Chapter 10: Mantle Melting and the Generation of Basaltic Magma
2 principal types of basalt in the ocean basins

**Tholeiitic Basalt and Alkaline Basalt**

Table 10.1  Common petrographic differences between tholeiitic and alkaline basalts

<table>
<thead>
<tr>
<th>Groundmass</th>
<th>Tholeiitic Basalt</th>
<th>Alkaline Basalt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usually fine-grained, intergranular</td>
<td>No olivine</td>
<td>Usually fairly coarse, intergranular to ophitic</td>
</tr>
<tr>
<td>Clinopyroxene = augite (plus possibly pigeonite)</td>
<td>Orthopyroxene (hypersthene) common, may rim ol.</td>
<td>Olivine common</td>
</tr>
<tr>
<td>Orthopyroxene (hypersthene) common, may rim ol.</td>
<td>No alkali feldspar</td>
<td>Titaniferous augite (reddish)</td>
</tr>
<tr>
<td>No alkali feldspar</td>
<td>Interstitial glass and/or quartz common</td>
<td>Orthopyroxene absent</td>
</tr>
<tr>
<td>Interstitial glass and/or quartz common</td>
<td></td>
<td>Interstitial alkali feldspar or feldspathoid may occur</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Phenocrysts</th>
<th>Tholeiitic Basalt</th>
<th>Alkaline Basalt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olivine rare, unzoned, and may be partially resorbed</td>
<td>Orthopyroxene uncommon</td>
<td>Olivine common and zoned</td>
</tr>
<tr>
<td>or show reaction rims of orthopyroxene</td>
<td></td>
<td>Orthopyroxene absent</td>
</tr>
<tr>
<td>Orthopyroxene uncommon</td>
<td>Early plagioclase common</td>
<td>Plagioclase less common, and later in sequence</td>
</tr>
<tr>
<td>Early plagioclase common</td>
<td>Clinopyroxene is pale brown augite</td>
<td>Clinopyroxene is titaniferous augite, reddish rims</td>
</tr>
<tr>
<td>Clinopyroxene is pale brown augite</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Each is chemically distinct
Evolve via FX as separate series along different paths

- Tholeiites are generated at mid-ocean ridges
  - Also generated at oceanic islands, subduction zones
- Alkaline basalts generated at ocean islands
  - Also at subduction zones
Sources of mantle material

- **Ophiolites**
  - Slabs of oceanic crust and upper mantle
  - Thrust at subduction zones onto edge of continent

- **Dredge samples** from oceanic crust

- **Nodules** and **xenoliths** in some basalts

- **Kimberlite xenoliths**
  - Diamond-bearing pipes blasted up from the mantle carrying numerous xenoliths from depth
Lherzolite is probably fertile unaltered mantle. Dunite and harzburgite are refractory residuum after basalt has been extracted by partial melting.

Lherzolite: A type of peridotite with Olivine > Opx + Cpx
Phase diagram for aluminous 4-phase lherzolite:

Al-phase =
- Plagioclase
  $\rightarrow$ shallow (< 50 km)
- Spinel
  $\rightarrow$ 50-80 km
- Garnet
  $\rightarrow$ 80-400 km
- Si $\rightarrow$ VI coord.
  $\rightarrow$ > 400 km

Figure 10.2 Phase diagram of aluminous lherzolite with melting interval (gray), sub-solidus reactions, and geothermal gradient. After Wyllie, P. J. (1981). Geol. Rundsch. 70, 128-153.
How does the mantle melt??

1) Increase the temperature

Figure 10.3. Melting by raising the temperature.
2) Lower the pressure

- **Adiabatic** rise of mantle with no conductive heat loss
- **Decompression partial melting** could melt at least 30%

*Figure 10.4. Melting by (adiabatic) pressure reduction. Melting begins when the adiabat crosses the solidus and traverses the shaded melting interval. Dashed lines represent approximate % melting.*
3) Add volatiles (especially $\text{H}_2\text{O}$)

Figure 10.4. Dry peridotite solidus compared to several experiments on H2O-saturated peridotites.
Fraction melted is limited by the availability of water.

Figure 7.22. Pressure-temperature projection of the melting relationships in the system albite-\(\text{H}_2\text{O}\). From Burnham and Davis (1974). A J Sci., 274, 902-940.
Heating of **amphibole-bearing** peridotite

1) Ocean geotherm
2) Shield geotherm

Figure 10.6 Phase diagram (partly schematic) for a hydrous mantle system, including the H2O-saturated lherzolite solidus of Kushiro et al. (1968), the dehydration breakdown curves for amphibole (Millhollen et al., 1974) and phlogopite (Modreski and Boettcher, 1973), plus the ocean and shield geotherms of Clark and Ringwood (1964) and Ringwood (1966). After Wyllie (1979). In H. S. Yoder (ed.), *The Evolution of the Igneous Rocks. Fiftieth Anniversary Perspectives*. Princeton University Press, Princeton, N. J, pp. 483-520.
Melts can be created under realistic circumstances

- Plates separate and mantle rises at mid-ocean ridges
  - Adibatic rise $\rightarrow$ decompression melting
- Hot spots $\rightarrow$ localized plumes of melt
- Fluid fluxing may give LVL
  - Also important in subduction zones and other settings
Generation of tholeiitic and alkaline basalts from a chemically uniform mantle

Variables (other than X)

- Temperature
- Pressure

Figure 10.2 Phase diagram of aluminous lherzolite with melting interval (gray), sub-solidus reactions, and geothermal gradient. After Wyllie, P. J. (1981). Geol. Rundsch. 70, 128-153.
Pressure effects:

Figure 10.8 Change in the eutectic (first melt) composition with increasing pressure from 1 to 3 GPa projected onto the base of the basalt tetrahedron. After Kushiro (1968), J. Geophys. Res., 73, 619-634.
Liquids and residuum of melted pyrolite

Figure 10.9 After Green and Ringwood (1967). *Earth Planet. Sci. Lett.* 2, 151-160.
Initial Conclusions:

- Tholeiites favored by **shallower melting**
  - 25% melting at <30 km → tholeiite
  - 25% melting at 60 km → olivine basalt

- Tholeiites favored by **greater % partial melting (F)**
  - 20% melting at 60 km → alkaline basalt
    - incompatibles (alkalis) → initial melts
  - 30% melting at 60 km → tholeiite
Crystal Fractionation of magmas as they rise

- Tholeiite $\rightarrow$ alkaline by FX at med to high P
- Not at low P
  - Thermal divide
- Al in pyroxenes at Hi P
  - Low-P FX $\rightarrow$ hi-Al shallow magmas ("hi-Al" basalt)

Other, more recent experiments on melting of fertile (initially garnet-bearing) lherzolite confirm that alkaline basalts are favored by high P and low F.
Primary magmas

- Formed at depth and not subsequently modified by FX or Assimilation

- Criteria
  - Highest Mg# (100Mg/(Mg+Fe)) really → parental magma
  - Experimental results of lherzolite melts
    - Mg# = 66-75
    - Cr > 1000 ppm
    - Ni > 400-500 ppm
    - Multiply saturated
Multiple saturation

- Low P
  - Ol then Plag then Cpx as cool
  - $\sim 70^\circ$C T range

Multiple saturation

- **Low P**
  - Ol then Plag then Cpx as cool
  - 70°C T range

- **High P**
  - Cpx then Plag then Ol

Multiple saturation

- Low P
  - Ol then Plag then Cpx as cool
  - 70°C T range
- High P
  - Cpx then Plag then Ol
- 25 km get all at once
  - = Multiple saturation
  - Suggests that 25 km is the depth of last equilibrium with the mantle
Summary

- A chemically homogeneous mantle can yield a variety of basalt types.
- Alkaline basalts are favored over tholeiites by deeper melting and by low % PM.
- Fractionation at moderate to high depths can also create alkaline basalts from tholeiites.
- At low P there is a thermal divide that separates the two series.
Review of REE
Review of REE

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.

increasing incompatibility
REE data for oceanic basalts

Figure 10.14a. REE diagram for a typical alkaline ocean island basalt (OIB) and tholeiitic mid-ocean ridge basalt (MORB). From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall. Data from Sun and McDonough (1989).
Figure 10.14b. Spider diagram for a typical alkaline ocean island basalt (OIB) and tholeiitic mid-ocean ridge basalt (MORB). From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall. Data from Sun and McDonough (1989).
Suggests different mantle source types, but isn’t conclusive.

Depleted mantle could → both MORB and OIB.
Figure 10.15 Chondrite-normalized REE diagrams for spinel (a) and garnet (b) lherzolites. After Basaltic Volcanism Study Project (1981). Lunar and Planetary Institute.
Review of Sr isotopes

- $^{87}\text{Rb} \rightarrow ^{87}\text{Sr}$  $\lambda = 1.42 \times 10^{-11}$ a
- Rb (parent) conc. in enriched reservoir (incompatible)
- **Enriched** reservoir
develops **more** $^{87}\text{Sr}$ over time
- **Depleted** reservoir
  (less Rb)
develops **less** $^{87}\text{Sr}$ over time

Review of Nd isotopes

- $^{147}\text{Sm} \to ^{143}\text{Nd}$ $\lambda = 6.54 \times 10^{-13}$ a
- Nd (daughter) $\to$ enriched reservoir $>$ Sm
- Enriched reservoir develops less $^{143}\text{Nd}$ over time
- Depleted res. (higher Sm/Nd) develops higher $^{143}\text{Nd}/^{144}\text{Nd}$ over time

Nd and Sr isotopes of Ocean Basalts

“Mantle Array”

Figure 10.16a. Initial $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ for oceanic basalts. From Wilson (1989). Igneous Petrogenesis. Unwin Hyman/Kluwer. Data from Zindler et al. (1982) and Menzies (1983).
Nd and Sr isotopes of Kimberlite Xenoliths

Figure 10.16b. Initial $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ for mantle xenoliths. From Wilson (1989). Igneous Petrogenesis. Unwin Hyman/Kluwer. Data from Zindler et al. (1982) and Menzies (1983).
“Whole Mantle” circulation model

Figure 10-17a After Basaltic Volcanism Study Project (1981). Lunar and Planetary Institute.
“Two-Layer” circulation model

- Upper depleted mantle = MORB source
- Lower undepleted & enriched OIB source

Figure 10-17b After Basaltic Volcanism Study Project (1981). Lunar and Planetary Institute.
Experiments on melting enriched vs. depleted mantle samples:

1. **Depleted Mantle**
   - Tholeiite easily created by 10-30% PM
   - More silica saturated at lower P
   - Grades toward alkalic at higher P

Figure 10-18a. Results of partial melting experiments on depleted lherzolites. Dashed lines are contours representing percent partial melt produced. Strongly curved lines are contours of the normative olivine content of the melt. “Opx out” and “Cpx out” represent the degree of melting at which these phases are completely consumed in the melt. After Jaques and Green (1980). Contrib. Mineral. Petrol., 73, 287-310.
Experiments on melting enriched vs. depleted mantle samples:

2. **Enriched Mantle**
   - Tholeiites extend to higher P than for DM
   - Alkaline basalt field at higher P yet
     - And lower % PM

Figure 10-18b. Results of partial melting experiments on fertile lherzolites. Dashed lines are contours representing percent partial melt produced. Strongly curved lines are contours of the normative olivine content of the melt. “Opx out” and “Cpx out” represent the degree of melting at which these phases are completely consumed in the melt. The shaded area represents the conditions required for the generation of alkaline basaltic magmas. After Jaques and Green (1980). Contrib. Mineral. Petrol., 73, 287-310.