Fig. 4.4. Isochron diagrams for the Stillwater complex: (a) Rb–Sr diagram showing scatter of mineral data; (b) Sm–Nd mineral isochron; (c) whole-rock data with reference line from (b). After DePaolo and Wasserburg (1979).
\[ \frac{^{143}\text{Nd}}{^{144}\text{Nd}} = \left( \frac{^{143}\text{Nd}}{^{144}\text{Nd}} \right)_0 + \left( \frac{^{147}\text{Sm}}{^{144}\text{Nd}} \times \text{slope} \right) \]

\[ \varepsilon_Y = \left( \left( \frac{^{143}\text{Nd}}{^{144}\text{Nd}} \right)_{\text{Sample}} \right) - 1 \right) \times 10,000 \]

**Table 6.8** $\varepsilon_Y$ calculation for the Sm–Nd data for lunar norite 77215

<table>
<thead>
<tr>
<th>Sample</th>
<th>Whole rock</th>
<th>Plagioclase</th>
<th>Pyroxene</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{147}\text{Sm}/^{144}\text{Nd}$</td>
<td>0.1754</td>
<td>0.1754</td>
<td>0.221</td>
</tr>
<tr>
<td>Measured $^{143}\text{Nd}/^{144}\text{Nd}$</td>
<td>0.512016</td>
<td>0.512016</td>
<td>0.513320</td>
</tr>
<tr>
<td>Isochron $^{143}\text{Nd}/^{144}\text{Nd}$</td>
<td>0.512018</td>
<td>0.512018</td>
<td>0.513315</td>
</tr>
<tr>
<td>$\varepsilon_Y$</td>
<td>-0.04</td>
<td>-0.04</td>
<td>0.10</td>
</tr>
</tbody>
</table>
Figure 7.1. Periodic table highlighting the rare earths (gray background) and Nd and Sm.

Table 6.2 Sm–Nd isotopic composition in atom%

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass</th>
<th>142</th>
<th>143</th>
<th>144</th>
<th>145</th>
<th>146</th>
<th>147</th>
<th>148</th>
<th>149</th>
<th>150</th>
<th>152</th>
<th>154</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.075</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nd&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
<td>27.168</td>
<td>12.197</td>
<td>23.794</td>
<td>8.290</td>
<td>17.177</td>
<td></td>
<td>5.748</td>
<td></td>
<td>5.626</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> Nd atomic abundances assume a $^{143}$Nd/$^{144}$Nd ratio of 0.51263.
Under most conditions all the REE are 3+, but they are not the same size.

Figure 7.05. Ionic radii of the lanthanide rare earth elements (3+ state except where noted). Promethium (Pm) has no isotope with a half-life longer than 5 years.
how REE plots would look without normalization to CI chondrites.

Normalized REE plots are smooth and easier to interpret.

Why the different shapes of the REE trends for MORB and continental crust?
**Major elements:** stoichiometric constituents of abundant phases

**Trace elements:**

- “low” concentrations in abundant phases
- Concentrations follow partition, or distribution, coefficients ($K_d$):
  
  *for example:* $K_d = \frac{C_{\text{solid}}}{C_{\text{liquid}}}$

  - $K_d < 1 \rightarrow$ element is incompatible in solid phase
  - $K_d > 1 \rightarrow$ element is compatible in solid phase

Say we have a silicate liquid (e.g., basaltic melt) just hanging out in equilibrium with solid mantle. How will concentrations of trace elements in this melt change as the liquid fraction goes up or down?
A simple mass balance equation (remember from a long time ago) can be combined with the definition of D (a weighted average of $K_d$s for the solid) and rearranged to give:

$$C_i = \frac{C_0}{F + D - FD}$$

This is called batch melting ($F$ increases) or batch crystallization ($F$ decreases).
When the mantle melts, the liquid (basically basalt) is less dense so rises toward the surface, where it may form crust. This differentiation of the Earth, over billions of years, has led to the mantle and crust having very different compositions.

Which of these reservoirs, crust or mantle, is relatively enriched in incompatible elements (think about Rb, Sr, Sm, Nd) and which is relatively depleted in them?
What are the main mantle minerals?

- olivine (~50%)
- orthopyroxene (~25%)
- clinopyroxene (~15-20%)
- Al-phase (~5-10%)
  - (garnet, spinel, plagioclase)
trace element ratio  
Rb/Sr  
Sm/Nd  
melt (becomes crust):  
higher  
lower  
mantle residue:  
lower  
higher  
isotope ratio  
$^{87}\text{Sr}/^{86}\text{Sr}$  
$^{143}\text{Nd}/^{144}\text{Nd}$  
crust  
increases relatively quickly  
increases relatively slowly  
mantle  
increases relatively slowly  
increases relatively quickly  

Fig. 6.81.1. Relative change in parent/daughter ratio in the melt (solid symbols) and residue of melting (open symbols) as a result of modal batch partial melting in the mantle.
Table 9.4. Ages and Primordial $^{143}\text{Nd}/^{144}\text{Nd}$ Ratios of Stony Meteorites and Martian Rocks
Determined by the Sm–Nd Method

<table>
<thead>
<tr>
<th>Meteorite</th>
<th>Age (Ga)</th>
<th>$\left(\frac{^{143}\text{Nd}}{^{144}\text{Nd}}\right)_i$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Achondrites</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Juvina</td>
<td>4.56 ± 0.08</td>
<td>0.50677 ± 10</td>
<td>1</td>
</tr>
<tr>
<td>Juvina</td>
<td>4.60</td>
<td>0.506616 ± 22</td>
<td>6</td>
</tr>
<tr>
<td>Angra dos Reis</td>
<td>4.55 ± 0.04</td>
<td>0.50682 ± 5</td>
<td>2</td>
</tr>
<tr>
<td>Angra dos Reis</td>
<td>4.562 ± 0.031</td>
<td>0.506664 ± 37</td>
<td>7</td>
</tr>
<tr>
<td>Pasamonte</td>
<td>4.58 ± 0.12</td>
<td>0.50681 ± 14</td>
<td>3</td>
</tr>
<tr>
<td>Moore County</td>
<td>4.60 ± 0.03</td>
<td>0.50676 ± 7</td>
<td>4</td>
</tr>
<tr>
<td>Moama</td>
<td>4.58 ± 0.05</td>
<td>0.50684 ± 8</td>
<td>5</td>
</tr>
<tr>
<td><strong>Chronites</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Murchison, Allende,</td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>4.60 Guareña,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peace River, St. Severin</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Juvina (achondrite)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Martian Rocks</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nakhla</td>
<td>1.26 ± 0.07</td>
<td>0.51181 ± 7</td>
<td>8</td>
</tr>
<tr>
<td>Shergotty, Zagami, Allan</td>
<td>1.34 ± 0.06</td>
<td>0.51020 ± 10</td>
<td>9</td>
</tr>
<tr>
<td>Hills 7705</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) All initial $^{143}\text{Nd}/^{144}\text{Nd}$ have been normalized to an isotope ratio in row 2 of Table 9.3 and are compatible with $^{166}\text{Nd}/^{144}\text{Nd} = 0.7219$.

bulk Earth values:

\[
\frac{^{143}\text{Nd}}{^{144}\text{Nd}}_{\text{today}} = 0.512638 \\
\frac{^{147}\text{Sm}}{^{144}\text{Nd}}_{\text{today}} = 0.1967 \\
\frac{^{143}\text{Nd}}{^{144}\text{Nd}}_{4.6 \text{ Ga}} = 0.506609
\]

we don’t know these for Rb/Sr system, why?
from Bill White
\[ \varepsilon_{Nd} = \left( \frac{\frac{^{143}Nd}{^{144}Nd_{sample}} - \frac{^{143}Nd}{^{144}Nd_{chondrites}}}{\frac{^{143}Nd}{^{144}Nd_{chondrites}}} \right) \times 10000 \]
Figure 18.2. Sr and Nd isotopic systematics of the crust and mantle. Oceanic island basalts and MORB sample major reservoirs in the mantle. Continental basalts represent mixtures of various components, including mantle plumes, subcontinental lithosphere, and continental crust.
Figure 18.3. Sr and Nd isotope ratios of the suboceanic mantle as sampled by oceanic basalts. Three fields are shown for MORB from the 3 ocean basins, other symbols are various oceanic islands and island chains.
Fig. 4.34. Initial $\varepsilon$ Nd for terrestrial rocks, compiled by Armstrong (1991), compared with his ‘big-bang’ MORB evolution line. The solid curve is an alternative MORB depletion line for a crustal growth model. Note that this is not expected to agree with the dashed arc-source model of DePaolo (1981).

Fig. 6.B2.1. Initial Nd isotopic composition of mafic rocks (MgO > 7 wt%) versus time compared to models for the isotopic evolution of the mantle. The line labeled “CHUR” shows the Nd isotope evolution of a mantle source with chondritic Sm/Nd ratio. The dashed curve shows a volume of mantle from which the continental crust is extracted at a rate of 0.35% of its current volume every 100 Ma. The solid curve assumes that the rate of continent extraction from the mantle falls off exponentially with time, whereas the gray line assumes a constant, superchondritic, Sm/Nd for the depleted mantle since Earth formation. The thin, positively sloped line is a schematic representation of the hypothetical isotopic evolution of a zero age granite. This line provides model ages for the source of the granite that range from 1.5 Ga (CHUR) to 2 Ga (constant rate crust formation) to 2.1 Ga (exponentially declining rate of continent formation) to 2.3 Ga (instantaneous continent formation at 4.567 Ga) to illustrate the importance of the assumed model evolution to the calculated model age. (Source: Data from EarthChem.)
the intersection of the depleted mantle (DM) trend and the back-tracked crustal sample trend gives you depleted mantle model age (TDM)

\[ T_{DM} \]

\[ 143\text{Nd}/144\text{Nd} \text{ of DM today: 0.51320} \]

\[ 147\text{Sm}/144\text{Nd} \text{ of DM today: 0.2148} \]
Fig. 6.10. Schematic isotope evolution diagrams illustrating the model age approach. The solid lines show the isotopic evolution of a bulk-silicate-Earth (BSE) and depleted-mantle (DM) model reservoir. The dotted line starts at the measured isotopic composition of a granite and is then extrapolated back in time using the measured parent/daughter ratio of the granite to determine the slope. The point of intersection of the dotted line with the evolution of the model reservoirs gives the model age.

Table 6.4 Reference reservoir parameters for Rb–Sr, Sm–Nd, and Lu–Hf

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Solar system initial (4.567 Ga)</th>
<th>CI chondrite</th>
<th>Bulk silicate earth</th>
<th>MORB mantle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{87}\text{Rb}/^{86}\text{Sr}$</td>
<td>0.698975</td>
<td>0.926</td>
<td>0.09</td>
<td>0.0535</td>
</tr>
<tr>
<td>$^{87}\text{Sr}/^{86}\text{Sr}$</td>
<td></td>
<td>0.75989</td>
<td>0.7049</td>
<td>0.7025</td>
</tr>
<tr>
<td>$^{147}\text{Sm}/^{144}\text{Nd}$</td>
<td></td>
<td>0.1980</td>
<td>0.1960</td>
<td>0.2148</td>
</tr>
<tr>
<td>$^{143}\text{Nd}/^{144}\text{Nd}$</td>
<td>0.506686</td>
<td>0.51269</td>
<td>0.51263</td>
<td>0.51320</td>
</tr>
<tr>
<td>$^{176}\text{Lu}/^{177}\text{Hf}$</td>
<td></td>
<td>0.0338</td>
<td>0.0336</td>
<td>0.0395</td>
</tr>
<tr>
<td>$^{176}\text{Hf}/^{177}\text{Hf}$</td>
<td>0.279784</td>
<td>0.282793</td>
<td>0.282785</td>
<td>0.28330</td>
</tr>
</tbody>
</table>

MORB, mid-ocean ridge basalt.
Figure 22.3. Age provinces of the North American continent (after Hurley and Rand, 1969).

Figure 6.33 Study of Colorado granites by the model age method. Top: tectonic provinces. Bottom: provinces mapped by neodymium model ages. The two distributions do not correspond exactly, but any apparent difference can be explained by reworking. After Bennett and DePaolo (1987).
Figure 6.34 Neodymium isotope study of the Rocky Mountains in California. The curves of the $\varepsilon_{\text{Nd}}$ isotope ratios are plotted. An E–W curve is shown below. The proportion of mantle decreases very rapidly eastwards. After Farmer and DePaolo (1983).
Nd (and Hf) Model age method

supposubly works for any rock type (shale, gneiss, basalt, rhyolite, sandstone, etc.)

supposubly can see through erosion, sedimentation, metamorphism, melting

assumes
1) Sm/Nd never changed
2) rock was derived from DM
3) we know $\varepsilon_{\text{Nd}}$ of DM through time
4) no mixing of sources when formed (or earlier)
erosion/sedimentation

Fig. 4.21. Plot of Nd model ages for river particulates against the area-weighted average crustal residence age of rocks within the watershed. Data are shown for igneous–metamorphic drainage basins only. After Goldstein and Jacobsen (1988).

Fig. 4.22. Plot of depleted-mantle model ages in mud versus sand-grade fractions from deep-sea turbidites in different tectonic environments. After McLennan et al. (1989).
mixing during erosion/sedimentation

Fig. 4.23. Plot of $\varepsilon$ Nd against modal percentage of lithic volcanic fragments, to show the petrographic dependence of the Sm–Nd system in sedimentary basins with mixed provenance. (■) = Hagar basin; (□) = Espanola basin. After Nelson and DePaolo (1988).
Fig. 4.26. Plot of $T_{\text{CHUR}}$ model ages for samples of the Harquahala granite (Arizona) as a function of distance from the Harquahala thrust. Solid and open symbols indicate samples from two different traverses. Approximate boundaries between deformation zones are shown. Data from Barovich and Patchett (1992).
Fig. 4.8. Sm–Nd isochron for a mixed suite of granitic, tonalitic and layered basic gneisses from the Lewisian complex of NW Scotland, yielding an age of 2920 Myr. After Hamilton et al. (1979).

Fig. 4.9. Sm–Nd ‘errorchron’ for Lewisian tonalitic gneisses, defining an age of 2600 Myr, attributed to granulite-facies metamorphism. After Whitehouse (1988).

Fig. 4.27. Nd isotope evolution diagrams for the Lewisian complex of NW Scotland: (a) showing initial ratios for layered mafic bodies and a suite of granulite-facies tonalitic gneisses; and (b) showing Sm–Nd evolution lines for individual tonalitic gneisses. After Whitehouse (1988).
Fig. 4.28. Schematic diagram of Nd isotope systematics, to show possible errors in model age arising from Sm/Nd fractionation during intra-crustal melting. After Nelson and DePaolo, (1985).

Fig. 4.29. Schematic illustration of magma mixing as a mechanism capable of generating mixed provenance ages, which do not date any real geological event. After Arndt and Goldstein (1987).
Fig. 4.18. Plot of $\varepsilon$ Nd against time, showing Colorado data relative to a model depleted-mantle evolution curve. After DePaolo (1981).
Evolution of granitoids in the Catalina metamorphic core complex, southeastern Arizona: U–Pb, Nd, and Hf isotopic constraints

Katherine F. Fornash · P. Jonathan Patchett · George E. Gehrels · Jon E. Spencer

Fig. 1 Geologic map of the Catalina metamorphic core complex, Arizona, showing the locations of samples. Note that the “leucogranites (Eocene)” near the center of the range are part of the Wilderness suite granites, but the main leucogranite occurrences are not differentiated from mixed gneissic rocks in this map. Figure 2 (area of box) shows the different leucogranite units. Sources of map data include Banks (1974), Force (1997), Dickinson (1999), Spencer et al. (2000), Spencer and Pearthree (2004)

Fig. 3 Cross section along line A–A' (shown in Figs. 1, 2) illustrating the relationships between the granitoid units sampled in this study. Note that the core complex consists almost entirely of presumed deformed Oracle Granite or younger granitoids emplaced into it.
Fig. 5 Initial $\varepsilon_{Nd}$ values of granites versus crystallization age. The depleted mantle (DM) evolution curve is from DePaolo (1981), and the Pinal Schist evolution is derived from the data of Eisele and Isachsen (2001). The evolution trend for Oracle Granite is from this paper, but agrees closely with determinations from the same outcrop by Farmer and DePaolo (1983) and Barovich (1991).
Fig. 4.30. Estimated areas of North American crustal basement attributable to different Rb–Sr age provinces: (a) map showing provinces of different ages (in Byr); and (b) histogram of growth rate against time. After Hurley et al. (1962).

Fig. 4.31. Estimated continental growth rates on a cumulative basis. After Jacobsen (1988).
Figure 11.19. \( \varepsilon_{Nd} \) in rock suites for which there is little evidence of involvement of much older crust in their genesis (after Smith and Ludden, 1989).
Fig. 6.B2.1. Initial Nd isotopic composition of mafic rocks (MgO > 7 wt%) versus time compared to models for the isotopic evolution of the mantle. The line labeled “CHUR” shows the Nd isotope evolution of a mantle source with chondritic Sm/Nd ratio. The dashed curve shows a volume of mantle from which the continental crust is extracted at a rate of 0.35% of its current volume every 100 Ma. The solid curve assumes that the rate of continent extraction from the mantle falls off exponentially with time, whereas the gray line assumes a constant, superchondritic, Sm/Nd for the depleted mantle since Earth formation. The thin, positively sloped line is a schematic representation of the hypothetical isotopic evolution of a zero age granite. This line provides model ages for the source of the granite that range from 1.5 Ga (CHUR) to 2.1 Ga (constant rate crust formation) to 2.3 Ga (exponentially declining rate of continent formation) to 4.5 Ga (instantaneous continent formation at 4.567 Ga) to illustrate the importance of the assumed model evolution to the calculated model age. (Source: Data from EarthChem.)
Figure 6.15 The standard model of the mantle. The mantle is separated into two layers: the MORB derived from the upper layer and the OIB from the deeper layer. The upper layer is depleted in some elements by extraction of the continental crust. The deeper layer is more primitive (that is, closer to the value of the Bulk Earth). The continents are made up of a series of provinces of varied ages $T_1, T_2, T_3, T_4$. 
\[
\sum_j M^j C^j e_{Nd}^j = 0
\]
\[
f_{Sm/Nd} = \frac{^{147}Sm/^{144}Nd - ^{147}Sm/^{144}Nd_{CHUR}}{^{147}Sm/^{144}Nd_{CHUR}}
\]
\[
\sum_j M^j C^j f_{Sm/Nd}^j = 0
\]
\[
\sum_j M^j C_{Nd}^j = M^0 C_{Nd}^0
\]
\[
\sum_j M^j = M^0
\]
\[
^{143}Nd/^{144}Nd = ^{143}Nd/^{144}Nd_i + ^{147}Sm/^{144}Nd \lambda t
\]
\[
e_{Nd} = e_{Nd}^i + f_{Sm/Nd} Q t
\]
\[
Q_{Nd} = 10^4 \lambda \frac{^{147}Sm/^{144}Nd_{CHUR}}{^{143}Nd/^{144}Nd_{CHUR}}
\]
\[
e_{Nd}^c = f_{Sm/Nd}^c Q T^c
\]
\[
M^{dm}/M^c = \left( \frac{C_{Nd}^c}{C_{Nd}^0} - 1 \right) - \left( \frac{C_{Nd}^c}{C_{Nd}^0} \right) \frac{Q f_{Sm/Nd}^c T^c}{e_{Nd}^{dm}}
\]

Figure 11.21. The three reservoir model of the mantle. The depleted mantle is the source of MORB and has \( e_{Nd} = +10 \), the lower mantle is primitive and has bulk Earth characteristics, e.g., \( e_{Nd} = 0 \).
$M_{dm}/M_c \sim 60$

and $M_{wm}/M_c \sim 200$

so $M_{dm}/M_c \times 1/(M_{wm}/M_c) = M_{dm}/M_{wm}$

$= 60 \times 1/200 = 0.3$

why is this 0.3 number interesting?

If you calculate the volume ratio of upper to lower mantle, it’s about 0.3

Figure 11.22. The relationship between ratio of mass of the depleted mantle to mass of the continental crust as a function of mean age of the crust calculated from equation 18.6 using various values of $\varepsilon_{Nd}$ for the depleted mantle. The arrows at the bottom enclose the range of probable values for the mean age of the crust.
Figure 6.15 The standard model of the mantle. The mantle is separated into two layers: the MORB derived from the upper layer and the OIB from the deeper layer. The upper layer is depleted in some elements by extraction of the continental crust. The deeper layer is more primitive (that is, closer to the value of the Bulk Earth). The continents are made up of a series of provinces of varied ages $T_1, T_2, T_3, T_4$. 
Figure 18.3. Sr and Nd isotope ratios of the suboceanic mantle as sampled by oceanic basalts. Three fields are shown for MORB from the 3 ocean basins, other symbols are various oceanic islands and island chains.