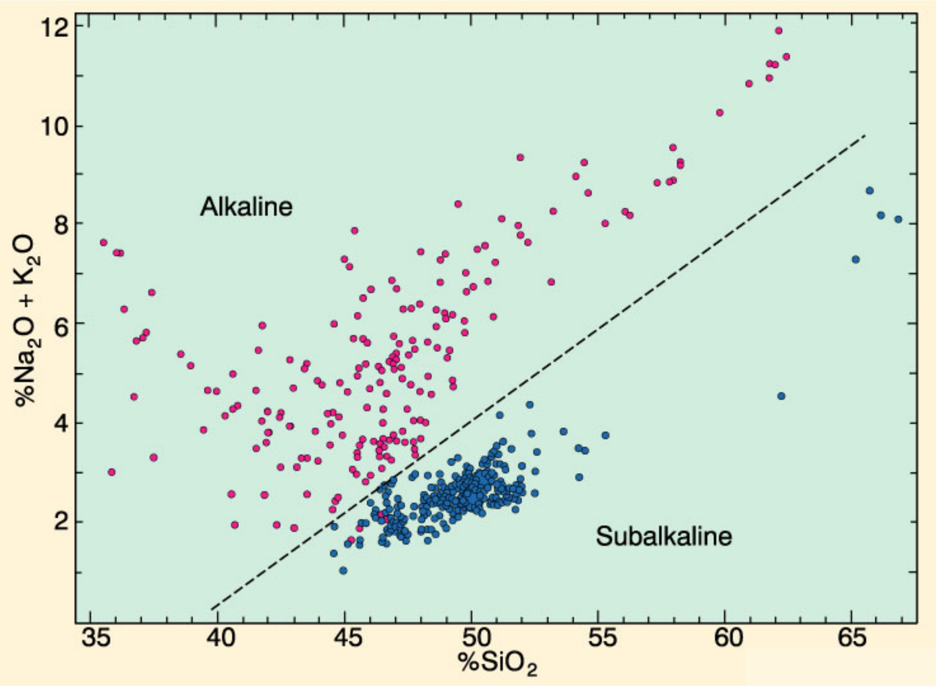
Mafic magma types (chemical distinction)

Alkalis vs silica plot



Alkali versus Silica plot was originally proposed to distinguish different types of Hawaiian basalts. Can be applied to other provinces. Data from McDonald (1968) GSA Memoir 116

Below right: Projection from Di (cpx) shows data from a variety of basalts classified on petrographic criteria as tholeiitic (black) or alkalic (orange). Note the revised dividing line. From Irvine and Barager (1971) Can J. Earth Sci, 8, 523

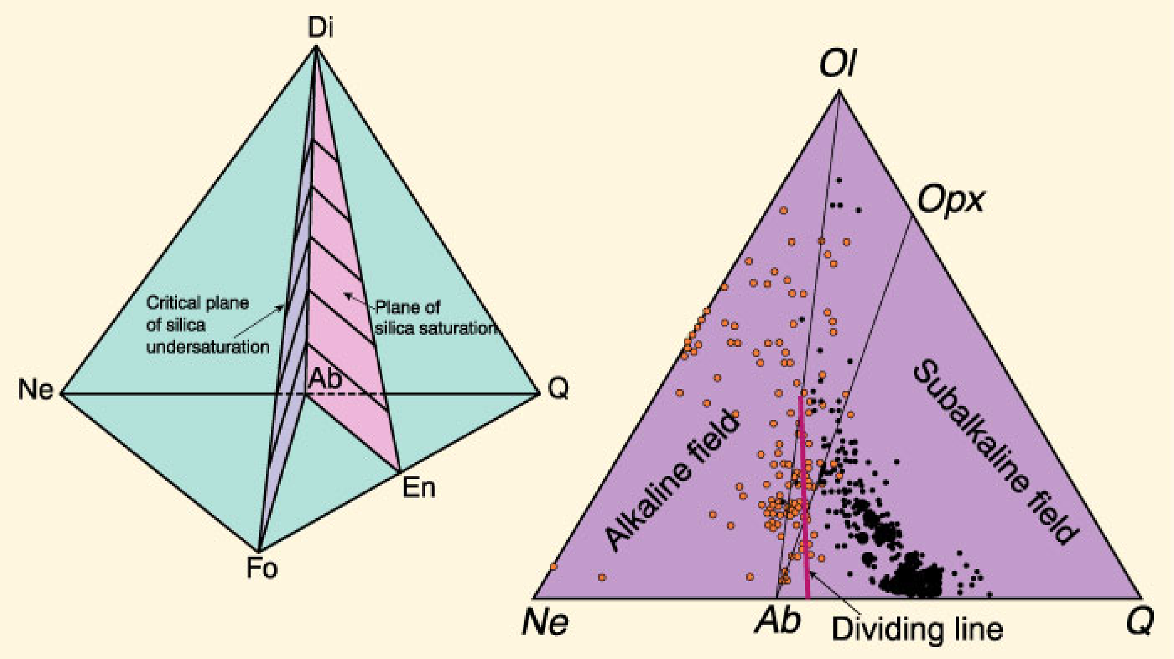
Basalt tetrahedron

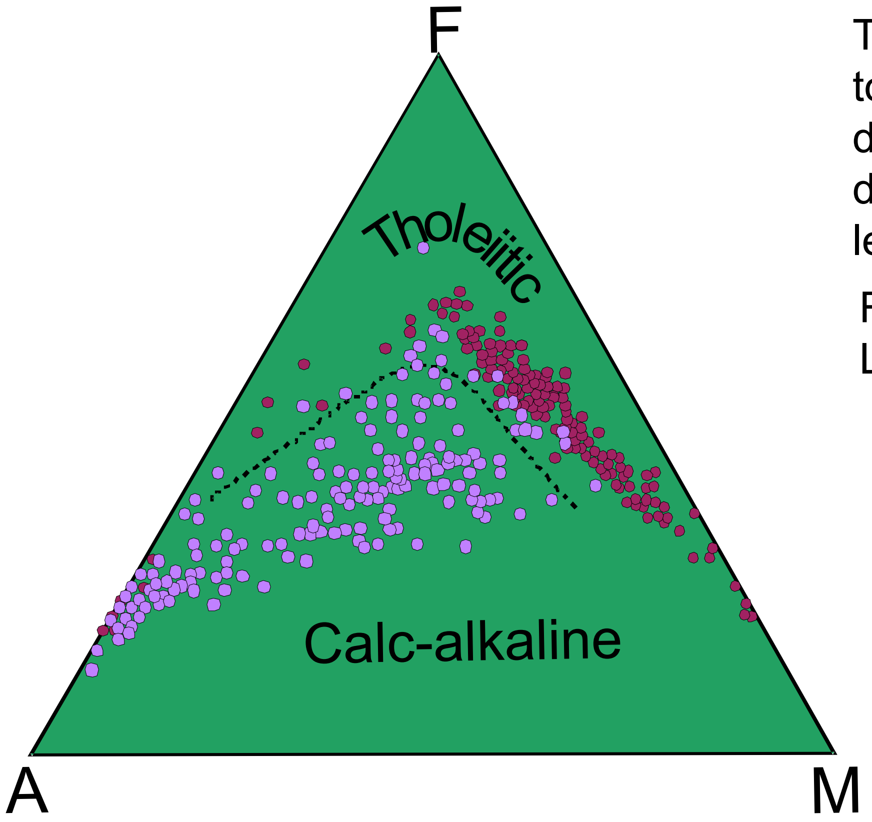
Basalt tetrahedron is based on normative minerals computed from chemical analysis

Norm incompatibilities: Ne and En (hyp)
Ne and Q, Fo (ol) and Q

Basalts will plot in one of the three sub-tetrahedra: Qz-normative (Quartz tholeiites), Ol+hyp normative (olivine tholeiites); Ne normative (alkalic basalts)

From: Yoder and Tilley (1962) J. Pet., 3, 342



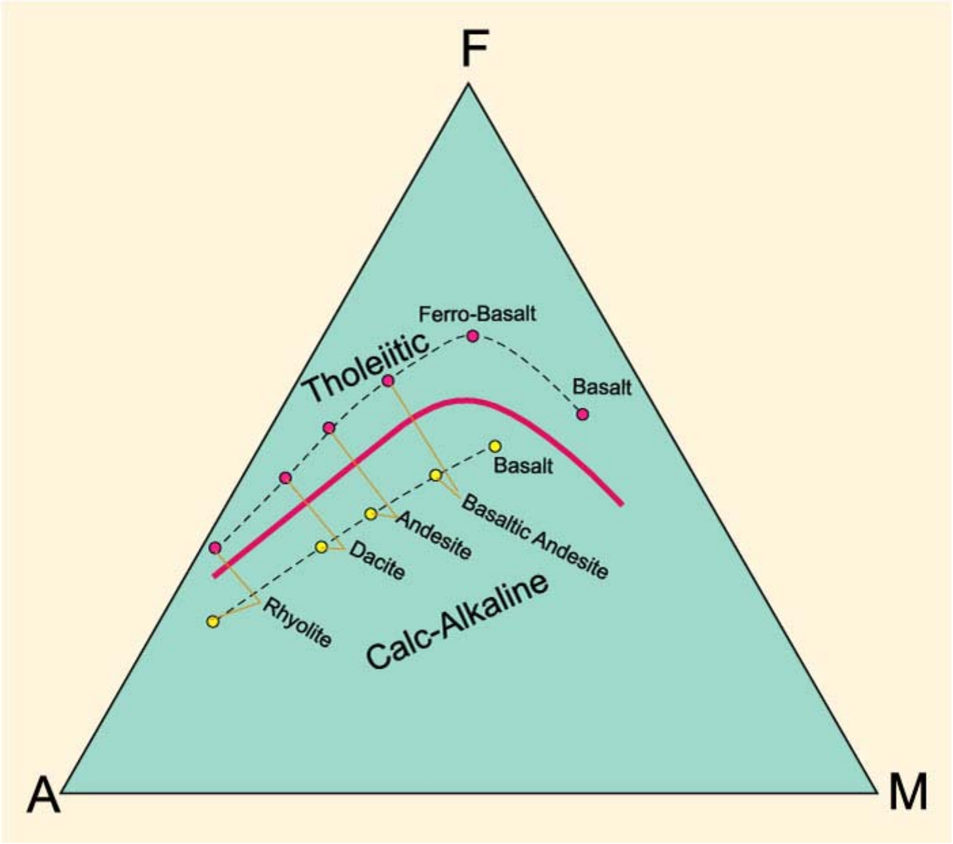


Triangular AFM diagrams may be used to used to distinguish tholeiitic basalts and their differentiates form calc-alkalic basalts and their differentiates. This subject will be discussed at length in later lectures.

Red dots: Iceland, MORB, CRB, Hawaii
Lilac dots: Cascades

$A = Na_2O + K_2O$
$F = FeO + 0.9Fe_2O_3$
$M = MgO$

(molar values)



Primary magma types

Subalkalic

Tholeiite (picrite > 25% olivine)

- MORB (mid-ocean ridge basalt)
- BABB (back arc basin basalt)
- OIT (Ocean island tholeiite)
- IAT (Island arc tholeiite)
- [HAB (high alumina basalt)]
- CFB (continental flood basalts)

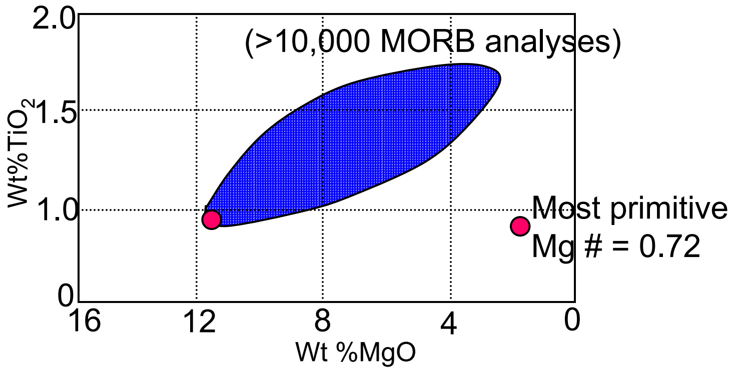
Komatiite
Boninite

Alkalic

Alkalic basalt
Basanite (K or Na)
Nephelinite
Leucitite
(Melilitite)
Lamproite
Lamprohyre (minette)
Kimberlite
Carbonatite
+ a plethora of rare types and names

Recognition of primary magmas

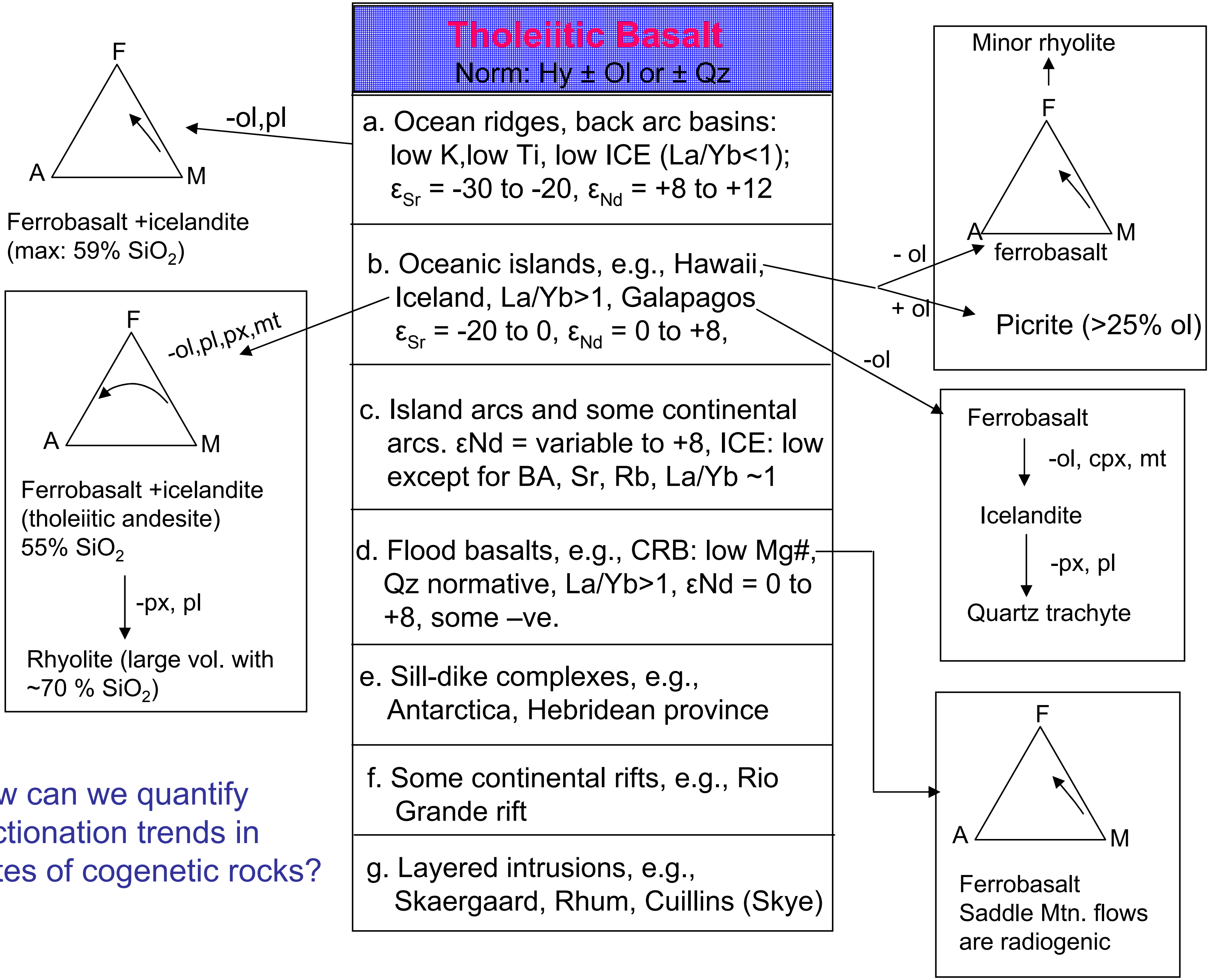
- Formed at depth and not subsequently modified by differentiation or assimilation
  - Geochemical Criteria
    - Highest Mg #, i.e., molar Mg/Mg+Fe
    - Cr > 1000 ppm
    - Ni > 400-500 ppm
    - Multiply saturated at “high” pressure



- Why are primary magma sought after?

They provide information on the source regions (inverse modeling/experiments)

Summary of basalt occurrences and fractionation trends



Ferrobasalt +icelandite
(max: 59% SiO_2)

Ferrobasalt +icelandite
(tholeiitic andesite)
55% SiO_2

-px, pl

Rhyolite (large vol. with ~70 % SiO_2)

Tholeiitic Basalt Norm: Hy ± Ol or ± Qz
a. Ocean ridges, back arc basins: low K,low Ti, low ICE (La/Yb<1); ε_{Sr} = -30 to -20, ε_{Nd} = +8 to +12
b. Oceanic islands, e.g., Hawaii, Iceland, La/Yb>1, Galapagos ε_{Sr} = -20 to 0, ε_{Nd} = 0 to +8,
c. Island arcs and some continental arcs. εNd = variable to +8, ICE: low except for BA, Sr, Rb, La/Yb ~1
d. Flood basalts, e.g., CRB: low Mg#, Qz normative, La/Yb>1, εNd = 0 to +8, some –ve.
e. Sill-dike complexes, e.g., Antarctica, Hebridean province
f. Some continental rifts, e.g., Rio Grande rift
g. Layered intrusions, e.g., Skaergaard, Rhum, Cuillins (Skye)

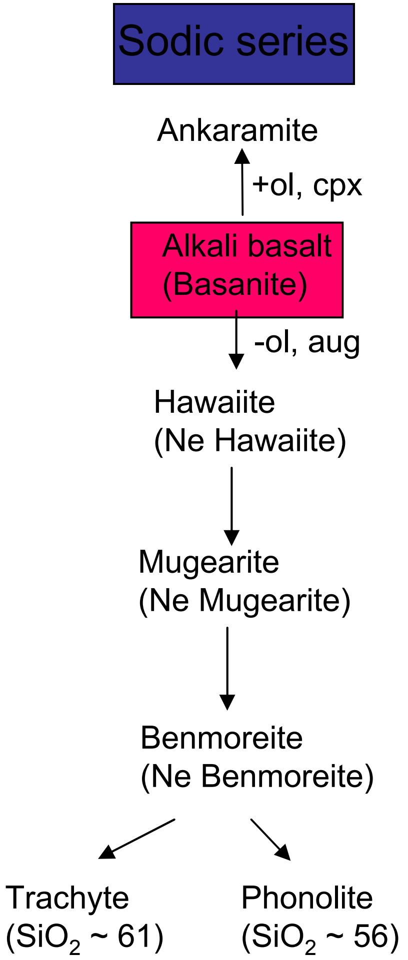
Minor rhyolite
↑
ferrobasalt

Picrite (>25% ol)

Ferrobasalt
↓ -ol, cpx, mt
Icelandite
↓ -px, pl
Quartz trachyte

Ferrobasalt
Saddle Mtn. flows are radiogenic

How can we quantify fractionation trends in suites of cogenetic rocks?



Sodic series

Ankaramite

+ol, cpx

Alkali basalt (Basanite)

-ol, aug

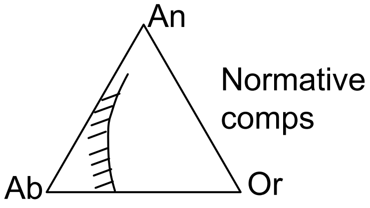
Hawaiite (Ne Hawaiite)

Mugearite (Ne Mugearite)

Benmoreite (Ne Benmoreite)

Trachyte (SiO_2 ~ 61)

Phonolite (SiO_2 ~ 56)



Alkalic basalt

Norm: Ol + 0-5 ne

Basanite

Norm: ol + >5 ne

a. **Ocean ridge**: very minor

b. **Oceanic islands** (hot spots)

Sodic series	Potassic series
Hawaii	Tristan
St. Helena	Gough
Tahiti	Kerguelen

c. **Island arcs, continental arc**:
Isolated volcanoes behind main volcanic arc

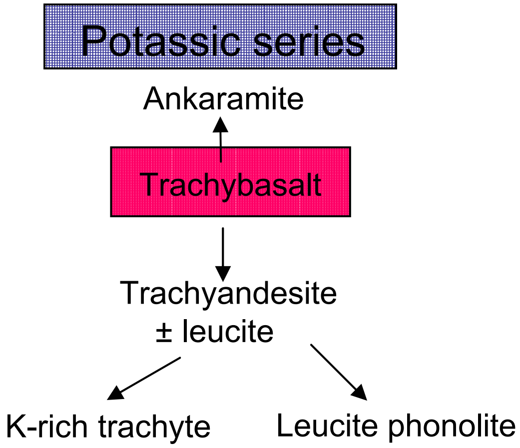
d. **Mixed**: e.g., Hebrides

e. **Crustal extension zones**
East African rift
Rhine Graben
Basin and Range, US

f. **Continental hot spots**
Cameroon line, Africa

Commonly contain spinel lherzolite mantle xenoliths

Eruptions tend to be small volume: more explosive than tholeiitic eruptions



Potassic series

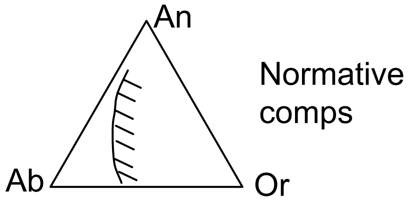
Ankaramite

Trachybasalt

Trachyandesite ± leucite

K-rich trachyte

Leucite phonolite



In sequence alkali basalt to trachyte or phonolite:

- Plag becomes more sodic
- Sanidine or anorthoclase crystallize later in the sequence
- Pyroxenes become richer in Na and Fe and tend toward aegerine
- Hydrous mins, e.g., biotite, become more abundant
- In phonlites, feldsparthoids such as nepheline, sodalite, nosean, hauyne

Fractionation Calculations

Suppose we have a suite of rocks (A, B, C, D,…) that we believe might be cogenetic and that we would like to document that this is a possibility

- •Need to know: Major and trace element whole rock compositions
- •Petrography of each sample
- •Composition of phenocryst minerals (a, b, c…) in A, B, C, D…

Set up a set of linear equations (one for each oxide component)

$A - x.a - y.b - z.c \;=\; B^*$ where B^* is a hypothetical daughter composition

e.g., $FeO^{A} - x.FeO^{ol} - y.FeO^{px} - z.FeO^{pl} \ldots \;=\; FeO^{B^*}$

↓

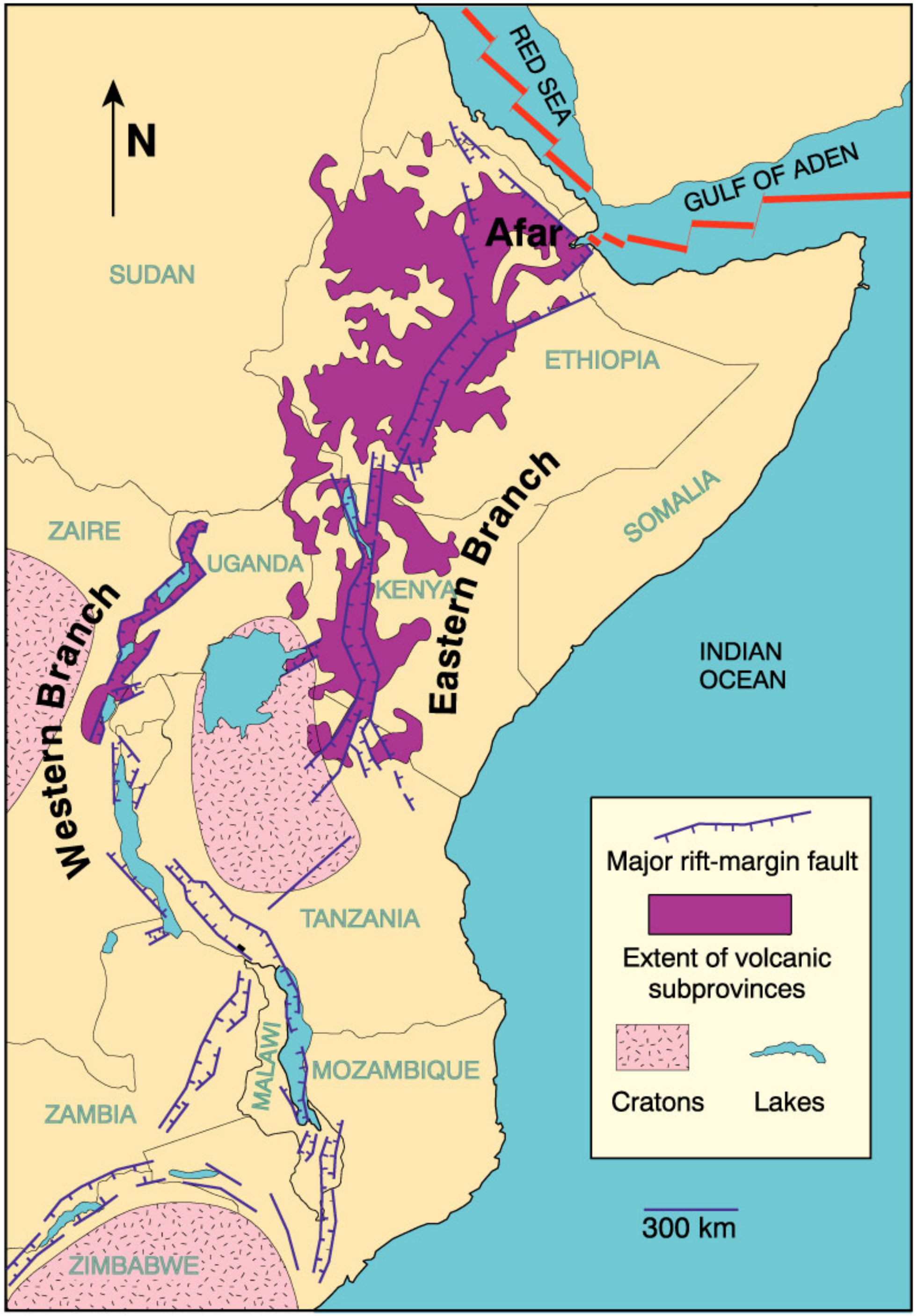
$Na_2O^{A} - x.Na_2O^{ol} - y.Na_2O^{px} - z.Na_2O^{pl} \;=\; Na_2O^{B^*}$

x, y and z are the proportions of phenocrysts x, y and z removed (or added)

The system is over-constrained because we have 10+ equations and 3 unknowns. To obtain a solution , x, y, and z are varied until **$\Sigma(B_i - B_i^*)^2$** is minimized. Least squares best fit solution. Magnitude of squared sum of residuals provides an estimate of the “goodness” of fit.

East African rift (~2000 km long)

- Follows “weaker” intercratonic mobile belts
- Domal structures (Ethiopian and Kenyan)
- Rift propagates from N to S and splits into two branches around Tanzanian craton
- Lithospheric thinning, Normal faulting (listric), asthenospheric rise, partial melt zone
- Magmatism: East rift: 40 Ma to present (flood basalts and rhyolite ash flows). West rift: 14 Ma to present (tholeiites and later alkali basalts). Flood phonolites (17-8 Ma) and trachyte tuffs and flows (<4 Ma) in Kenya. Locally >3 km thick & spills over edges of rift.
- Amazing variety of volcanic rock types, particularly alkalic rock types, carbonatites, kimberlites (Tanzanian craton)
- Parental magmas ranging from tholeiitic to ultra-alkalic represent variable partial melts of a metasomatized mantle source. Superimposed is extensive frac^{l} cryst^{n} (± assimilation). Rhyolites are crustal melts

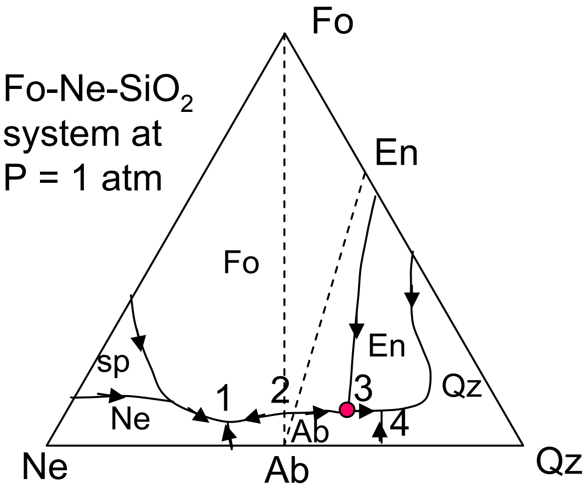


Some questions of "basalt" petrogenesis

1. How are tholeiites produced? Experimental petrology, trace element modeling and isotope data indicate that tholeiitic magmas are produced by relatively high degrees of melting (20-25 %) of "normal" mantle, i.e., mantle that can range from depleted (MORB) to slightly enriched (some ocean island and island arc tholeiites).

2. **How can we explain the range of comp^{ns} from picritic tholeiites to quartz tholeiites to high alumina tholeiites?** After making corrections for the effects of fractionation, i.e., comparing only "primary magmas", experimental studies show that increasing pressure increases the MgO content of the melt produced. At 25 Kb basalts with MgO contents of 16 wt. % are formed, 14.5 wt. % MgO at 20 kb and 12.5 wt%. MgO at 15 kb… Quartz tholeiites are common in the CRB province and appear to be the result of fractionation.

3. Can alkalic basalts be formed by fractionation of tholeiites or vice versa?
Certainly not at low pressure because of the thermal divide, i.e., can't go from ne normative to hyp or qz normative or vice versa



1 (1058°C): L1 (Fo, Ne, Ab)
2 (1118°C): L2 (Fo, Ab): thermal maximum
3 (1070°C): L3 (Fo, En, Ab). Reaction at 3?
4 (1062°C): L4 (En, Qz, Ab)

At 3: Fo + L ⟶ En + Ab (peritectic)

What happens when Ca is added to the system?

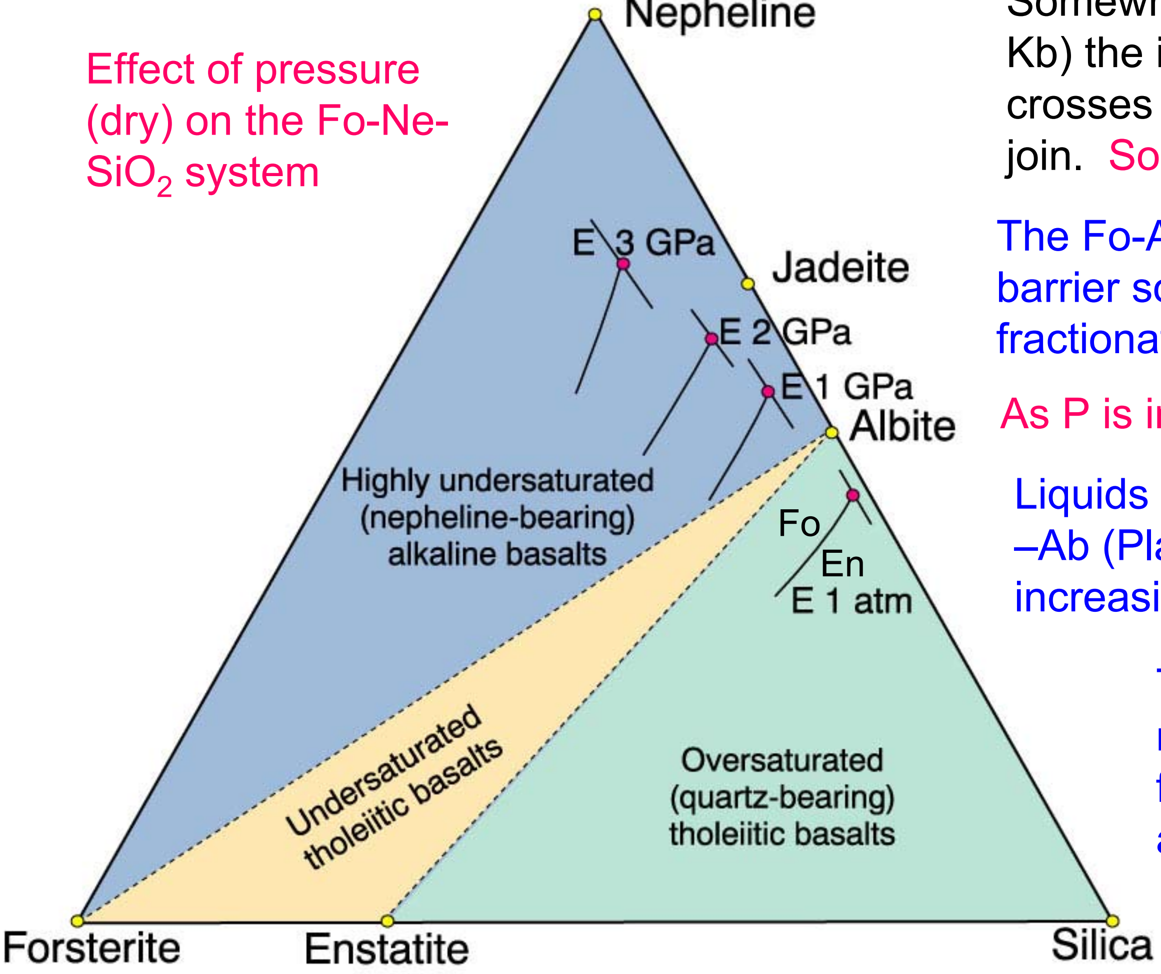
Diopside (cpx) becomes stable and feldspar is now plag ss

However, the olivine-cpx-plag join remains a thermal barrier

OK, but what happens at P is increased? Look at point 3.

Basalt petrogenesis (cont.)

Effect of pressure (dry) on the Fo-Ne-SiO_2 system



Somewhere between 1 atm and 1 GPa (10 Kb) the invariant reaction equilibrium crosses the En-Ab join and then the Fo-Ab join. So what?

The Fo-Ab join is no longer a thermal barrier so, in theory, subalkalic melts could fractionate to alkalic melts.

As P is increased further, what happens?

Liquids in equilibrium with Fo (Ol) –En (Opx) –Ab (Plag or Spinel/Gnt at higher P) become increasingly alkalic (ne normative)

Tentative conclusions: (1) melting of mantle at higher pressures favors the formation of alkalic basalts (2) melting at low P favors silica-rich melts

What is the effect of adding volatiles to this system?

Addition of H_2O tends to produce more silica-rich basalts
Addition of CO_2 tends to produce more alkali basalts.