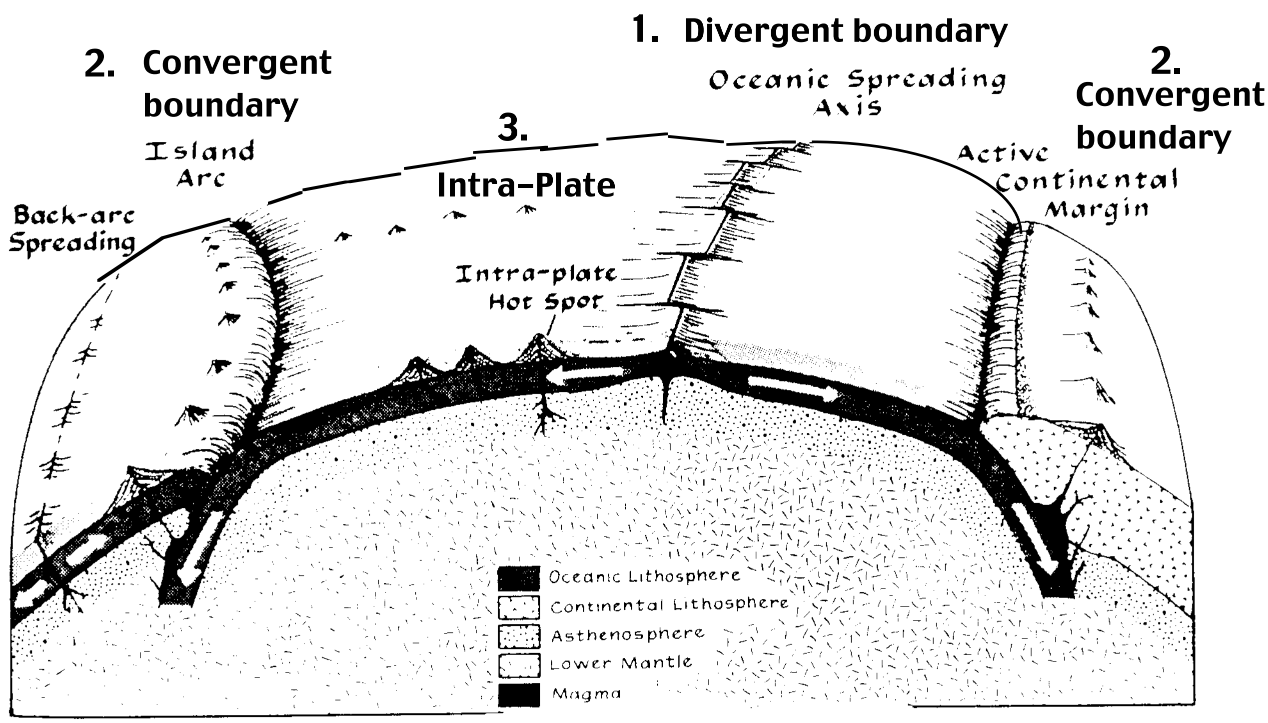
GEOLOGY 326
INTRODUCTION TO PETROLOGY

## Petros = Rock

**Igneous** = Ultimate source of all rocks
**Sedimentary** = Weathering erosion of pre-existing rocks
**Metamorphic** = Change in form

The chemical and petrologic characteristics of igneous rocks depend on the TECTONIC SETTING where they form.

## 3 BASIC SETTINGS:




**1. DIVERGENT PLATE BOUNDARIES == Mid-Ocean Ridge Basalts**

**2. CONVERGENT PLATE MARGINS == Orogenic Arcs**

**3. INTRAPLATE VOLCANISM == Plume-related**

## 1. DIVERGENT PLATE BOUNDARIES = Mid-Ocean Ridge Basalts (MORB)

- Most abundant source of volcanic rocks on earth
- Oldest known MORB < 170 million years in age
- Oldest Continental crust at least 4.1 billion years in age
- Ocean crust contributes indirectly to continental growth during subduction at deep sea trenches

## 2. CONVERGENT PLATE MARGINS == Orogenic Arcs

**Intra-oceanic** trenches = **Island Arcs**, e.g., Marianas, Tonga
**Continental Margins** = **Andean Arcs**, e.g., Andes, Cascades

- Wide variety of rocks formed, mostly **Andesite**.
- Arcs are 2$^{nd}$ only to MORB as most voluminous volcanic rocks.
- Batholith complexes like the Sierra Nevada in California
  = Subvolcanic equivalents of volcanic Andean Arc

## 3. INTRAPLATE VOLCANISM ==>> Hot Spots/Plumes

- Plumes originate deep within the earth
- Not directly associated with plate motions
- Spectacular in chemical and mineralogic variations

**Intra-Oceanic** = **Ocean Islands,** e.g., Hawaii, Tahiti.

**Intra-Continental** = **Flood basalts, Plume Tracks, Rift zones**

Flood Basalts = Plume Heads, e.g., Columbia River Basalts
Plume Tracks = Plume Tails, e.g., Snake River Plain (Idaho)
Rift zones = Incipient Plate Margins, e.g., East Africa, Rio Grande.

Basalts, Alkaline Basalts, Nephelinites, Carbonatites, Kimberlites

# IGNEOUS ROCKS CLASSIFICATION

2 Parallel systems: Volcanic Rocks == rapidly cooled
Plutonic rocks == slowly cooled

Mineralogy of rocks reflects chemistry: 99% of most rocks = 8 oxides.

| | Average Continental Crust | Average Oceanic Crust |
|---|---|---|
| $SiO_2$ | 58 % | 50 % |
| $Al_2O_3$ | 15 % | 16 % |
| $Fe_2O_3$ | 2.5 % | 3.8 % |
| $FeO$ | 4.3 % | 7.0 % |
| $CaO$ | 7.0 % | 12 % |
| $MgO$ | 4.0 % | 7.0 % |
| $Na_2O$ | 3.0 % | 2.5 % |
| $K_2O$ | 2.3 % | 0.3 % |
| $TiO_2$ | 0.8 % | 2.0 % |

Most abundant: $SiO_2$ + $Al_2O_3$ = 65-75% almost all rocks

$SiO_4^{4-}$ Tetrahedron == Basic Building Block of ALL SILICATE MINERALS.

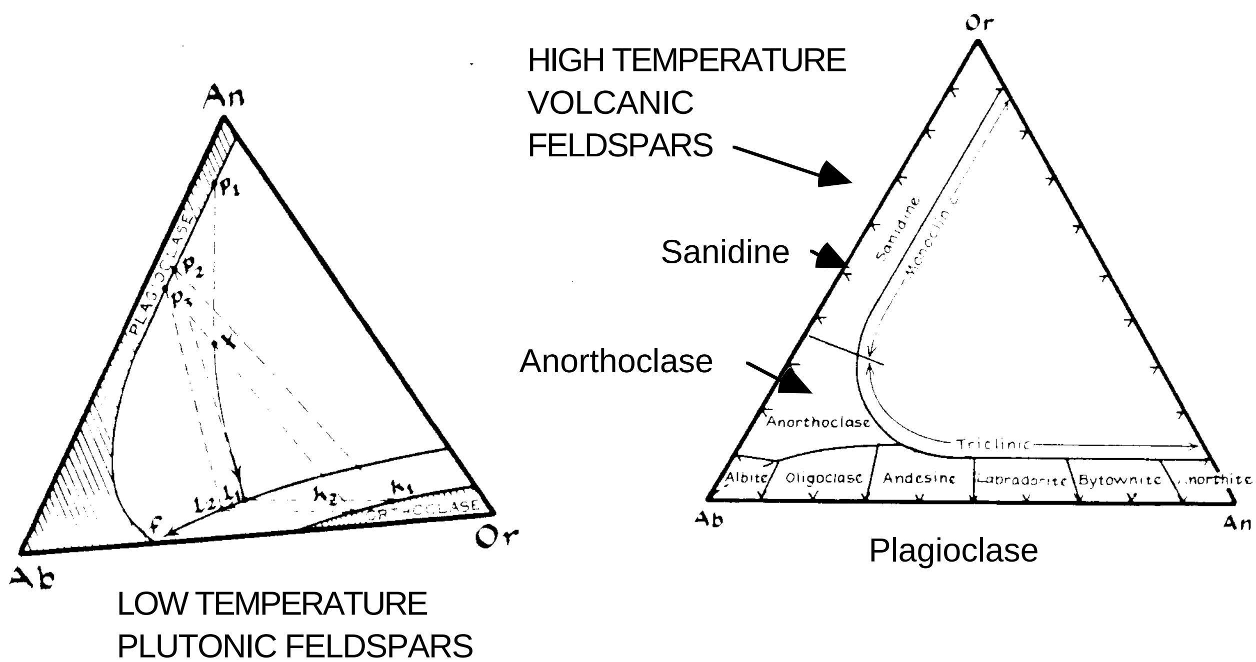
When ALL Corners Shared Si/O ratio = 1/2 ==>>> $SiO_2$ **Quartz**

**Feldspars**: substitute $Al^{3+}$ (0.47 A) for $Si^{4+}$ (0.34 A)

Charge balance with Na+ , K+, or Ca++

| | |
|---|---|
| $KAlSi_3O_8$ | **K-spar = orthoclase, microcline, sanidine** |
| $NaAlSi_3O_8$ | **Albite** |
| $CaAl_2Si_2O_8$ | **Anorthite** |

**FELDSPAR TERNARY DIAGRAMS:**




If rock poor in $SiO_2$ form **FELDSPATHOIDS** in Addition to FELDSPAR:

Albite - 2 * Quartz = **Nepheline** ($NaAlSiO_4$)
Kspar - 1* Quartz = **Luecite** ($KAlSi_2O_6$)

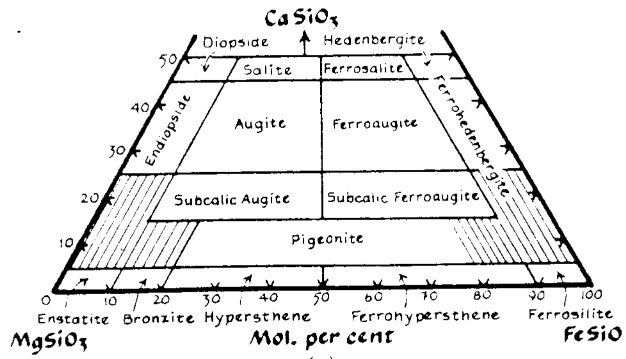
QUARTZ, FELDSPARS, and FELDSPATHOIDS account for 50% most rocks.

# MAFIC MINERALS

**MgO, $FeO+Fe_2O_3$, CaO** = Form **MAFIC** minerals.

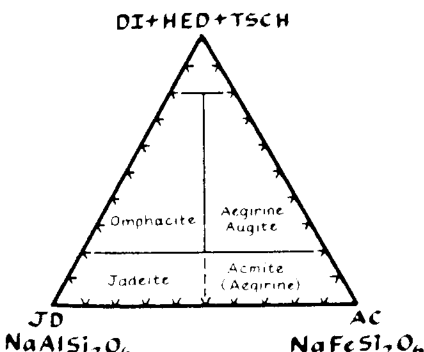
**PYROXENES: Single Chain Silicates**

| | | | |
|---|---|---|---|
| **Diopside** | $CaMgSi_2O_6$ | **Hedenbergite** | $CaFeSi_2O_6$ |
| **Enstatite** | $MgSiO_3$ | **Ferrosilite** | $FeSiO_3$ |



(a)

## SODIC PYROXENES



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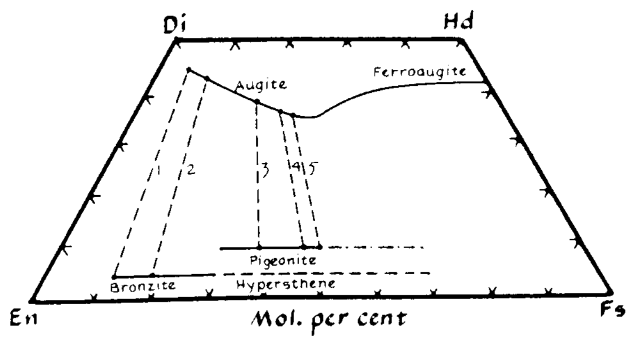

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Other pyroxenes = solid solutions of these, e.g.,

**AUGITE** = $Ca(Mg,Fe)Si_2O_6$

Sodic pyroxenes contain **Na** in place of **Ca:**

**Jadeite** $NaAl^{3+}Si_2O_6$ **Aegerine/Acmite** $NaFe^{3+}Si_2O_6$

Note that the Na+ is charge balanced by the trivalent Al and Fe.
Sodic Pyroxenes: High P/T metamorphics, Some Alkaline rocks.

**Olivine = Solid Solution**

**Forsterite** = $Mg_2SiO_4$ **Fayalite** = $Fe_2SiO_4$

Give composition in mole % Fo (e.g., Fo89 = 89% Fo, 11% Fa).

Silica over-saturated rocks (free quartz) DO NOT contain Mg-rich olivine:

$Mg_2Si_2O_6$ (Enstatite) - $SiO_2$ = $Mg_2SiO_4$ (Forsterite)

**Amphiboles: Double Chain Silicates**

- Similar to Pyroxenes with alkalis, $H_2O$ added.
- Most Common = Calcic Amphiboles

**Actinolite** $Ca_2(Mg,Fe)_5(Si_8)O_{22}*(OH)_2$

**Hornblende** $(Na,K)_{0-1}Ca_2(Mg,Fe^{2+},Fe^{3+},Al)_5(Al_2Si_6)O_{22}*(OH)_2$

- Less Common = Magnesian, Sodic Amphiboles

**Cummingtonite** $(Mg,Fe^{2+})_7(Si_8)O_{22}*(OH)_2$

**Glaucophane** $Na_2Mg_3Al_2(Si_8)O_{22}*(OH_2)$

**Riebeckite** $Na_2Fe^{2+}{}_3Fe^{3+}{}_2(Si_8)O_{22}*(OH_2)$

**MICAS: Sheet Silicates**

**Muscovite** $K_2Al_4$ $(Si_6Al_2)O_{20}(OH,F)_4$
**Phlogopite** $K_2(Mg,Fe)_6(Si_6Al_2)O_{20}(OH,F)_4$
**Biotite** $K_2(Mg,Fe)_{4-6}(Fe^{3+},Al,Ti)_{0-2}(Si_6Al_2)O_{20}*(OH,F)_4$

## HOW DO WE NAME ROCKS ??

**PLUTONIC ROCKS = ** Coarse grained, minerals visible

- Modal mineralogy , i.e., volume % of specific minerals
- Most common: IUGS system (See Handouts on IUGS system).
- Most igneous rocks rich in feldspar + quartz or feldspathoids.

Quartz-bearing rocks: Quartz/Plagioclase/Alkali Feldspar
Nepheline-bearing rocks: Nepheline/Plagioclase/Alkali feldspar

**Normalize these 3 minerals to 100%**

Diorites, gabbros, anorthosites all plot in same corner of diagram; Must use additional criteria to distinguish:

Diorite: Plag < An50 Na-rich
Gabbro: Plag > An50 Ca-rich
Anorthosite: Plag > 90% of mode.

Mafic rich plutonic rocks: Need separate ternary diagram -- all with calcic plagioclase.

**Mafic Plutonic Rock Names:**

Gabbro: Plag + Cpx
Norite: Plag + Opx
Gabbronorite: Plag + Opx + Cpx
Troctolite: Plag + Olivine
Oliv Gabbro: Plag + Cpx + Olivine
Dunite: Olivine > 90%
Pyroxenite: Pyroxene > 90%
Anorthosite: Plagioclase > 90%
Peridotites: Olivine +/- Pyroxene
  Lherzolite: Olivine + Opx + Cpx +/- (Plag, Spinel, Garnet)
  Harzburgite: Olivine + Opx +/- (Cr-Spinel, Garnet)
  Wehrlite: Olivine + Cpx
  Dunite: Olivine > 90%

**VOLCANIC ROCKS**

Too fine grained to use modal mineralogy , also many contain glass:

MUST USE CHEMISTRY !!!

Since variations in $SiO_2$ are fundamental, can use $SiO_2$ directly:

| Rock | Basalt | Andesite | Dacite | Rhyolite |
|---|---|---|---|---|
| $SiO_2$ % | 45-52% | 53-63% | 64-68% | 68-76% |

Modifiers used for other chemical characteristics:

**Peraluminous:** $Al_2O_3 > CaO + Na_2O + K_2O$ (Excess Alumina)

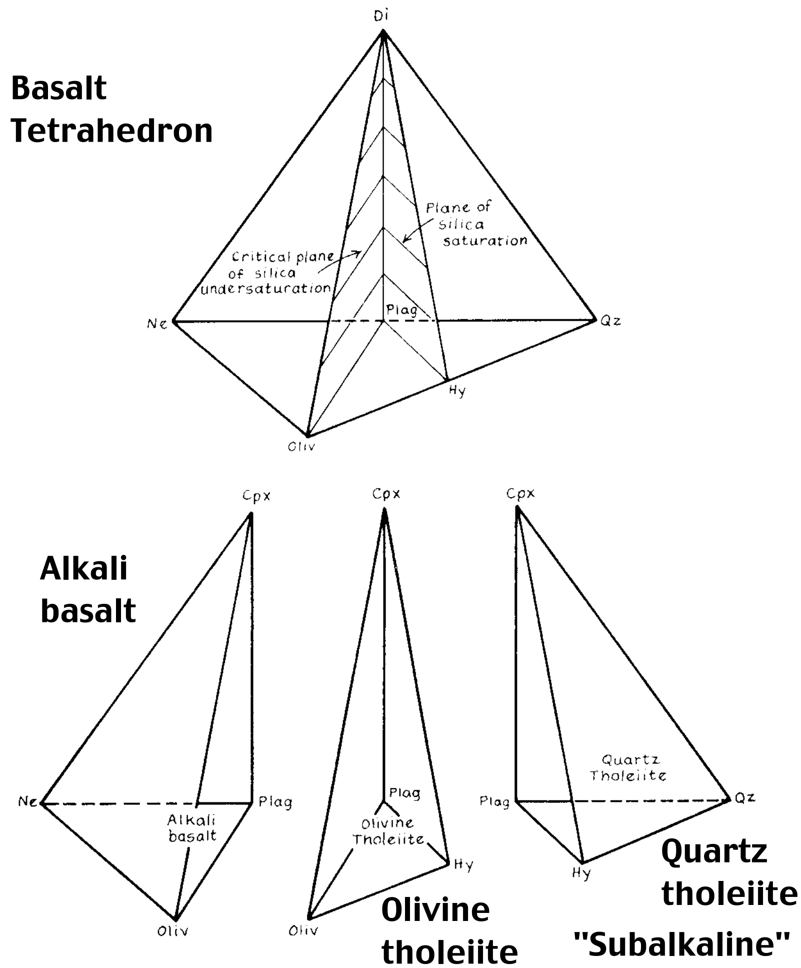
**Metaluminous**: $Al_2O_3 < CaO + Na_2O + K_2O$ (Normal)
$Al_2O_3 > Na_2O + K_2O$

**Subaluminous:** $Al_2O_3 = Na_2O + K_2O$ (Basalts, Andesites)

**Peralkaline:** $Al_2O_3 < Na_2O + K_2O$ (Some Dacite, Rhyolites)

MINERAL NORM:

- Calculate minerals that would normally crystallize from a dry magma at low pressure if cooled slowly.
- Most common **CIPW NORM**
- Can plot volcanic rock NORM on IUGS ternary to classify
- Works fine for quartz, feldspar-rich rocks ==> Naturally poor in FM minerals.
- Rocks with high FM content need more, especially Basalts.




Basalt Tetrahedron Assumes: Anorthite saturation.

**Alkali Basalts:**

>> Critically undersaturated in silica,
>> Normative or modal Feldspathoids.
>> *NO* normative or modal hypersthene, quartz.

**Subalkaline Basalts:**

>> Either olivine normative or quartz normative.
>> *All* hypersthene normative.
>> *Subalkaline* magmas most common.

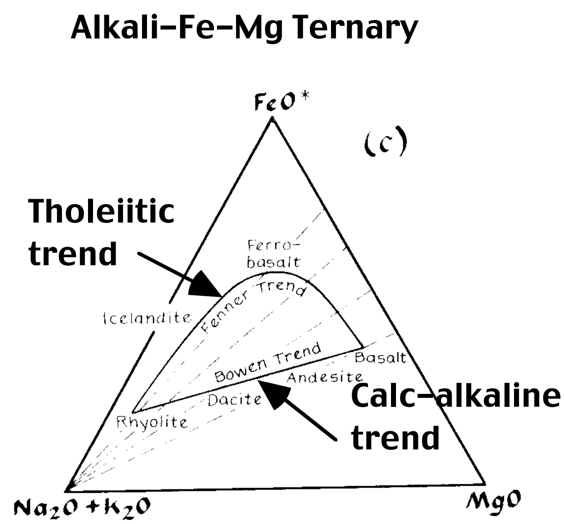
>> Subalkaline basalts divided two groups:
1. Tholeiitic basalts
2. Calc-alkaline basalts (high-alumina)

Big Debate in 1920s 1930s N.L. Bowen vs C.N. Fenner

**Bowen:** Fractionation of basic magma = Alkali, $SiO_2$ enrichment

**Fenner:** Fractionation of basic magma = Fe-enrichment

Both were right, but for different rock suites:




Both series: SiO2 = 50%-70% Basalt ==> Rhyolite

**Calc-Alkaline Series** = Island arcs, continental margin arcs

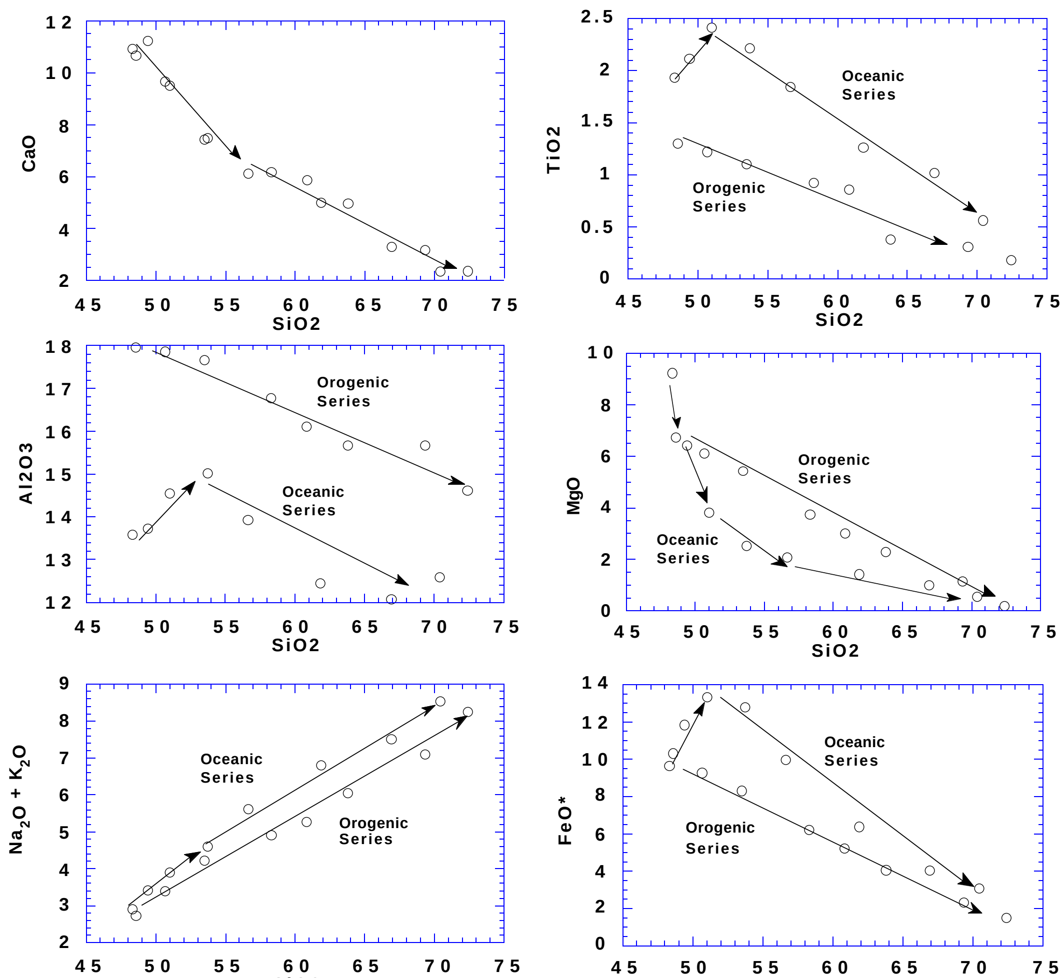
**Tholeiitic Series** = Flood basalts, MORB, Oceanic Islands

Tholeiitic series characterized by early Fe, Ti-enrichment,

Calc-alkaline series characterized by Fe, Ti-depletion throughout.

Tholeiitic Series = Fenner trend = "Oceanic"

Calc-alkaline Series = Bowen trend = "Orogenic"




These silica-variation diagrams -- often called Harker diagrams -- show the variation in oxide composition of two rock series: an Oceanic series (the Fenner trend) and an orogenic series (the Bowen trend). Compare these variations to those seen in the AFM diagram on the previous page.