A Quantitative Link Between Recycling and Osmium Isotopes

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Recycled subducted ocean crust has been traced by elevated $^{187}\text{Os}/^{188}\text{Os}$ in some studies and by high nickel and low manganese contents in others. Here we show that these tracers are linked for Quaternary lavas of Iceland, strengthening the recycling model. An estimate of the osmium isotopic composition of both the recycled crust and the mantle peridotite implies that Icelandic Quaternary lavas are derived in part from an ancient crustal component with model ages between $1.1 \times 10^9$ and $1.8 \times 10^9$ years and from a peridotitic end-member close to present day oceanic mantle.
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Formation, subduction, and incomplete mixing of oceanic crust produces chemical and isotopic heterogeneity in Earth’s mantle (1, 2). The signature of these processes in the mantle over time and the importance of recycling in explaining the origins and compositions of volcanic rocks remain major questions. Recently, osmium isotopes have proved to be an important tracer (3, 4). Basaltic ocean crust has much higher Re/Os ratios than mantle peridotite, from which it is derived through partial melting, because osmium remains mostly in the solid (mantle residue), whereas Re preferentially enters the melt. The decay of long-lived $^{187}$Re to stable $^{187}$Os forms an olivine-free hybrid, pyroxenite similar to estimates of present-day oceanic mantle $^{187}$Os/$^{188}$Os = 0.125 (4). The calculated isotopic composition of pyroxenite is $^{187}$Os/$^{188}$Os = 0.140 to 0.155. The analogous correlation based on Mn (Fig. 1B) is consistent with this result, although the scatter is slightly greater. These values can be modeled as 1.1- to 1.8-billion-year-old oceanic crust reacted with present-day oceanic peridotite shortly before final melting (10). The calculated age range for recycled component in Icelandic mantle is consistent with similar age estimations from Pb isotopes (11) and Os and He isotope relationships (6). The obtained isotopic compositions of the peridotitic and pyroxenitic components for Iceland also support independently “olivine-based” estimates of source proportions (9), as well as the qualitative idea of the presence of ancient recycled materials in Icelandic mantle sources (5–7, 11).

References and Notes
12. We thank I. A. Sigurdsson for help on a field trip in Iceland. This work was supported by Wolfgang Paul and Humboldt research awards to A.V.S. of Russian Federation (grant HIII-150.2008.5), Russian Academy of Science (Department of Earth Sciences), Russian Basic Research Foundation (grants 06-05-65234 and 06-05-65227), and Deutsche Forschungsgemeinschaft (grant HO 1026/16-3) are also acknowledged for partial support to A.V.S. and V.G.B.

Supporting Online Material
www.sciencemag.org/cgi/content/full/321/5888/536/DC1
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31 March 2008; accepted 22 May 2008
10.1126/science.1158452

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Fig. 1. (A and B) Measured bulk rock $^{187}$Os/$^{188}$Os versus estimated proportion of pyroxenite derived melt ($X_{px}$) (table S1). $X_{px}$ is defined as a following linear functions of average olivine composition (10): $X_{px} \text{Ni} = 10.54 \times \text{NiO/} (\text{Mg/} \text{FeO}) - 0.4368$; $X_{px} \text{Mn} = 3.483 - 207.139 \times \text{(Mn/Fe)}$. Solid lines represent linear regression with parameters shown. DMM and PM stand for depleted and primitive present day mantle estimates, respectively (4). Dashed lines indicate mixing of melt derived from peridotite with $^{187}$Os/$^{188}$Os = 0.125 and from pyroxenite with $^{187}$Os/$^{188}$Os ratio indicated in italics (10).

Fig. 2. Plot of $^{187}$Os/$^{188}$Os for bulk rock versus $X_{px} \text{Mn}$ for Iceland (A) and DMM (B). Linear regression lines are shown for each data set with parameters given in the table. The best correlation for DMM is $X_{px} \text{Mn} = 0.0$; whereas for Iceland it is $X_{px} \text{Mn} = 0.388$.
Supporting Online Material for

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DOI: 10.1126/science.1158452

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Samples
All samples are Icelandic picrites and olivine basalts less than about 2 Ma old. Olivine analyses and bulk rock {187}Os/188Os ratios are reported for the same samples (8 cases) or for the same localities and flows (7 cases).

Os isotope analyses
Eight samples were newly analyzed for Os concentrations and {187}Os/188Os at Max-Planck Institute for Chemistry, Mainz. These measurements were made on bulk rock powder, following the techniques described in (S1). The total procedural blanks for Os were less than 1 pg. The error (2σ) for {187}Os/188Os ratio was less than 0.5%.

Proportion of pyroxenite derived melt
The proportion of pyroxenite derived melt in lavas was defined as a function of Mn/Fe of average olivine phenocrysts (S2). The relation of this proportion with Ni/(Mg/Fe) of olivine (see Fig. 1 caption) was defined in the same way using olivine-melt Ni partition after Kinzler et al (S3).

Table S1. Average olivine compositions and {187}Os/188Os in Quaternary rocks of Iceland

<table>
<thead>
<tr>
<th>Sample</th>
<th>locality</th>
<th>Lat, Long</th>
<th>n</th>
<th>Fe</th>
<th>Mn/Fe</th>
<th>Ni#</th>
<th>Xpx Mn</th>
<th>±2σ</th>
<th>Xpx Ni</th>
<th>±2σ</th>
<th>Ref1</th>
<th>187Os/188Os ±2σ</th>
<th>Ref2</th>
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</thead>
<tbody>
<tr>
<td>03-140</td>
<td>Kistufel, MVZ</td>
<td>64°47'51.67&quot;N; 17°12'12.15&quot;W</td>
<td>46</td>
<td>88.55</td>
<td>0.0153</td>
<td>0.069</td>
<td>0.318</td>
<td>0.008</td>
<td>0.288</td>
<td>0.012</td>
<td>(S6)</td>
<td>0.13275</td>
<td>0.00047</td>
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<td>03-137</td>
<td>Kistufel, MVZ</td>
<td>64°47'41.24&quot;N; 17°13'25.06&quot;W</td>
<td>100</td>
<td>88.24</td>
<td>0.0154</td>
<td>0.067</td>
<td>0.294</td>
<td>0.016</td>
<td>0.270</td>
<td>0.009</td>
<td>new</td>
<td>0.13193</td>
<td>0.00023</td>
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<td>03-122</td>
<td>Skridufel, ERZ</td>
<td>64°7'3.01&quot;N; 19°56'26.03&quot;W</td>
<td>291</td>
<td>88.98</td>
<td>0.0153</td>
<td>0.076</td>
<td>0.309</td>
<td>0.006</td>
<td>0.368</td>
<td>0.006</td>
<td>new</td>
<td>0.13752</td>
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<td>03-122h</td>
<td>Skridufel, ERZ</td>
<td>64°7'3.01&quot;N; 19°56'26.03&quot;W</td>
<td>100</td>
<td>87.37</td>
<td>0.0148</td>
<td>0.083</td>
<td>0.410</td>
<td>0.023</td>
<td>0.441</td>
<td>0.018</td>
<td>new</td>
<td>0.13913</td>
<td>0.00022</td>
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<td>03-122a</td>
<td>Skridufel, ERZ</td>
<td>64°7'3.01&quot;N; 19°56'26.03&quot;W</td>
<td>97</td>
<td>87.71</td>
<td>0.0150</td>
<td>0.083</td>
<td>0.367</td>
<td>0.019</td>
<td>0.440</td>
<td>0.018</td>
<td>new</td>
<td>0.13879</td>
<td>0.00016</td>
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<tr>
<td>03-101</td>
<td>Lagafell, WRZ</td>
<td>63°52'54.42&quot;N; 22°32'38.44&quot;W</td>
<td>51</td>
<td>90.14</td>
<td>0.0160</td>
<td>0.058</td>
<td>0.157</td>
<td>0.011</td>
<td>0.176</td>
<td>0.010</td>
<td>new</td>
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<td>03-102</td>
<td>Lagafell, WRZ</td>
<td>63°52'54.36&quot;N; 22°32'36.66&quot;W</td>
<td>51</td>
<td>90.04</td>
<td>0.0161</td>
<td>0.059</td>
<td>0.138</td>
<td>0.017</td>
<td>0.180</td>
<td>0.012</td>
<td>new</td>
<td>0.13254</td>
<td>0.00034</td>
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<tr>
<td>Avg (4)</td>
<td>Halebunga, WRZ</td>
<td>63°48'56.72&quot;N; 22°38'45.72&quot;W</td>
<td>304</td>
<td>90.09</td>
<td>0.0159</td>
<td>0.062</td>
<td>0.197</td>
<td>0.021</td>
<td>0.213</td>
<td>0.004</td>
<td>new</td>
<td>0.13174</td>
<td>0.00046</td>
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<td>Avg (6)</td>
<td>Hengill, Maidfell, WRZ</td>
<td>64°69'45.5&quot;N; 21°10'30.08&quot;W</td>
<td>443</td>
<td>87.84</td>
<td>0.0156</td>
<td>0.061</td>
<td>0.246</td>
<td>0.018</td>
<td>0.211</td>
<td>0.005</td>
<td>new</td>
<td>0.13296</td>
<td>0.00035</td>
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<tr>
<td>Avg (6)</td>
<td>Hengill, Maidfell, WRZ</td>
<td>64°10'52.52&quot;N; 21°44.83&quot;W</td>
<td>394</td>
<td>88.49</td>
<td>0.0157</td>
<td>0.062</td>
<td>0.270</td>
<td>0.014</td>
<td>0.213</td>
<td>0.007</td>
<td>new</td>
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<td>Avg (5)*</td>
<td>Borggarthraun, NRZ</td>
<td>65°49'46.10&quot;N; 16°59'48.53&quot;W</td>
<td>118</td>
<td>91.65</td>
<td>0.0161</td>
<td>0.054</td>
<td>0.145</td>
<td>0.020</td>
<td>0.127</td>
<td>0.028</td>
<td>new</td>
<td>0.12800</td>
<td>0.00030</td>
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<tr>
<td>Avg (5)</td>
<td>Langavintshraun, NRZ</td>
<td>65°56'16.51&quot;N; 16°52'23.37&quot;W</td>
<td>341</td>
<td>90.15</td>
<td>0.0157</td>
<td>0.057</td>
<td>0.236</td>
<td>0.008</td>
<td>0.167</td>
<td>0.004</td>
<td>new</td>
<td>0.13145</td>
<td>0.00030</td>
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<td>Avg (2)</td>
<td>Storavintshraun, NRZ</td>
<td>65°50'36.81&quot;N; 17°02'47.4&quot;W</td>
<td>46</td>
<td>86.61</td>
<td>0.0153</td>
<td>0.073</td>
<td>0.313</td>
<td>0.017</td>
<td>0.333</td>
<td>0.007</td>
<td>new</td>
<td>0.13420</td>
<td>0.00030</td>
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<td>01-41</td>
<td>Thirstáreykirshraun, NRZ</td>
<td>65°57'32.83&quot;N; 17°47.41&quot;W</td>
<td>55</td>
<td>88.63</td>
<td>0.0154</td>
<td>0.074</td>
<td>0.299</td>
<td>0.009</td>
<td>0.340</td>
<td>0.007</td>
<td>(S6)</td>
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<td>01-56-1</td>
<td>Laurantshraun, NRZ</td>
<td>65°56'16.62&quot;N; 17°52'22.46&quot;W</td>
<td>100</td>
<td>89.77</td>
<td>0.0159</td>
<td>0.060</td>
<td>0.186</td>
<td>0.010</td>
<td>0.192</td>
<td>0.010</td>
<td>new</td>
<td>0.13256</td>
<td>0.00024</td>
</tr>
</tbody>
</table>

Notes for Table S1. Fo = Mg/Mg+Fe in atomic %, Ni# = NiO/(MgO+FeO) in wt%. Standard error for olivine (ε) is the standard error of the mean for the number (n) of olivine grains measured for a particular sample or for the shown number of samples. Uncertainty for {187}Os/188Os ratios corresponds to the in-run 2-sigma error of the measurement, except for samples from Halebunga, Hengill and Longavintshraun where the quoted error is the standard error of the mean for the averaged samples. Avg (m) – stands for average of olivine averages from m samples from the same locality, in these cases n indicate total amount of considered olivine grains.

* - for Borggarthraun flow only high-Mg olivine (Fo > 91) was considered for Xpx calculations because of very early crystallization of clinopyroxene, which leads to significant overestimation of Xpx. WRZ, ERZ, NRZ – Western, Eastern and Northern rift zones respectively. MVZ - Mid-Icelandic Volcanic Zone. Ref1 - reference for olivine composition; Ref2 - reference for {187}Os/188Os data; new - newly analyzed in this work.

DOI: 10.1126/science.1158452 www.sciencemag.org SCIENCE VOL 321 25 JULY 2008