotopic and trace element data have rejected the possibility of core-mantle interaction (*16*). One reason cited is that Pb in plumes, potentially originating from the D″ layer, shows no evidence of a highly unradiogenic component, as would be expected for Pb from the core (*17*). The concentration of Pb in the core, however, is difficult to predict because Pb is volatile and both chalcophile and siderophile. Widom *et al.* (*13*) noted that if the concentration of Pb in the outer core is less than about 0.5 parts per million (ppm) and if approximately 0.3% metal is incorporated into a plume at the D″ layer, then the core effects on Pb should be minimal. The influence of core-mantle interaction might also be seen in the abundances of siderophile elements. These effects would be subtle, however, and difficult to distinguish from melting and crystal-liquid fractionation effects (*17*).

The highly siderophile and refractory behavior of Re and Os likely means that Earth's complement of these elements is almost wholly contained in the core. Because the core likely formed early in Earth's history (*8*), the Re/Os ratio in the bulk core is thought to resemble closely that of H-group ordinary chondrites (*18*). Using the present-day average ^{187}Os/^{188}Os ratio of 0.1288 ± 0.0003 for H-group chondrites (*19*) and an iron meteorite initial ^{187}Os/^{188}Os ratio of 0.09600 (*20*), we calculated a ^{187}Re/^{188}Os ratio of 0.4224 for the bulk core (*21*). Present-day upper mantle, in contrast, has an Os isotopic composition more similar to that of carbonaceous chondrites, with an average ^{187}Os/^{188}Os ratio of 0.1271 (*22*), a value lower than that of H-group chondrites. Consequently, even without further processing, the bulk core would have a present-day γ_{Os} of $\sim$+1.3 relative to the upper mantle source of MORBs [see (*7*) for a definition of γ_{Os}].

Crystallization of the inner core, which accounts for 5.5 weight % of the bulk core, may have further fractionated Re from Os. Conditions affecting solid metal–liquid metal partitioning at the outer core–inner core boundary are poorly constrained. As a first approximation, the early stages of asteroidal core solidification may be a guide, as illustrated by two well-studied magmatic iron meteorite groups. For the least fractionated (lowest Ni) members of the IIAB and IIIAB meteorite groups, plots of log[Re] versus log[Os] are highly correlated linearly with similar slopes: 0.776 ± 0.013 (IIA) and 0.824 ± 0.027 (IIIA) (*23*, *24*). The slopes represent the ratio $(k_{Re} - 1)/(k_{Os} - 1)$, where k is the solid metal–liquid metal partition coefficient. The close agreement between the slopes for meteorites derived from liquids of different starting compositions and crystallization histories (*25*, *26*) suggests that this ratio is relatively constant even though individual values of k may change. Consequently, as metal precipitates, the Re/Os ratio increases in the remaining liquid. Group IIA meteorites are derived from a liquid with $\sim$5% Ni (*26*), which closely approximates that expected for Earth's core; hence, the ratio of k in the IIA system gives an estimate of partitioning between Earth's inner and outer cores. Morgan *et al.* (*23*) calculated the Re and Os solid metal–liquid metal distribution coefficients to be 15 and 19, respectively, for the IIA system, using a distribution coefficient of 14 for Ir (*27*) in combination with Ir-Re and Re-Os trends in the iron subgroup. For these distribution coefficients, the predicted ^{187}Re/^{188}Os ratio of Earth's outer core after 5.5% of the inner core has crystallized is 0.530 (Fig. 1A) (*28*). Using the concentrations of Re and Os in H5 ordinary chondrite metal for the bulk core, we predict outer core Re and Os concentrations to be 0.119 and 1.08 ppm (Fig. 1B) (*28*). Consequently, if the entire inner core formed very

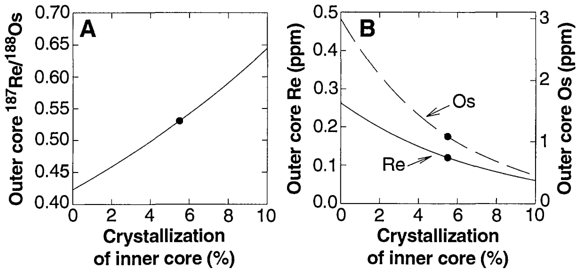

Fig. 1. (**A**) ^{187}Re/^{188}Os of Earth's outer core versus the percent crystallization of the inner core. The plot shows that as the inner core crystallized, the ^{187}Re/^{188}Os ratio of the outer core increased from 0.4403 to 0.5303, assuming the modeling parameters described in the text. The solid circle indicates the resulting composition of the outer core. (**B**) Re and Os concentrations of the outer core (in parts per million) versus the percent crystallization of the inner core. The solid circles represent the concentrations of these elements in the outer core, assuming the modeling parameters described in the text.

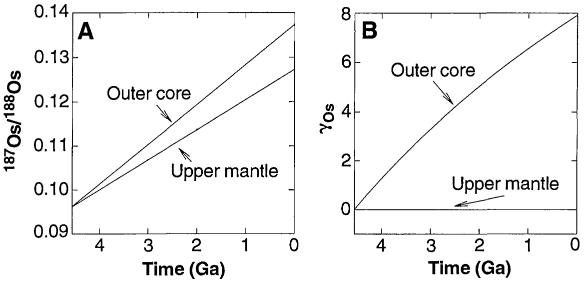

Fig. 2. (**A**) ^{187}Os/^{188}Os versus time [in units of 10^9 years ago (Ga)] for the outer core and upper mantle with carbonaceous chondritic Os characteristics. (**B**) γ_{Os} versus time for the outer core and upper mantle with carbonaceous chondritic Os characteristics.

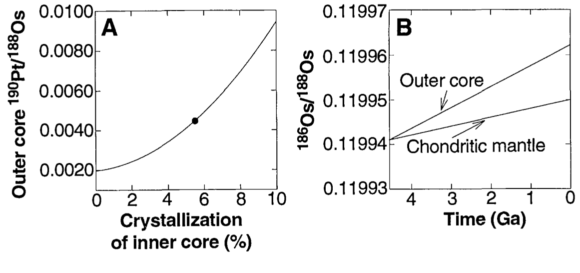

Fig. 3. (**A**) ^{190}Pt/^{188}Os of Earth's outer core versus the percent crystallization of the inner core. The plot shows that as the inner core crystallized, the ^{190}Pt/^{188}Os ratio of the outer core increased from 0.00183 to 0.00446, assuming the modeling parameters described in the text. The solid circle indicates the resulting composition of the outer core. (**B**) ^{186}Os/^{188}Os versus time (in Ga) for the outer core and upper mantle with carbonaceous chondritic Os characteristics.

early, the $^{187}Os/^{188}Os$ ratio of the outer core would be 0.1372 ($\gamma_{Os} = +7.9$) at present with the above parameters (Fig. 2). Core-enriched plumes would likely carry a significant portion of the ^{187}Os-enriched material to the surface. Metal-enriched materials ultimately derived from the D″ layer might have higher Re and Os concentrations than corresponding upper mantle materials, making them less likely to have their Os isotopic compositions diluted by plume-mantle interactions (*29*).

Admittedly, the crystallization trends in small asteroidal cores are not necessarily viable natural analogs for the terrestrial core. Earth's inner core formed at much higher pressures and temperatures than asteroidal cores, and some minor constituents in the core, such as S, could have significant effects on partition coefficients for siderophile elements. Differences in the partitioning characteristics of Re and Os in Earth's core may have been greater or less than those observed in asteroids. Experimental study of solid metal–liquid metal partitioning for highly siderophile elements at high pressure and for diverse compositions should help resolve these questions.

Examination of the $^{186}Os/^{188}Os$ ratio of plume-derived materials, in addition to the $^{187}Os/^{188}Os$ ratio, may help in evaluating whether outer core–lower mantle interactions exist and result in the addition of enriched Os in some mantle sources of plumes. Osmium-186 is the α-decay product of ^{190}Pt which has a decay constant of $\sim 1.04 \times 10^{-12}$ year^{-1} and an atom % of ~ 0.0124 (*30*). If inner core crystallization produced similar relative differences in the abundances of highly siderophile elements as occurred in asteroidal cores, the Pt/Os ratio of the outer core should also have increased as a consequence of inner core formation. This increase would ultimately result in an outer core with a higher $^{186}Os/^{188}Os$ ratio than is found in chondrites. The level of enrichment is difficult to model because of the limited data for the distribution of Pt between metal and liquid states. The solid metal–liquid metal distribution coefficient for Pt, however, can be calculated in the same manner as was done for Os and Re (*23*). The slope of the plot of log[Pt] versus log[Os] for IIA iron meteorites is 0.117 ± 0.012 with published Pt data (*31*). When combined with a k_{Os} of 19, a k_{Pt} of 3.1 results. With these distribution coefficients, a $^{190}Pt/^{188}Os$ ratio of 0.00446 is calculated for the outer core as compared with a chondritic ratio of 0.00183 (*32*, *33*). Assuming a rapidly crystallized inner core, this enrichment in Pt relative to Os leads to a $\geq 0.01\%$ increase in the $^{186}Os/^{188}Os$ ratio as compared with chondrites over 4.56×10^9 years (Fig. 3). Consequently, if 1 to 3% metal is added to some plume sources, increases in the $^{186}Os/^{188}Os$ ratio should correlate positively with increases in the $^{187}Os/^{188}Os$ ratio.

Core-mantle interactions can be distinguished from mantle-crust mixing by contrasting the $^{186}Os/^{188}Os$ ratio with the $^{187}Os/^{188}Os$ ratio. Unlike Re, which is enriched in oceanic crust, Pt and Os are not correspondingly enriched in the oceanic crust and most sediments relative to the mantle. For example, the mantle has Pt concentrations of >5 ppb, but oceanic diabases typically have <1 ppb of Pt and normally <50 parts per thousand (ppt) of Os (*34*). Hence, recycling of oceanic crust would minimally affect the Pt/Os ratio of any crust-mantle mix, unlike the Re/Os ratio, and consequently not affect the $^{186}Os/^{188}Os$ ratio of the mix either at the time of mixing or subsequent to the mixing. At present, sufficiently precise $^{186}Os/^{188}Os$ data have not been reported for plume-derived systems, so ^{187}Os-^{186}Os correlations have not been examined. Precision on the order of ±0.005% for calculations of the $^{186}Os/^{188}Os$ ratio will be required to determine whether the correlation exists.

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$$(^{187}\mathrm{Re}/^{188}\mathrm{Os})_L = 0.4229\mathrm{L}^{(k_{\mathrm{RE}} - k_{\mathrm{Os}})}$$

where $(^{187}Re/^{188}Os)_L$ is the ratio in the outer core, k_{Re} and k_{Os} are 15 and 19, respectively (see text), 0.4229 is the $^{187}Re/^{188}Os$ ratio of ordinary chondrites, and L is the fraction of liquid in the core.
29. The addition of just 1% of metal with the concentrations noted above to a portion of lower mantle would raise the concentrations of Re and Os in the mixture to >1.0 ppb and >11 ppb, respectively. These concentrations compare with average Re and Os concentrations of approximately 0.25 and 3.3 ppb in the upper mantle (*37*). Because the outer core is likely to be enriched in Re and Os by greater than a factor of 300 relative to the lower mantle, any mixture resulting from metal-mantle mixing above the 1% level will have an Os isotopic composition dominated by the metal component. Also, if late accretion added highly siderophile elements to only the upper mantle, and the upper mantle has been convectively isolated from the lower mantle, then the lower mantle may have lower concentrations of these elements and the effect of metal-silicate mixing may be even greater.
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High-^{3}He Plume Origin and Temporal-Spatial Evolution of the Siberian Flood Basalts

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An olivine nephelinite from the lower part of a thick alkalic ultrabasic and mafic sequence of volcanic rocks of the northeastern part of the Siberian flood basalt province (SFBP) yielded a ^{40}Ar/^{39}Ar plateau age of 253.3 ± 2.6 million years, distinctly older than the main tholeiitic pulse of the SFBP at 250.0 million years. Olivine phenocrysts of this rock showed ^{3}He/^{4}He ratios up to 12.7 times the atmospheric ratio; these values suggest a lower mantle plume origin. The neodymium and strontium isotopes, rare earth element concentration patterns, and cerium/lead ratios of the associated rocks were also consistent with their derivation from a near-chondritic, primitive plume. Geochemical data from the 250-million-year-old volcanic rocks higher up in the sequence indicate interaction of this high-^{3}He SFBP plume with a suboceanic-type upper mantle beneath Siberia.

More than 20 years after Morgan (*1*) postulated the connections between continental flood basalt provinces (CFBPs), mantle plume activity, and continental rifting, there is now some general agreement on the role of deep mantle plumes in CFBP generation. Questions remain, however, regarding the nature of dispersal of the plume head in the upper mantle beneath the relatively cooler and rigid lithosphere, and the timing of melting initiated by the arrival of the hot plume at the base of the lithosphere is a topic of current investigations (*2–5*). In this report, we use ^{3}He/^{4}He as a diagnostic tracer to infer a lower mantle plume origin for the SFBP, the largest Phanerozoic CFBP; on the basis of combined isotopic and trace element characteristics, we also infer the involvement of an upper mantle component analogous to the present-day suboceanic mantle. We provide ^{40}Ar/^{39}Ar geochronologic data, He isotopic measurements, rare earth element (REE) data, and Sm-Nd and Rb-Sr isotope systematics data on a suite of alkalic ultrabasic and mafic volcanic rocks from the Maimecha-Kotui section of the SFBP. These data allow comparison with the flood basalts of the Deccan traps in India, which also contain high-^{3}He rocks (*3*).

The SFBP erupted by mantle plume volcanism at the Permian-Triassic boundary (*6–13*). However, as with other flood basalt provinces, opinions vary concerning the relative amounts of magma contributed by crustal, subcontinental lithospheric, and upper and lower mantle sources (*14*). We attempted to resolve this issue by focusing on a suite of alkalic ultrabasic and basic rocks from the Maimecha-Kotui section (Fig. 1). These rocks make up about 2% of the SFBP by volume and are located northeast of the main Putorana sequence (Fig. 1). The Maimecha-Kotui suite of rocks forms a relatively thick series of alkaline, subalkaline, and ultrabasic rocks and includes different alkalic basalts, trachybasalts, trachyandesites, alkali trachytes, and rare maimechites (olivine-phyric picrites) (*15, 16*). This alkalic volcanic subprovince is located in an elongated region, presumably a graben, situated between the Tunguska basin to the west and the Anabar antiform to the east (*17*). The tectonic setting for these alkalic rocks is markedly different from that of the rest of the Siberian platform, which is covered by thick, monotonous tholeiites of the SFBP.

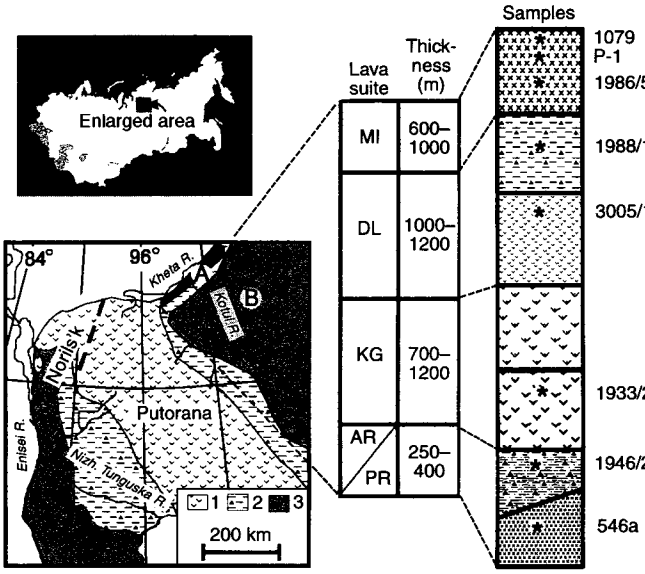

Fig. 1. Schematic geological map, on the left, of the Permian-Triassic volcanic rocks from the Siberian platform [modified after (*6*)] showing Norils'k, Putorana, and Maimecha-Kotui (in black), the three main sections of the SFBP. The Tertiary-Quaternary sediments are in white; other lithologies are 1, basalt trap; 2, intrusive trap and tuffs; and 3, platform sedimentary sequence. The thick dashed line represents the Norils'k-Putorana boundary. Two alkalic ultrabasic complexes are also shown: Gulin (A) and Odikhinca (B). The column on the right represents a composite volcano stratigraphy (*15*) of the Maimecha-Kotui section, with the relative locations of the samples analyzed in this study shown with asterisks. The lava suites and their approximate thicknesses are also shown in the middle two columns. The lava suites are as follows: Maimechinskay (MI), lavas, tuffs, and intrusive maimechites; Delkanskay (DL), lava flows of subalkaline basalts, trachybasalts, trachyandesites, andesites, shoshonites, and alkali picrites (upper sequence) and lava flows of augites, limburgites, nephelinites, analcitites, and tuffs (lower sequence); Kogotokskay (KG), subalkali basalts and trachybasalts (upper sequence) and tholeiitic and olivine basalts (lower sequence); and Aridgangskay (AR) and Pravobojrskay (PR), lava flows of augites, nephelinites, melilitites, picrites, tuffs, and olivine basalts.

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