Chapter 9: Trace Elements

Note magnitude of major element changes

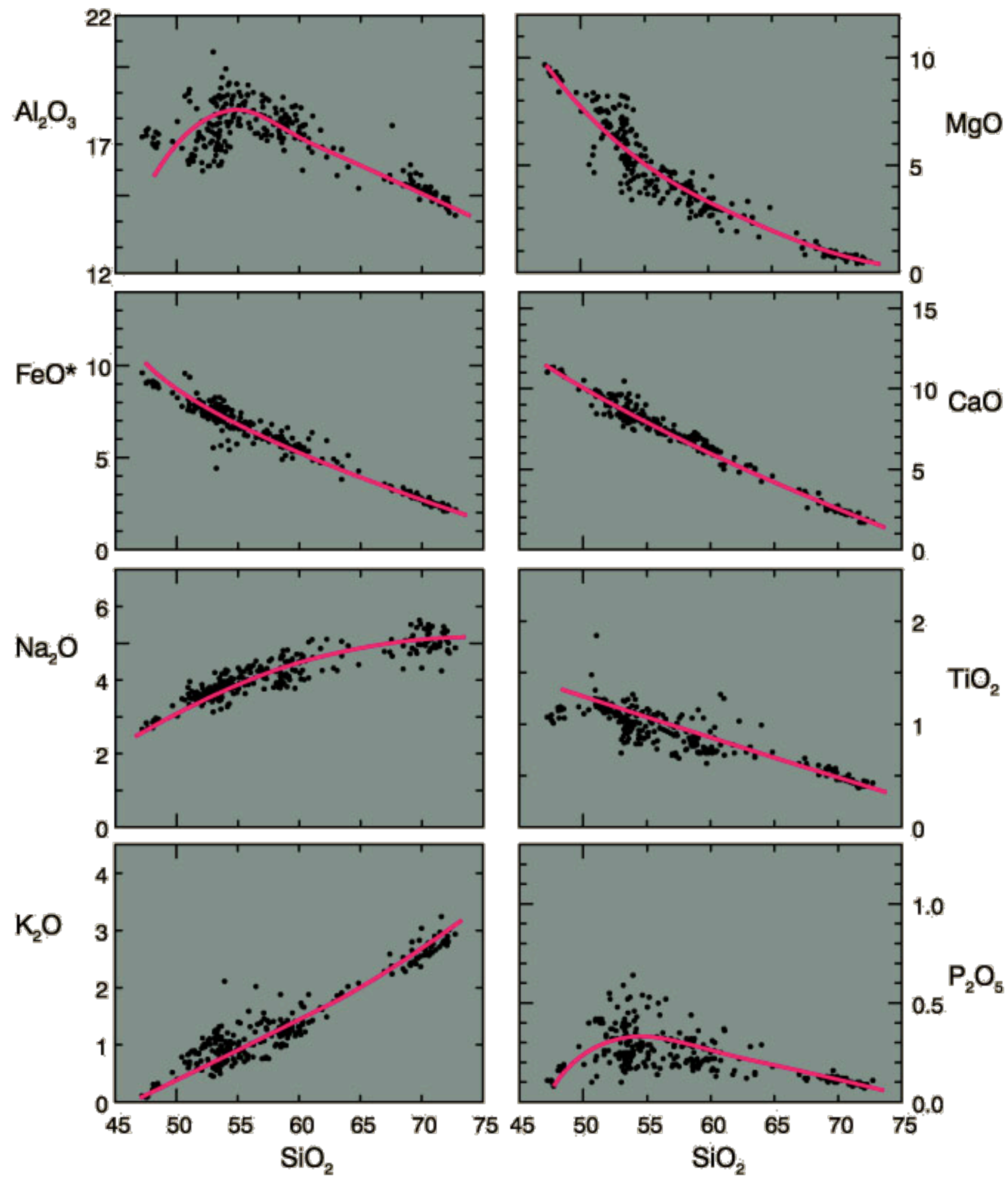

Figure 8.2. Harker variation diagram for 310 analyzed volcanic rocks from Crater Lake (Mt. Mazama), Oregon Cascades. Data compiled by Rick Conrey (personal communication). From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Chapter 9: Trace Elements

Now note magnitude of trace element changes

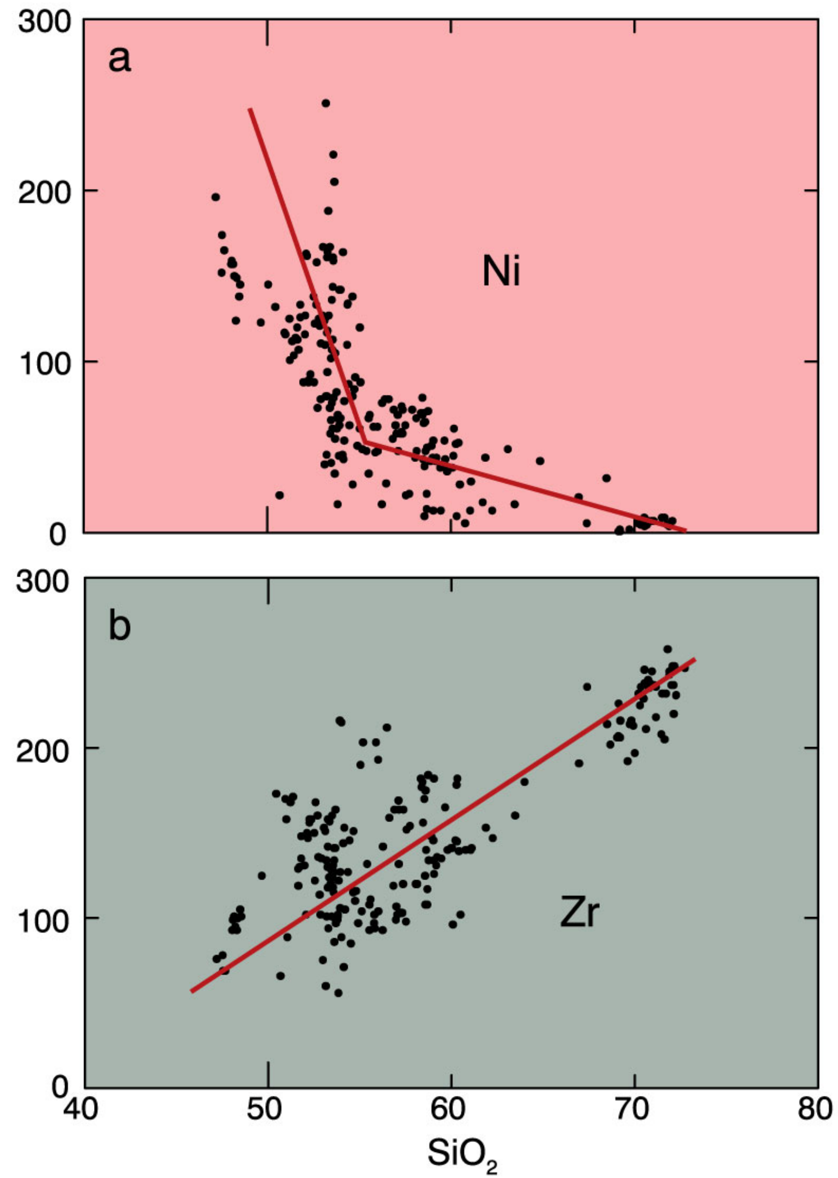

Figure 9.1. Harker Diagram for Crater Lake. From data compiled by Rick Conrey. From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Compatibility depends on minerals and melts involved.

Which are incompatible? Why?

Table 9-1. Partition Coefficients (C_S/C_L) for Some Commonly Used Trace Elements in Basaltic and Andesitic Rocks

		Olivine	Opx	Cpx	Garnet	Plag	Amph	Magnetite
	Rb	0.01	0.022	0.031	0.042	0.071	0.29	
	Sr	0.014	0.04	0.06	0.012	1.83	0.46	
	Ba	0.01	0.013	0.026	0.023	0.23	0.42	
	Ni	*14.0*	5.0	*7.0*	0.955	*0.01*	6.8	29.
	Cr	0.7	10.0	34.0	1.345	*0.01*	2.0	7.4
Rare Earth Elements	La	0.007	*0.03*	0.056	0.001	0.148	0.544	2.
	Ce	0.006	0.02	0.092	0.007	0.082	0.843	2.
	Nd	0.006	0.03	0.23	0.026	0.055	1.34	2.
	Sm	0.007	0.05	0.445	0.102	0.039	1.804	1.
	Eu	0.007	0.05	0.474	0.243	0.1/1.5*	1.557	1.
	Dy	0.013	0.15	0.582	3.17	0.023	2.024	1.
	Er	0.026	0.23	0.583	6.56	0.02	1.74	1.5
	Yb	0.049	0.34	0.542	11.5	0.023	1.642	1.4
	Lu	0.045	0.42	0.506	11.9	0.019	1.563	

Data from Rollinson (1993).

* Eu^{3+}/Eu^{2+} *Italics* are estimated

- For a rock, determine the bulk distribution coefficient $\bar{D}$ for an element by calculating the contribution for each mineral

eq. 9.4: $$\bar{D}_i = \Sigma W_A D_{i,A}$$

W_A = weight % of mineral A in the rock

$D_{i,A}$ = partition coefficient of element i in mineral A

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Rb		0.010	0.022	0.031	0.042	0.071	0.29	
Sr		0.014	0.040	0.060	0.012	1.830	0.46	
Ba		0.010	0.013	0.026	0.023	0.23	0.42	
Ni		*14*	5	7	0.955	*0.01*	6.8	29
Cr		0.70	10	34	1.345	*0.01*	2.00	7.4
La	Rare Earth Elements	0.007	*0.03*	0.056	0.001	0.148	0.544	2
Ce		0.006	0.02	0.092	0.007	0.082	0.843	2
Nd		0.006	0.03	0.230	0.026	0.055	1.340	2
Sm		0.007	0.05	0.445	0.102	0.039	1.804	1
Eu		0.007	0.05	0.474	0.243	1.5	1.557	1
Dy		0.013	0.15	0.582	1.940	0.023	2.024	1
Er		0.026	0.23	0.583	4.700	0.020	1.740	1.5
Yb		0.049	0.34	0.542	6.167	0.023	1.642	1.4
Lu		0.045	0.42	0.506	6.950	0.019	1.563	

Data from Rollinson (1993). * Eu^{3+}/Eu^{2+} *Italics* are estimated

Example: hypothetical garnet lherzolite = 60% olivine, 25% orthopyroxene, 10% clinopyroxene, and 5% garnet (all by *weight*), using the data in Table 9.1, is:

$$\overline{D}_{Er} = (0.6 \cdot 0.026) + (0.25 \cdot 0.23) + (0.10 \cdot 0.583) + (0.05 \cdot 4.7) = 0.366$$

- Trace elements strongly partitioned into a single mineral
- Ni - olivine in Table 9.1 = 14

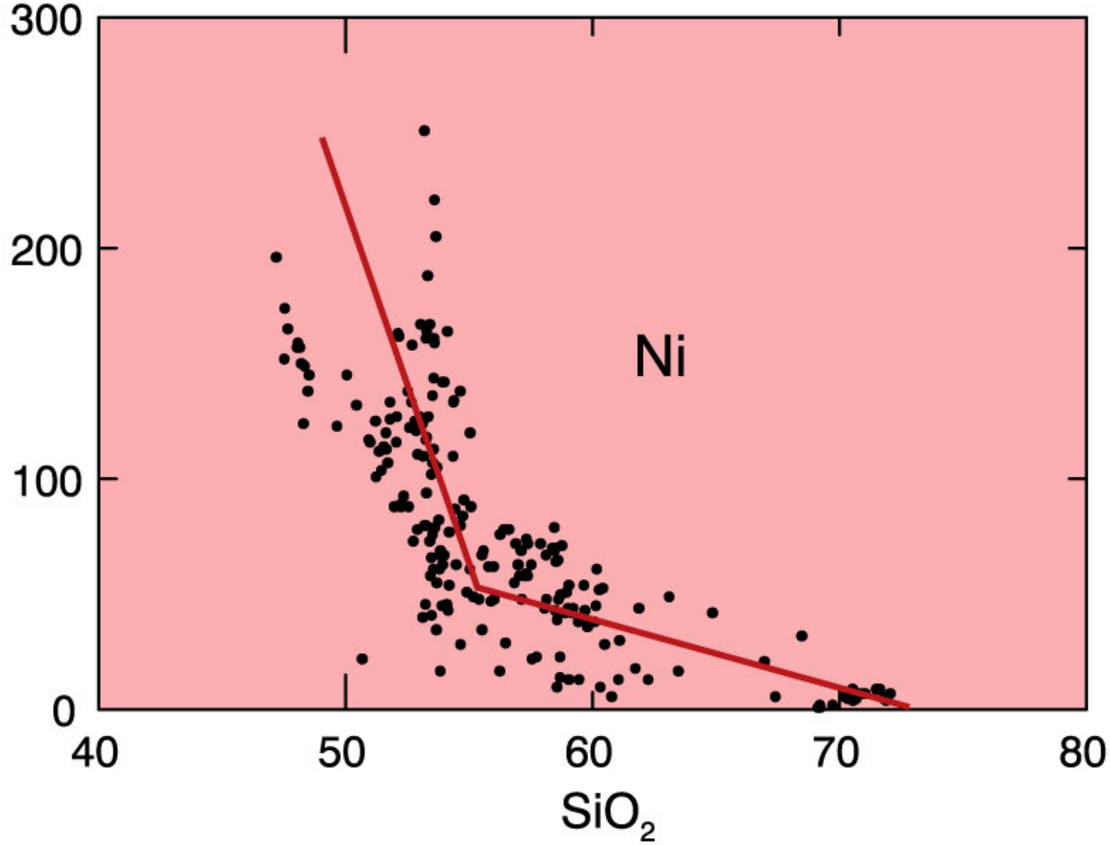

Figure 9.1a. Ni Harker Diagram for Crater Lake. From data compiled by Rick Conrey. From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

- Incompatible trace elements concentrate → liquid
- Reflect the proportion of liquid at a given state of crystallization or melting

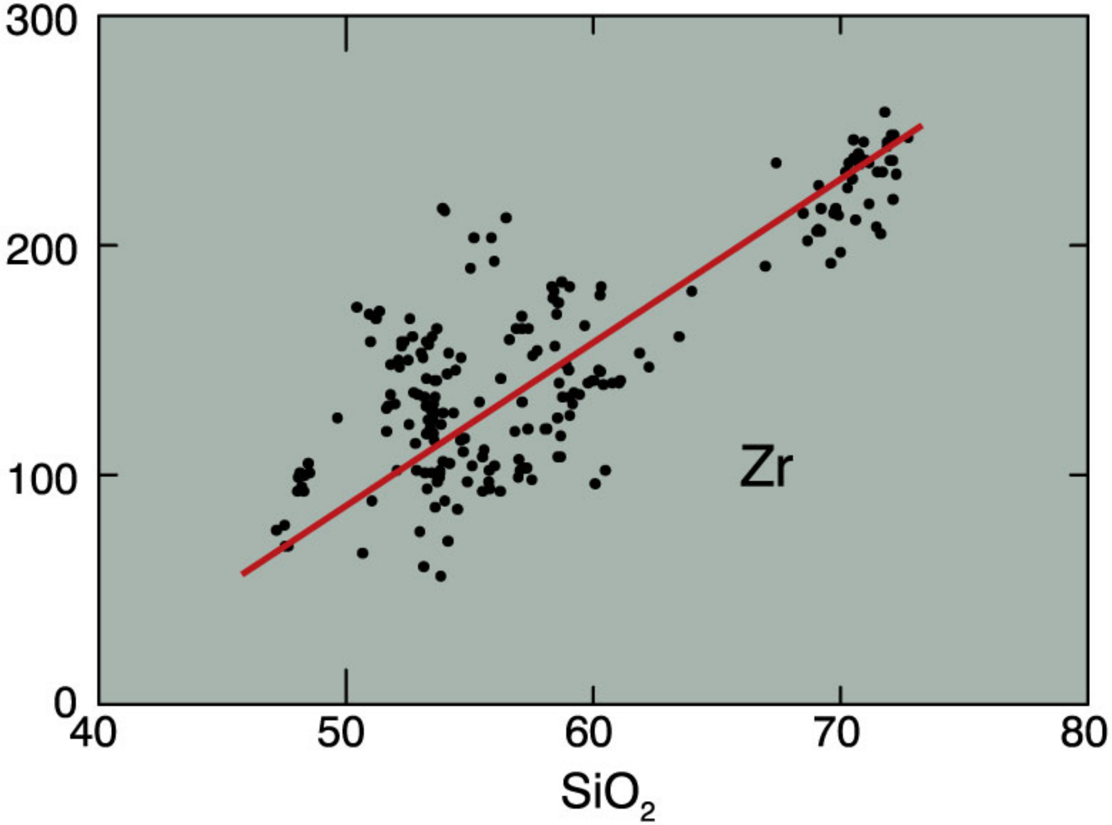

Figure 9.1b. Zr Harker Diagram for Crater Lake. From data compiled by Rick Conrey. From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

- Sr and Ba (also *incompatible* elements)
  - Sr is excluded from most common minerals except plagioclase
  - Ba similarly excluded except in alkali feldspar

Table 9-1. Partition Coefficients (C_S/C_L) for Some Commonly Used Trace Elements in Basaltic and Andesitic Rocks

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Rare Earth Elements: La	0.007	*0.03*	0.056	0.001	0.148	0.544	2
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Er	0.026	0.23	0.583	4.700	0.020	1.740	1.5
Yb	0.049	0.34	0.542	6.167	0.023	1.642	1.4
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Data from Rollinson (1993). * Eu^{3+}/Eu^{2+} *Italics* are estimated

Compatible example:

- Ni strongly fractionated → olivine > pyroxene
- Cr and Sc → pyroxenes » olivine
- Ni/Cr or Ni/Sc can distinguish the effects of olivine and augite in a partial melt or a suite of rocks produced by fractional crystallization

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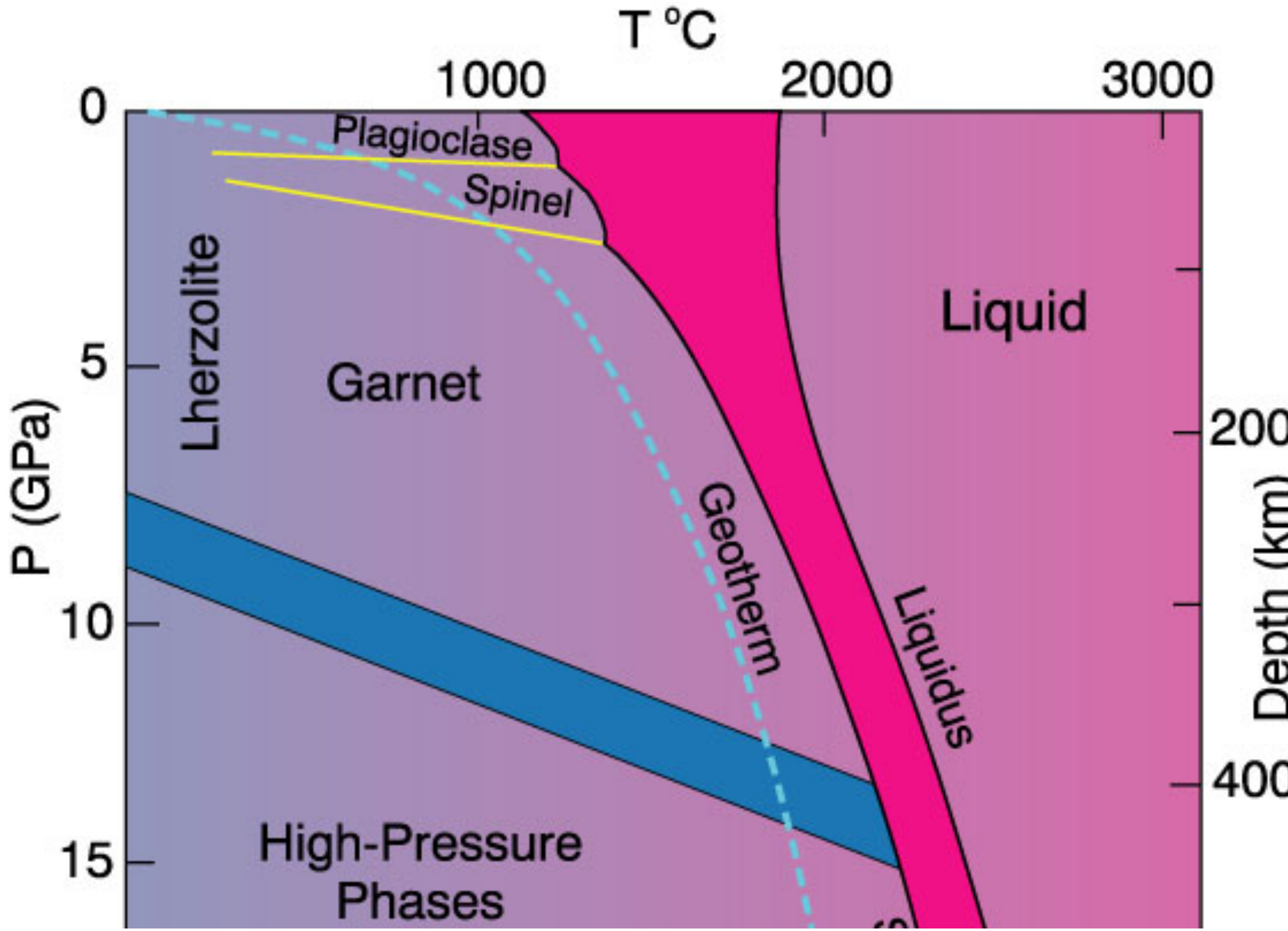

T °C
1000
2000
3000
0
5
10
15
P (GPa)
200
400
Depth (km)
Plagioclase
Spinel
Lherzolite
Garnet
Liquid
Geotherm
Liquidus
High-Pressure
Phases

REE diagrams using batch melting model of a garnet lherzolite for various values of F:

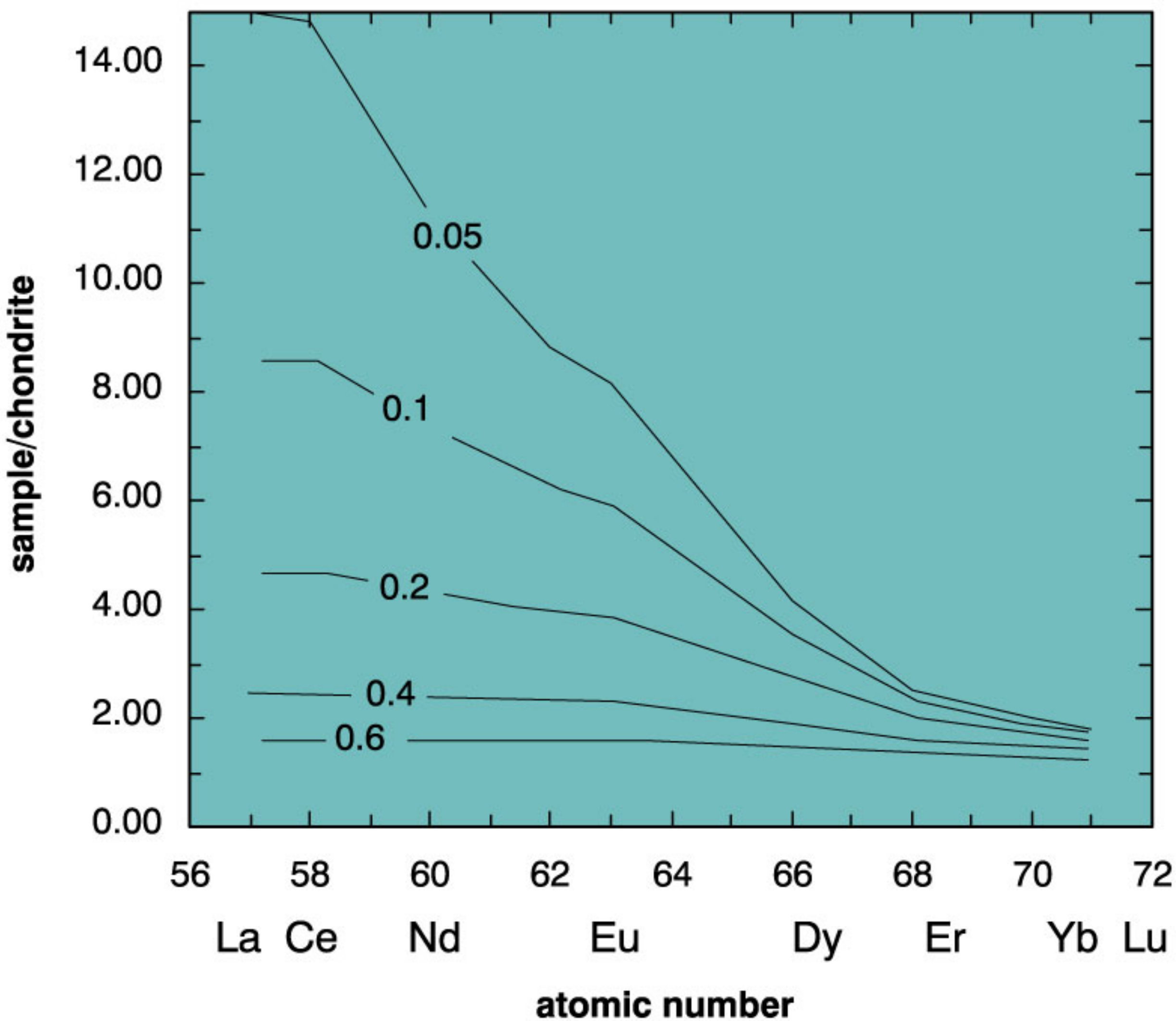
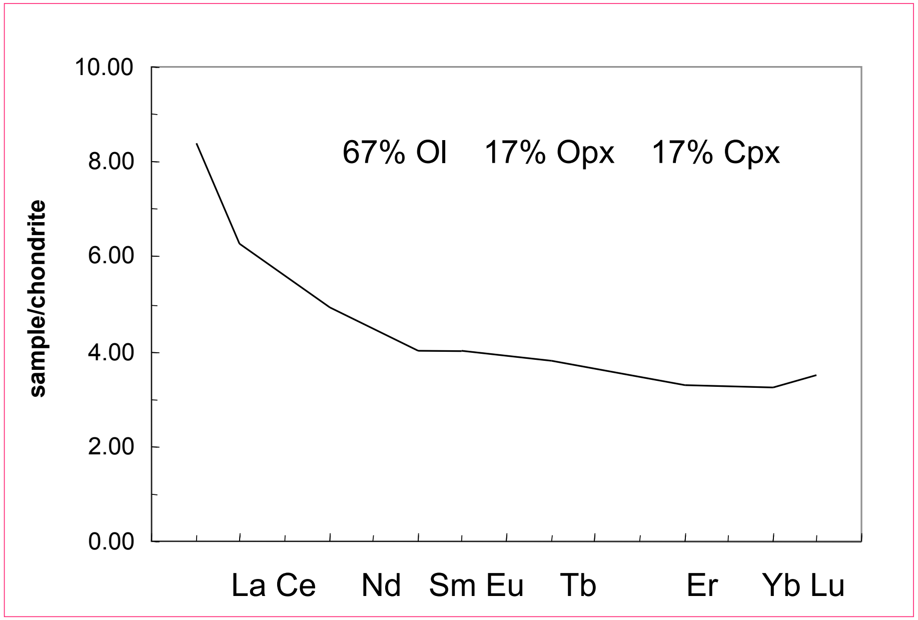
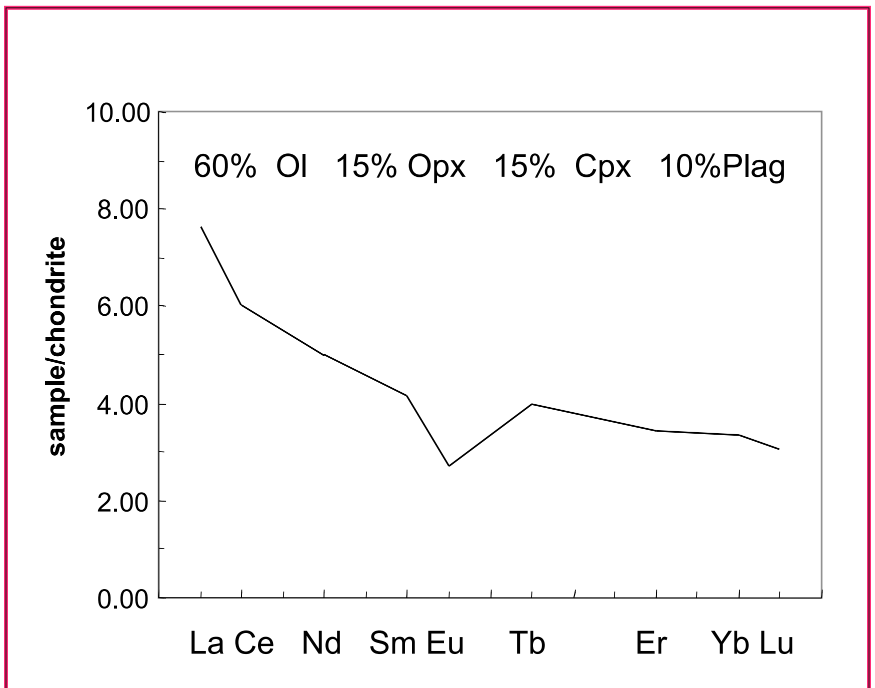


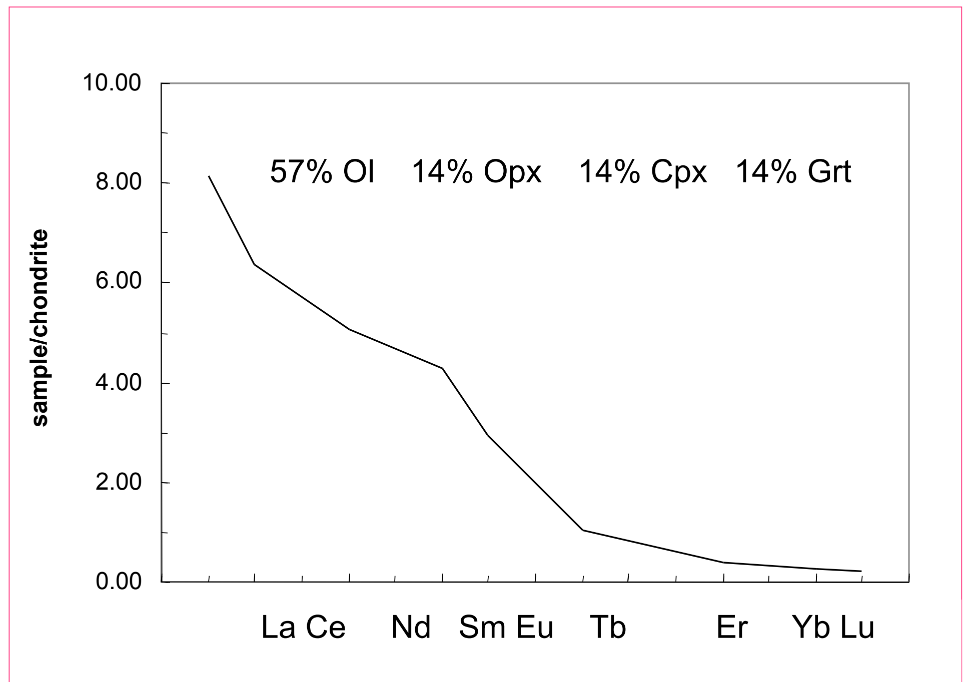
Figure 9.4. Rare Earth concentrations (normalized to chondrite) for melts produced at various values of F via melting of a hypothetical garnet lherzolite using the batch melting model (equation 9.5). From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

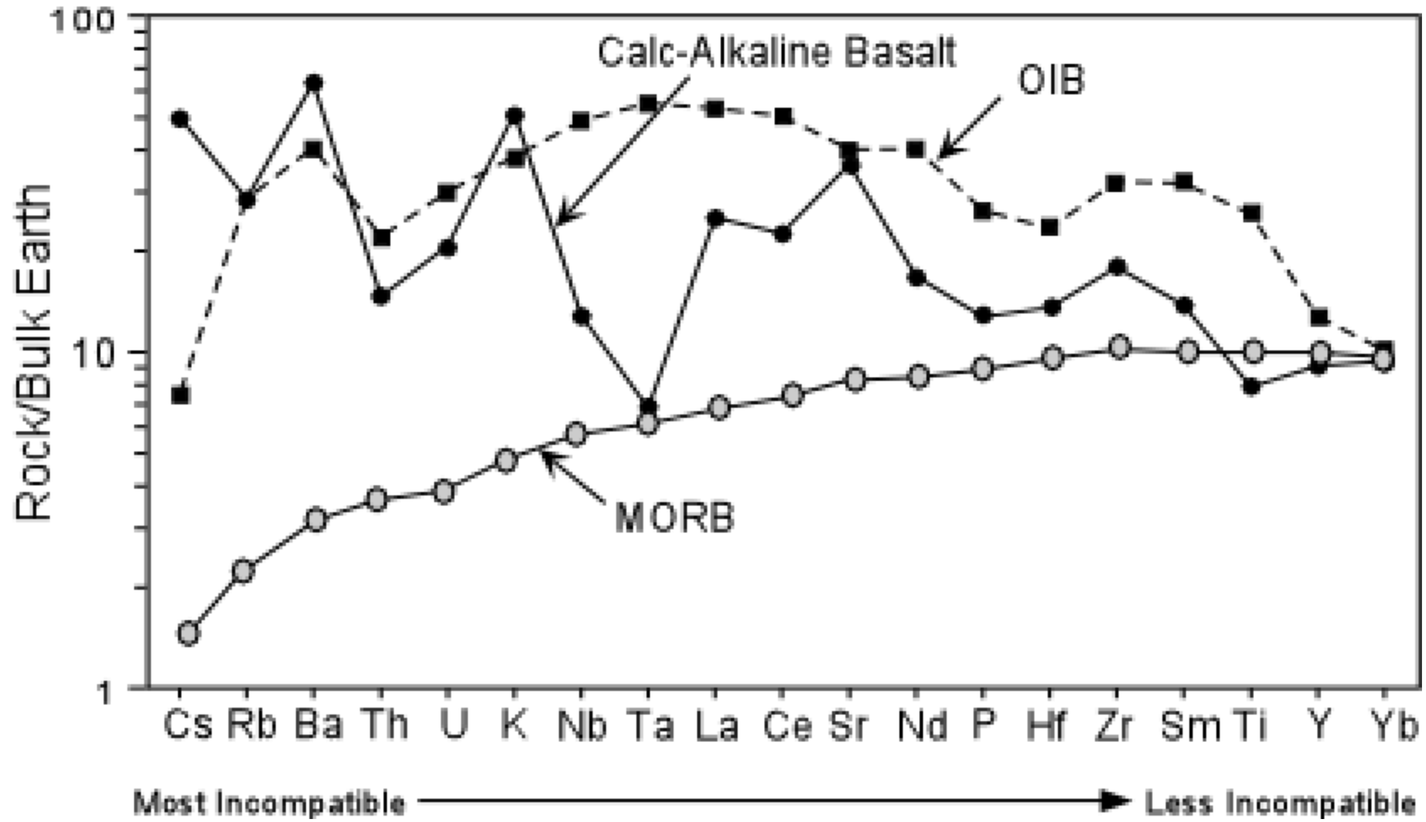
Garnet and Plagioclase effect on HREE

Partial melts of a source that contains garnet (lower right), plagioclase (lower left) and neither (upper left). What was the melt fraction F? (You should be able to work it out).







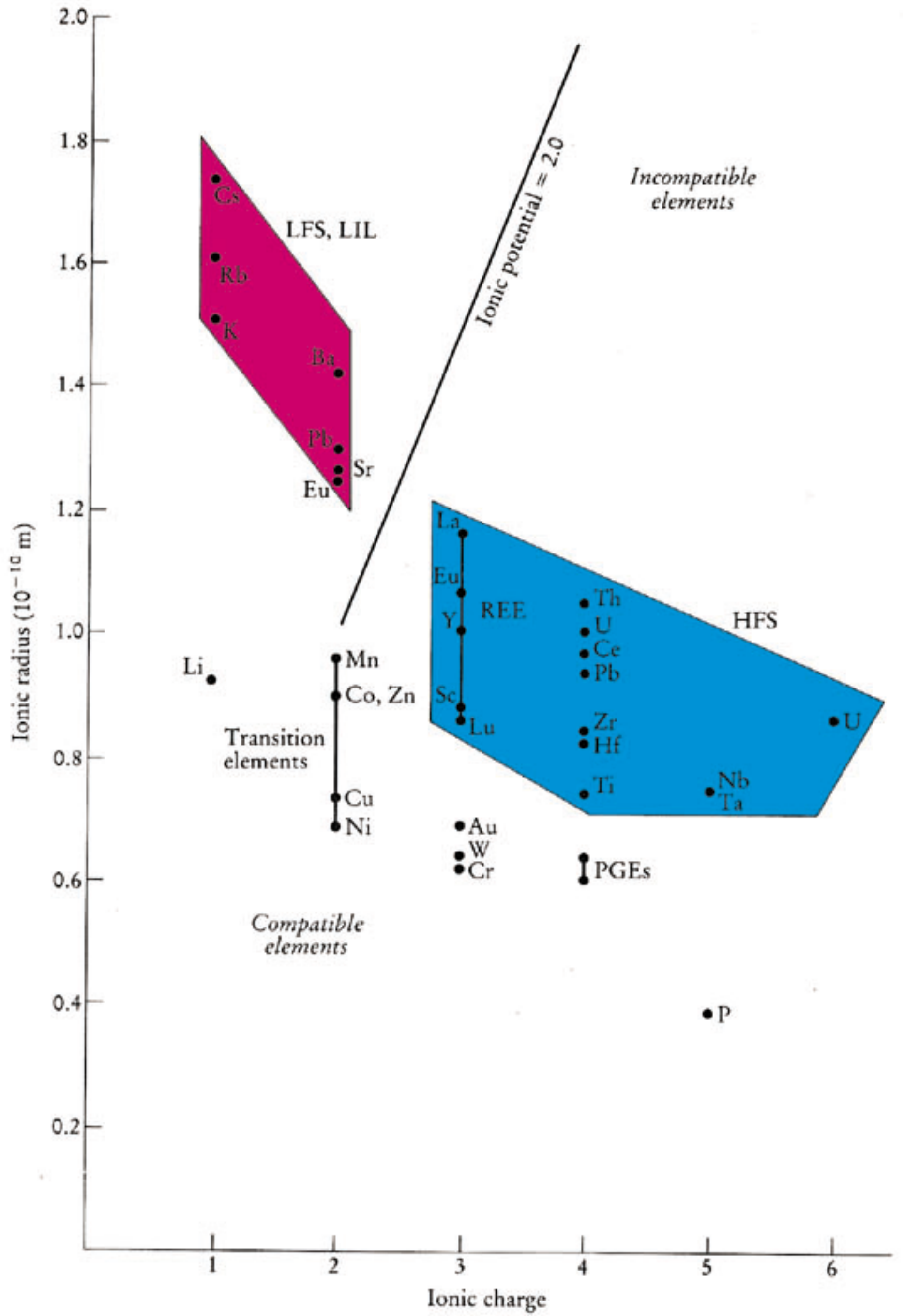


Same idea as a chondrite-normalized REE diagram

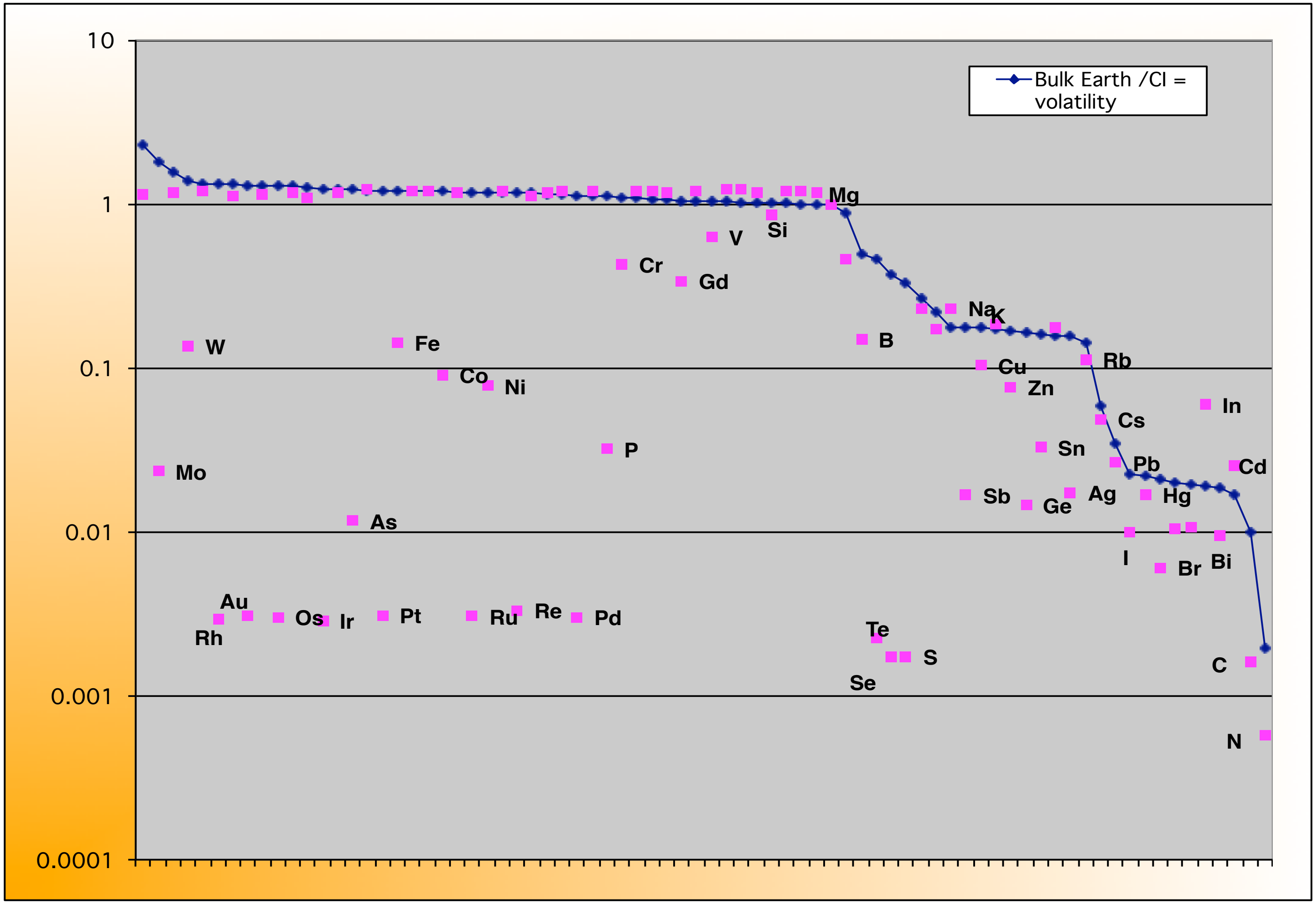
Order the elements to give a smooth, monotonic MORB pattern

For arc (calc-alkaline) basalt, notice depletion of Th, U, Nb, Ta, Ti relative to adjacent elements

- Incompatible elements commonly → two subgroups
  - Smaller, highly charged ***high field strength (HFS) elements*** (REE, Th, U, Ce, Pb^{4+}, Zr, Hf, Ti, Nb, Ta)
  - Low field strength ***large ion lithophile (LIL) elements*** (K, Rb, Cs, Ba, Pb^{2+}, Sr, Eu^{2+}) are more mobile, particularly if a fluid phase is involved



Core separation - chemical evidence (Source: Asimow lecture notes on the Web)



Relative to volatility trend, some elements are grossly depleted in silicate portion of the earth (factors of 10-200). What do these depleted elements have in common? These are the siderophile elements, partitioned into the core. Note – the most highly depleted elements are in chondritic relative proportions, which is unexpected if they are a small residue from core extraction.