Announcements

• Reading: p.167-179 (tough stuff)
• Focus on Rb-Sr system (p.172-175)
• Homework issues after lecture
Partition coefficients

- For dilute solutions:

\[ D = \frac{C_S}{C_L} \]

Where \( C_S \) = the concentration of some element in the solid phase

\( C_L \) = the concentration of the element in the liquid phase
• **incompatible** elements are concentrated in the melt

\[(K_D \text{ or } D) \ll 1\]

• **compatible** elements are concentrated in the solid

\[K_D \text{ or } D \gg 1\]
Incompatible elements commonly divided into two subgroups

- Smaller, highly charged high field strength (HFS) elements (REE, Th, U, Ce, Pb$^{4+}$, Zr, Hf, Ti, Nb, Ta)
- Low field strength large ion lithophile (LIL) elements (K, Rb, Cs, Ba, Pb$^{2+}$, Sr, Eu$^{2+}$) are more mobile, particularly if a fluid phase is involved
Lanthanide series: Rare earth elements
All 3+ (Eu can be 3+ or 2+)
Ionic radius decreases with increasing atomic number (lanthanide contraction)
Compatibility depends on minerals and melts involved.

Which are incompatible? Why?

**Table 9-1. Partition Coefficients (C_S/C_L) for Some Commonly Used Trace Elements in Basaltic and Andesitic Rocks**

<table>
<thead>
<tr>
<th></th>
<th>Olivine</th>
<th>Opx</th>
<th>Cpx</th>
<th>Garnet</th>
<th>Plag</th>
<th>Amph</th>
<th>Magnetite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rb</td>
<td>0.010</td>
<td>0.022</td>
<td>0.031</td>
<td>0.042</td>
<td>0.071</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>Sr</td>
<td>0.014</td>
<td>0.040</td>
<td>0.060</td>
<td>0.012</td>
<td>1.830</td>
<td>0.46</td>
<td></td>
</tr>
<tr>
<td>Ba</td>
<td>0.010</td>
<td>0.013</td>
<td>0.026</td>
<td>0.023</td>
<td>0.23</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td>14</td>
<td>5</td>
<td>7</td>
<td>0.955</td>
<td><strong>0.01</strong></td>
<td>6.8</td>
<td>29</td>
</tr>
<tr>
<td>Cr</td>
<td>0.70</td>
<td>10</td>
<td>34</td>
<td>1.345</td>
<td><strong>0.01</strong></td>
<td>2.00</td>
<td>7.4</td>
</tr>
<tr>
<td>La</td>
<td>0.007</td>
<td>0.03</td>
<td>0.056</td>
<td>0.001</td>
<td>0.148</td>
<td>0.544</td>
<td>2</td>
</tr>
<tr>
<td>Ce</td>
<td>0.006</td>
<td>0.02</td>
<td>0.092</td>
<td>0.007</td>
<td>0.082</td>
<td>0.843</td>
<td>2</td>
</tr>
<tr>
<td>Nd</td>
<td>0.006</td>
<td>0.03</td>
<td>0.230</td>
<td>0.026</td>
<td>0.055</td>
<td>1.340</td>
<td>2</td>
</tr>
<tr>
<td>Sm</td>
<td>0.007</td>
<td>0.05</td>
<td>0.445</td>
<td>0.102</td>
<td>0.039</td>
<td>1.804</td>
<td>1</td>
</tr>
<tr>
<td>Eu</td>
<td>0.007</td>
<td>0.05</td>
<td>0.474</td>
<td>0.243</td>
<td>0.1/1.5*</td>
<td>1.557</td>
<td>1</td>
</tr>
<tr>
<td>Dy</td>
<td>0.013</td>
<td>0.15</td>
<td>0.582</td>
<td>1.940</td>
<td>0.023</td>
<td>2.024</td>
<td>1</td>
</tr>
<tr>
<td>Er</td>
<td>0.026</td>
<td>0.23</td>
<td>0.583</td>
<td>4.700</td>
<td>0.020</td>
<td>1.740</td>
<td>1.5</td>
</tr>
<tr>
<td>Yb</td>
<td>0.049</td>
<td>0.34</td>
<td>0.542</td>
<td>6.167</td>
<td>0.023</td>
<td>1.642</td>
<td>1.4</td>
</tr>
<tr>
<td>Lu</td>
<td>0.045</td>
<td>0.42</td>
<td>0.506</td>
<td>6.950</td>
<td>0.019</td>
<td>1.563</td>
<td></td>
</tr>
</tbody>
</table>

Data from Rollinson (1993). * Eu^{3+}/Eu^{2+} **Italics** are estimated.
REE Diagrams

Plots of concentration as the ordinate (y-axis) against increasing atomic number

– Degree of compatibility increases from left to right across the diagram
– Eliminate Oddo-Harkins effect and make y-scale more functional by normalizing to a standard
  • estimates of primordial mantle REE
  • chondrite meteorite concentrations
What would an REE diagram look like for an analysis of a chondrite meteorite?
REE diagrams using batch melting model of a garnet lherzolite for various values of F:

Figure 9-4. Rare Earth concentrations (normalized to chondrite) for melts produced at various values of F via melting of a hypothetical garnet lherzolite using the batch melting model (equation 9-5). From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.
Continental Arc
Magmatism: South American Arc

Figure 17-4. Chondrite-normalized REE diagram for selected Andean volcanics. NVZ (6 samples, average SiO$_2$ = 60.7, K$_2$O = 0.66, data from Thorpe et al. 1984; Geist, pers. comm.). CVZ (10 samples, ave. SiO$_2$ = 54.8, K$_2$O = 2.77, data from Deruelle, 1982; Davidson, pers. comm.; Thorpe et al., 1984). SVZ (49 samples, average SiO$_2$ = 52.1, K$_2$O = 1.07, data from Hickey et al. 1986; Deruelle, 1982; López-Escobar et al. 1981). Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.
Lunar rocks

- Model igneous processes with REE
• Europium anomaly when plagioclase is
  – a fractionating phenocryst
  or
  – a residual solid in source

Figure 9-5. REE diagram for 10% batch melting of a hypothetical herzolite with 20% plagioclase, resulting in a pronounced negative Europium anomaly. From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.
Summary of important points

• Partition coefficients

• Rare earth elements (REE)
  • Normalization to chondritic values
  • Model melting or fractional crystallization in presence of certain minerals (garnet, plagioclase)