Lecture 13 Major Elements

Friday, March 4th, 2005

Chapter 8: Major Elements

"Wet-chems": gravimetric/volumetric

Chapter 8: Major Elements

Modern Spectroscopic Techniques

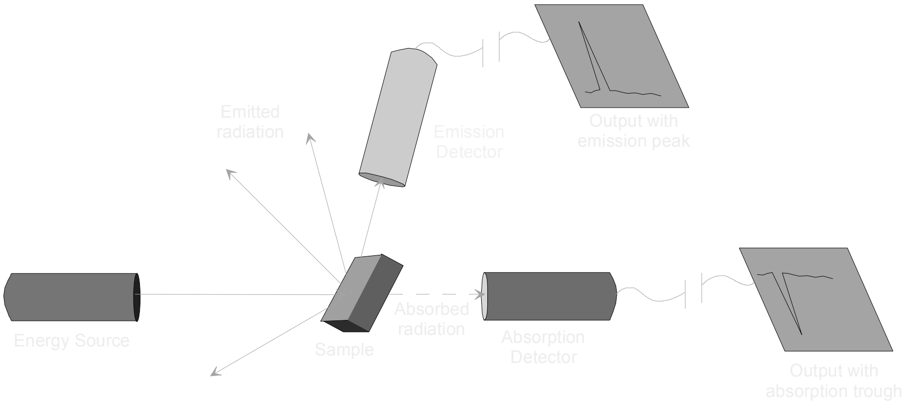


Figure 8-1. The geometry of typical spectroscopic instruments. From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Element	Wt % Oxide	Atom %
O		60.8
Si	59.3	21.2
Al	15.3	6.4
Fe	7.5	2.2
Ca	6.9	2.6
Mg	4.5	2.4
Na	2.8	1.9

Abundance of the elements in the Earth’s crust

Major elements: usually greater than 1%

SiO_2 Al_2O_3 FeO* MgO CaO Na_2O K_2O H_2O

Minor elements: usually 0.1 - 1%

TiO_2 MnO P_2O_5 CO_2

Trace elements: usually < 0.1%

everything else

A typical rock analysis

Wt. % Oxides to Atom % Conversion

Oxide	Wt. %	Mol Wt.	Atom prop	Atom %
SiO_2	49.20	60.09	0.82	12.25
TiO_2	1.84	95.90	0.02	0.29
Al_2O_3	15.74	101.96	0.31	4.62
Fe_2O_3	3.79	159.70	0.05	0.71
FeO	7.13	71.85	0.10	1.48
MnO	0.20	70.94	0.00	0.04
MgO	6.73	40.31	0.17	2.50
CaO	9.47	56.08	0.17	2.53
Na_2O	2.91	61.98	0.09	1.40
K_2O	1.10	94.20	0.02	0.35
H_2O^+	0.95	18.02	0.11	1.58
(O)			4.83	72.26
Total	99.06		6.69	100.00

Must multiply by # of cations in oxide ↑

Table 8-3. Chemical analyses of some representative igneous rocks

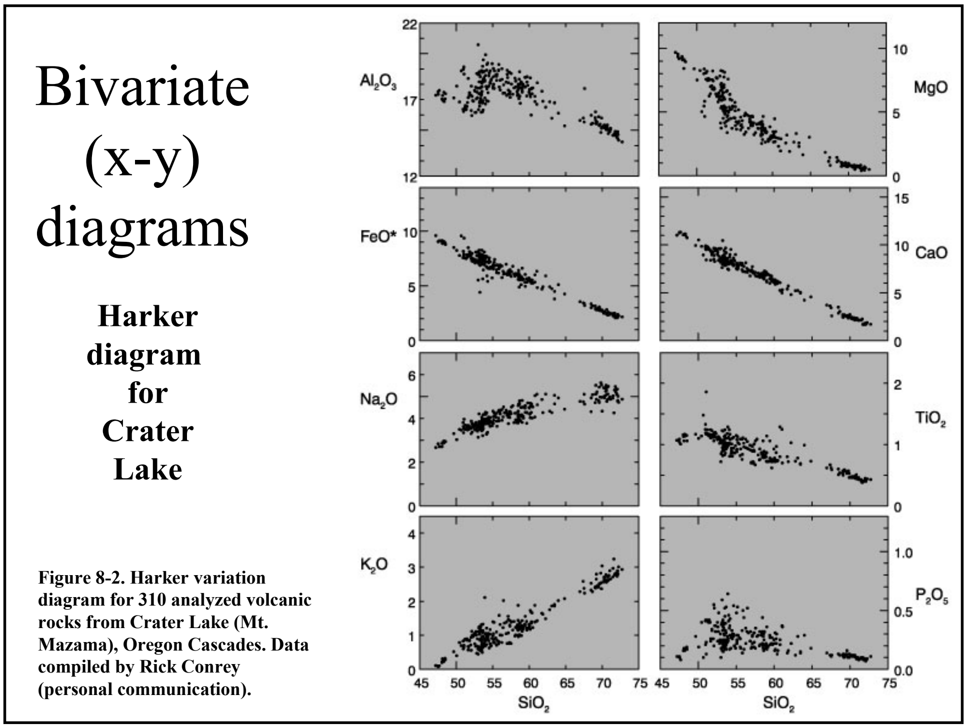
	Peridotite	Basalt	Andesite	Rhyolite	Phonolite
SiO2	42.26	49.20	57.94	72.82	56.19
TiO2	0.63	1.84	0.87	0.28	0.62
Al2O3	4.23	15.74	17.02	13.27	19.04
Fe2O3	3.61	3.79	3.27	1.48	2.79
FeO	6.58	7.13	4.04	1.11	2.03
MnO	0.41	0.20	0.14	0.06	0.17
MgO	31.24	6.73	3.33	0.39	1.07
CaO	5.05	9.47	6.79	1.14	2.72
Na2O	0.49	2.91	3.48	3.55	7.79
K2O	0.34	1.10	1.62	4.30	5.24
H2O+	3.91	0.95	0.83	1.10	1.57
Total	98.75	99.06	99.3	99.50	99.23

CIPW Norm

- Mode is the volume % of minerals seen
- Norm is a calculated “idealized” mineralogy

Variation Diagrams

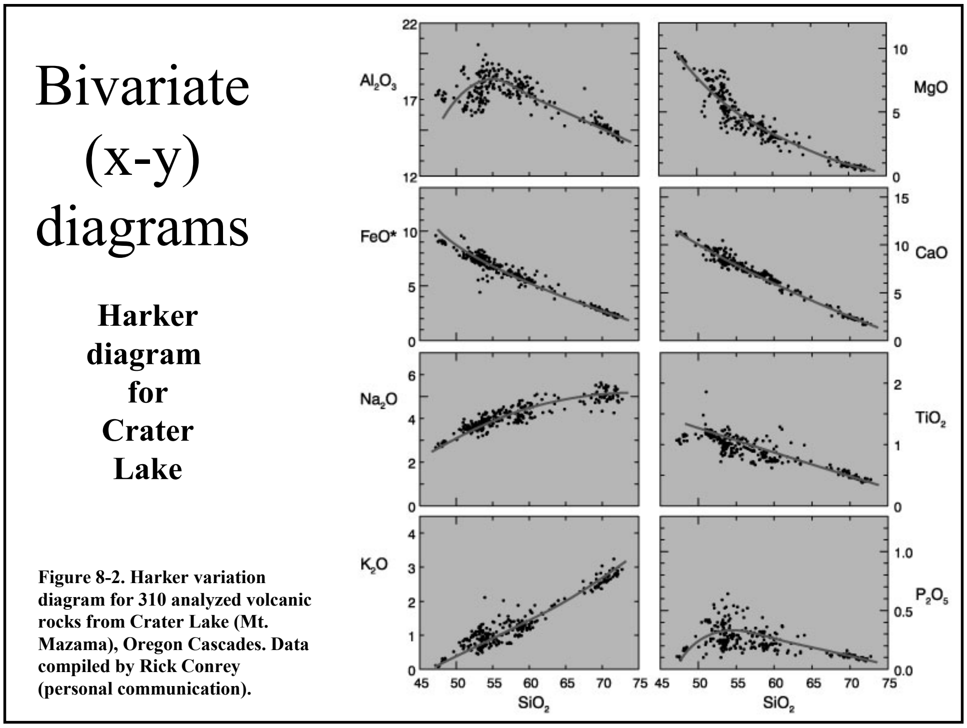
How do we display chemical data in a meaningful way?



Bivariate (x-y) diagrams

Harker diagram for Crater Lake

Figure 8-2. Harker variation diagram for 310 analyzed volcanic rocks from Crater Lake (Mt. Mazama), Oregon Cascades. Data compiled by Rick Conrey (personal communication).



Bivariate (x-y) diagrams

Harker diagram for Crater Lake

Figure 8-2. Harker variation diagram for 310 analyzed volcanic rocks from Crater Lake (Mt. Mazama), Oregon Cascades. Data compiled by Rick Conrey (personal communication).

Ternary Variation Diagrams

Example: AFM diagram

(alkalis-FeO*-MgO)

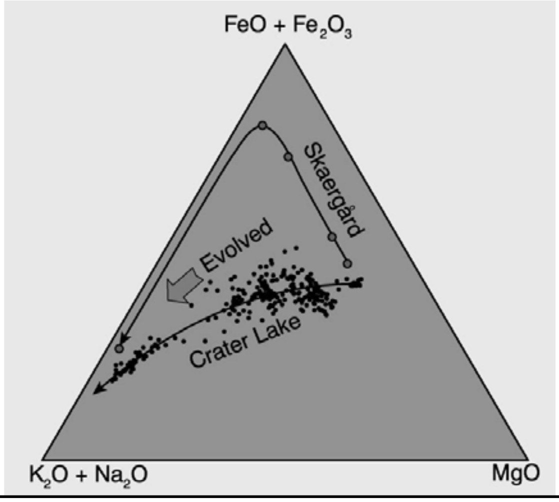


Figure 8-2. AFM diagram for Crater Lake volcanics, Oregon Cascades. Data compiled by Rick Conrey (personal communication).

Models of Magmatic Evolution

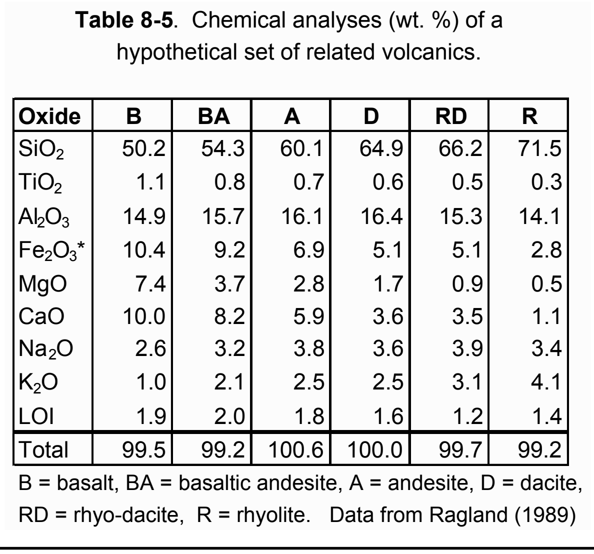


Table 8-5. Chemical analyses (wt. %) of a hypothetical set of related volcanics.

Oxide	B	BA	A	D	RD	R
SiO_2	50.2	54.3	60.1	64.9	66.2	71.5
TiO_2	1.1	0.8	0.7	0.6	0.5	0.3
Al_2O_3	14.9	15.7	16.1	16.4	15.3	14.1
Fe_2O_3*	10.4	9.2	6.9	5.1	5.1	2.8
MgO	7.4	3.7	2.8	1.7	0.9	0.5
CaO	10.0	8.2	5.9	3.6	3.5	1.1
Na_2O	2.6	3.2	3.8	3.6	3.9	3.4
K_2O	1.0	2.1	2.5	2.5	3.1	4.1
LOI	1.9	2.0	1.8	1.6	1.2	1.4
Total	99.5	99.2	100.6	100.0	99.7	99.2

B = basalt, BA = basaltic andesite, A = andesite, D = dacite, RD = rhyo-dacite, R = rhyolite. Data from Ragland (1989)

Harker diagram

- Smooth trends
- Model with 3 assumptions:

1 Rocks are related by FX

2 Trends = liquid line of descent

3 The basalt is the parent magma from which the others are derived

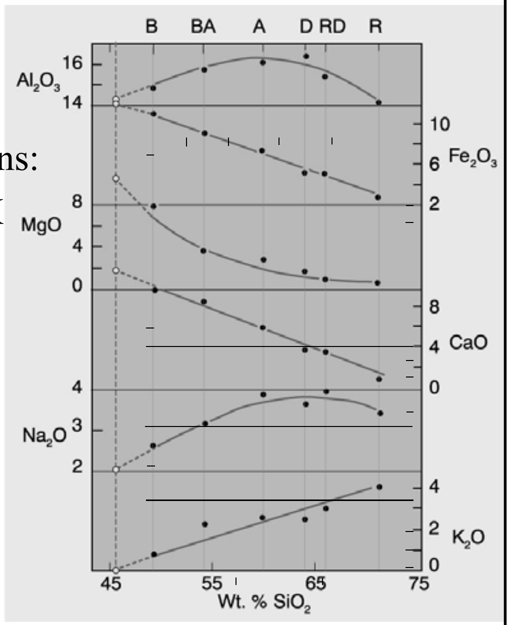


Figure 8-6. Stacked variation diagrams of hypothetical components X and Y (either weight or mol %). P = parent, D = daughter, S = solid extract, A, B, C = possible extracted solid phases. For explanation, see text. From Ragland (1989). Basic Analytical Petrology, Oxford Univ. Press.

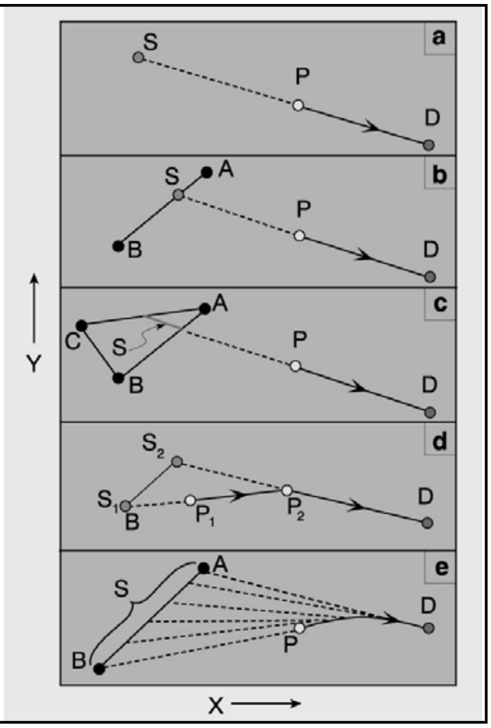
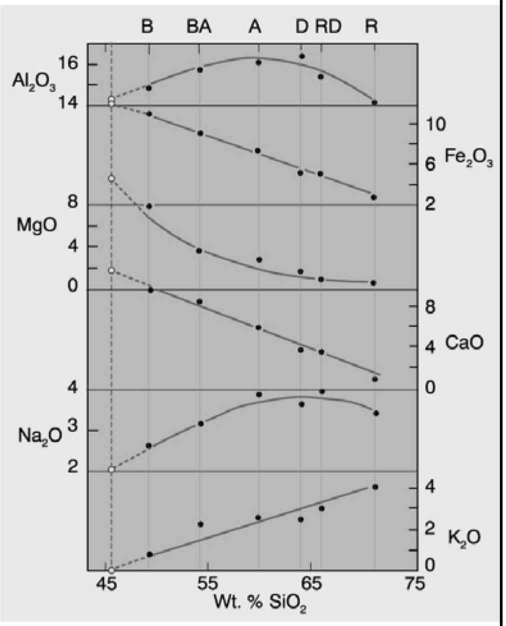


Figure 8-7. Stacked Harker diagrams for the calc-alkaline volcanic series of Table 8-5 (dark circles). From Ragland (1989). Basic Analytical Petrology, Oxford Univ. Press.

- Extrapolate BA → B and further to low SiO_2
- K_2O is first element to → (at $SiO_2 = 46.5$ red line)



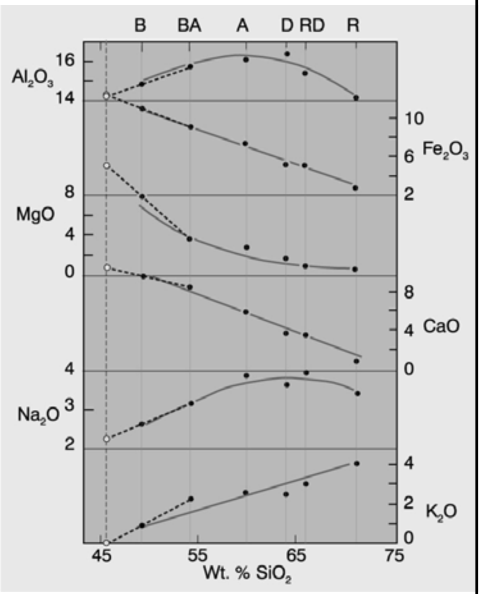
Thus the blue line → the concentration of all other oxides

Figure 8-7. Stacked Harker diagrams for the calc-alkaline volcanic series of Table 8-5 (dark circles). From Ragland (1989). Basic Analytical Petrology, Oxford Univ. Press.

Extrapolate the other curves back BA → B → blue line and read off X of mineral extract

Results:

Remove plagioclase, olivine, pyroxene and Fe-Ti oxide



Oxide	Wt%	Cation Norm	
SiO_2	46.5	ab	18.3
TiO_2	1.4	an	30.1
Al_2O_3	14.2	di	23.2
Fe_2O_3*	11.5	hy	4.7
MgO	10.8	ol	19.3
CaO	11.5	mt	1.7
Na_2O	2.1	il	2.7
K_2O	0		
Total	98.1		100

Then repeat for each increment BA → A etc.

Instead of calculating a graphical solution it is much easier and more satisfactory to calculate a mathematical solution using least-squares analysis to solve simultaneous mixing equations (see Igpet)

Parental Magma$_{SiO2}$ = (W)Evolved Magma$_{SiO2}$ + (X)Olivine$_{SiO2}$ + (Y)Plagioclase$_{SiO2}$ + (Z)Augite$_{SiO2}$

Parental Magma$_{TiO2}$ = (W)Evolved Magma$_{TiO2}$ + (X)Olivine$_{TiO2}$ + (Y) Plagioclase$_{TiO2}$ + (Z)Augite$_{tiO2}$

Parental Magma$_{FeO}$ = (W)Evolved Magma$_{Feo}$ + (X)Olivine$_{FeO}$ + (Y) Plagioclase$_{FeO}$ + (Z)Augite$_{FeO}$

Parental Magma$_{Al2O3}$ = (W)Evolved Magma$_{Al2O3}$ + (X)Olivine$_{Al2O3}$ + (Y) Plagioclase$_{Al2O3}$ + (Z) Augite$_{Al2O3}$

Parental Magma$_{MgO}$ = (W)Evolved Magma$_{MgO}$ + (X)Olivine$_{MgO}$ + (Y) Plagioclase$_{MgO}$ + (Z)Augite$_{MgO}$

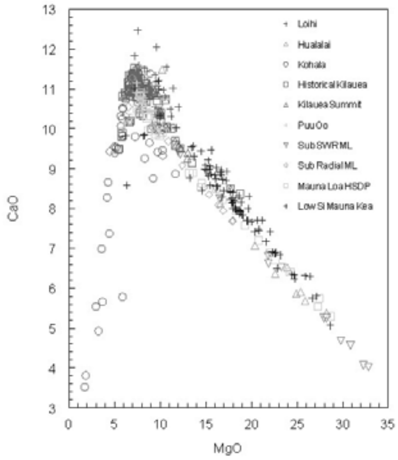
Parental Magma$_{CaO}$ = (W)Evolved Magma$_{CaO}$ + (X)Olivine$_{CaO}$ + (Y) Plagioclase$_{CaO}$ + (Z)Augite$_{CaO}$

Parental Magma$_{Na2O}$ = (W)Evolved Magma$_{Na2O}$ + (X)Olivine$_{Na2O}$ + (Y) Plagioclase$_{Na2O}$ + (Z)Augite$_{Na2O}$

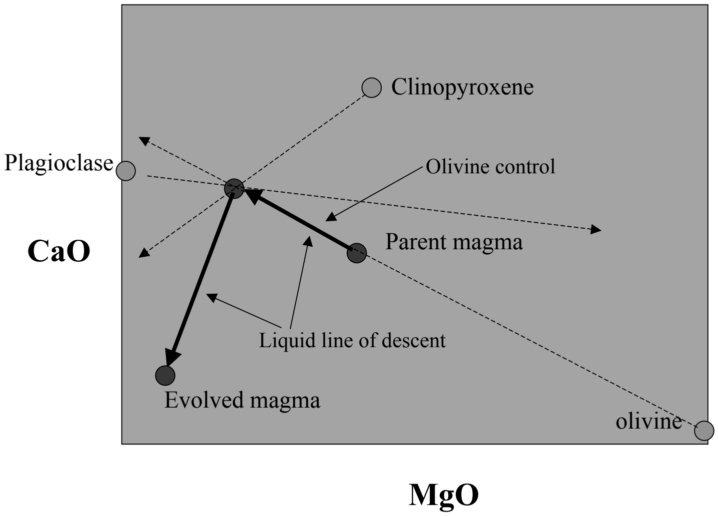
Parental Magma$_{K2O}$ = (W)Evolved Magma$_{K2O}$ + (X)Olivine$_{K2O}$ + (Y) Plagioclase$_{K2O}$ + (Z)Augite$_{K2O}$

Solve for W, X, Y and Z
Where X, Y, and Z are weight fractions

MgO vs CaO



For basaltic magmas plots against MgO are more useful than SiO_2



Magma Series

Can chemistry be used to distinguish families of magma types?

Early on it was recognized that some chemical parameters were very useful in regard to distinguishing magmatic groups

- Total Alkalis ($Na_2O + K_2O$)
- Silica (SiO_2) and silica saturation
- Alumina (Al_2O_3)

Alkali vs. Silica diagram for Hawaiian volcanics:

Seems to be two distinct groupings: alkaline and subalkaline

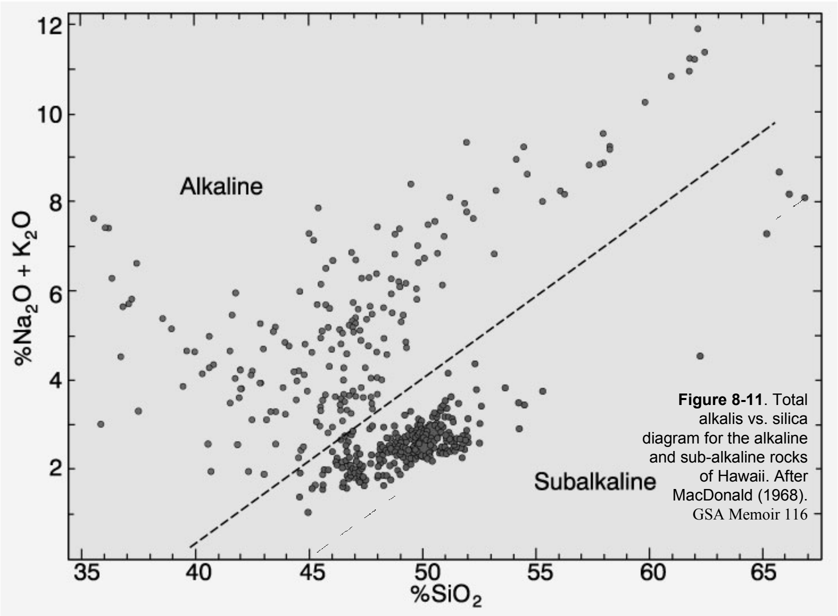


Figure 8-11. Total alkalis vs. silica diagram for the alkaline and sub-alkaline rocks of Hawaii. After MacDonald (1968). GSA Memoir 116

The Basalt Tetrahedron and the Ne-Ol-Q base

Alkaline and subalkaline fields are again distinct

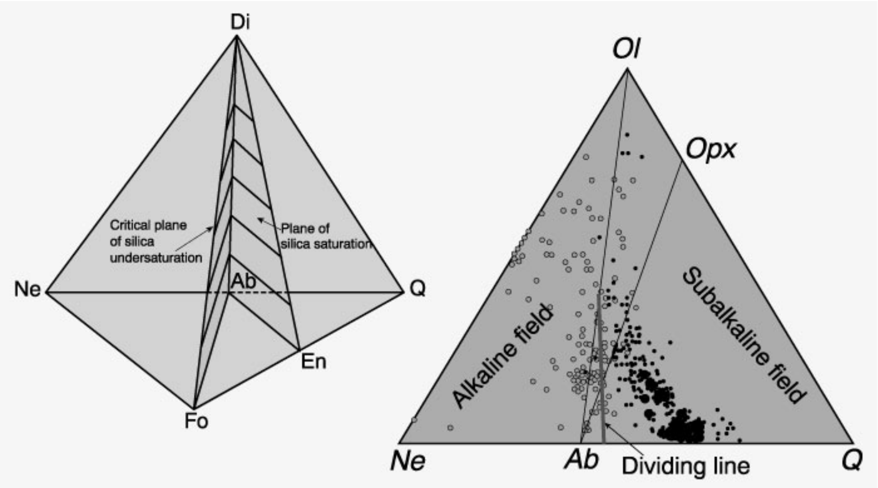
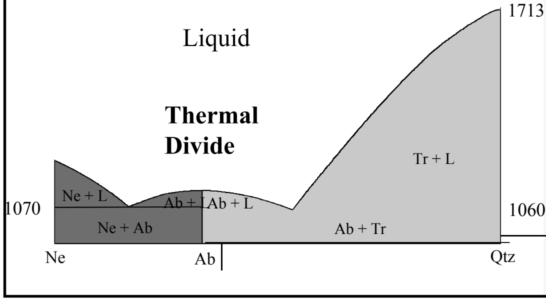
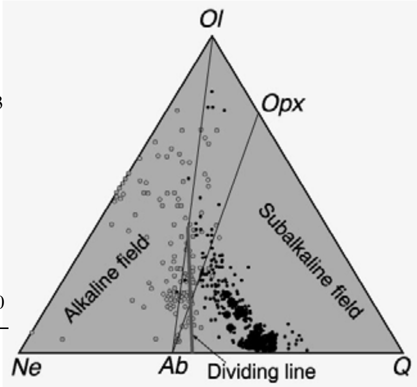


Figure 8-12. Left: the basalt tetrahedron (after Yoder and Tilley, 1962). J. Pet., 3, 342-532. Right: the base of the basalt tetrahedron using cation normative minerals, with the compositions of subalkaline rocks (black) and alkaline rocks (gray) from Figure 8-11, projected from Cpx. After Irvine and Baragar (1971). Can. J. Earth Sci., 8, 523-548.

Thermal divide separates the silica-saturated (subalkaline) from the silica-undersaturated (alkaline) fields at low pressure

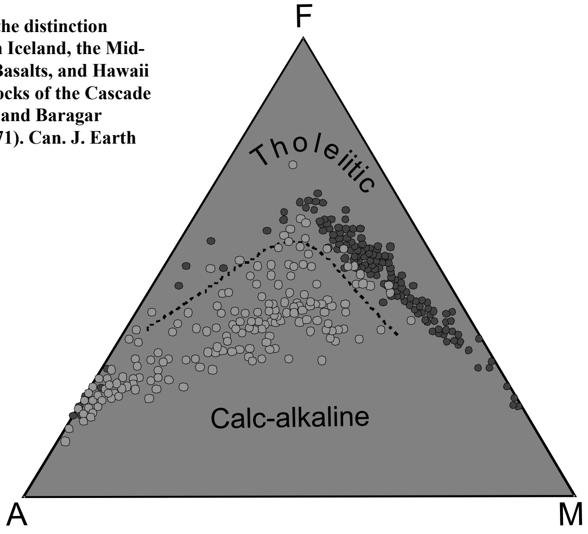
Cannot cross this divide by FX, so can’t derive one series from the other (at least via low-P FX)

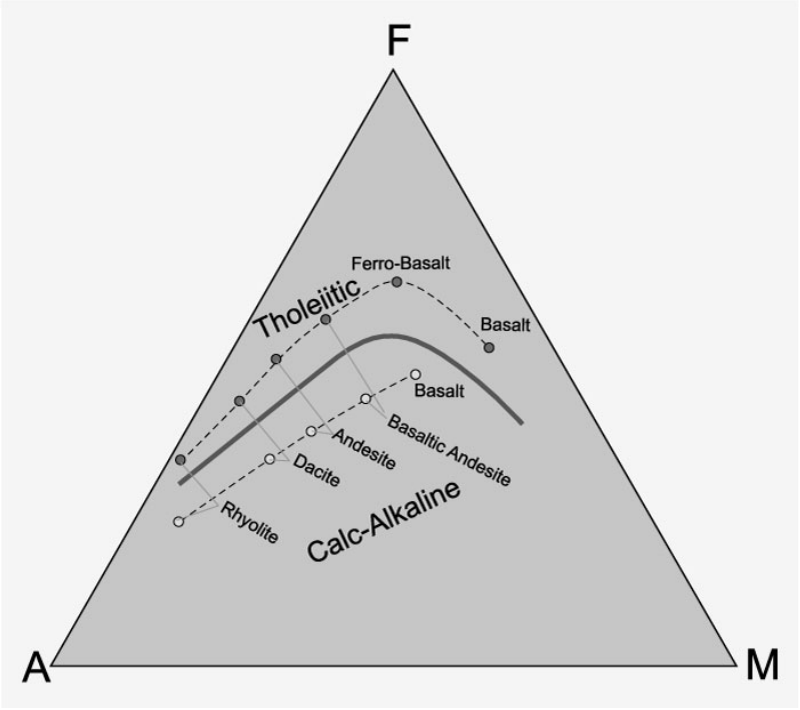




AFM diagram: can further subdivide the subalkaline magma series into a tholeiitic and a calc-alkaline series

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.





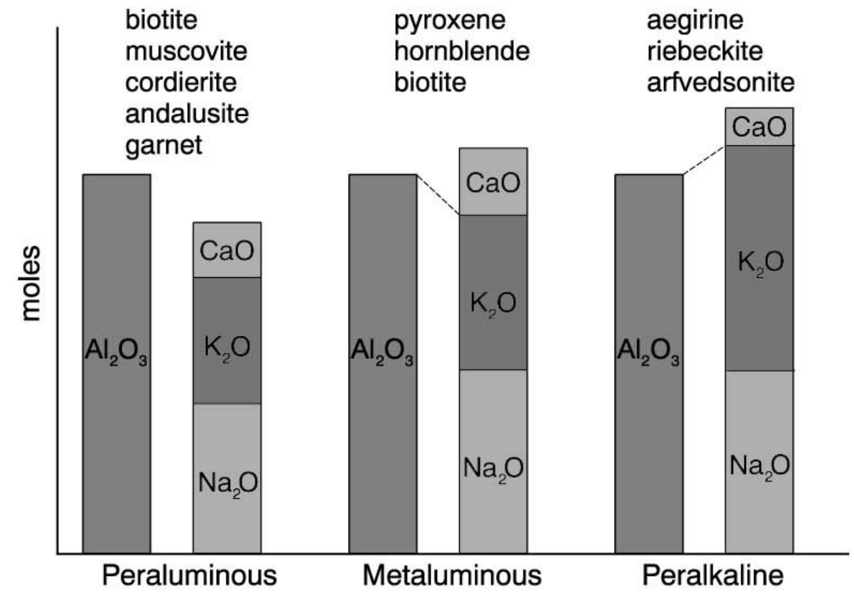


Figure 18-2. Alumina saturation classes based on the *molar* proportions of $Al_2O_3/(CaO+Na_2O+K_2O)$ (“A/CNK”) after Shand (1927). Common non-quartzo-feldspathic minerals for each type are included. After Clarke (1992). Granitoid Rocks. Chapman Hall.

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

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

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