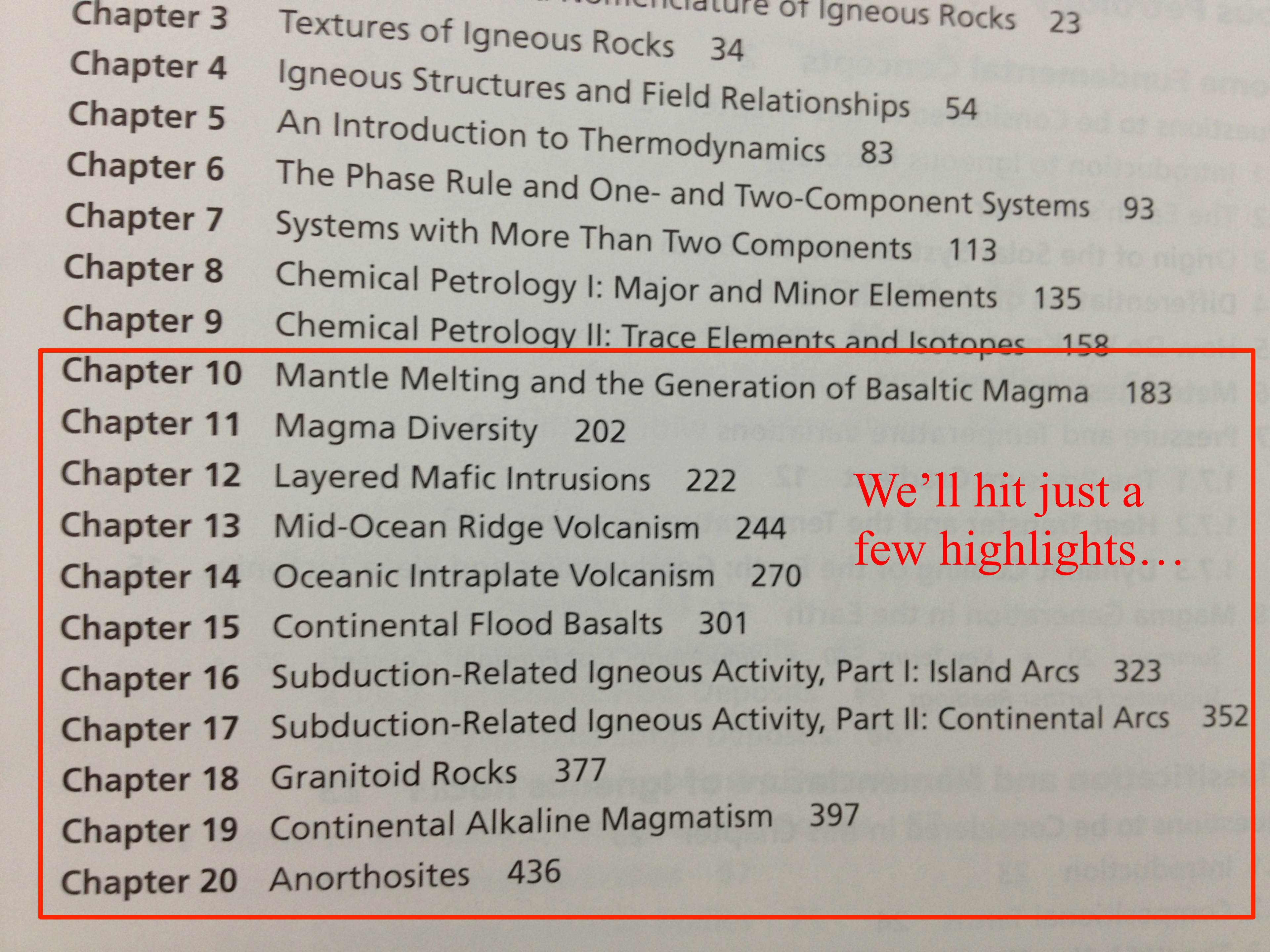


We'll hit just a few highlights…

A world-wide survey suggests that there may be some important differences between the three series

Characteristic	**Plate Margin**		**Within Plate**	
Series	**Convergent**	**Divergent**	**Oceanic**	**Continental**
Alkaline	yes		yes	yes
Tholeiitic	yes	yes	yes	yes
Calc-alkaline	yes			

After Wilson (1989). Igneous Petrogenesis. Unwin Hyman - Kluwer

Alkali vs. Silica diagram for Hawaiian volcanics:

Seems to be two distinct groupings: *alkaline* and *subalkaline*

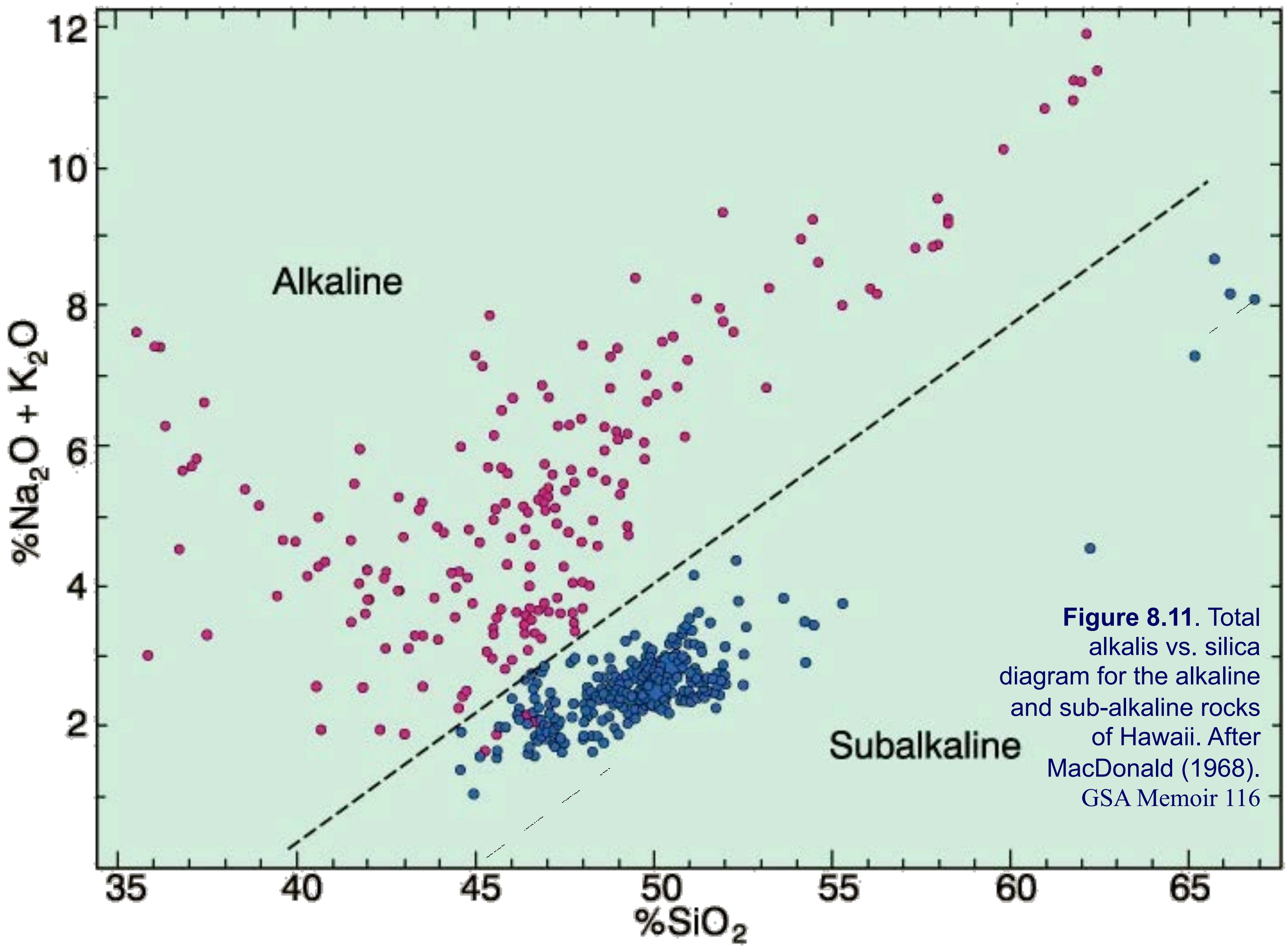
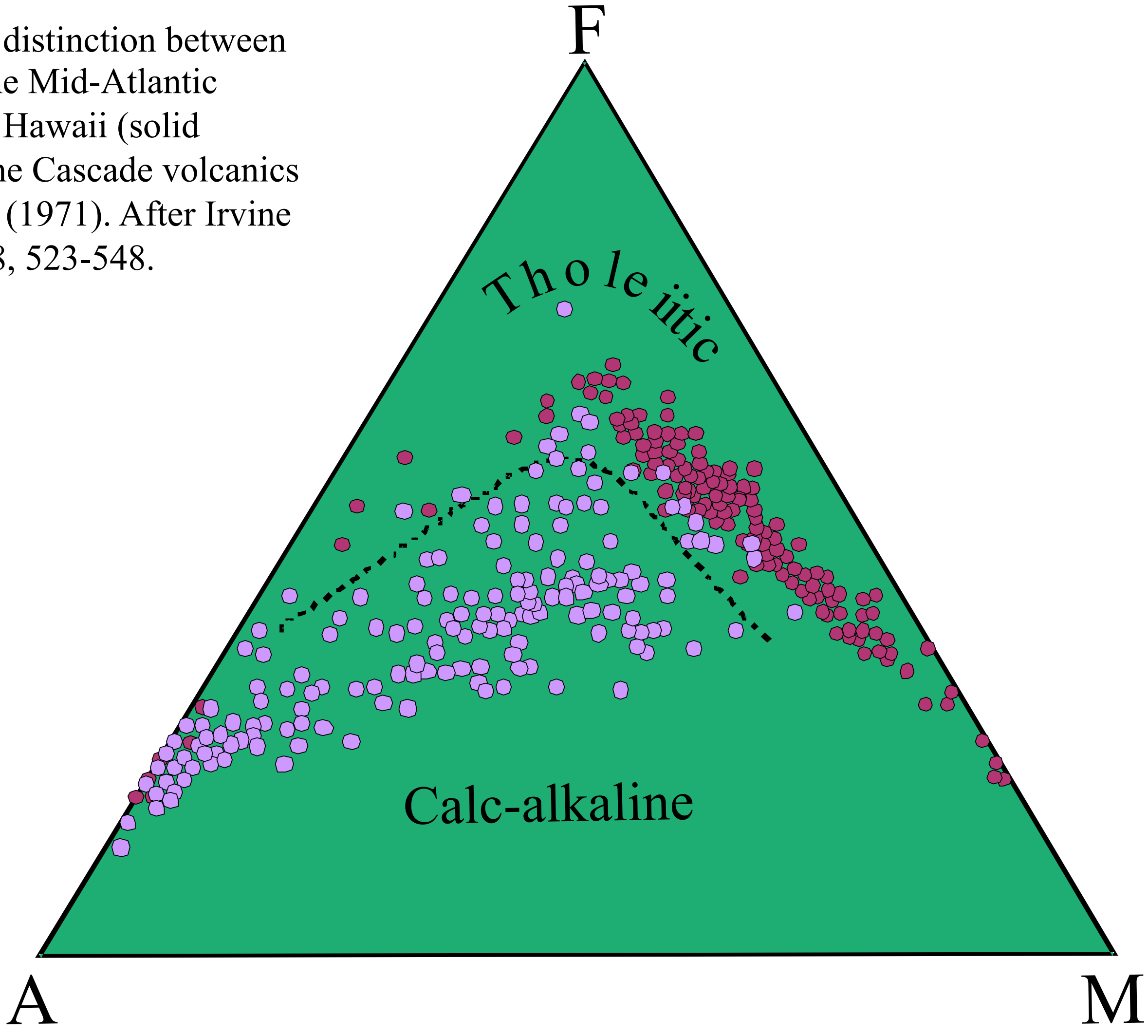


Figure 8.11. Total alkalis vs. silica diagram for the alkaline and sub-alkaline rocks of Hawaii. After MacDonald (1968). GSA Memoir 116

AFM diagram: can further subdivide the subalkaline magma series into a ***tholeiitic*** and a *calc-alkaline* series

Figure 8.14. AFM diagram showing the distinction between selected tholeiitic rocks from Iceland, the Mid-Atlantic Ridge, the Columbia River Basalts, and Hawaii (solid circles) plus the calc-alkaline rocks of the Cascade volcanics (open circles). From Irving and Baragar (1971). After Irvine and Baragar (1971). Can. J. Earth Sci., 8, 523-548.



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Characteristic	**Plate Margin**		**Within Plate**	
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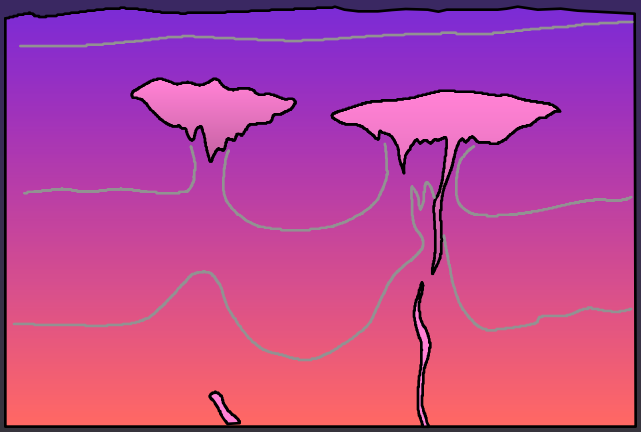
Calc-alkaline	yes			

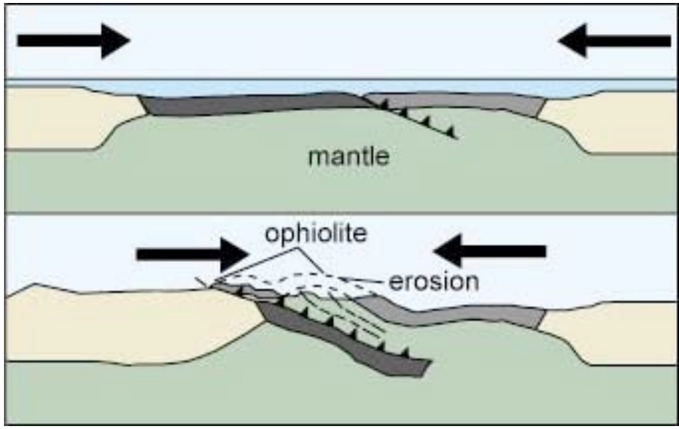
After Wilson (1989). Igneous Petrogenesis. Unwin Hyman - Kluwer

Chapter 10: Mantle Melting and the Generation of Basaltic Magma



Geology 346- Petrology

Sources of mantle material



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

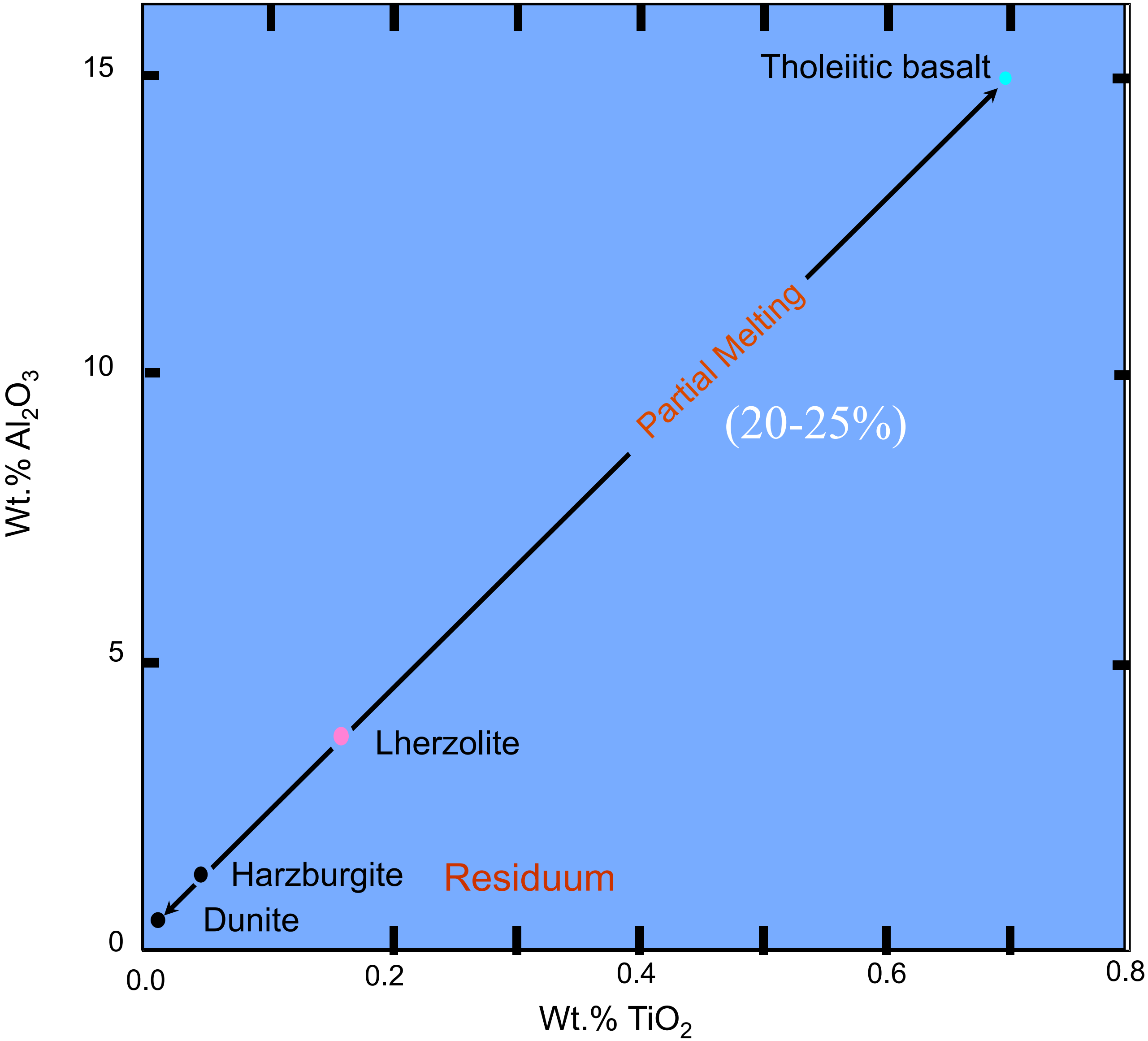


Figure 10-1 Brown and Mussett, A. E. (1993), *The Inaccessible Earth: An Integrated View of Its Structure and Composition.* Chapman & Hall/Kluwer.

Lherzolite: A type of peridotite with Olivine > Opx + Cpx

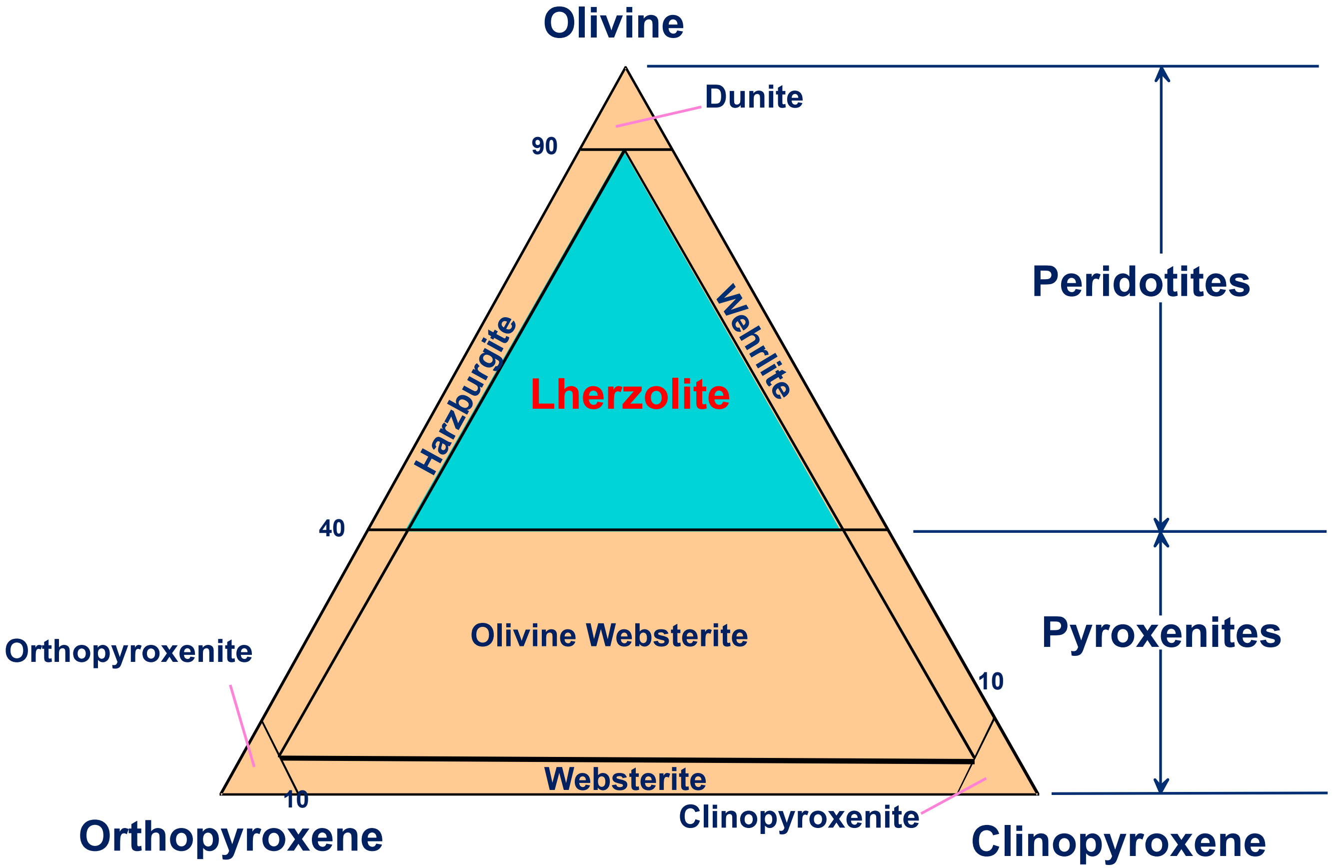


Figure 2.2 C After IUGS

Phase diagram for aluminous 4-phase lherzolite:

Al-phase =

- Plagioclase
  - shallow (< 50 km)
- Spinel ($MgAl_2O_4$)
  - 50-80 km
- Garnet ($Mg_3Al_2[SiO_4]_3$)
  - 80-400 km
- Si → VI coord.
  - > 400 km

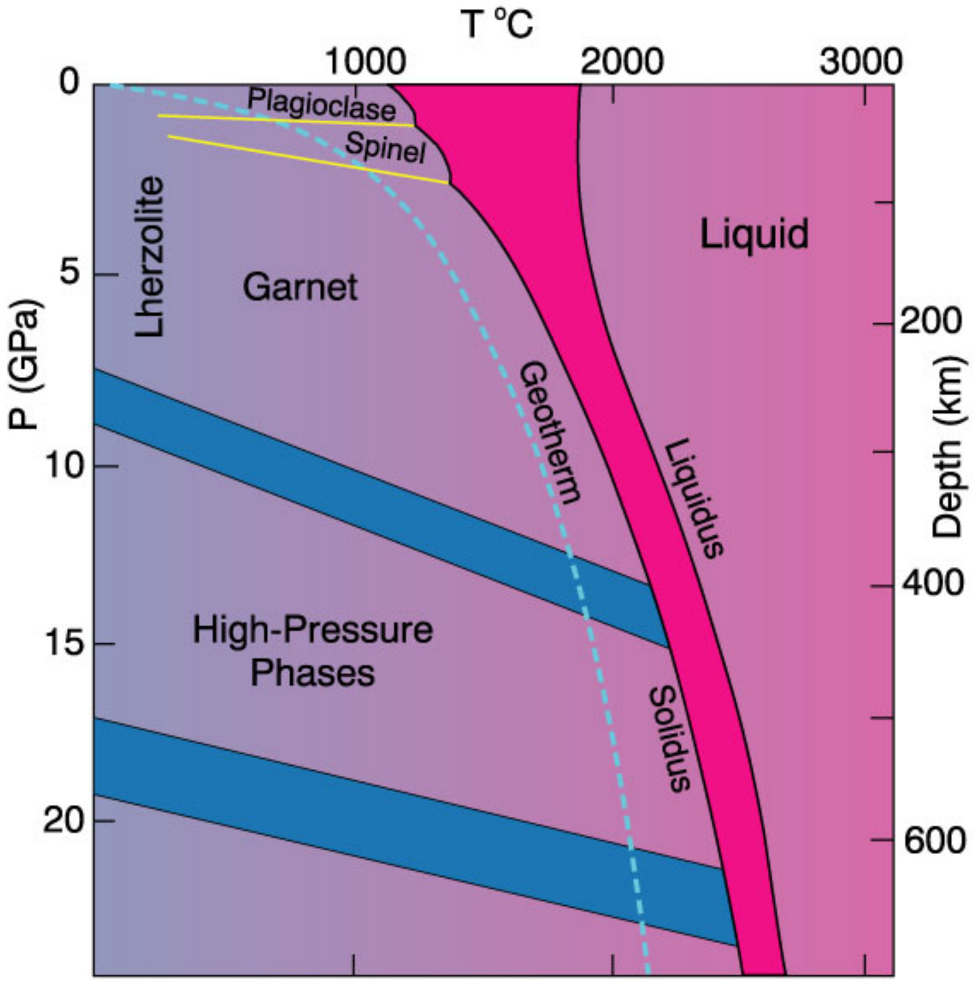


Figure 10.2 Phase diagram of aluminous lherzolite with melting interval (gray), sub-solidus reactions, and geothermal gradient. After Wyllie, P. J. (1981). Geol. Rundsch. 70, 128-153.

How does the mantle melt??

1) Increase the temperature

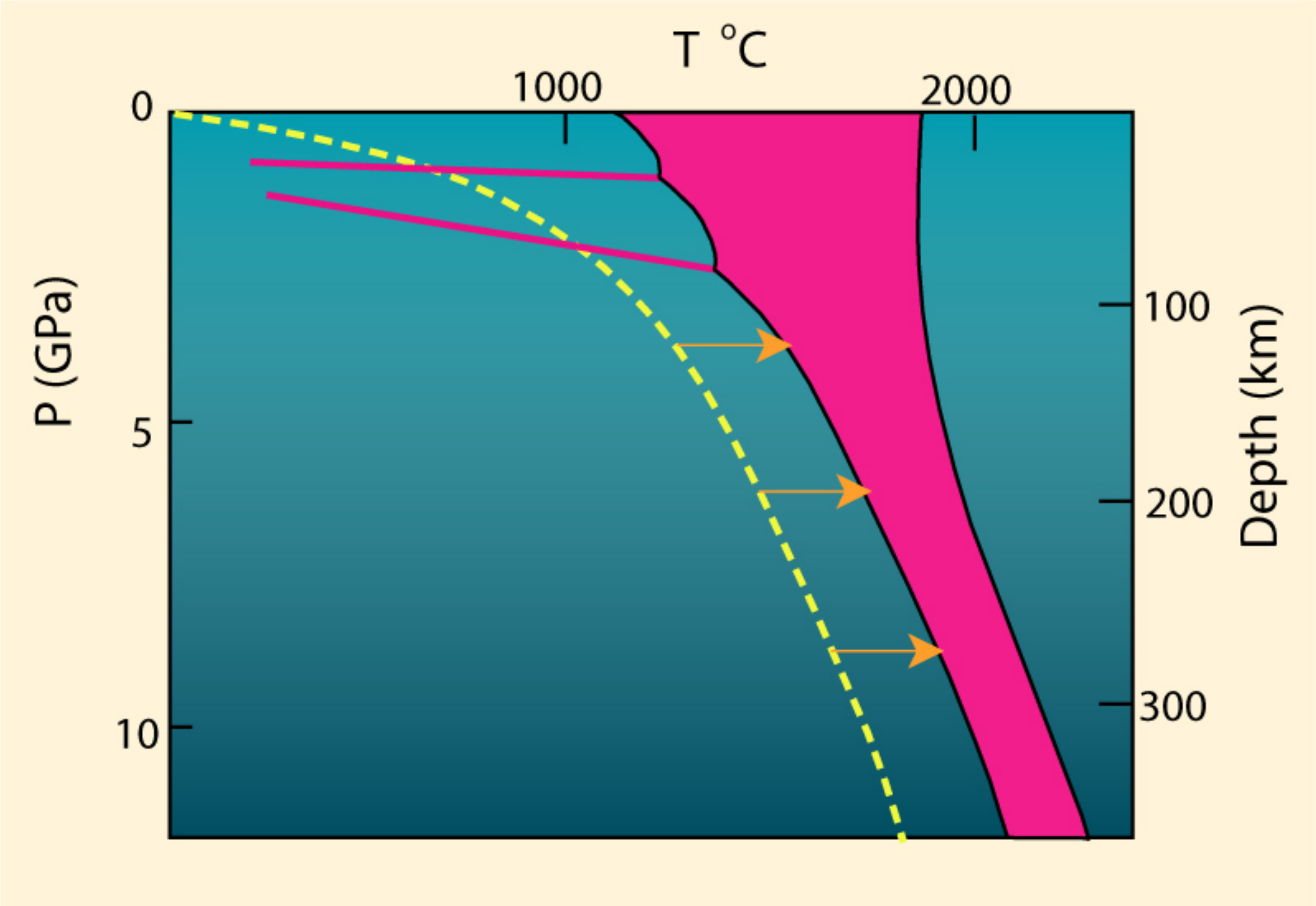


Figure 10.3. Melting by raising the temperature.

2) Lower the pressure

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

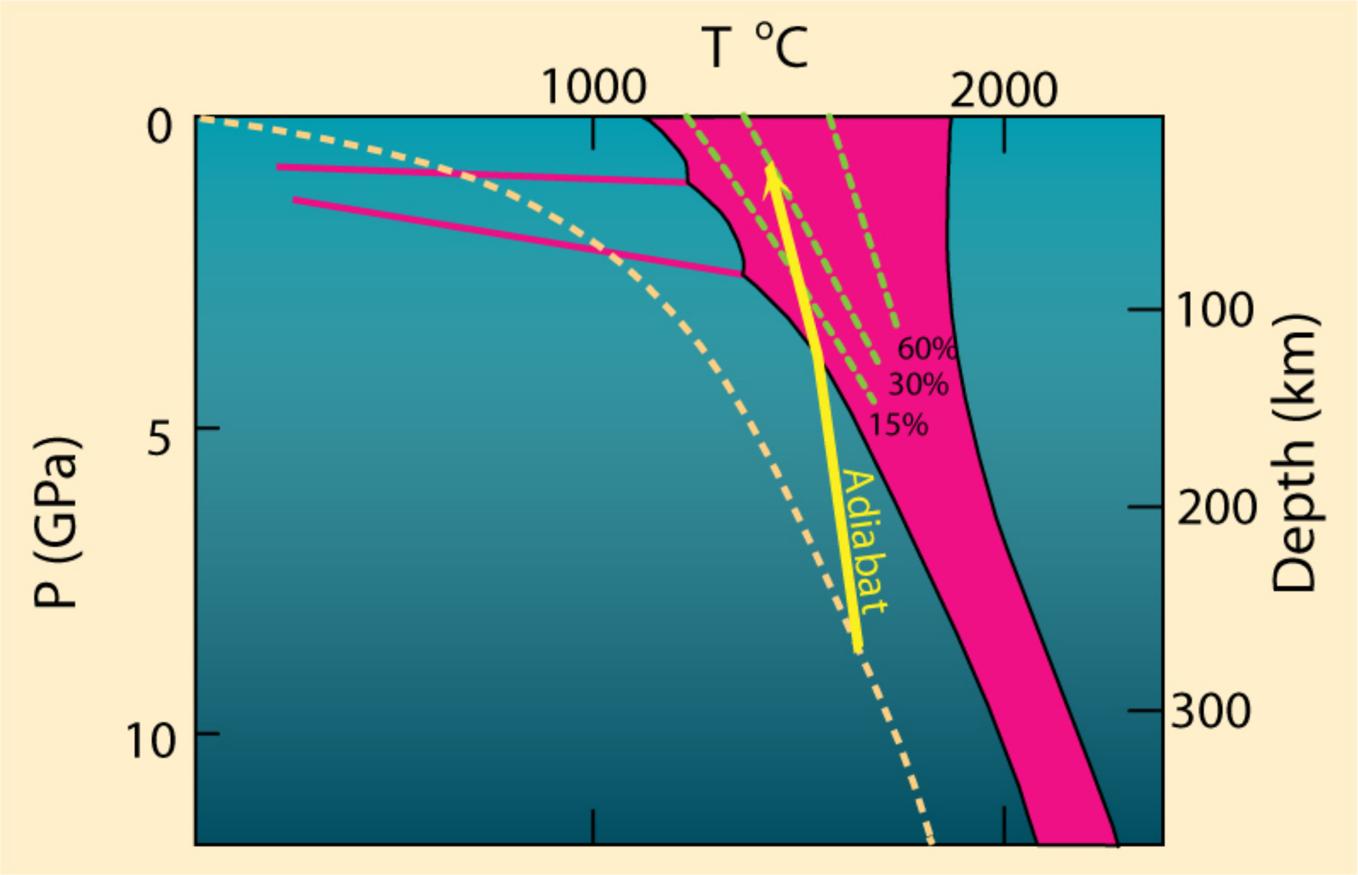


Figure 10.4. Melting by (adiabatic) pressure reduction. Melting begins when the adiabat crosses the solidus and traverses the shaded melting interval. Dashed lines represent approximate % melting.

3) Add volatiles (especially H_2O)

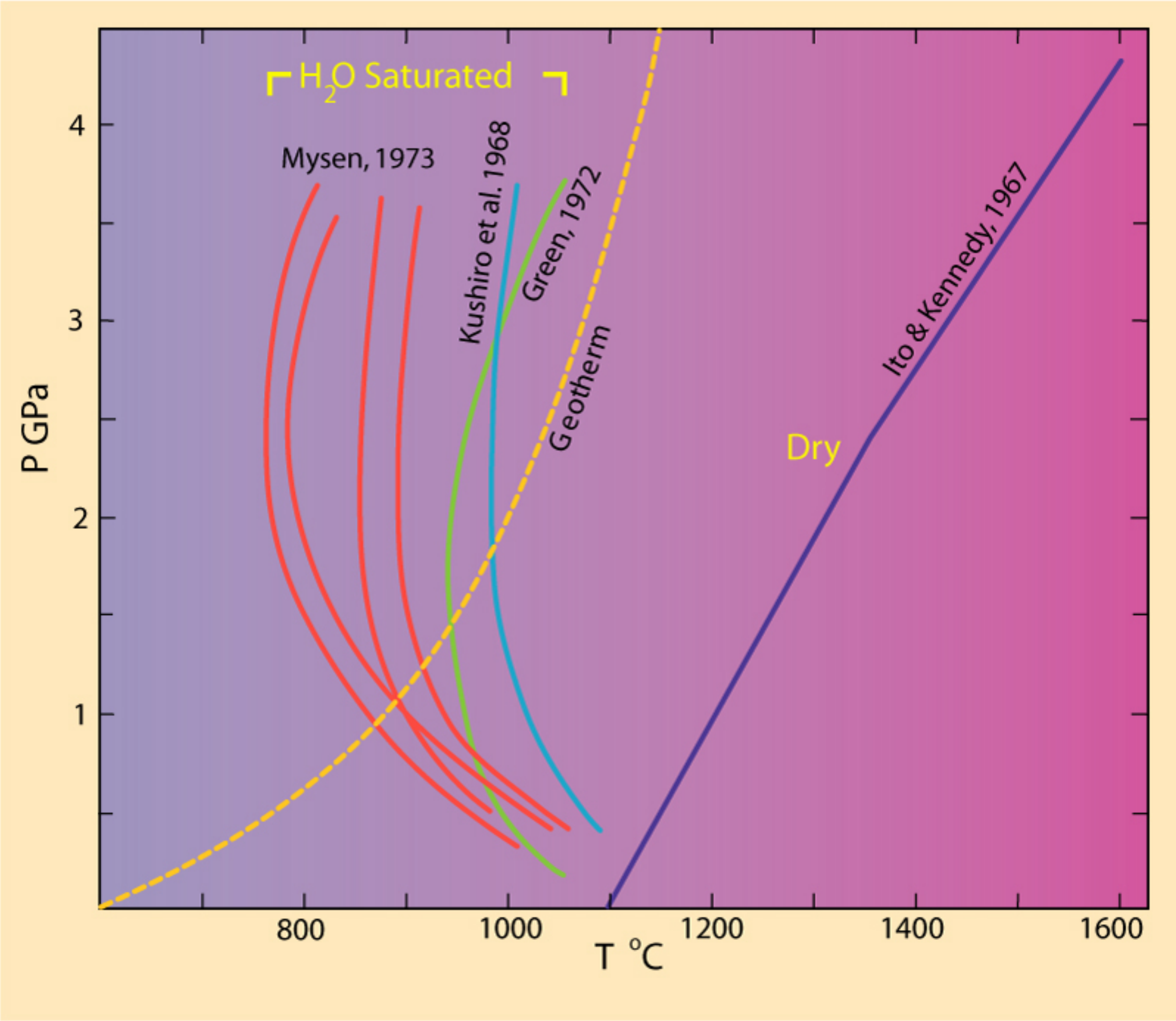


Figure 10.4. Dry peridotite solidus compared to several experiments on H2O-saturated peridotites.

Melts can be created under realistic circumstances

- Plates separate and mantle rises at mid-ocean ridges
  - Adiabatic rise → decompression melting
- Hot spots → localized plumes of melt
- Fluid fluxing may give low-velocity layer
  - 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

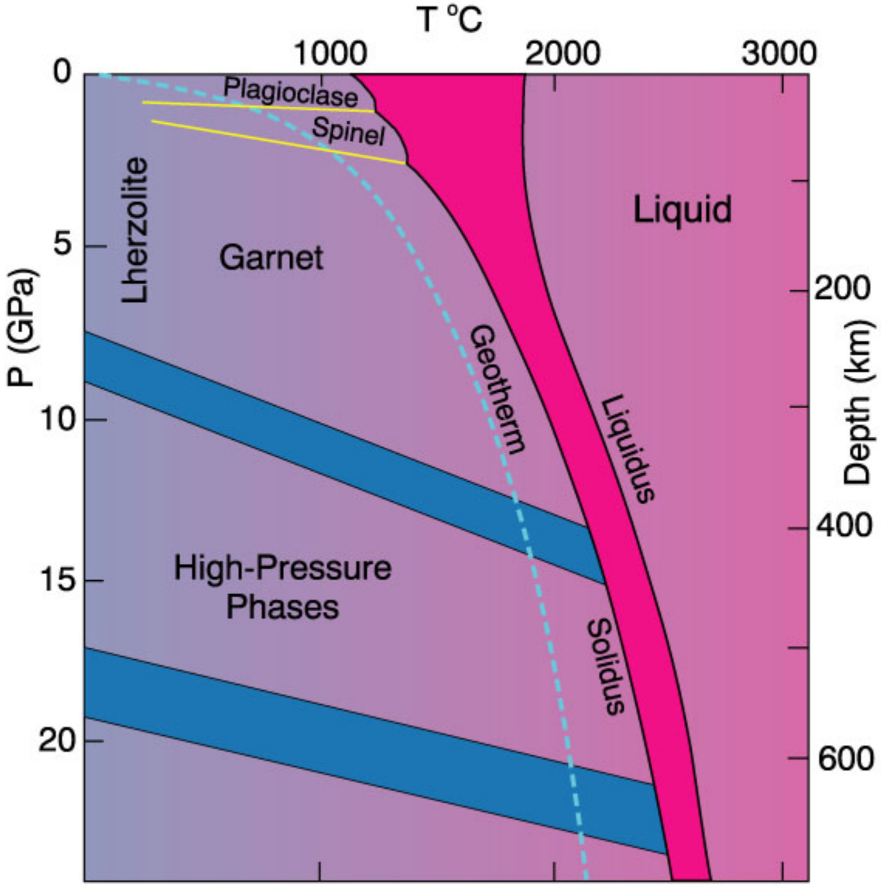


Figure 10.2 Phase diagram of aluminous lherzolite with melting interval (gray), sub-solidus reactions, and geothermal gradient. After Wyllie, P. J. (1981). Geol. Rundsch. 70, 128-153.

Pressure effects:

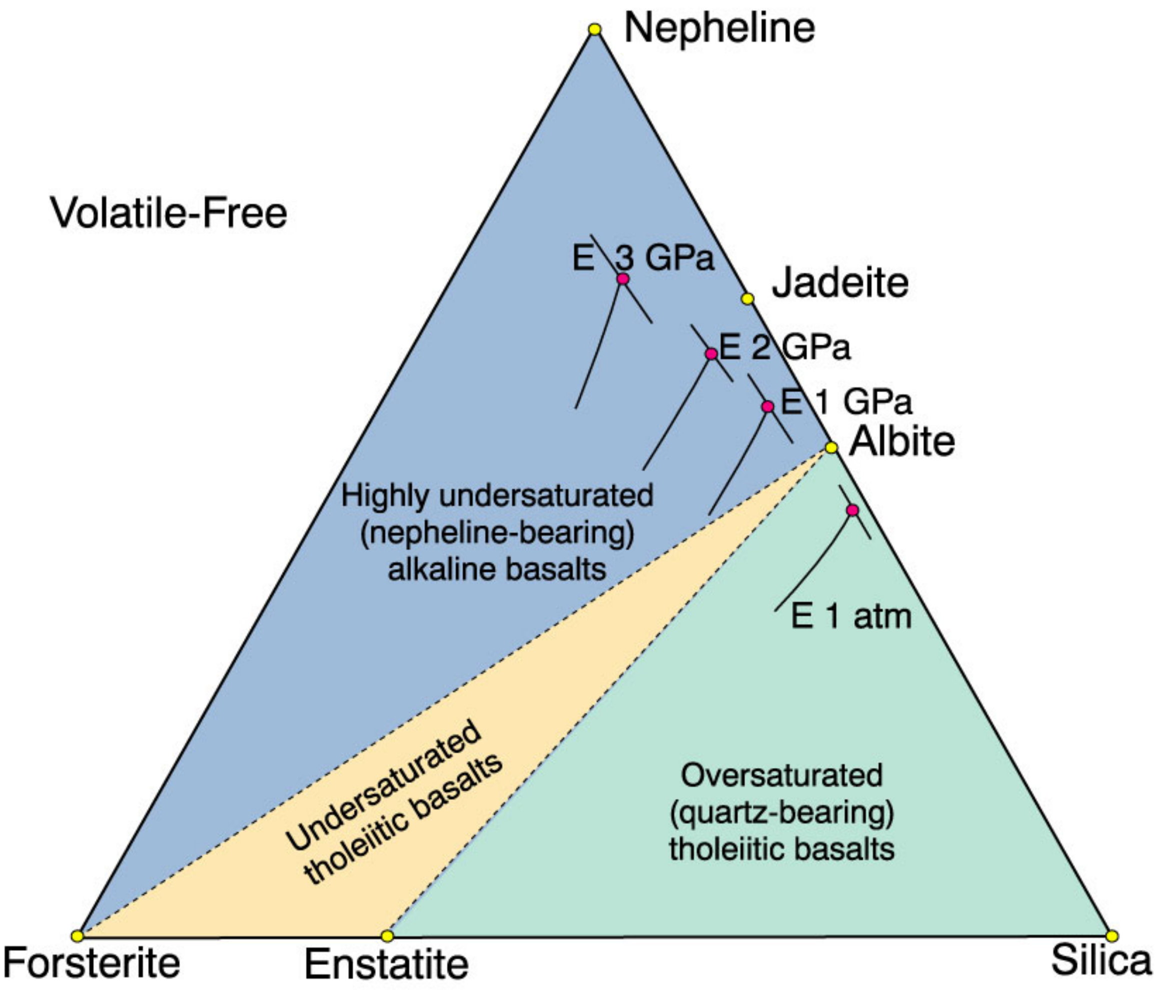


Figure 10.8 Change in the eutectic (first melt) composition with increasing pressure from 1 to 3 GPa projected onto the base of the basalt tetrahedron. After Kushiro (1968), J. Geophys. Res., 73, 619-634.

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

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 – batch melting

- Enrich LREE > HREE
- Greater enrichment for lower % PM

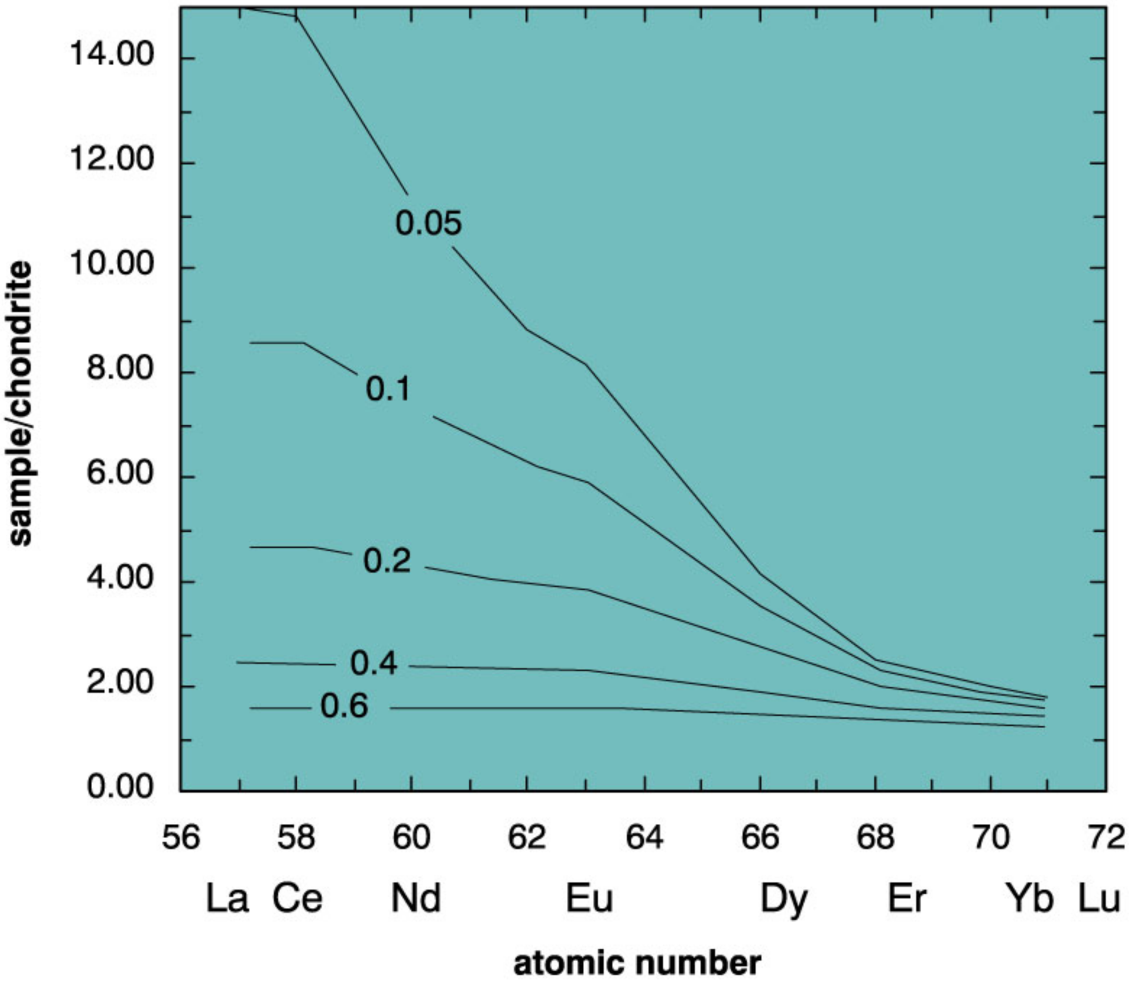
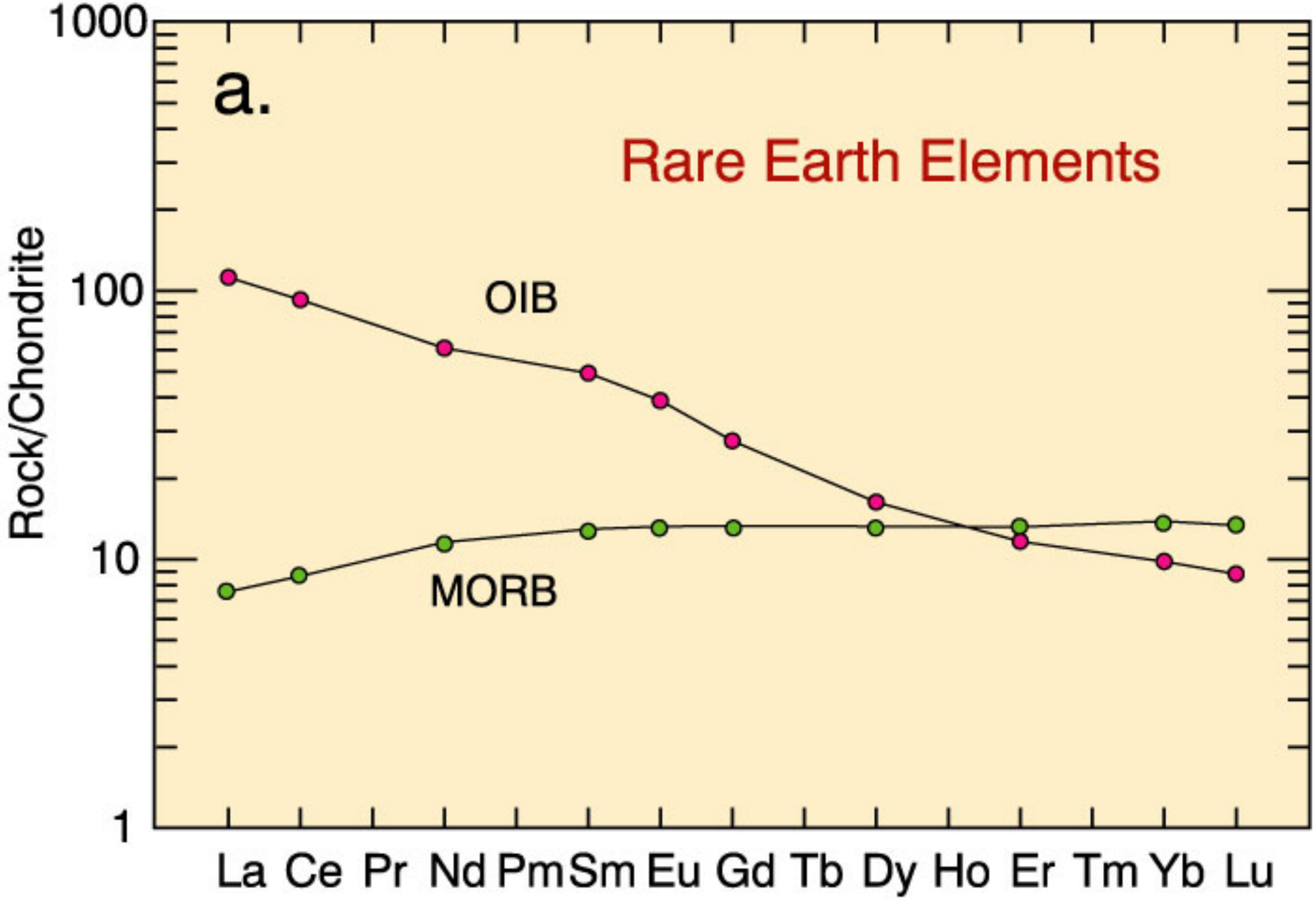


Figure 9.4. Rare Earth concentrations (normalized to chondrite) for melts produced at various values of F via melting of a hypothetical garnet lherzolite using the batch melting model (equation 9-5). From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

← **increasing incompatibility**

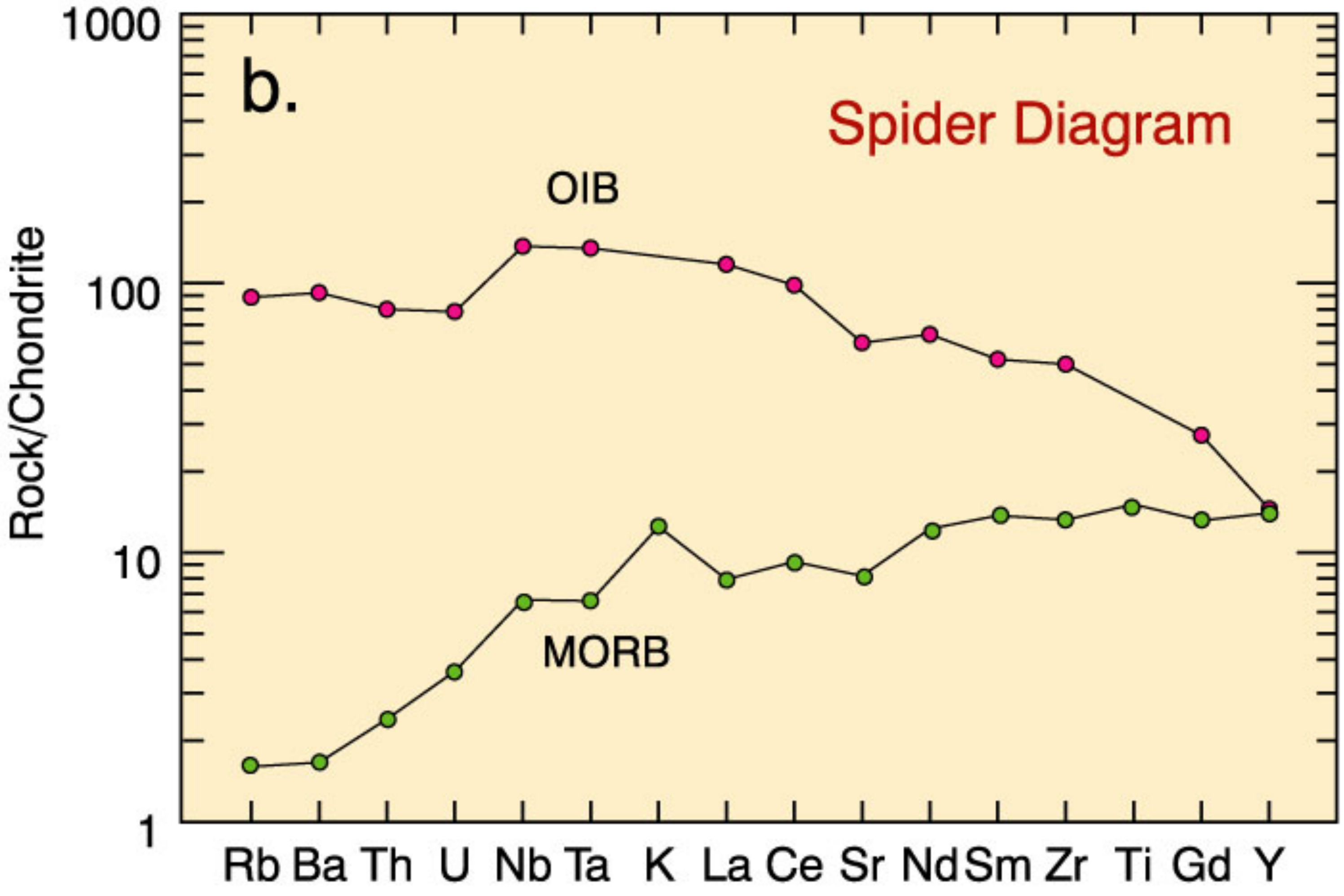
REE data for oceanic basalts



← **increasing incompatibility**

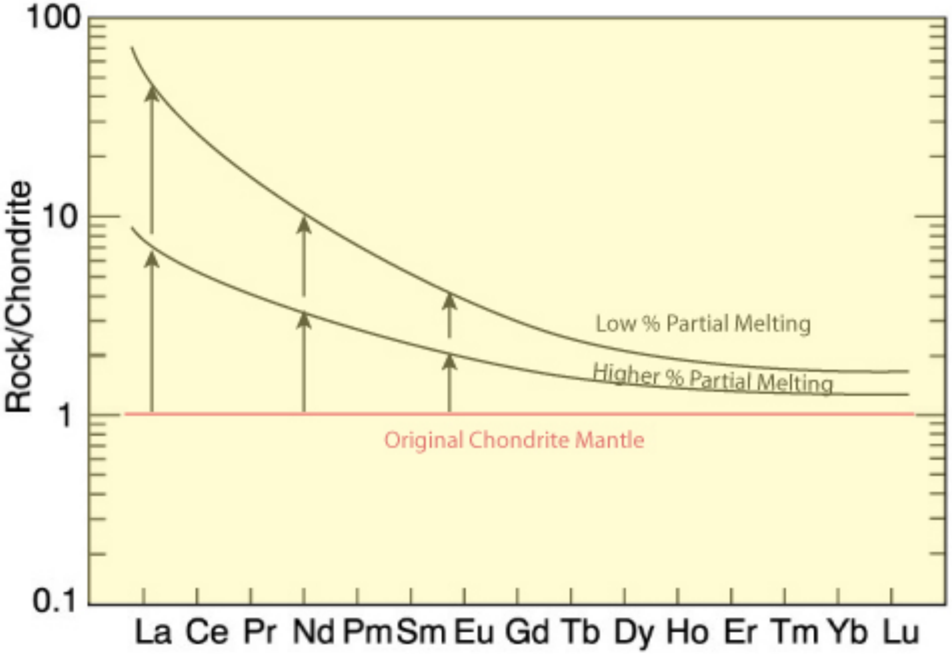
Figure 10.14a. REE diagram for a typical alkaline ocean island basalt (OIB) and tholeiitic mid-ocean ridge basalt (MORB). From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall. Data from Sun and McDonough (1989).

Spider diagram for oceanic basalts



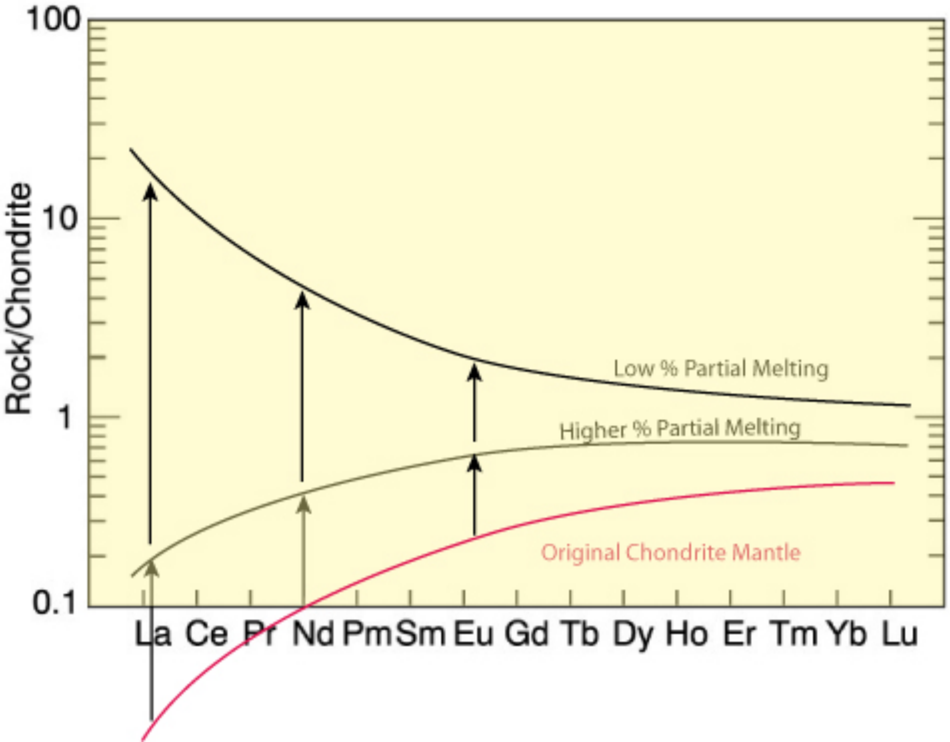
← **increasing incompatibility**

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.



REE data for UM xenoliths

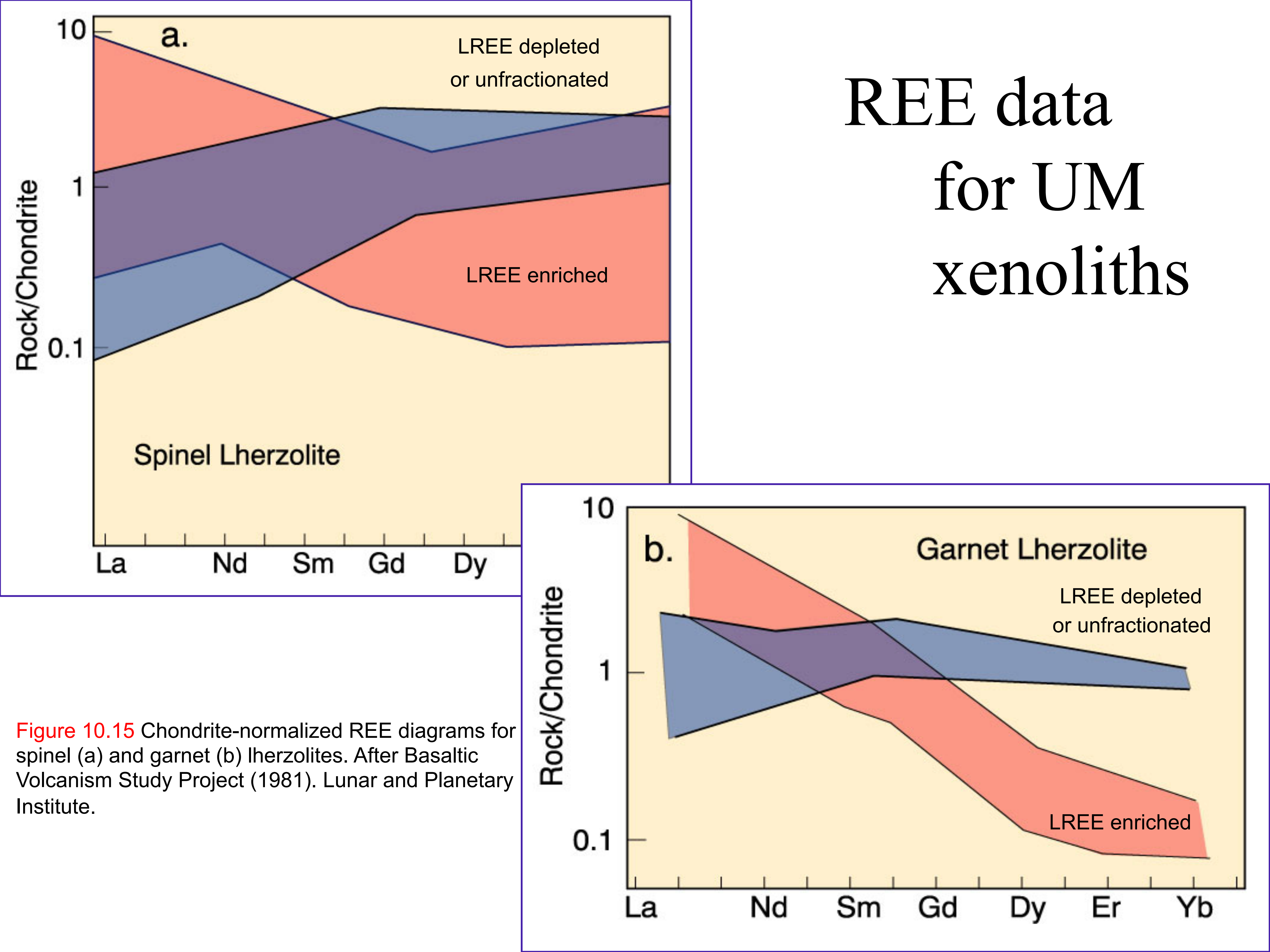


Figure 10.15 Chondrite-normalized REE diagrams for spinel (a) and garnet (b) lherzolites. After Basaltic Volcanism Study Project (1981). Lunar and Planetary Institute.

"Whole Mantle" circulation model

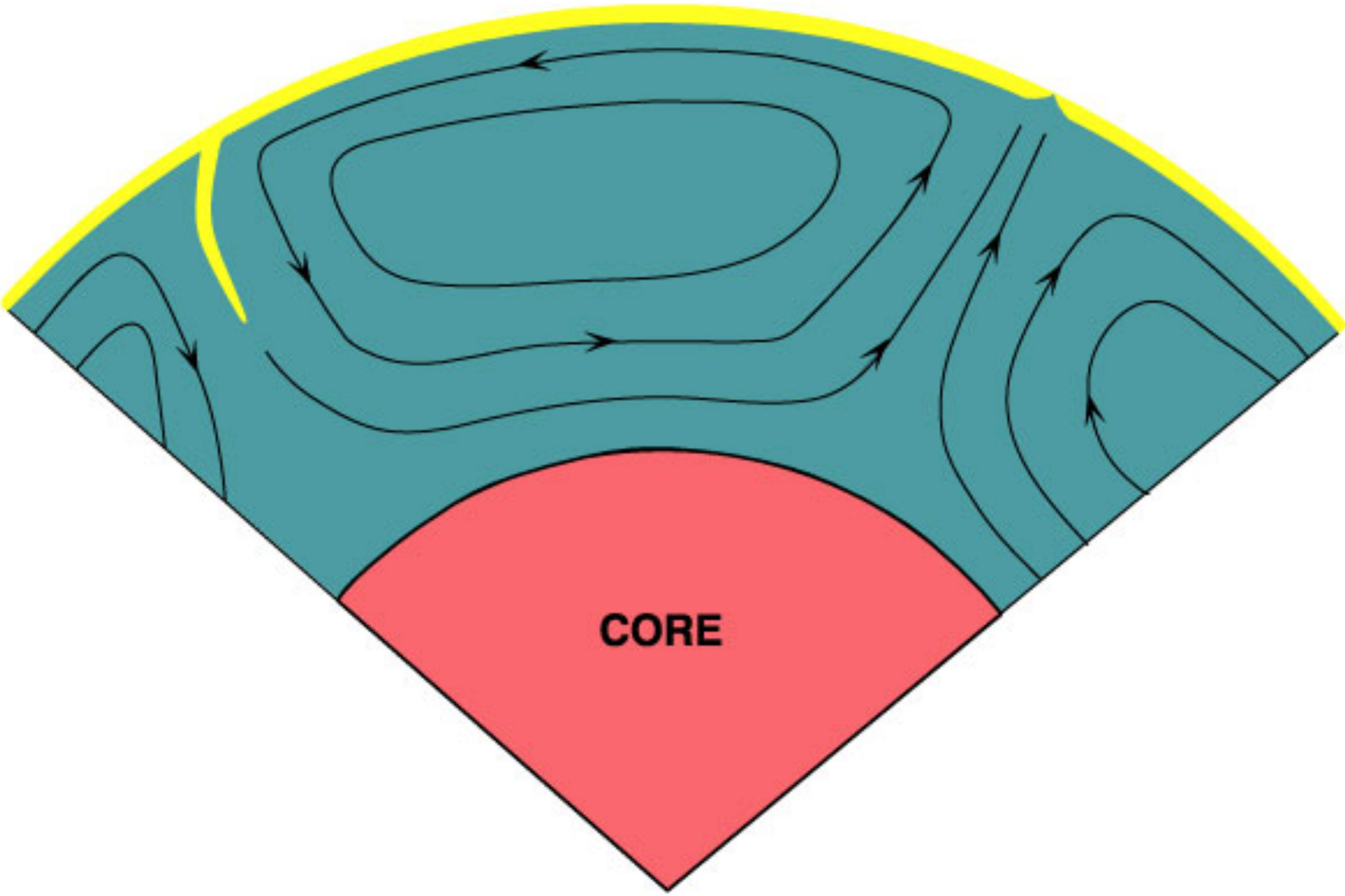


Figure 10-17a After Basaltic Volcanism Study Project (1981). Lunar and Planetary Institute.

"Two-Layer" circulation model

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

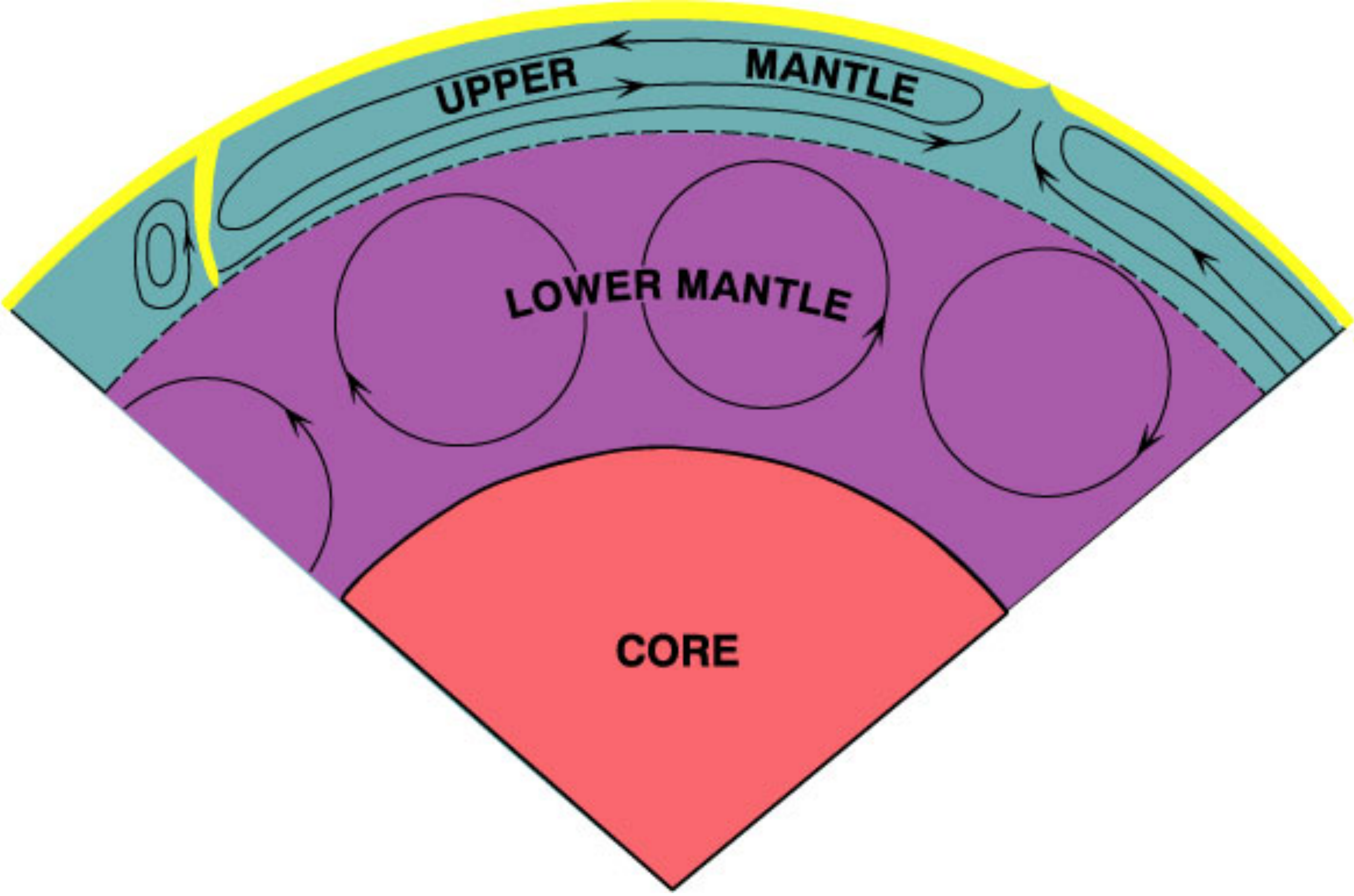


Figure 10-17b After Basaltic Volcanism Study Project (1981). Lunar and Planetary Institute.

Chapter 16. Island Arc Magmatism

- Arcuate volcanic island chains along subduction zones
- Distinctly different from mainly basaltic provinces thus far
  - Composition more diverse and silicic
  - Basalt generally subordinate
  - More explosive
  - Strato-volcanoes most common volcanic landform

Ocean-ocean → Island Arc (IA)
Ocean-continent → Continental Arc or
Active Continental Margin (ACM)

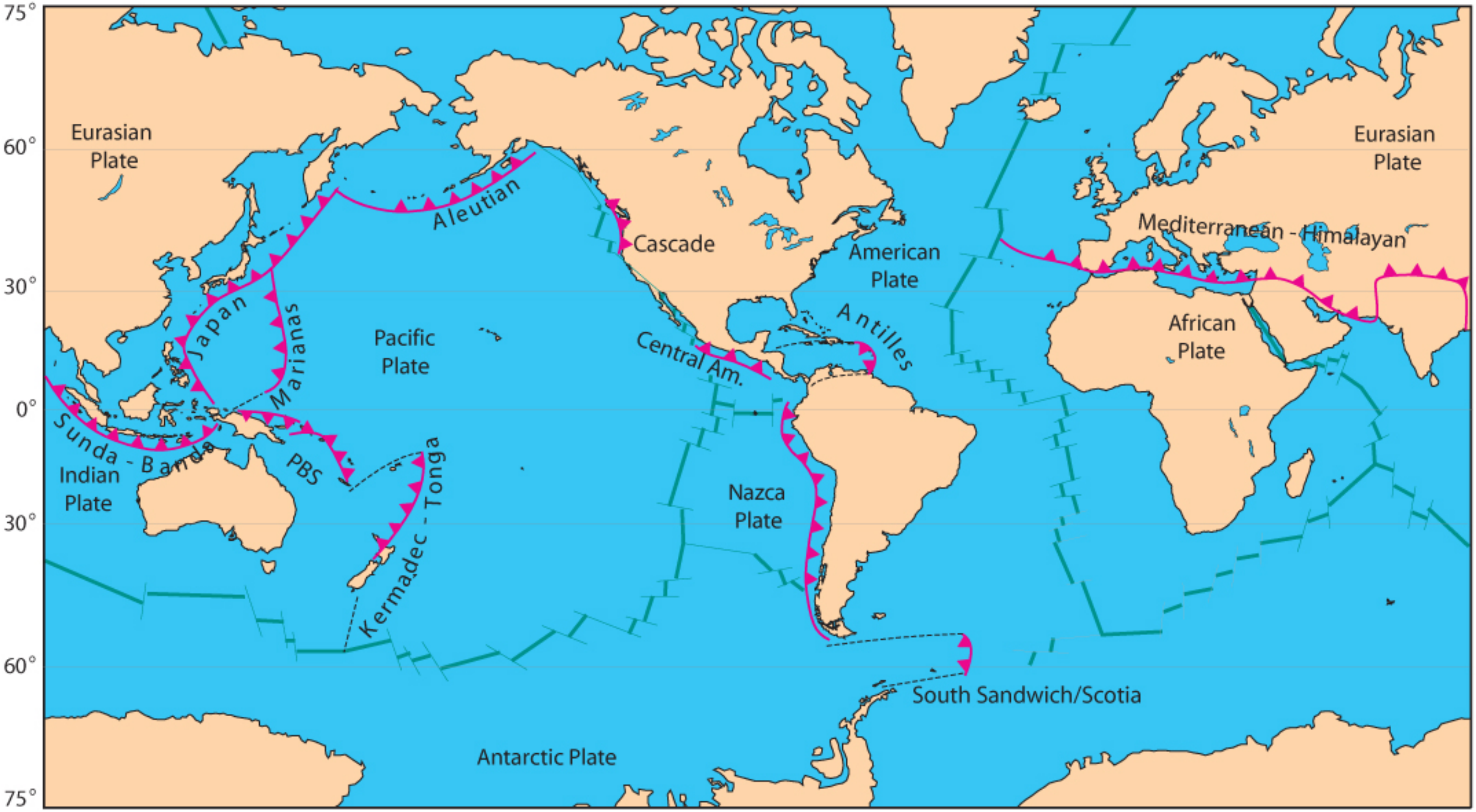


Figure 16.1. Principal subduction zones associated with orogenic volcanism and plutonism. Triangles are on the overriding plate. PBS = Papuan-Bismarck-Solomon-New Hebrides arc. After Wilson (1989) Igneous Petrogenesis, Allen Unwin/Kluwer.

Subduction Products

- Characteristic igneous associations
- Distinctive patterns of metamorphism
- Orogeny and mountain belts

Complexly Interrelated

Structure of an Island Arc

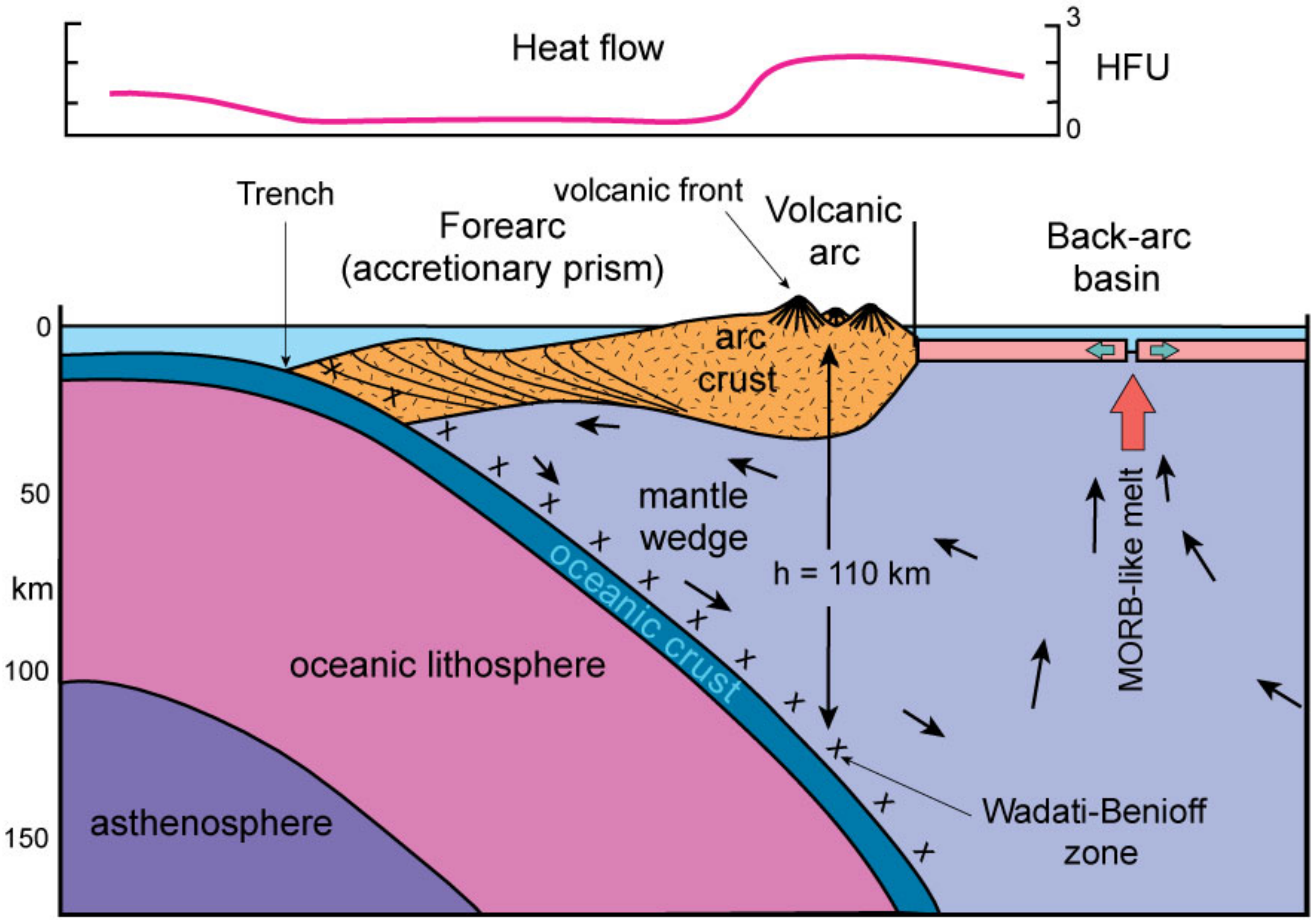


Figure 16.2. Schematic cross section through a typical island arc after Gill (1981), Orogenic Andesites and Plate Tectonics. Springer-Verlag. HFU= heat flow unit (4.2 x 10^{-6} joules/cm^2/sec)

Volcanic Rocks of Island Arcs

- Complex tectonic situation and broad spectrum of volcanic products
- High proportion of basaltic andesite and andesite
  - Most andesites occur in subduction zone settings

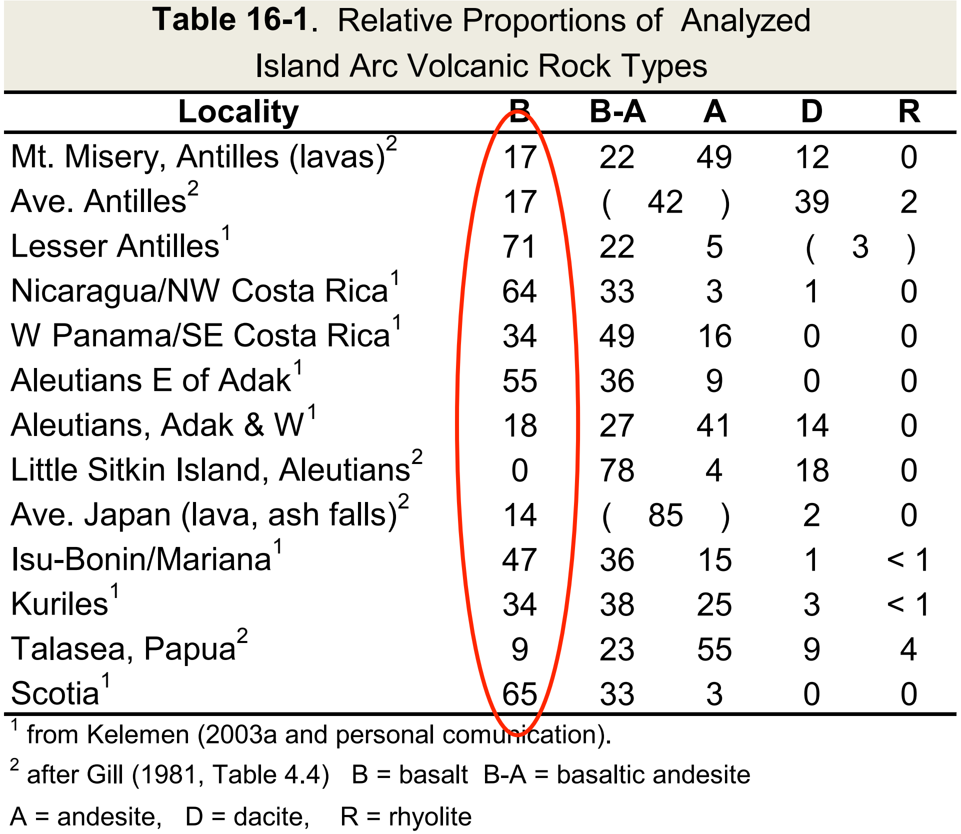


Table 16-1. Relative Proportions of Analyzed Island Arc Volcanic Rock Types

Locality	**B**	**B-A**	**A**	**D**	**R**
Mt. Misery, Antilles (lavas)[2]	17	22	49	12	0
Ave. Antilles[2]	17	(42)		39	2
Lesser Antilles[1]	71	22	5	(3)	
Nicaragua/NW Costa Rica[1]	64	33	3	1	0
W Panama/SE Costa Rica[1]	34	49	16	0	0
Aleutians E of Adak[1]	55	36	9	0	0
Aleutians, Adak & W[1]	18	27	41	14	0
Little Sitkin Island, Aleutians[2]	0	78	4	18	0
Ave. Japan (lava, ash falls)[2]	14	(85)		2	0
Isu-Bonin/Mariana[1]	47	36	15	1	< 1
Kuriles[1]	34	38	25	3	< 1
Talasea, Papua[2]	9	23	55	9	4
Scotia[1]	65	33	3	0	0

[1] from Kelemen (2003a and personal comunication).

[2] after Gill (1981, Table 4.4) B = basalt B-A = basaltic andesite

A = andesite, D = dacite, R = rhyolite

Basalts are still very common and important!

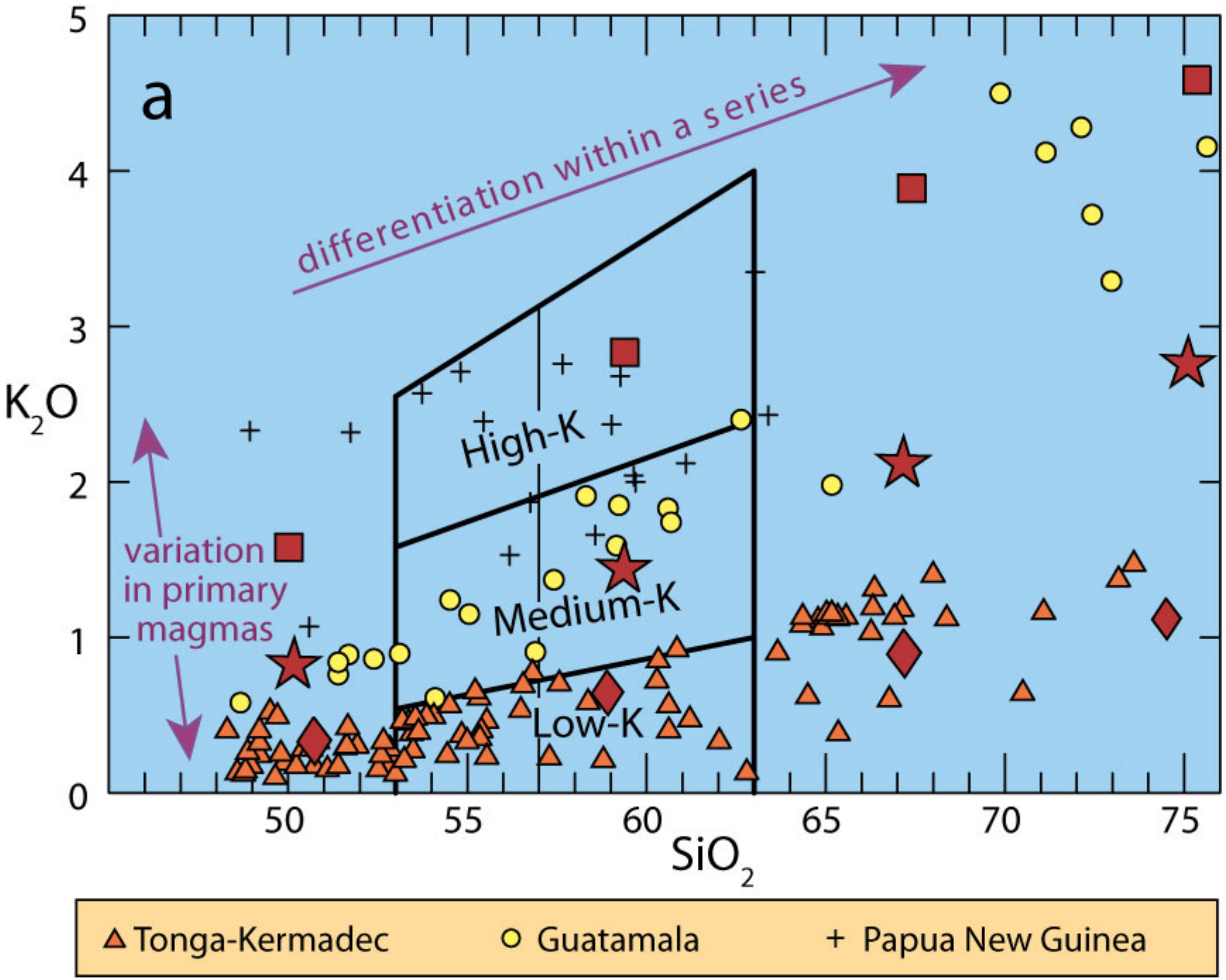


Figure 16.6. a. K_2O-SiO_2 diagram distinguishing high-K, medium-K and low-K series. Large squares = high-K, stars = med.-K, diamonds = low-K series from Table 16-2. Smaller symbols are identified in the caption. Differentiation within a series (presumably dominated by fractional crystallization) is indicated by the arrow. Different primary magmas (to the left) are distinguished by vertical variations in K_2O at low SiO_2. After Gill, 1981, Orogenic Andesites and Plate Tectonics. Springer-Verlag.

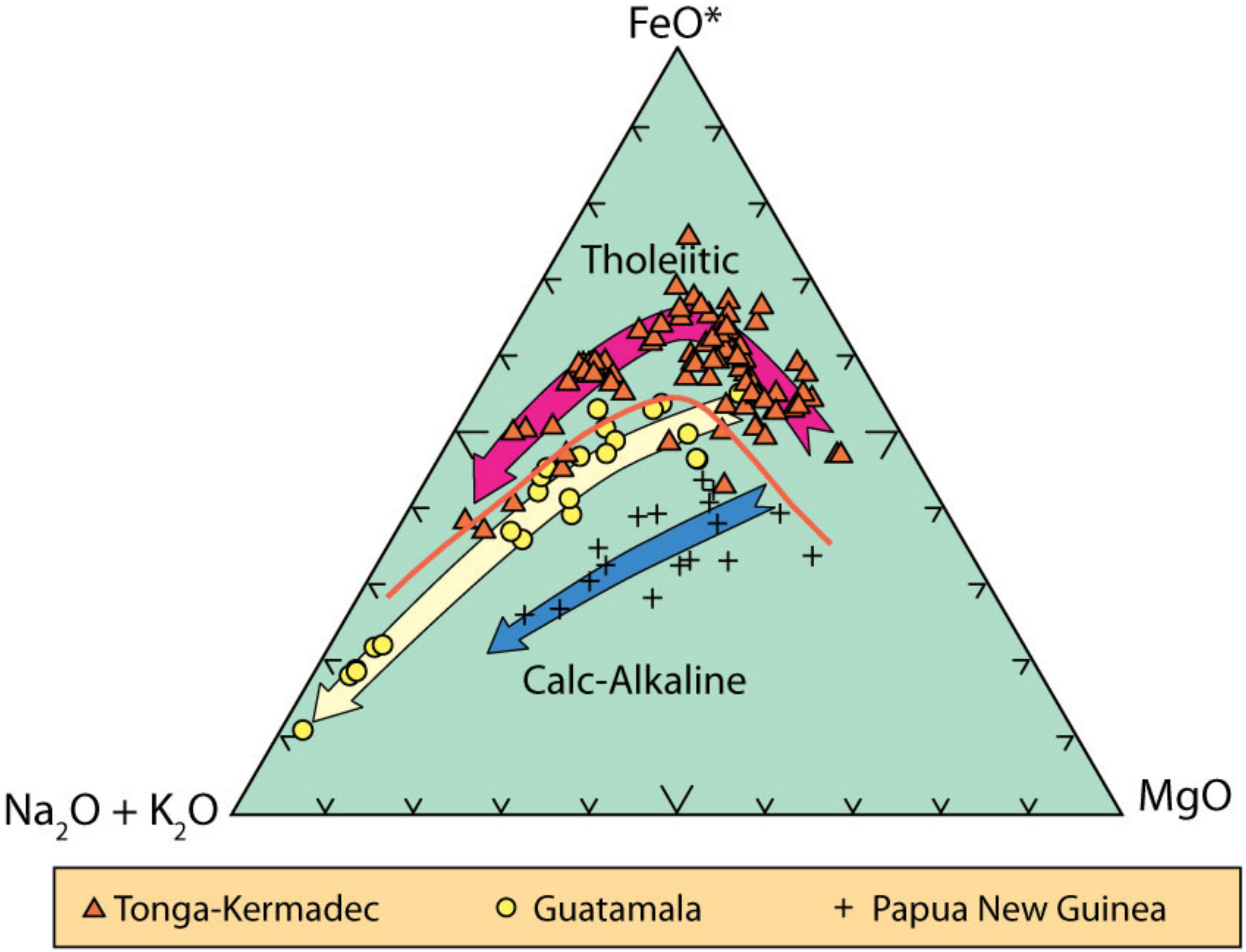


Figure 16.6. b. AFM diagram distinguishing tholeiitic and calc-alkaline series. Arrows represent differentiation trends within a series.

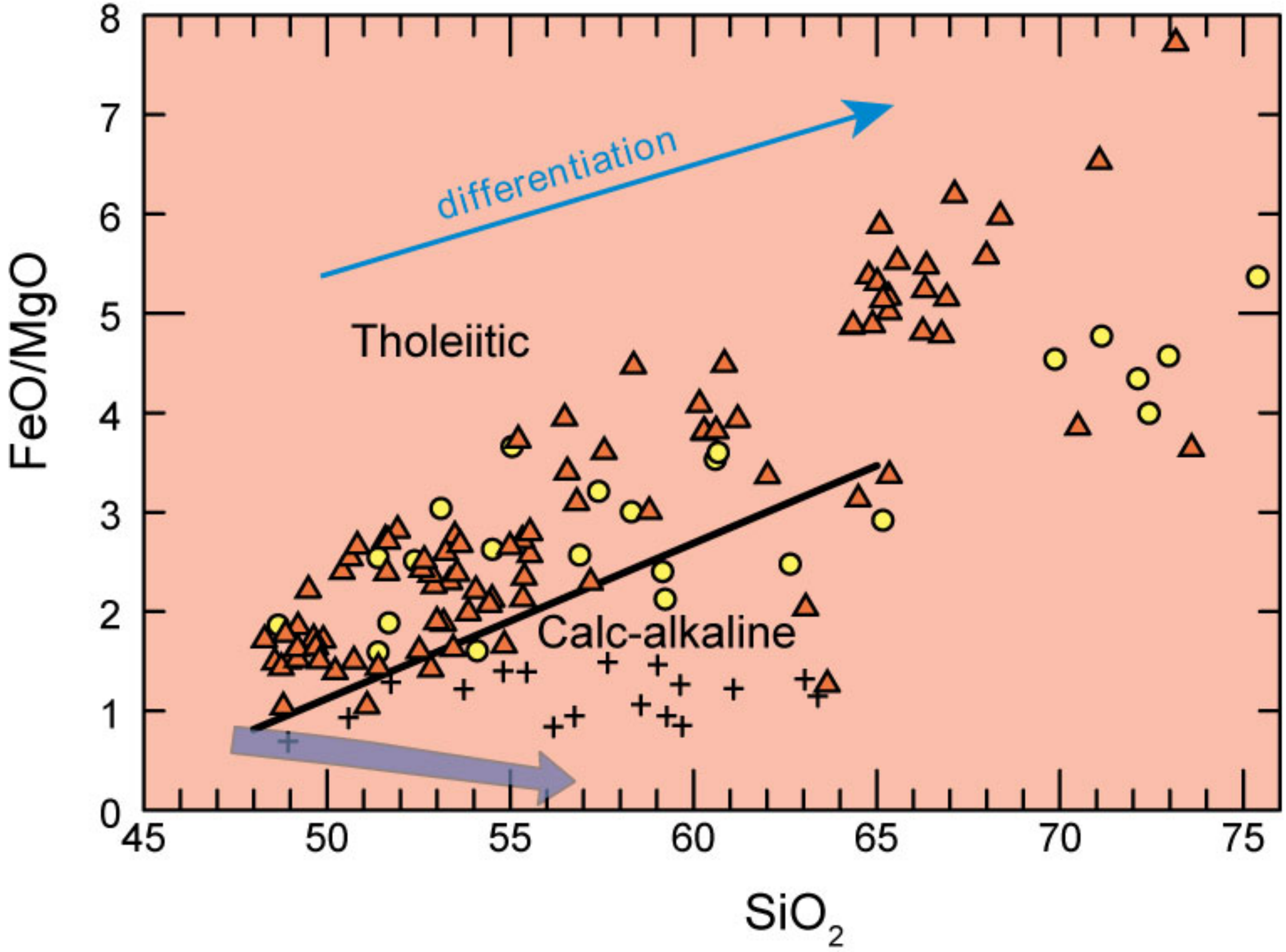


Figure 16.6. c. FeO*/MgO vs. SiO_2 diagram distinguishing tholeiitic and calc-alkaline series. The gray arrow near the bottom is the progressive fractional melting trend under hydrous conditions of Grove et al. (2003).

Calc-alkaline differentiation

- Early crystallization of Fe-Ti oxide

  Probably related to the high water content of calc-alkaline magmas in arcs, dissolves → high f_{O_2}
- High P_{H_2O} also depresses plagioclase liquidus → more An-rich
- As hydrous magma rises, ΔP → plagioclase liquidus moves to higher T → crystallization of considerable An-rich-SiO_2-poor plagioclase
- The crystallization of anorthitic plagioclase and low-silica, high-Fe hornblende may be an alternative mechanism for the observed calc-alkaline differentiation trend

Chapter 20: Anorthosites

- Plutonic rocks with over 90% plagioclase
  - No known volcanic equivalents
- Highly felsic nature and their location in continental areas they share with granitoid rocks
- The felsic mineral, however, is a calcic plagioclase, which, along with associated high-temperature mafic minerals, suggests a stronger similarity to basaltic rocks

Classification of Mafic Intrusive Rocks

A simplified version…

E.g., orthopyroxene gabbro should really be "norite" **

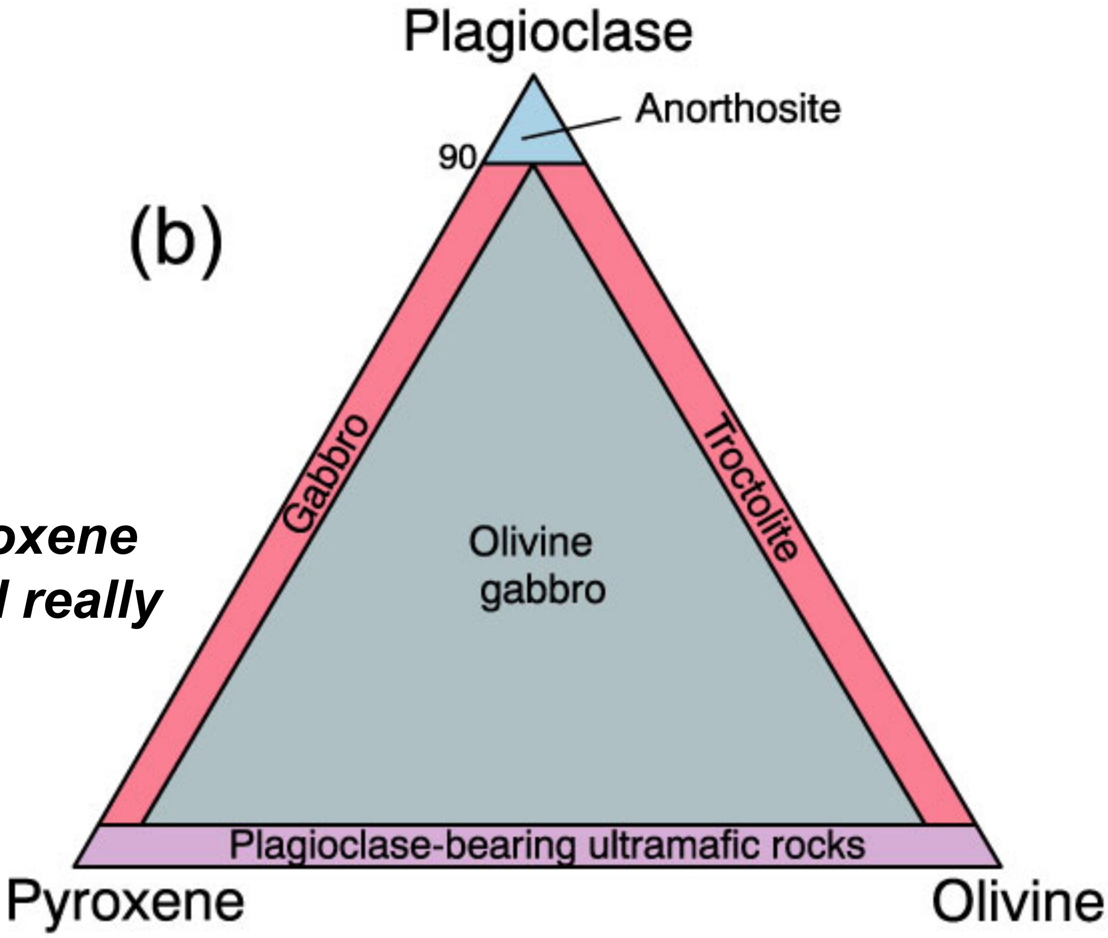


Figure 2.2b. A classification of the phaneritic igneous rocks: Gabbroic rocks. After IUGS.

Chapter 20: Anorthosites

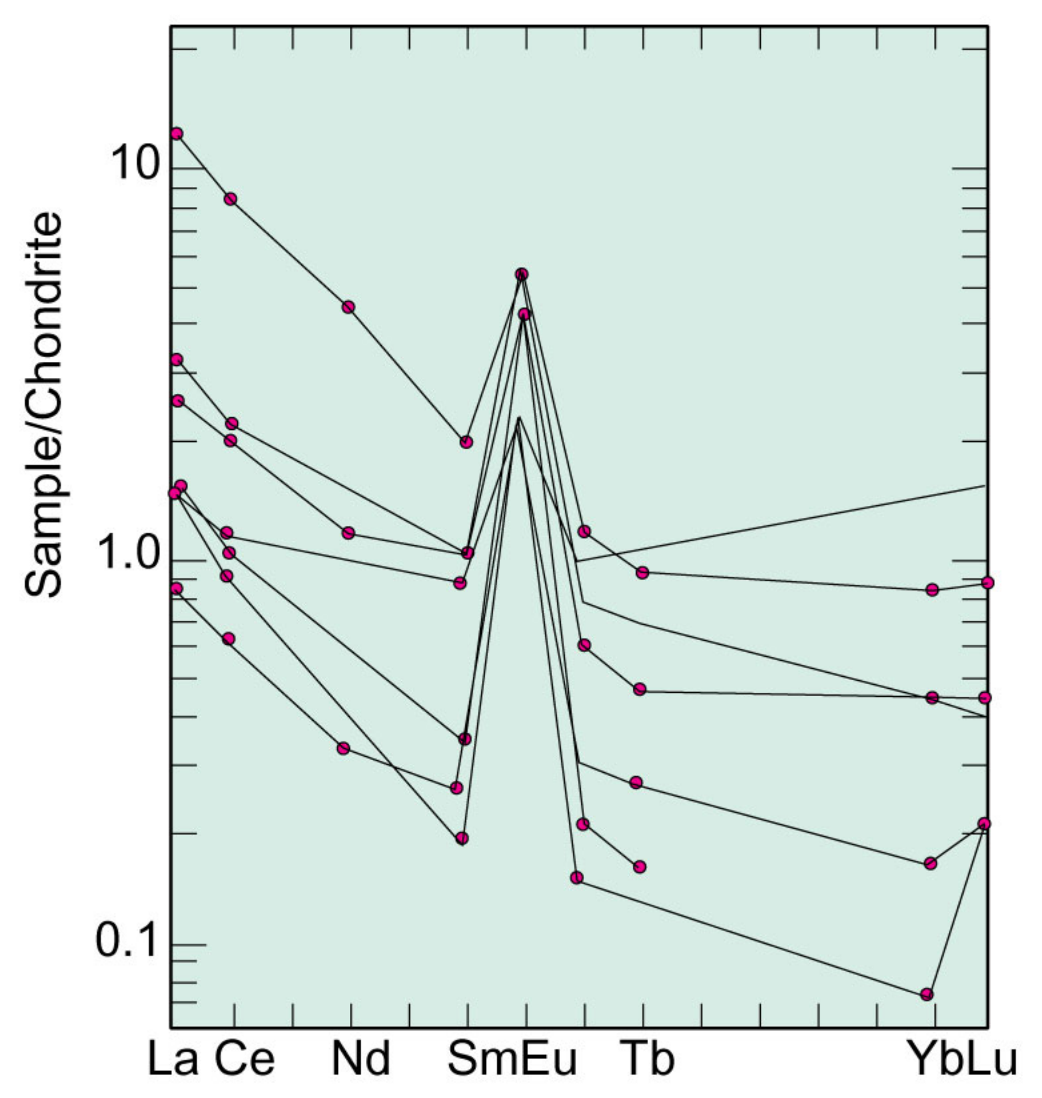
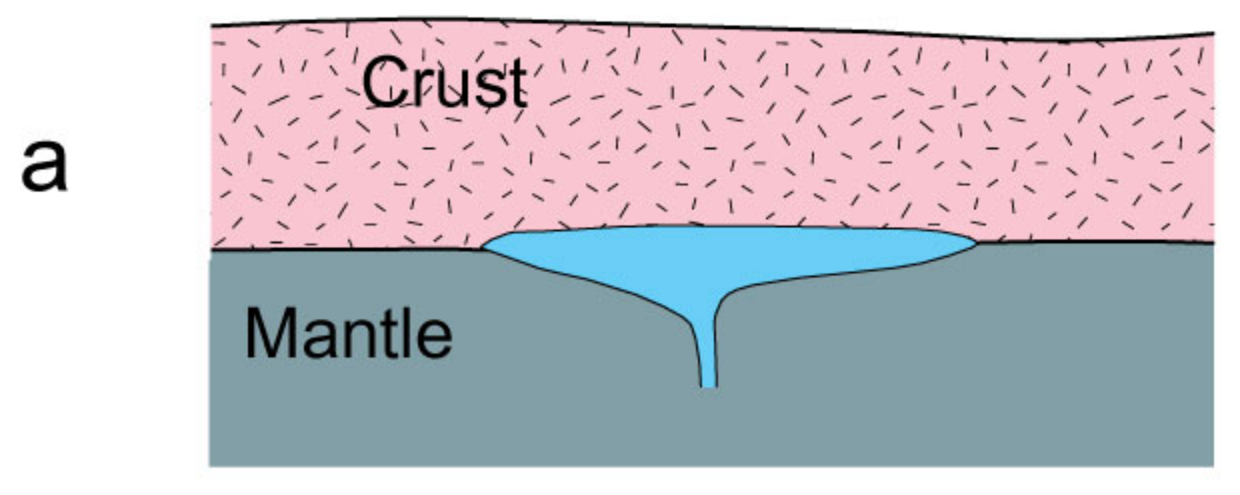


Figure 20.2. Chondrite-normalized rare earth element diagram for some typical Archean anorthosites from the Bad Vermillion (Ontario) and Fiskenæsset (Greenland) bodies. Data from Seifert *et al*. (1997) *Can. J. Earth Sci.*, 14, 1033-1045; Simmons and Hanson (1978) *Contrib. Mineral. Petrol.*, 66, 19-135; and Ashwal *et al*. (1989) *Earth Planet. Sci. Lett.*, 91, 261-270. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

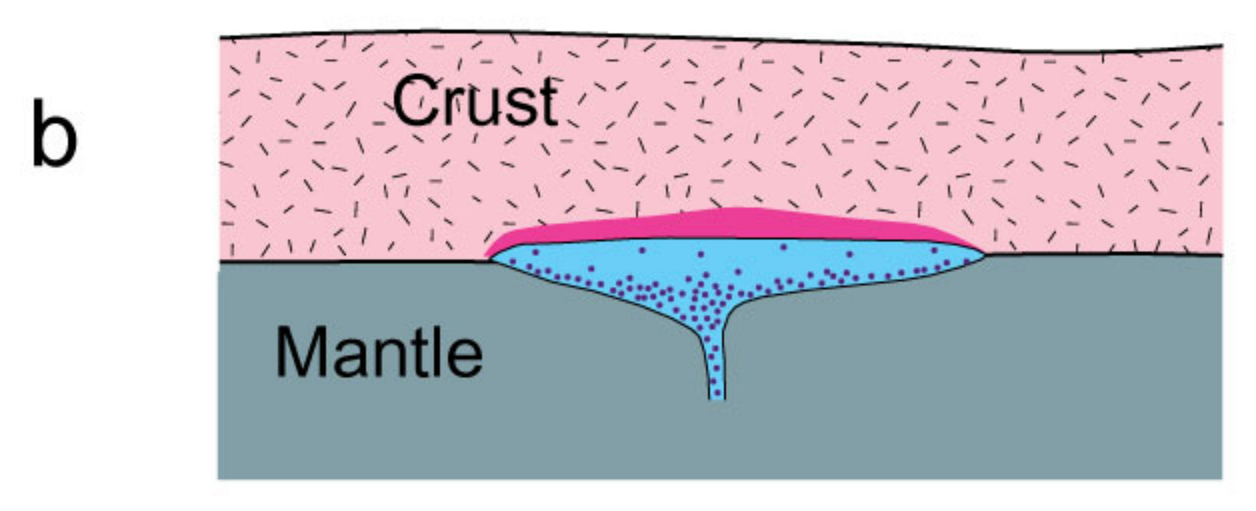
Chapter 20: Anorthosites



a. Mantle-derived magma underplates the crust as it becomes density equilibrated.

Figure 20.2. Model for the generation of Massif-type anorthosites. From Ashwall (1993) *Anorthosites*. Springer-Verlag. Berlin. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

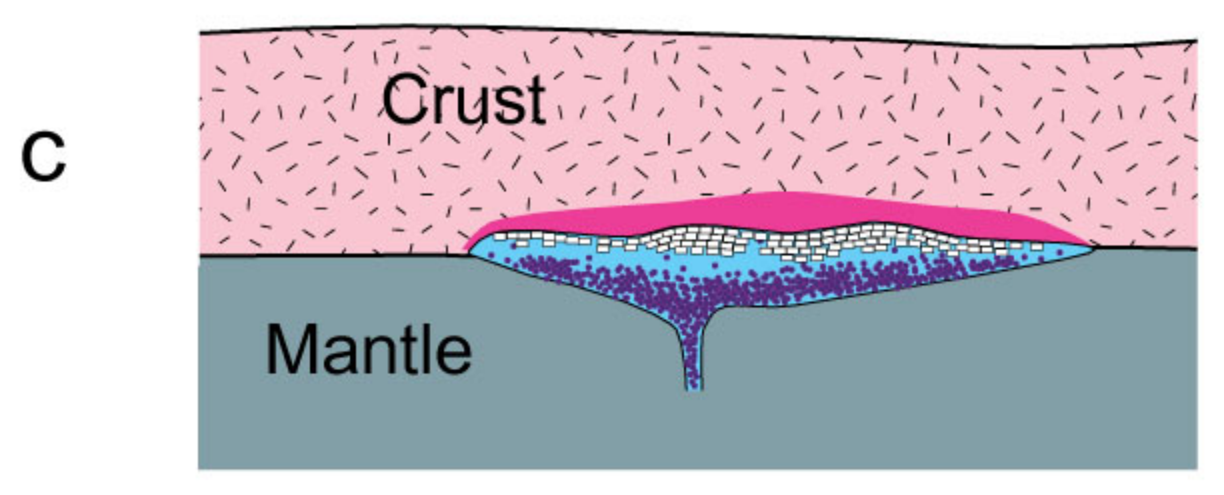
Chapter 20: Anorthosites



b. Crystallization of mafic phases (which sink), and partial melting of the crust above the ponded magma. The melt becomes enriched in Al and Fe/Mg.

Figure 20.2. Model for the generation of Massif-type anorthosites. From Ashwall (1993) *Anorthosites*. Springer-Verlag. Berlin. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

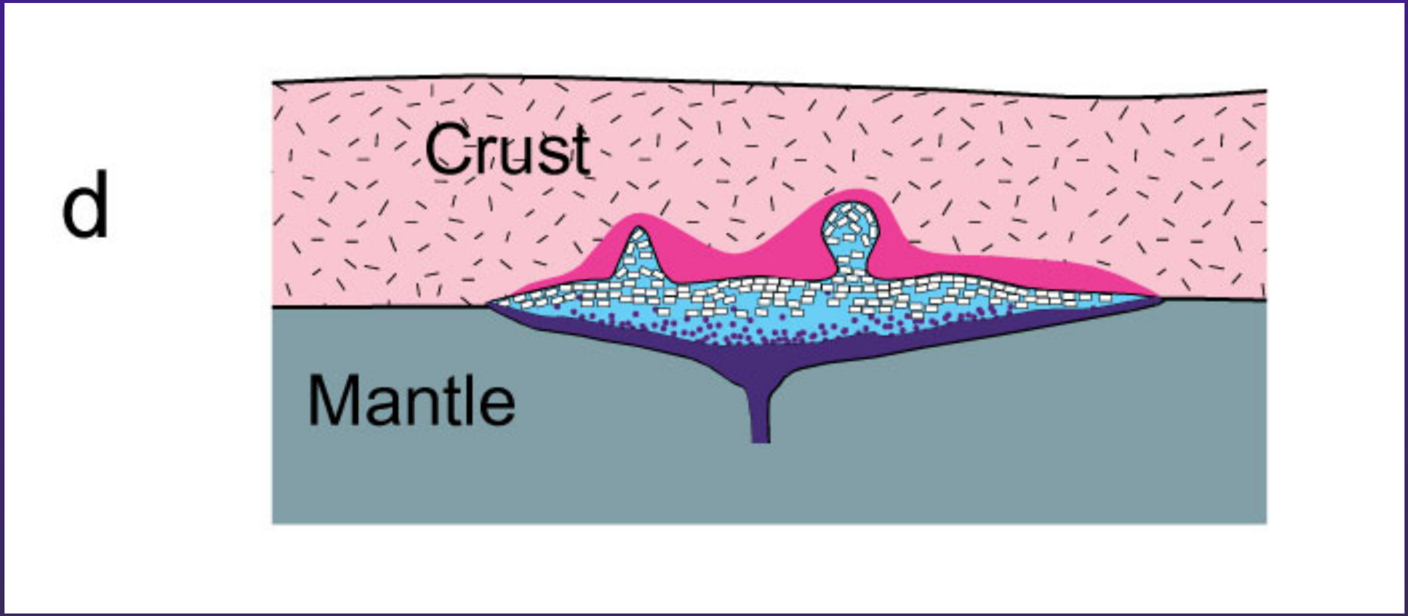
Chapter 20: Anorthosites



c. Plagioclase forms when the melt is sufficiently enriched. Plagioclase rises to the top of the chamber whereas mafics sink.

Figure 20.2. Model for the generation of Massif-type anorthosites. From Ashwall (1993) *Anorthosites*. Springer-Verlag. Berlin. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

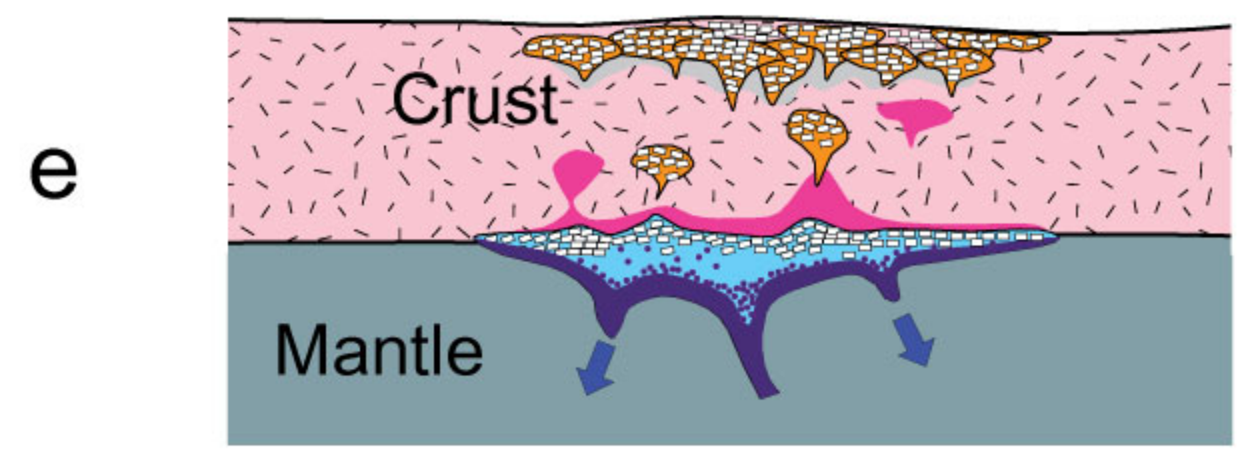
Chapter 20: Anorthosites



d. Plagioclase accumulations become less dense than the crust above and rise as crystal mush plutons.

Figure 20.2. Model for the generation of Massif-type anorthosites. From Ashwall (1993) *Anorthosites*. Springer-Verlag. Berlin. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Chapter 20: Anorthosites



e. Plagioclase plutons coalesce to form massif anorthosite, whereas granitoid crustal melts rise to shallow levels as well. Mafic cumulates remain at depth or detach and sink into the mantle.

Figure 20.2. Model for the generation of Massif-type anorthosites. From Ashwall (1993) *Anorthosites*. Springer-Verlag. Berlin. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Lunar magma ocean = global anorthosite