

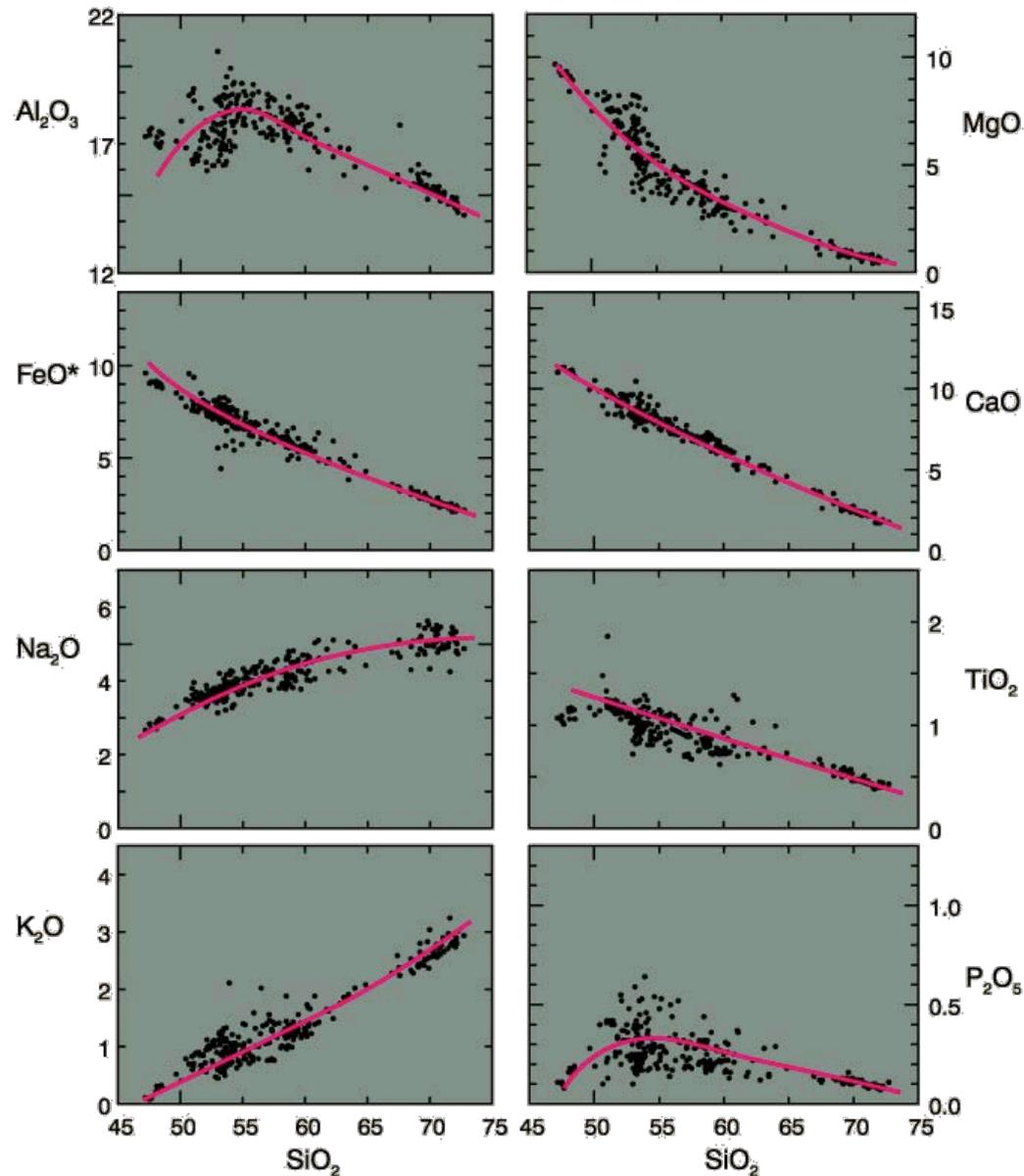
Chapter 9: Trace Elements

Don't *govern the appearance* of a phase,
but enter various phases by *substitution*

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
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changes

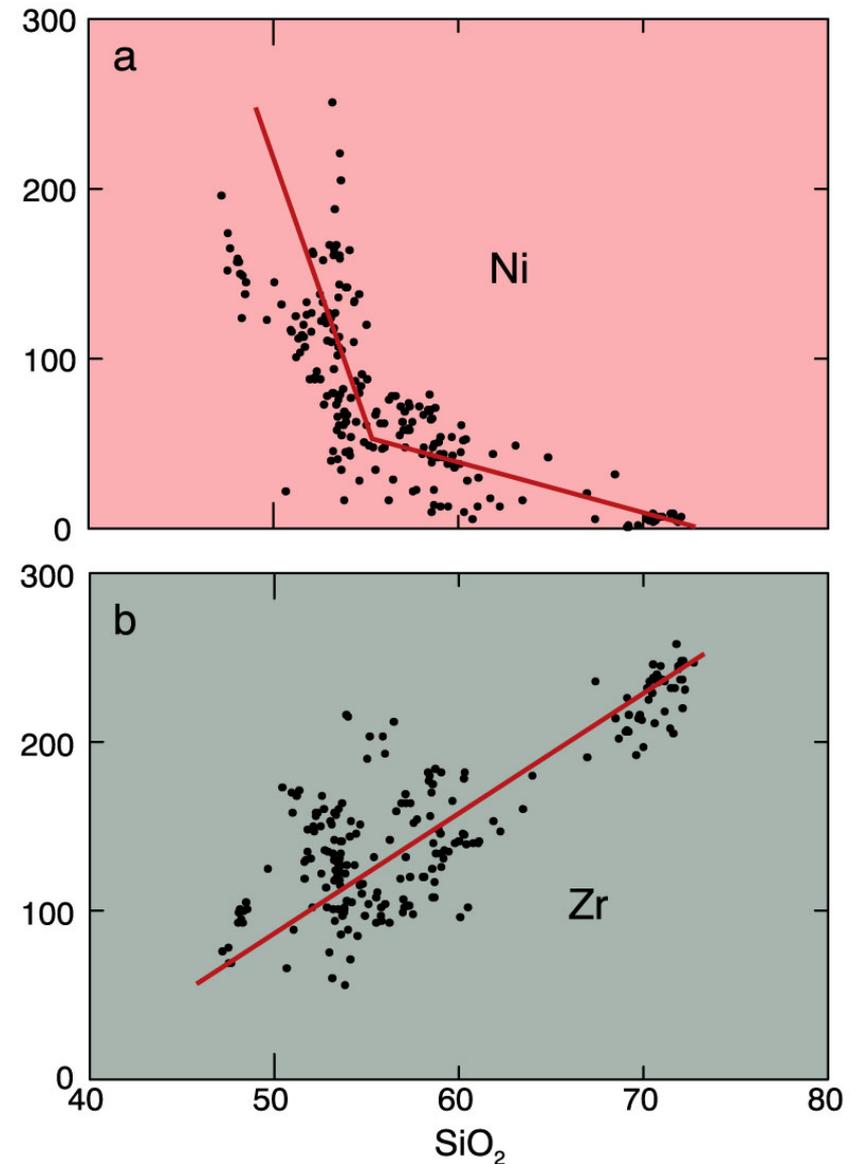


Figure 9.1. Harker Diagram for Crater Lake. From data compiled by Rick Conrey. From Winter (2001) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.

Element Distribution

Goldschmidt's rules – a reminder
(simplistic, but useful)

1. 2 ions with the same valence and radius should exchange easily and enter a solid solution in amounts equal to their overall proportions

How does Rb behave? Ni?

Rb follows K → Kspar, mica, & late melt

Ni follows Mg → olivine

1	1																18	
	1																	2
	1	2																10
	3	4																10
2	3	4																10
	5	6																10
	7	8																10
3	11	12																10
	13	14																10
	15	16																10
	17	18																10
4	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
5	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
	55	56	57	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
6	55	56	57	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
	87	88	89	104	105	106	107	108	109	110	111	112						
7	87	88	89	104	105	106	107	108	109	110	111	112						
	(223)	(226)	(227)	(261.1)	(262.1)	(263.1)	(262.1)	(265.1)	(266.1)	(269)	(272)	(277)						

Lanthanide Series	58	59	60	61	62	63	64	65	66	67	68	69	70	71
	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
	140.12	140.91	144.24	(144.9)	150.36	151.97	157.25	158.93	162.5	164.93	167.26	168.93	173.04	174.97
Actinide Series	90	91	92	93	94	95	96	97	98	99	100	101	102	103
	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
	232.04	231.04	238.03	(237)	(244.1)	(243.1)	(247.1)	(247.1)	(251.1)	(252.1)	(257.1)	(258.1)	(259.1)	

Group Legend

- Alkali Metal
- Alkali Earth
- Metal
- Trans. Met.
- Actinides
- Lanthanides
- Non-metal
- Halogen
- Noble Gas

Goldschmidt's rules

2. If 2 ions have a similar radius and the same valence: the smaller ion is preferentially incorporated into the solid over the liquid

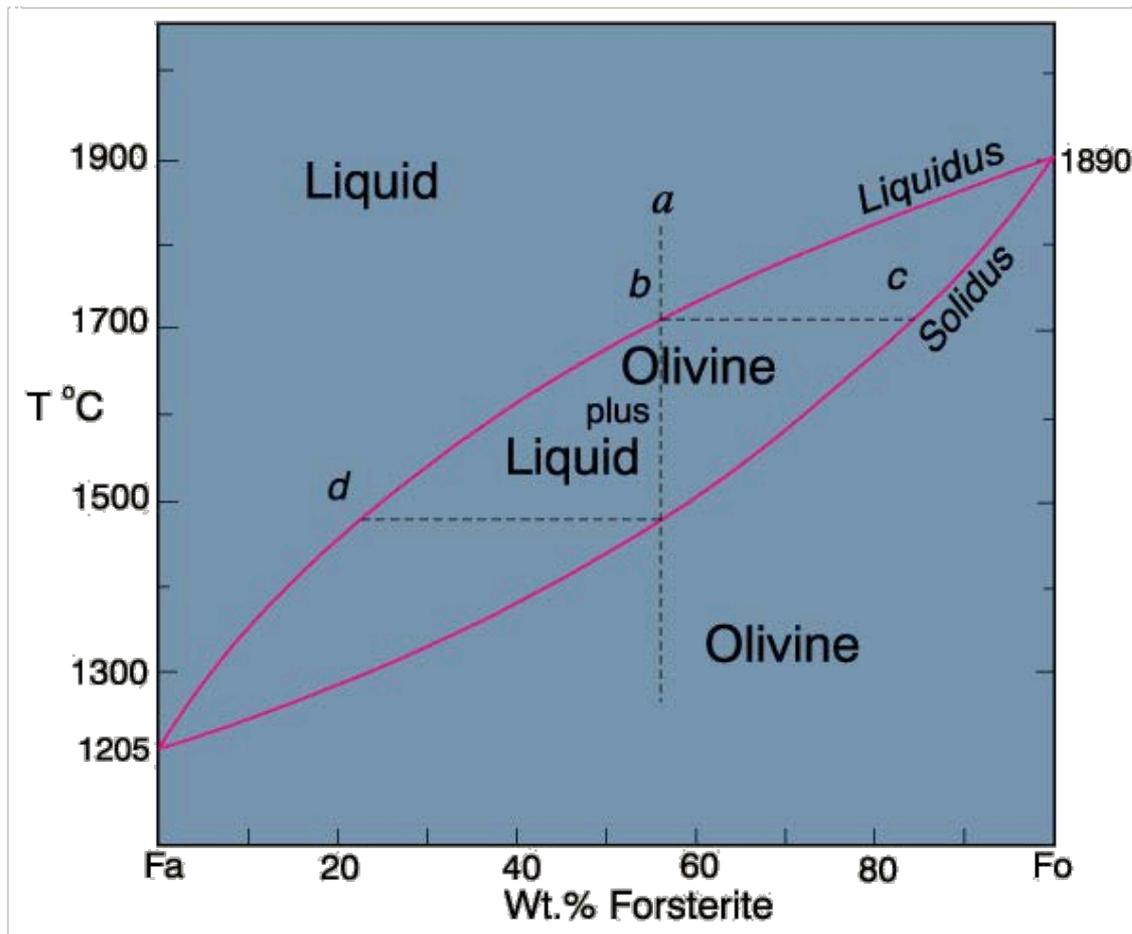


Fig. 6.10. Isobaric T-X phase diagram at atmospheric pressure After Bowen and Shairer (1932), Amer. J. Sci. 5th Ser., **24**, 177-213. From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

3. If 2 ions have a similar radius, but different valence: the ion with the higher charge is preferentially incorporated into the solid over the liquid

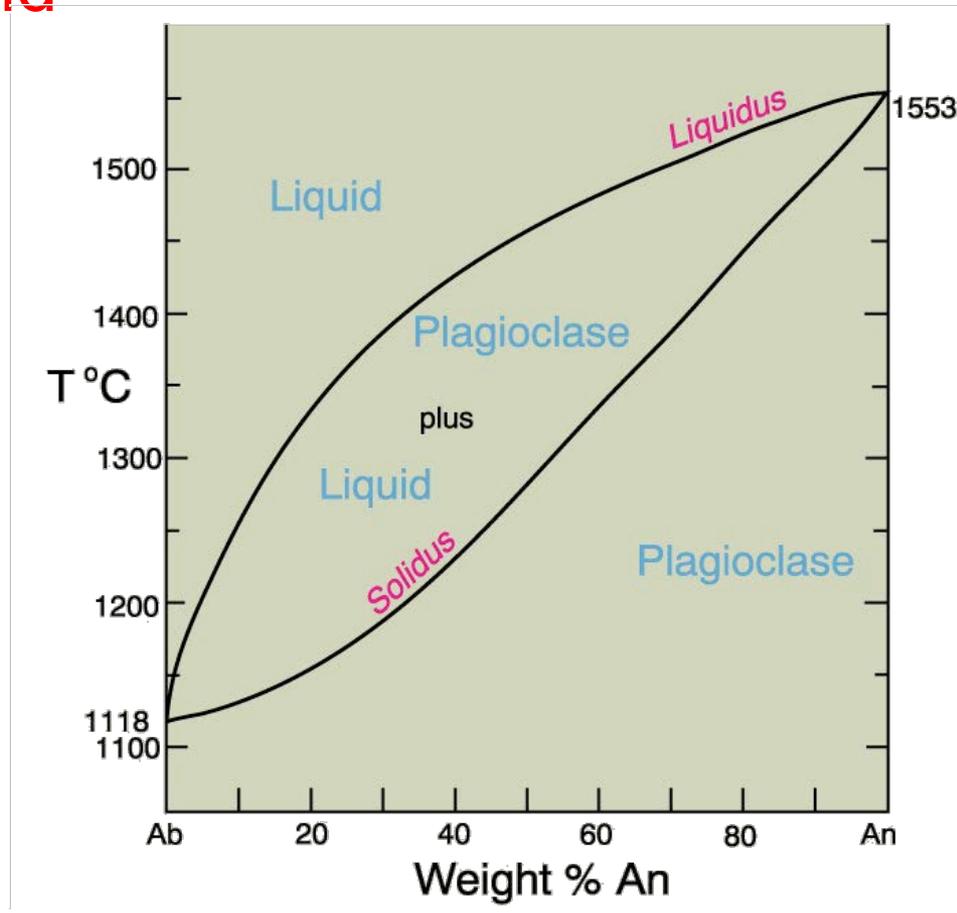


Fig. 6.8. Isobaric T-X phase diagram at atmospheric pressure. After Bowen (1913) Amer. J. Sci., 35, 577-599.

Chemical Fractionation

- The uneven distribution of an ion between two competing (equilibrium) phases

Exchange equilibrium of a *component* i between two *phases* (solid and liquid)

Reaction: $i_{(\text{liquid})} = i_{(\text{solid})}$

eq. 9.2
$$K = \frac{a_i^{\text{solid}}}{a_i^{\text{liquid}}} = \frac{\gamma_i X_i^{\text{solid}}}{\gamma_i X_i^{\text{liquid}}}$$

$K =$ *equilibrium constant*

- Trace element concentrations are in the Henry's Law region of concentration, so their activity varies in direct relation to their concentration in the system
- Thus if X_{Ni} in the system doubles the X_{Ni} in all phases will double
 - ◆ This does not mean that X_{Ni} in all phases is the same, since trace elements do fractionate. Rather the X_{Ni} within each phase will vary in proportion to the system concentration

- For dilute solutions can substitute D (partition coefficient) for K_D :

$$D = \frac{C_S}{C_L}$$

Where C_S = the concentration of some element in the solid phase

- ***incompatible*** elements are concentrated in the melt

$$(K_D \text{ or } D) \ll 1$$

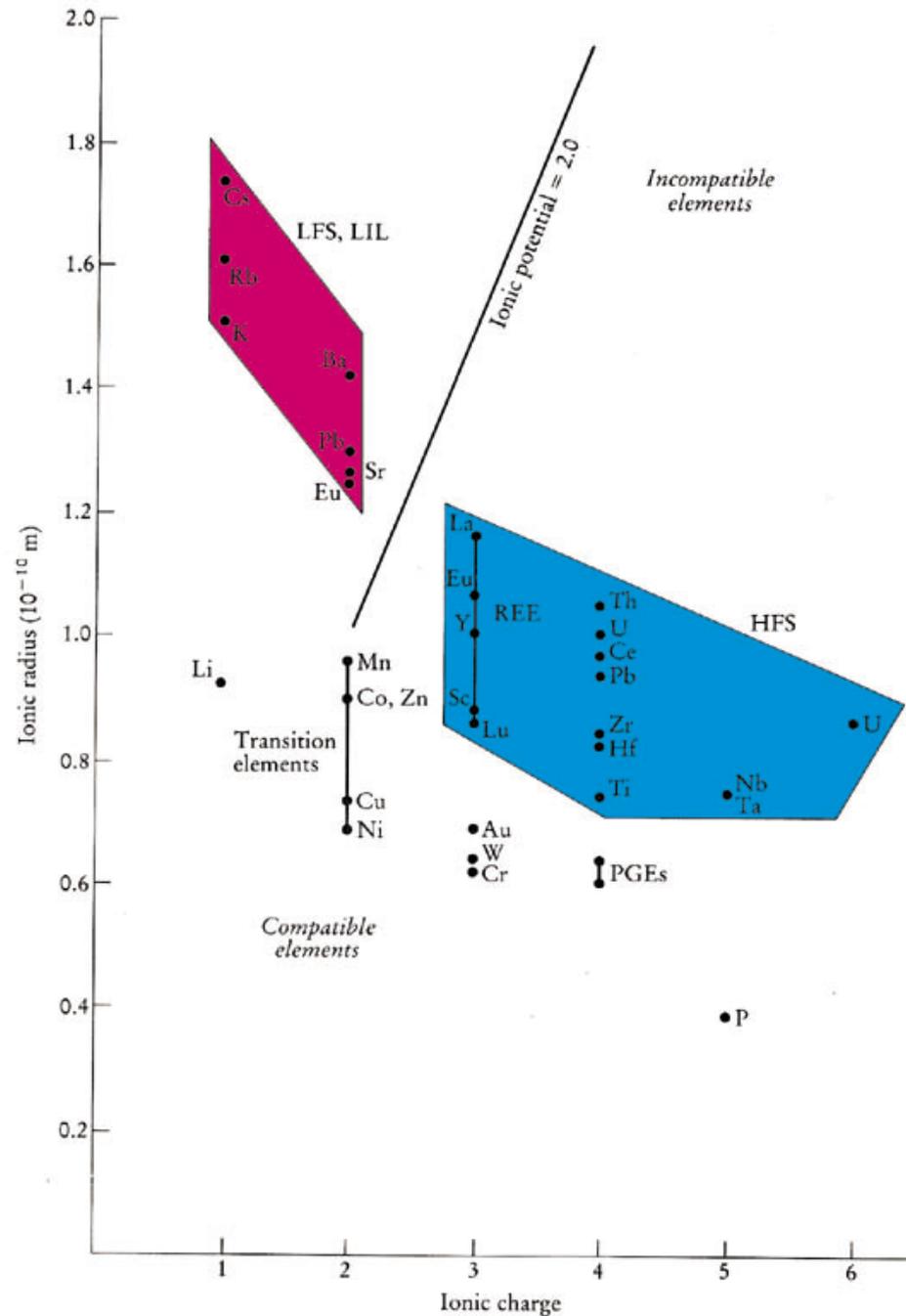
- ***compatible*** elements are concentrated in the solid

$$K_D \text{ or } D \gg 1$$

Commonly standardized to mantle compositions (olivine, pyroxenes, and perhaps garnet)

Thus the major elements Mg and Fe would usually be referred to as compatible, while K and Na as incompatible

- **Incompatible** elements commonly → two subgroups
 - ◆ Smaller, highly charged **high field strength (HFS) elements** (REE, Th, U, Ce, Pb⁴⁺, Zr, Hf, Ti, Nb, Ta)
 - ◆ Low field strength **large ion lithophile (LIL) elements** (K, Rb, Cs, Ba, Pb²⁺, Sr, Eu²⁺) are more mobile, particularly if a fluid phase is involved



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	0.010	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	<i>0.01</i>	6.8	29
Cr	0.70	10	34	1.345	<i>0.01</i>	2.00	7.4
La	0.007	<i>0.03</i>	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	0.1/1.5*	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).

* $\text{Eu}^{3+}/\text{Eu}^{2+}$ *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:
$$\bar{D}_i = \sum W_A D_{iA}$$

W_A = weight % of mineral A in the rock

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

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

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

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

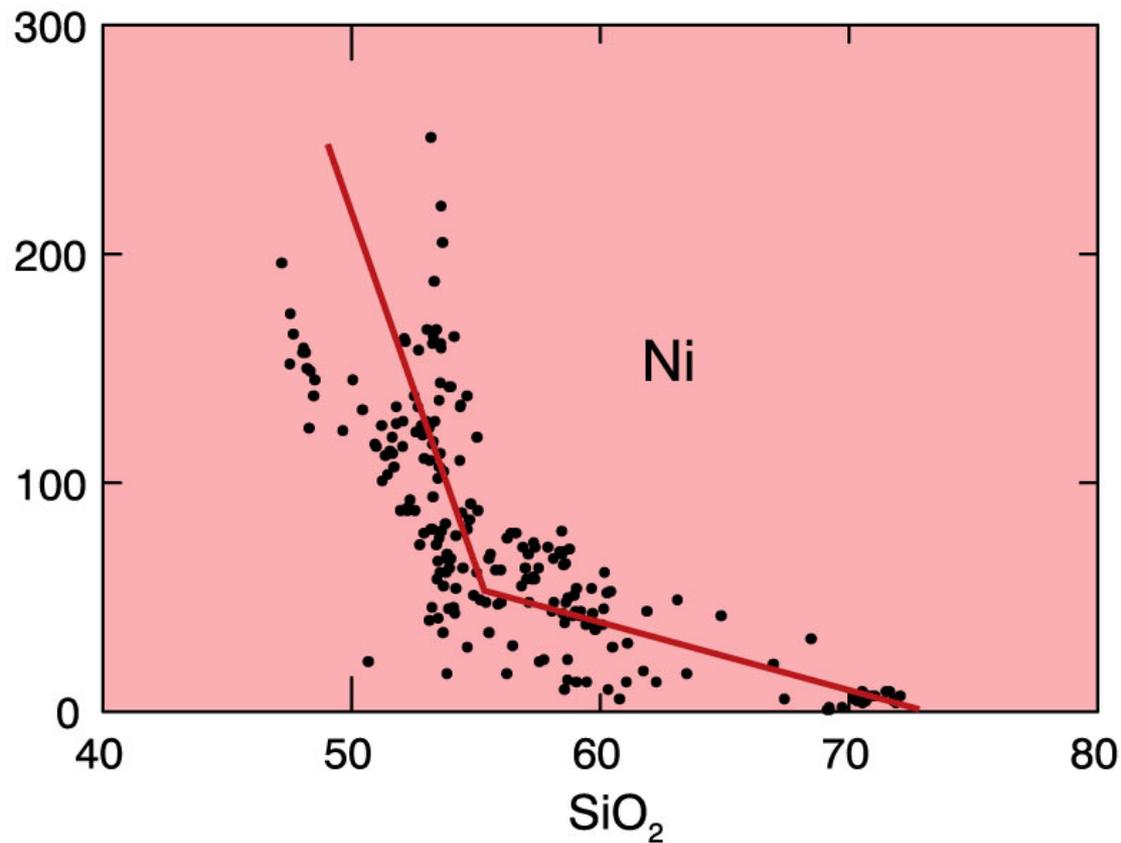


Figure 9.1a. Ni Harker Diagram for Crater Lake. From data compiled by Rick Conrey. From Winter (2001) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.

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

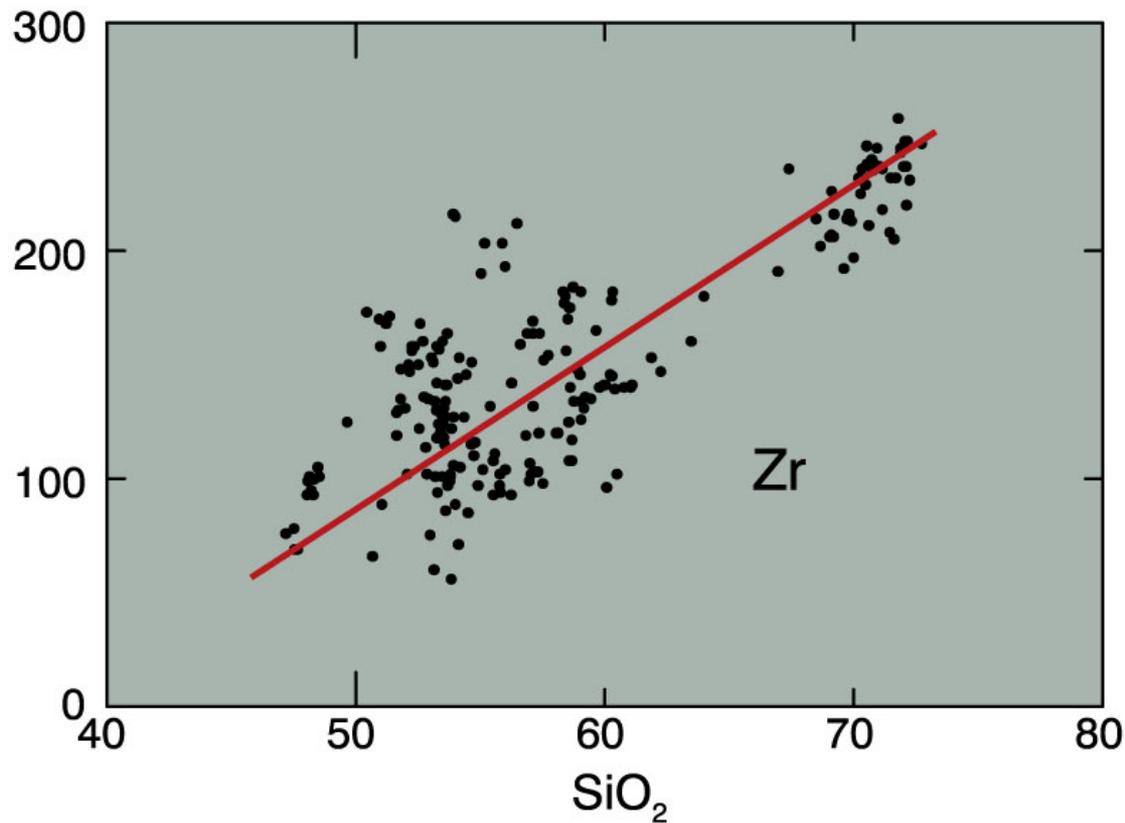
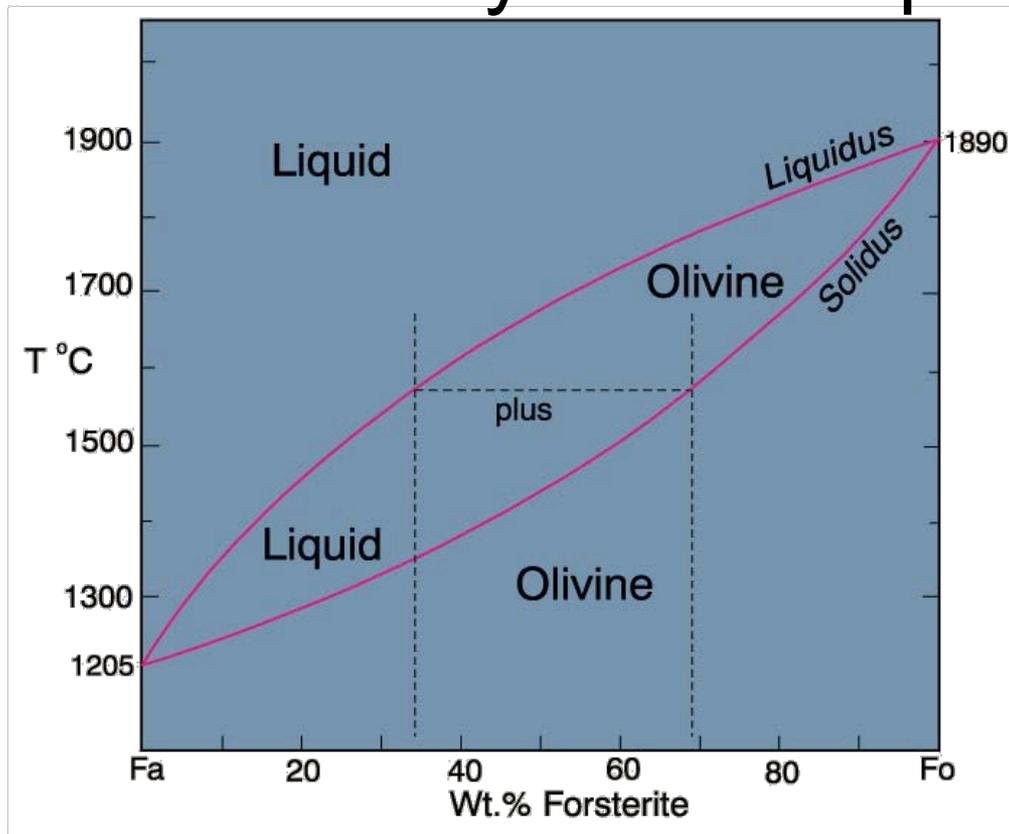


Figure 9.1b. Zr Harker Diagram for Crater Lake. From data compiled by Rick Conrey. From Winter (2001) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.

Trace Element Behavior

- The concentration of a **major** element in a phase is usually buffered by the system, so that it varies little in a phase as the system composition changes



At a given T we could vary X_{bulk} from 35 \rightarrow 70 % Mg/Fe without changing the composition of the melt or the olivine

Trace element concentrations are in the Henry's Law region of concentration, so their activity varies in direct relation to their concentration in the system

Thus if X_{Ni} in the system doubles the X_{Ni} in all phases will double

Because of this, the *ratios* of trace elements are often superior to the concentration of a single element in identifying the role of a specific mineral

- **K/Rb** often used → the importance of **amphibole** in a source rock
 - ◆ K & Rb behave very similarly, so **K/Rb should be ~ constant**
 - ◆ Amphibole has a D of about 1.0 for K and 0.3 for Rb
 - ◆ Other factors being equal, a magma produced by partial melting of an amphibole-bearing source rock would have a lower K/Rb than one derived from amphibole-free source

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

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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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Models of Magma Evolution

- ***Batch Melting***

- ◆ The melt remains in equilibrium with solid until at some point it is released and moves upward
- ◆ Equilibrium melting process with variable % melting

Models of Magma Evolution

- Batch Melting

$$\text{eq. 9.5 } \frac{C_L}{C_o} = \frac{1}{D_i(1-F)+F}$$

C_L = trace element concentration in the liquid

C_o = trace element concentration in the original rock before melting began

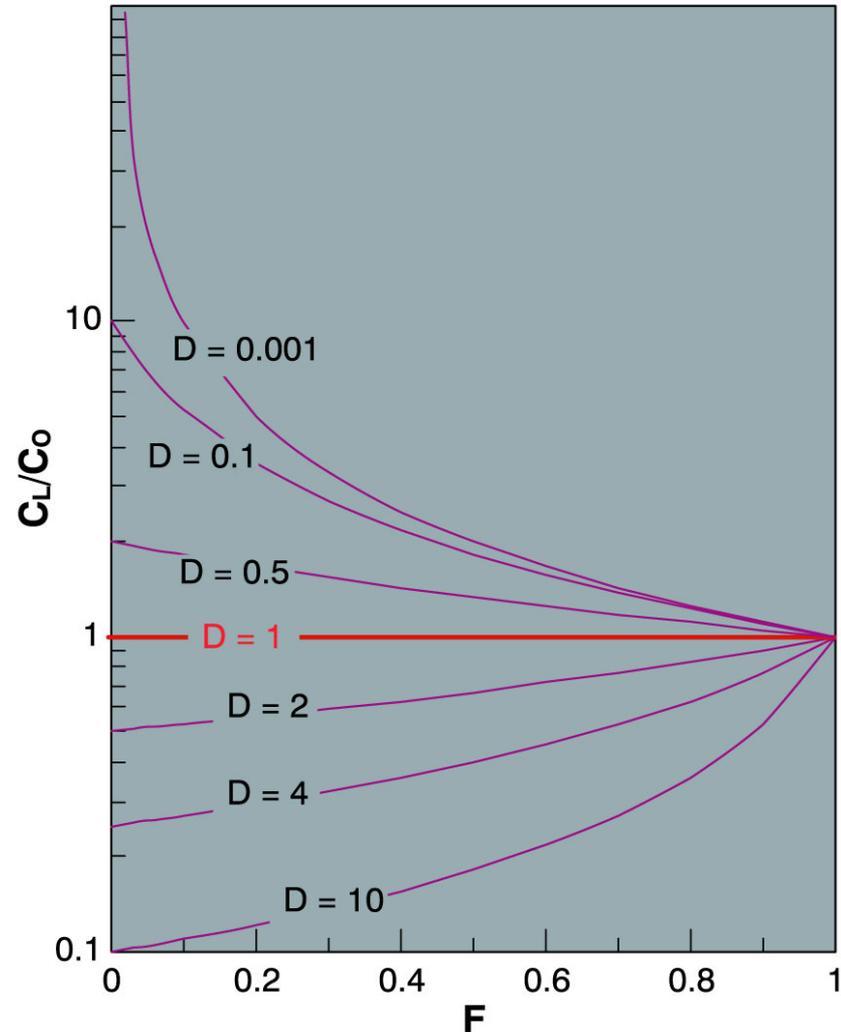
F = wt fraction of melt **produced** = melt/(melt + rock)

Batch Melting

A plot of C_L/C_O vs. F for various values of D_i using eq. 9.5

◆ $D_i = 1.0$

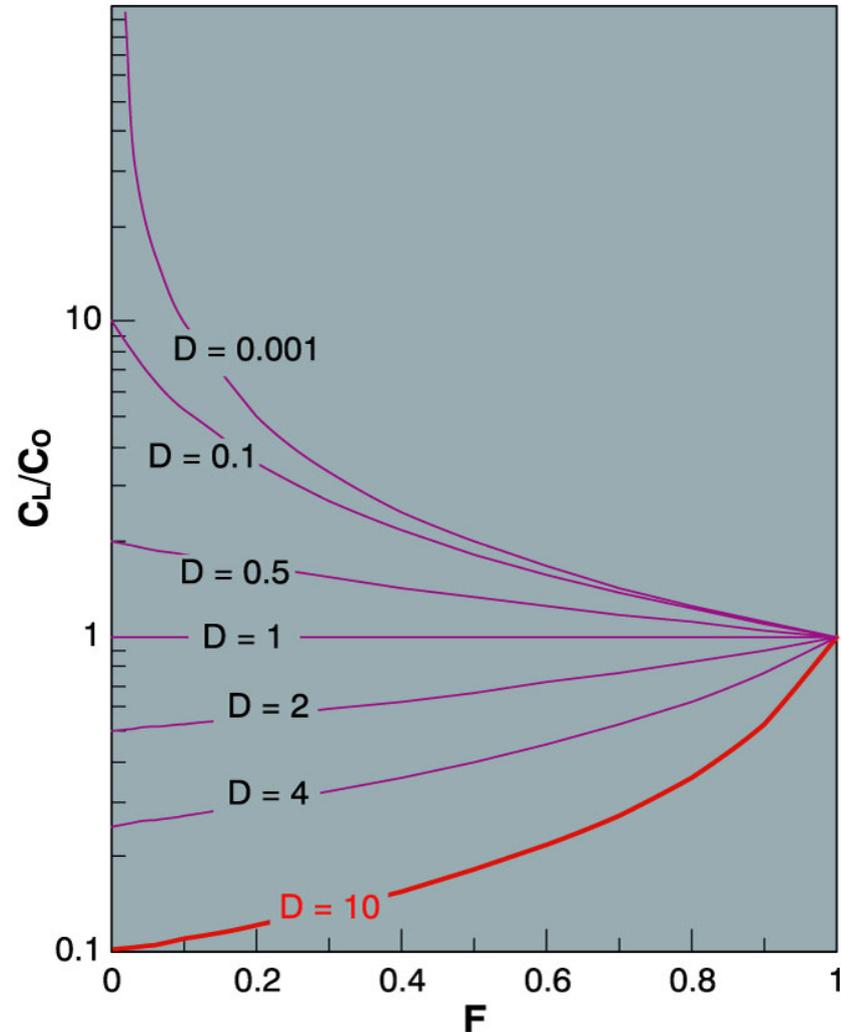
Figure 9.2. Variation in the relative concentration of a trace element in a liquid vs. source rock as a function of D and the fraction melted, using equation (9.5) for equilibrium batch melting. From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.



$D_i \gg 1.0$ (**compatible**
element)

- ◆ Very low concentration in melt
- ◆ Especially for low % melting (low F)

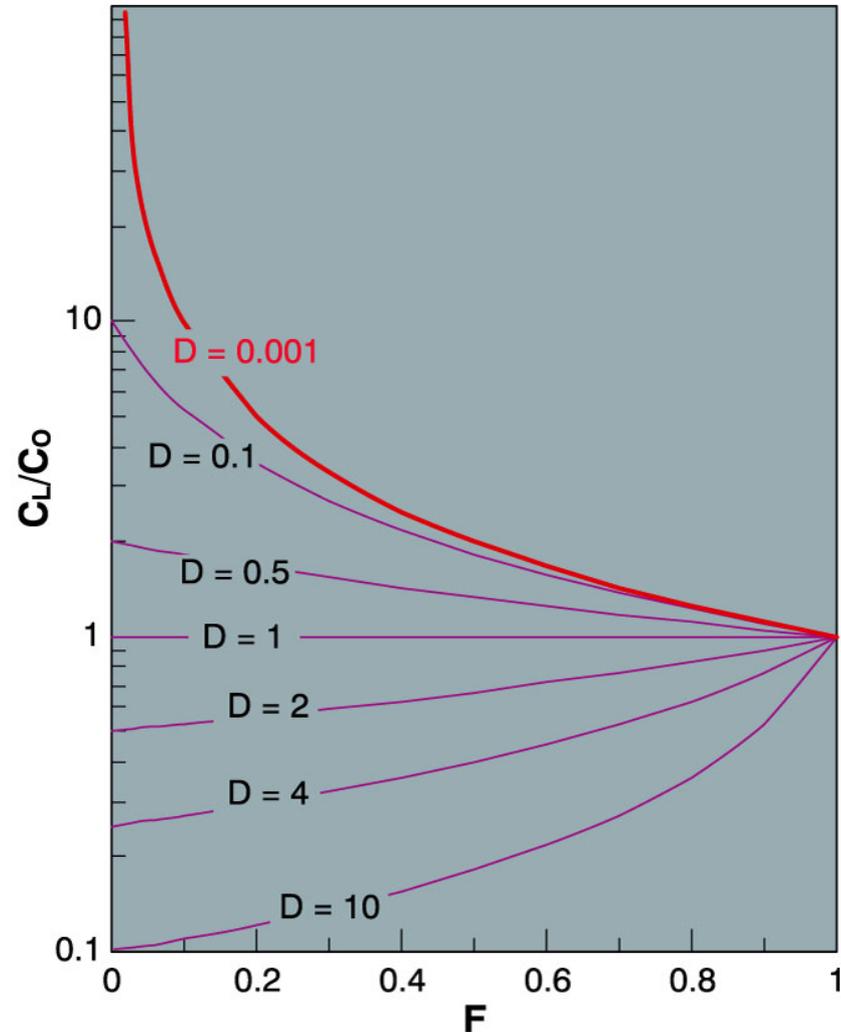
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Highly incompatible elements

- ◆ Greatly concentrated in the initial small fraction of melt produced by partial melting
- ◆ Subsequently diluted as F increases

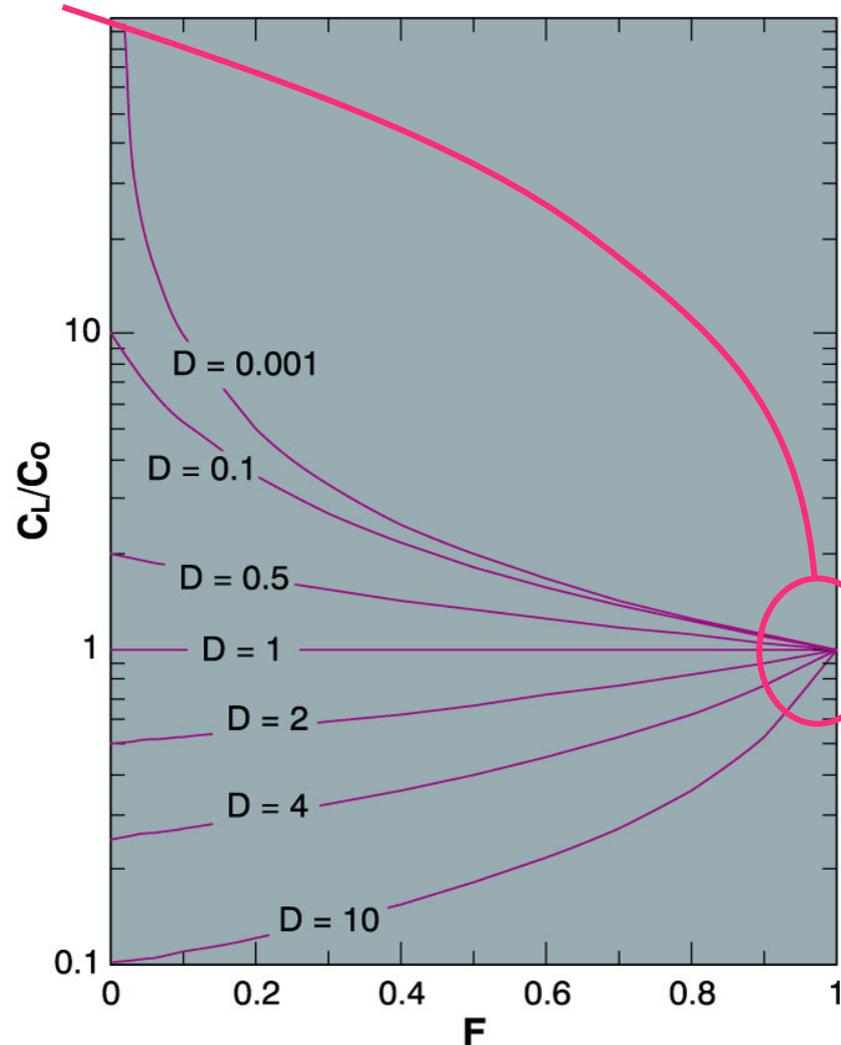
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- As $F \rightarrow 1$ the concentration of **every** trace element in the liquid = the source rock ($C_L / C_O \rightarrow 1$)

$$\frac{C_L}{C_O} = \frac{1}{\bar{D}_i(1-F) + F} \quad \text{As } F \rightarrow 1 \quad C_L/C_O \rightarrow 1$$

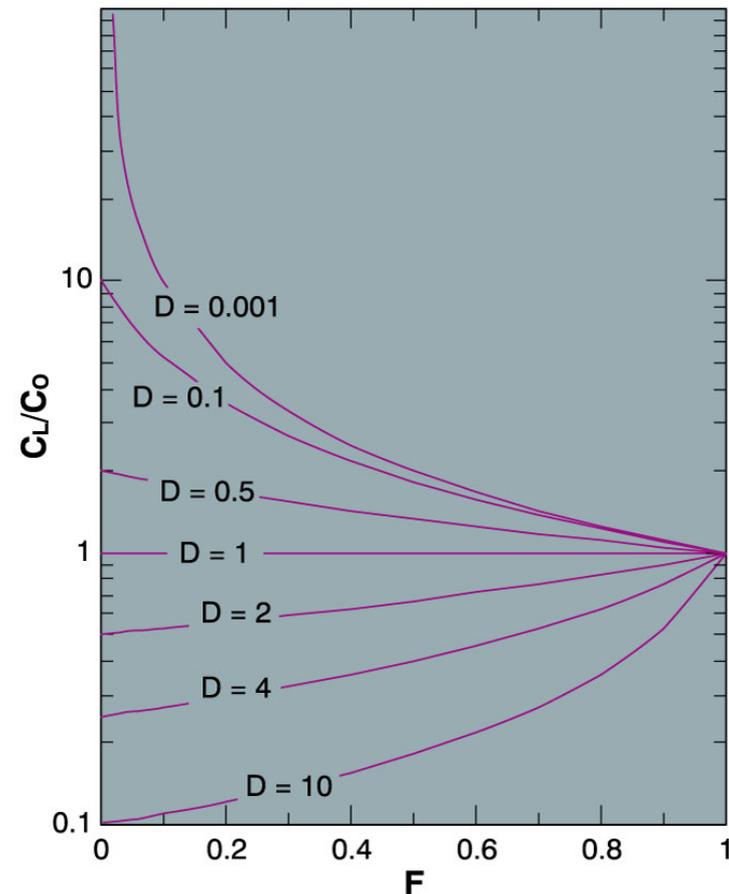
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As $F \rightarrow 0$ $C_L/C_O \rightarrow 1/\bar{D}_i$ $\frac{C_L}{C_O} = \frac{1}{\bar{D}_i(1-F)+F}$

If we know C_L of a magma derived by a small degree of batch melting, and we know D_i we can estimate the concentration of that element in the source region (C_O)

Figure 9.2. Variation in the relative concentration of a trace element in a liquid vs. source rock as a function of D and the fraction melted, using equation (9.5) for equilibrium batch melting. From Winter (2001) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.



- For very **incompatible** elements as $\bar{D}_i \rightarrow$

0

equation 9.5

$$\frac{C_L}{C_O} = \frac{1}{\bar{D}_i(1 - F) + F}$$

reduces to:

$$\frac{C_L}{C_O} = \frac{1}{F}$$

eq. 9.7

If we know the concentration of a very incompatible element in both a magma and the source rock, we can determine the fraction of partial melt produced

Other models are used to analyze

- Mixing of magmas
- Wall-rock assimilation
- Zone refining
- Combinations of processes

The Rare Earth Elements (REE)

PERIODIC TABLE OF THE ELEMENTS

PERIOD	Metals										Non-Metals																										
	GROUP 1 IA	GROUP 2 IIA		TRANSITION METALS										GROUP 13 IIIA	GROUP 14 IVA	GROUP 15 VA	GROUP 16 VIA	GROUP 17 VIIA	GROUP 18 VIIIA																		
1	1.01 H H ⁺ 0.46 Hydrogen																																				
2	6.94 Li Li ⁺ 0.68 Lithium	9.01 Be Be ²⁺ 0.25 Beryllium											10.81 B B ³⁺ 0.10 Boron	12.01 C C ⁰ 0.77 Carbon	14.01 N N ³⁺ 0.16 Nitrogen	16.00 O O ²⁻ 1.30 Oxygen	19.00 F F ⁻ 1.23 Fluorine	20.18 Ne Neon																			
3	22.99 Na Na ⁺ 1.24 Sodium	24.305 Mg Mg ²⁺ 0.80 Magnesium											26.98 Al Al ³⁺ 0.61 Aluminum	28.09 Si Si ⁴⁺ 0.34 Silicon	30.97 P P ⁵⁺ 0.55 Phosphorus	32.065 S S ⁶⁺ 0.37 Sulfur	35.45 Cl Cl ⁻ 1.72 Chlorine	39.95 Ar Argon																			
4	39.10 K K ⁺ 1.68 Potassium	40.08 Ca Ca ²⁺ 1.20 Calcium	44.96 Sc Sc ³⁺ 0.83 Scandium	47.87 Ti Ti ⁴⁺ 0.69 Titanium	50.94 V V ³⁺ 0.72 Vanadium	52.00 Cr Cr ³⁺ 0.70 Chromium	54.94 Mn Mn ²⁺ 0.80 Manganese	55.845 Fe Fe ²⁺ 0.74 Fe ³⁺ 0.64 Iron	58.93 Co Co ³⁺ 0.72 Cobalt	58.93 Ni Ni ²⁺ 0.77 Nickel	63.546 Cu Cu ²⁺ 0.81 Copper	65.39 Zn Zn ²⁺ 0.83 Zinc	69.72 Ga Ga ³⁺ 0.70 Gallium	72.64 Ge Ge ⁴⁺ 0.62 Germanium	74.92 As As ⁵⁺ 0.58 Arsenic	78.96 Se Se ⁶⁺ 0.37 Selenium	79.90 Br Br ⁻ 1.88 Bromine	83.80 Kr Krypton																			
5	85.47 Rb Rb ⁺ 1.81 Rubidium	87.62 Sr Sr ²⁺ 1.33 Strontium	88.91 Y Y ³⁺ 0.98 Yttrium	91.22 Zr Zr ⁴⁺ 0.80 Zirconium	92.91 Nb Nb ⁵⁺ 0.72 Niobium	95.94 Mo Mo ⁶⁺ 0.80 Molybdenum	(98) Tc Tc ⁴⁺ 0.72 Technetium	101.07 Ru Ru ⁴⁺ 0.70 Ruthenium	102.91 Rh Rh ³⁺ 0.75 Rhodium	106.42 Pd Pd ²⁺ 0.80 Palladium	107.87 Ag Ag ⁺ 1.26 Silver	112.41 Cd Cd ²⁺ 0.97 Cadmium	114.82 In In ³⁺ 1.00 Indium	118.71 Sn Sn ⁴⁺ 0.77 Tin	121.76 Sb Sb ⁵⁺ 0.69 Antimony	127.60 Te Te ⁶⁺ 0.60 Tellurium	126.90 I I ⁻ 1.97 Iodine	131.29 Xe Xenon																			
6	132.91 Cs Cs ⁺ 1.96 Cesium	137.33 Ba Ba ²⁺ 1.50 Barium	67-71 La-Lu Lanthanide	178.49 Hf Hf ⁴⁺ 0.79 Hafnium	180.95 Ta Ta ⁵⁺ 0.72 Tantalum	183.84 W W ⁶⁺ 0.68 Tungsten	186.21 Re Re ⁴⁺ 0.71 Rhenium	190.23 Os Os ⁴⁺ 0.71 Osmium	192.22 Ir Ir ⁴⁺ 0.71 Iridium	195.08 Pt Pt ²⁺ 0.80 Platinum	196.97 Au Au ³⁺ 0.78 Gold	200.59 Hg Hg ²⁺ 1.10 Mercury	204.38 Tl Tl ³⁺ 1.08 Thallium	207.2 Pb Pb ²⁺ 1.57 Lead	208.98 Bi Bi ³⁺ 1.19 Bismuth	(209) Po Po ⁴⁺ 1.16 Polonium	(210) At Astatane	(222) Rn Radon																			
7	(223) Fr Francium	(226) Ra Ra ²⁺ 1.56 Radium	89-103 Ac-Lr Actinide																																		
																			Halogens		Noble Gases																
																			Alkali Metals				Alkaline Earth Metals														
																			Lanthanide series											Eu ²⁺ is LIL Eu ³⁺ is HFS							
																			57 138.91 La La ³⁺ 1.25 Lanthanum	58 140.12 Ce Ce ³⁺ 1.22 Cerium	59 140.91 Pr Pr ³⁺ 1.22 Praseodymium	60 144.24 Nd Nd ³⁺ 1.20 Neodymium	(145) Pm Promethium	62 150.36 Sm Sm ³⁺ 1.17 Samarium	63 151.96 Eu Eu ³⁺ 1.15 Europium	64 157.25 Gd Gd ³⁺ 1.14 Gadolinium	65 158.93 Tb Tb ³⁺ 1.12 Terbium	66 162.50 Dy Dy ³⁺ 1.11 Dysprosium	67 164.93 Ho Ho ³⁺ 1.10 Holmium	68 167.26 Er Er ³⁺ 1.08 Erbium	69 168.93 Tm Tm ³⁺ 1.07 Thulium	70 173.04 Yb Yb ³⁺ 1.06 Ytterbium	71 174.97 Lu Lu ³⁺ 1.05 Lutetium				
																			Actinide series																		
																			89 (227) Ac Ac ³⁺ 1.18 Actinium	90 232.04 Th Th ⁴⁺ 1.12 Thorium	91 231.04 Pa Pa ³⁺ 1.09 Protactinium	92 238.03 U U ⁴⁺ 1.08 Uranium	(237) Np Neptunium	(244) Pu Plutonium	(243) Am Americium	(247) Cm Curium	(247) Bk Berkelium	(251) Cf Californium	(252) Es Einsteinium	(257) Fm Fermium	(258) Md Mendelevium	(259) No Nobelium	(262) Lr Lawrencium				

Contrasts and similarities in the D values: All are incompatible

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	<i>14.0</i>	5.0	<i>7.0</i>	0.955	<i>0.01</i>	6.8	29.
Cr	0.7	10.0	34.0	1.345	<i>0.01</i>	2.0	7.4
La	0.007	<i>0.03</i>	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).

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

Also Note:

HREE are less
incompatible

Especially in
garnet

Eu can $\rightarrow 2+$
which conc.
in *plagioclase*

REE Diagrams

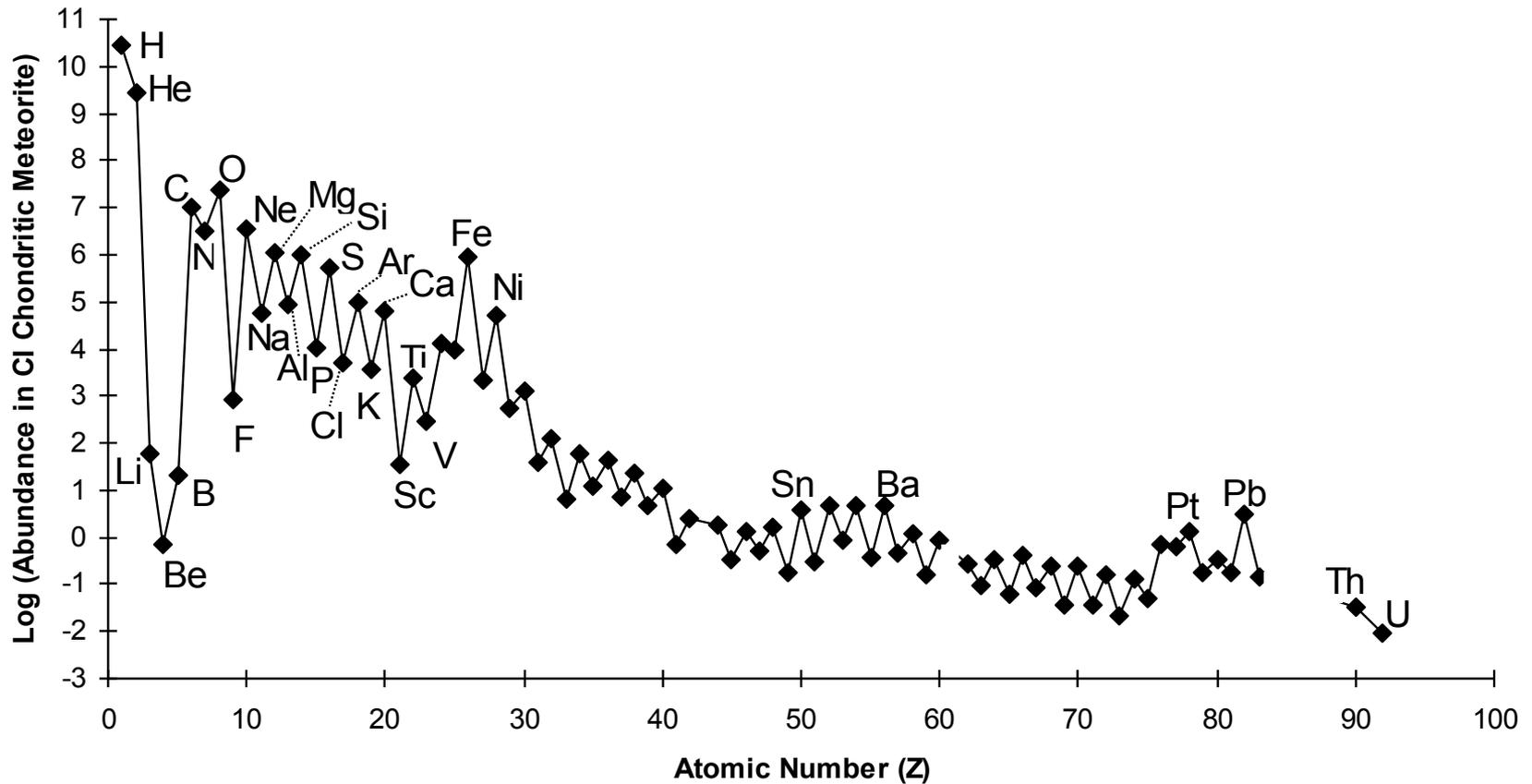
Plots of concentration as the ordinate (y-axis) against increasing atomic number

- ◆ Degree of compatibility increases from left to right across the diagram (“lanthanide contraction”)

Ac-Lr Actinide	Lanthanide series														Halogen	Noble Gas
	Eu ²⁺ is LIL Eu ³⁺ is HFS															
6	57 138.91 La Lanthanum	58 140.12 Ce Cerium	59 140.91 Pr Praseodymium	60 144.24 Nd Neodymium	61 (145) Pm Promethium	62 150.36 Sm Samarium	63 151.96 Eu Europium	64 157.25 Gd Gadolinium	65 158.93 Tb Terbium	66 162.50 Dy Dysprosium	67 164.93 Ho Holmium	68 167.26 Er Erbium	69 168.93 Tm Thulium	70 173.04 Yb Ytterbium	71 174.97 Lu Lutetium	
	La ³⁺ 1.25	Ce ³⁺ 1.22	Pr ³⁺ 1.22	Nd ³⁺ 1.20		Sm ³⁺ 1.17	Eu ³⁺ 1.15	Gd ³⁺ 1.14	Tb ³⁺ 1.12	Dy ³⁺ 1.11	Ho ³⁺ 1.10	Er ³⁺ 1.08	Tm ³⁺ 1.07	Yb ³⁺ 1.06	Lu ³⁺ 1.05	

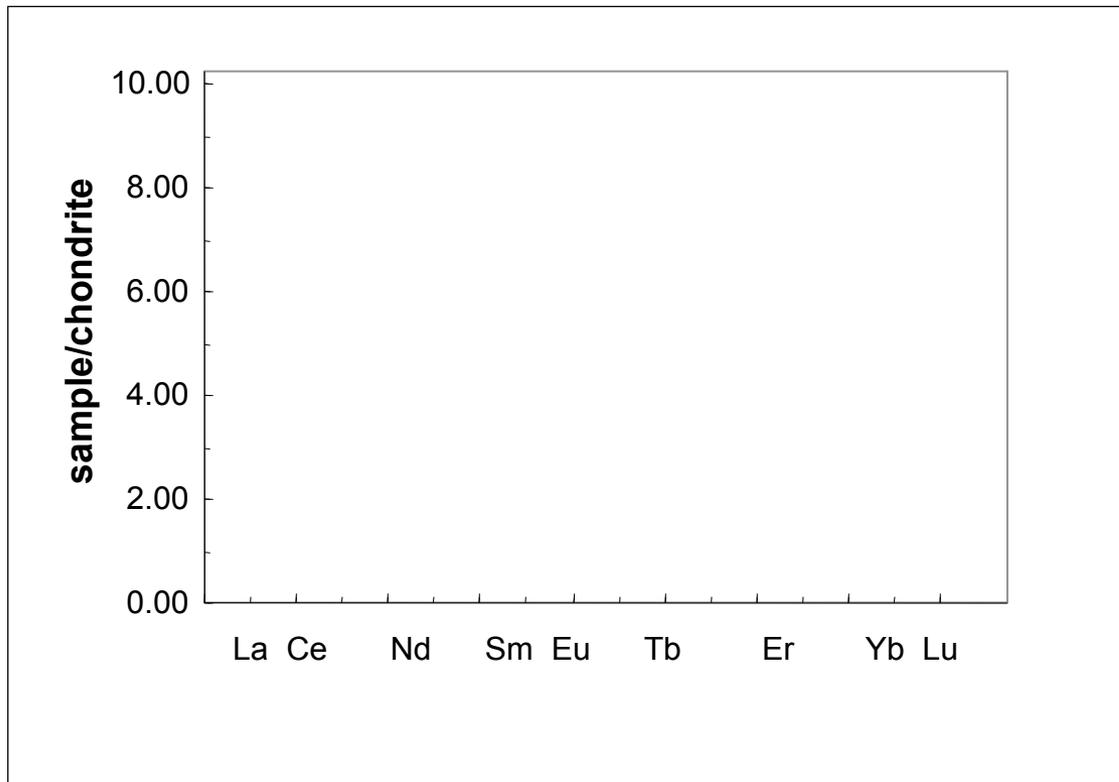
Concentration ↑

La Ce Nd Sm Eu Tb Er Dy Yb Lu



- ◆ Eliminate Oddo-Harkins effect and make y-scale more functional by normalizing to a standard
 - ▲ estimates of primordial mantle REE
 - ▲ chondrite meteorite concentrations

Divide each element in analysis by the concentration in a chondrite standard



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

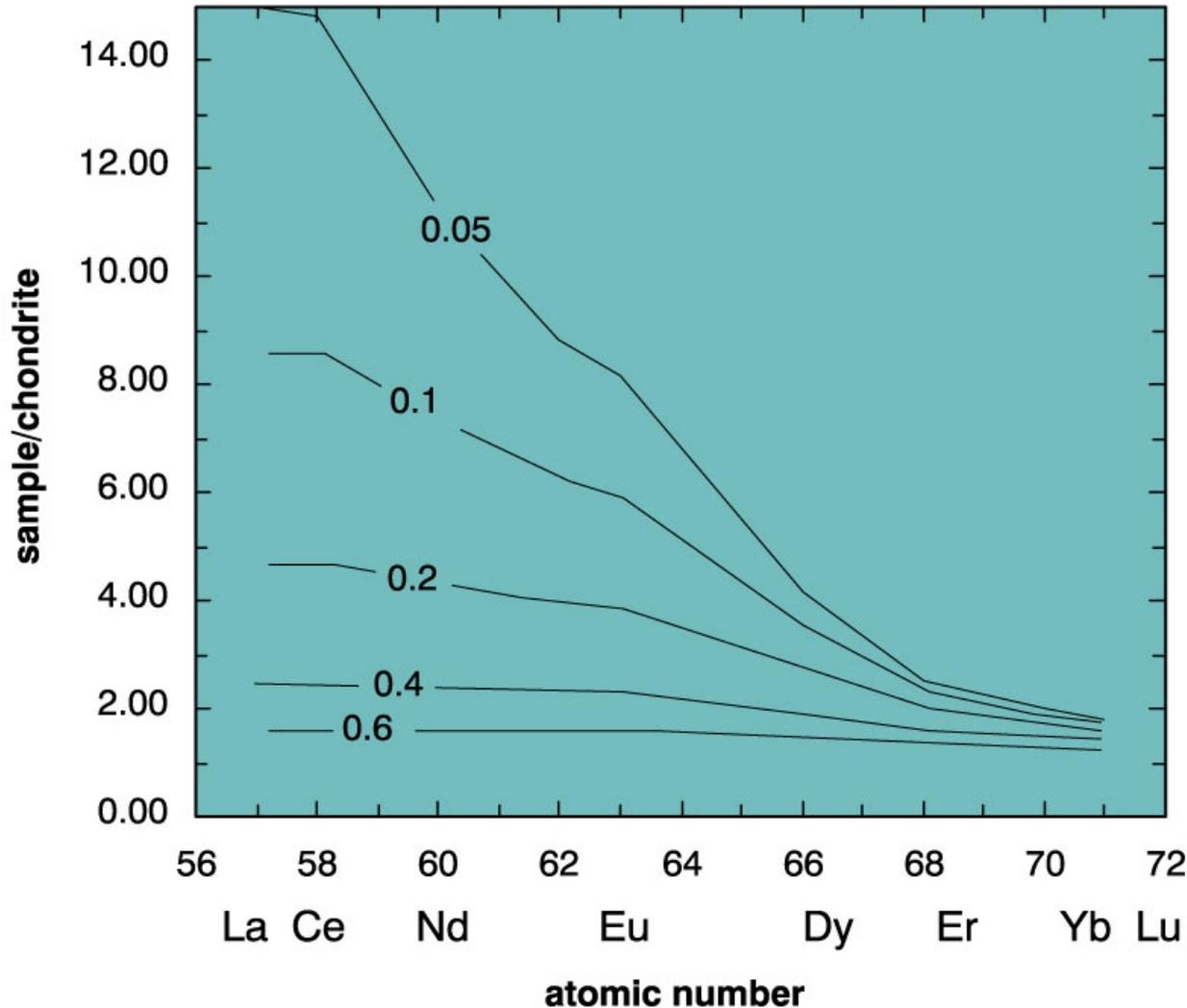


Figure 9.4. Rare Earth concentrations (normalized to chondrite) for melts produced at various values of F via melting of a hypothetical garnet lherzolite using the batch melting model (equation 9.5). From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

- **Europium anomaly** when plagioclase is
 - ◆ a fractionating phenocryst
 - or
 - ◆ a residual solid in source

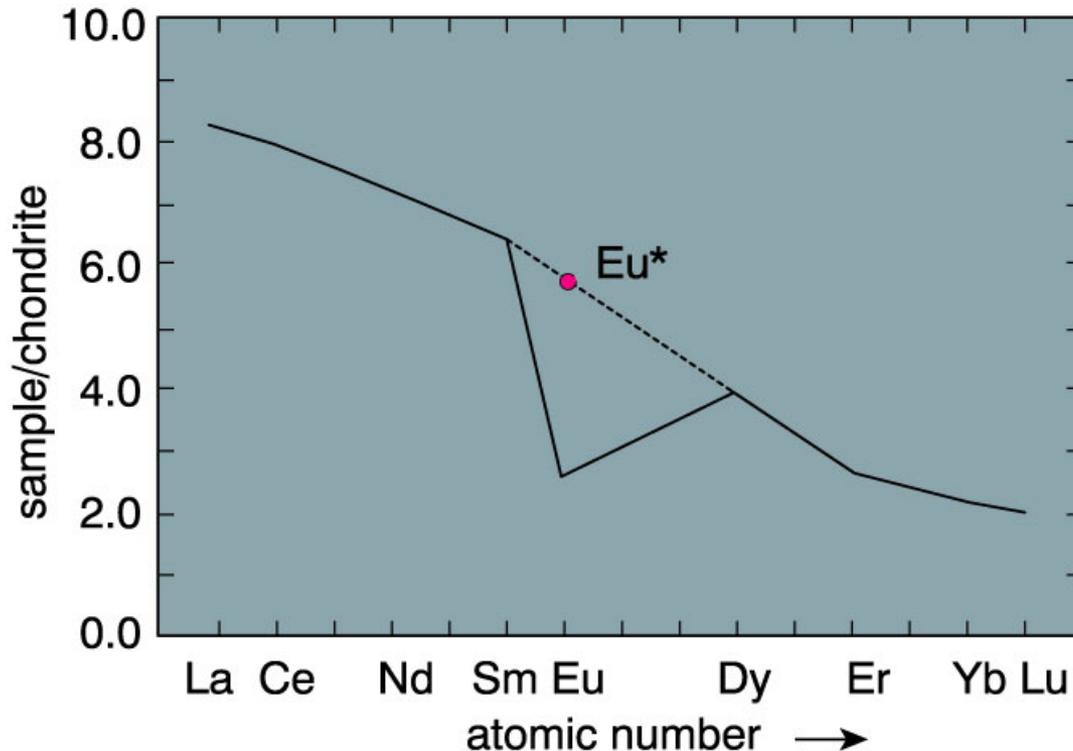


Figure 9.5. REE diagram for 10% batch melting of a hypothetical lherzolite with 20% plagioclase, resulting in a pronounced negative Europium anomaly. From Winter (2001) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.

Normalized Multielement (Spider) Diagrams

An extension of the normalized REE technique to a broader spectrum of elements

Chondrite-normalized spider diagrams are commonly organized by (the author's estimate) of increasing incompatibility $L \leftarrow R$

Different estimates \rightarrow different ordering (poor standardization)

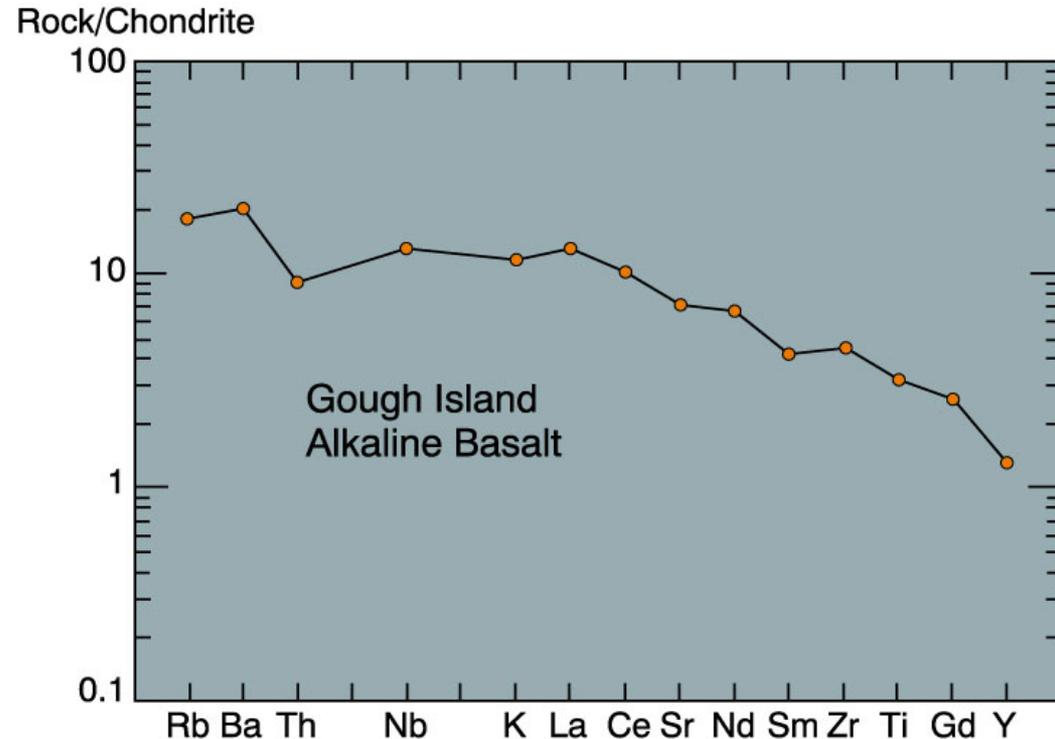


Fig. 9.6. Spider diagram for an alkaline basalt from Gough Island, southern Atlantic. After Sun and MacDonough (1989). In A. D. Saunders and M. J. Norry (eds.), *Magmatism in the Ocean Basins*. Geol. Soc. London Spec. Publ., **42**. pp. 313-345.

MORB-normalized Spider

Separates LIL and HFS

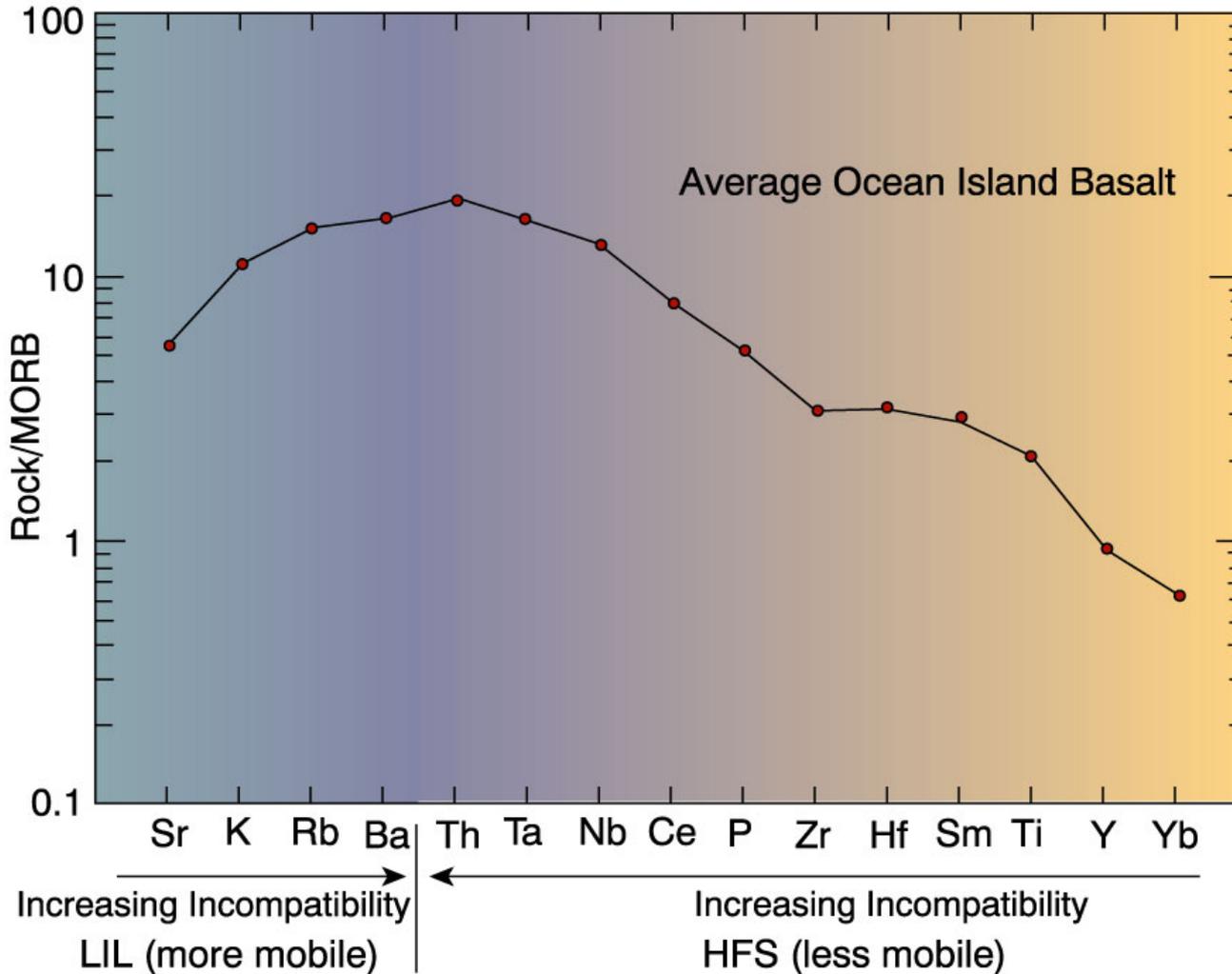
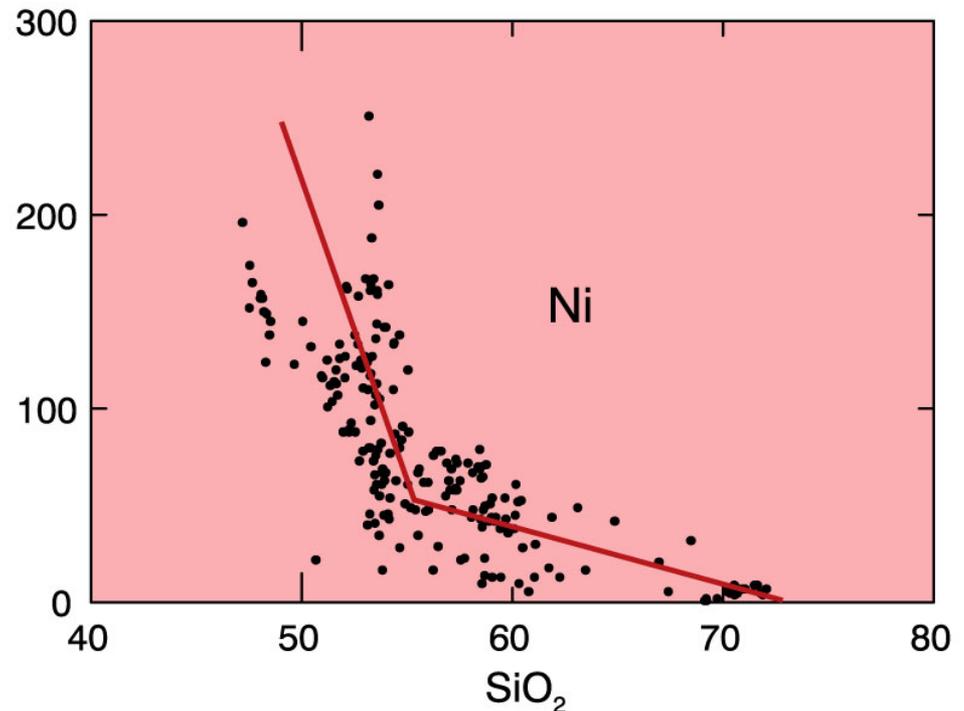


Figure 9.7. Ocean island basalt plotted on a mid-ocean ridge basalt (MORB) normalized spider diagram of the type used by Pearce (1983). Data from Sun and McDonough (1989). From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

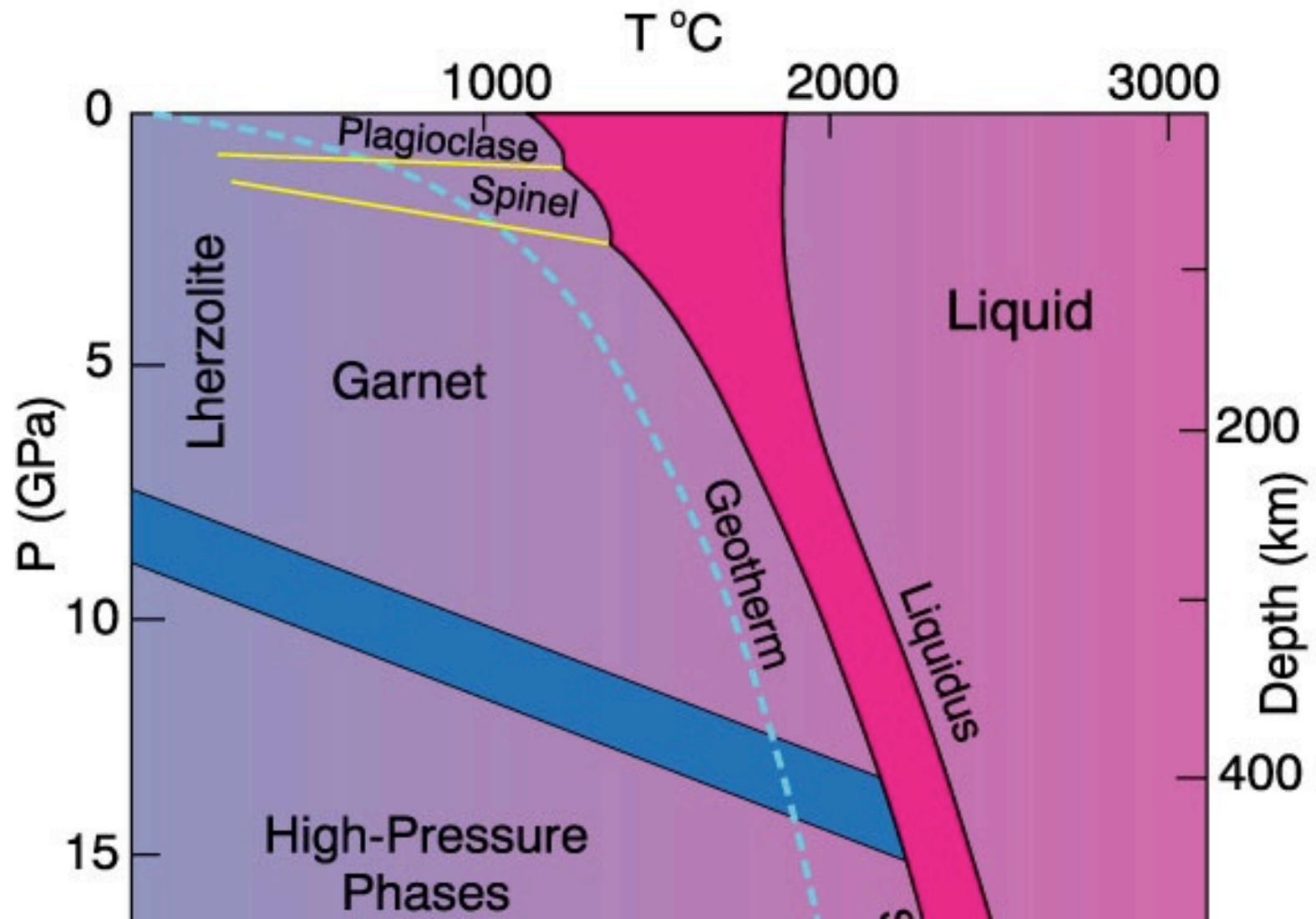
Application of Trace Elements to Igneous Systems

1. Use like major elements on variation diagrams to document FX, assimilation, etc. in a suite of rocks
 - ◆ More sensitive → larger variations as process continues

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.



2. Identification of the source rock or a particular mineral involved in either partial melting or fractional crystallization processes



Garnet concentrates the HREE and fractionates among them

Thus if garnet is in equilibrium with the partial melt (a residual phase in the source left behind) expect a steep (-) slope in REE **and HREE**

Shallow (< 40 km) partial melting of the mantle will have **plagioclase** in the residuum and a **Eu anomaly** will result

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	
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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
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	0.115*	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).

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

Garnet and Plagioclase effect on HREE

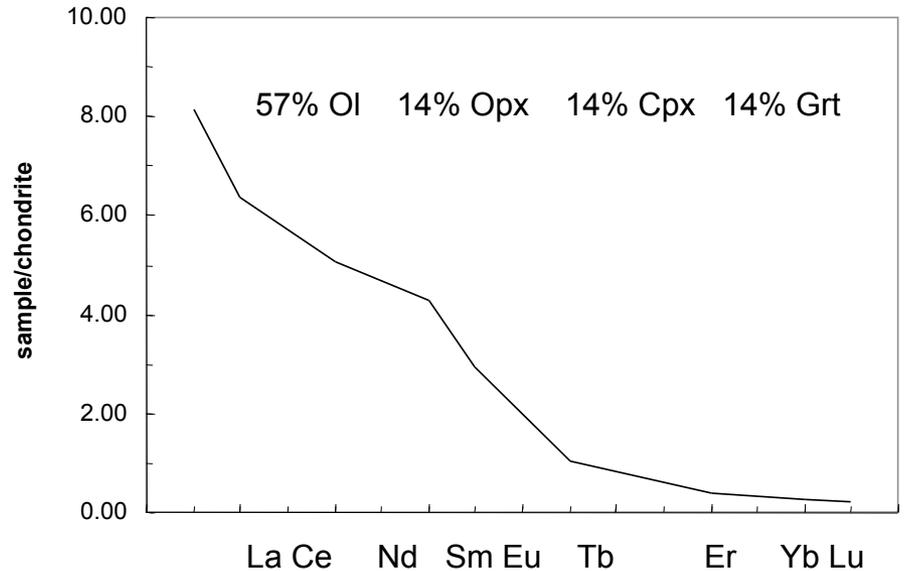
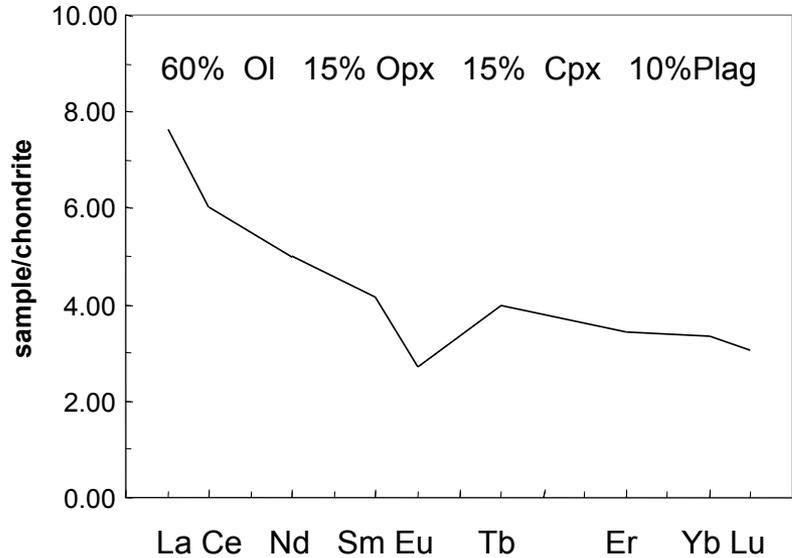
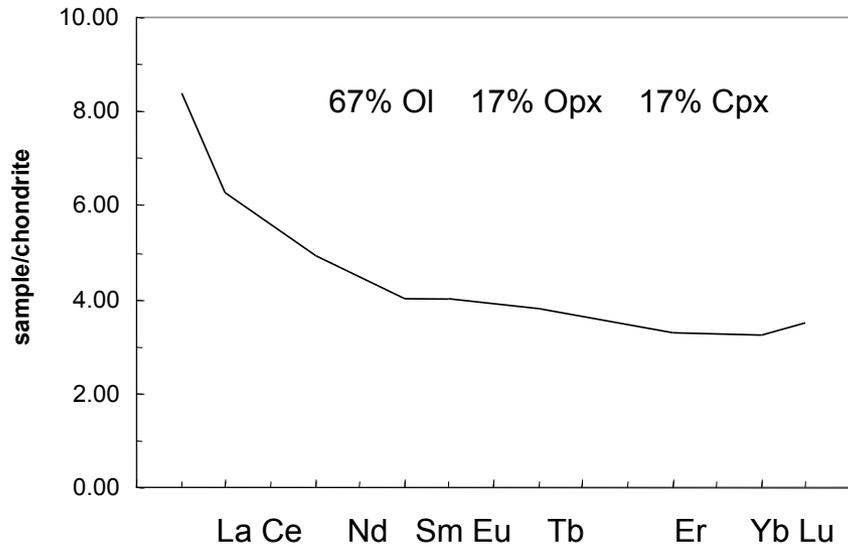
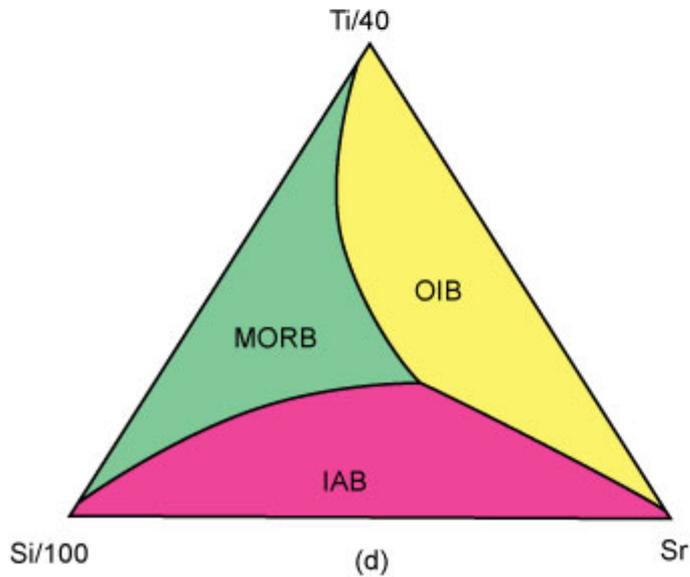
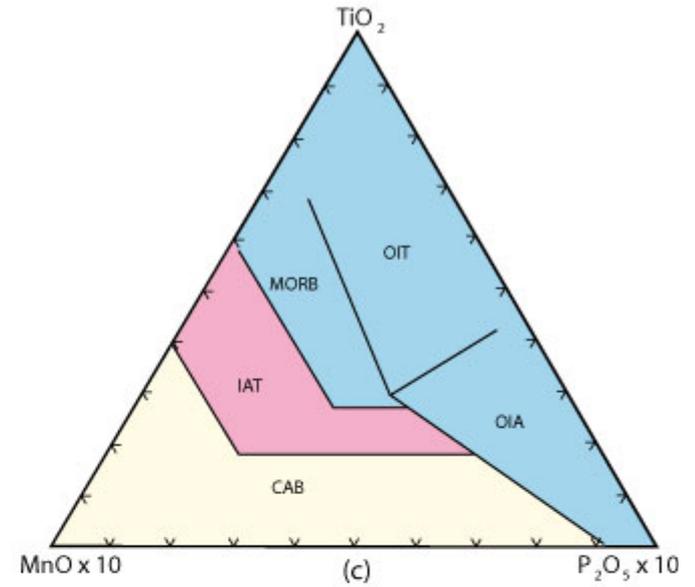
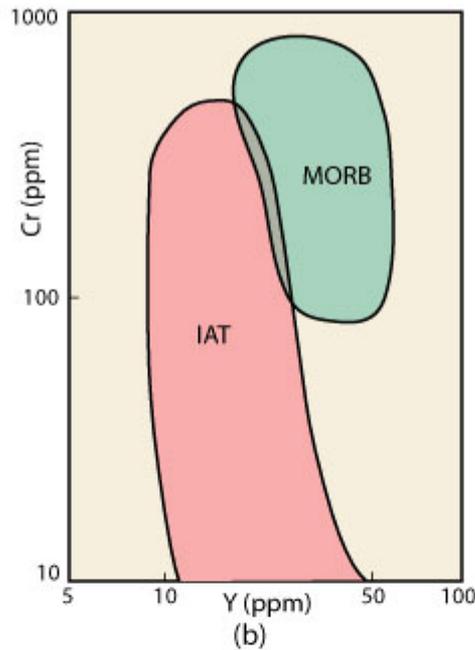
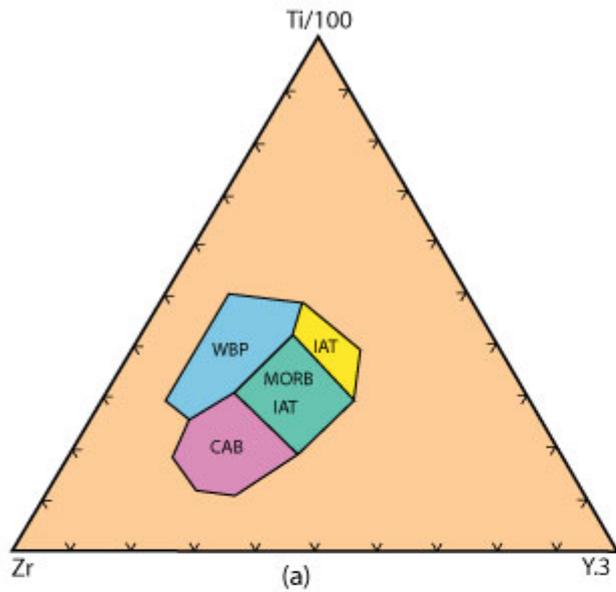


Table 9.6 A Brief Summary of Some Particularly Useful Trace Elements in Igneous Petrology

Element	Use as a Petrogenetic Indicator
Ni, Co, Cr	Highly compatible elements. Ni and Co are concentrated in olivine, and Cr in spinel and clinopyroxene. High concentrations indicate a mantle source, limited fractionation, or crystal accumulation.
Zr, Hf	Very incompatible elements that do not substitute into major silicate phases (although they may replace Ti in titanite or rutile). High concentrations imply an enriched source or extensive liquid evolution.
Nb, Ta	High field-strength elements that partition into Ti-rich phases (titanite, Ti-amphibole, Fe-Ti oxides. Typically low concentrations in subduction-related melts.
Ru, Rh, Pd, Re, Os, Ir, Pd	Platinum group elements (PGEs) are siderophile and used mostly to study melting and crystallization in mafic-ultramafic systems in which PGEs are typically hosted by sulfides. The Re/Os isotopic system is controlled by initial PGE differentiation and is applied to mantle evolution and mafic melt processes.
Sc	Concentrates in pyroxenes and may be used as an indicator of pyroxene fractionation.
Sr	Substitutes for Ca in plagioclase (but not in pyroxene), and, to a lesser extent, for K in K-feldspar. Behaves as a compatible element at low pressure where plagioclase forms early, but as an incompatible element at higher pressure where plagioclase is no longer stable.
REE	Myriad uses in modeling source characteristics and liquid evolution. Garnet accommodates the HREE more than the LREE, and orthopyroxene and hornblende do so to a lesser degree. Titanite and plagioclase accommodates more LREE. Eu^{2+} is strongly partitioned into plagioclase.
Y	Commonly incompatible. Strongly partitioned into garnet and amphibole. Titanite and apatite also concentrate Y, so the presence of these as accessories could have a significant effect.

Trace elements as a tool to determine paleotectonic environment

- Useful for rocks in mobile belts that are no longer recognizably in their original setting
- Can trace elements be discriminators of igneous environment?
- Approach is **empirical** on **modern** occurrences
- Concentrate on elements that are immobile during low/medium grade metamorphism



Explanation

- WBP within-plate basalts
- IAT island-arc tholeiites
- CAB calc-alkaline basalts
- MORB mid-ocean ridge basalts
- OIT ocean island tholeiite
- OIA ocean island alkaline basalt
- IAB island-arc basalts

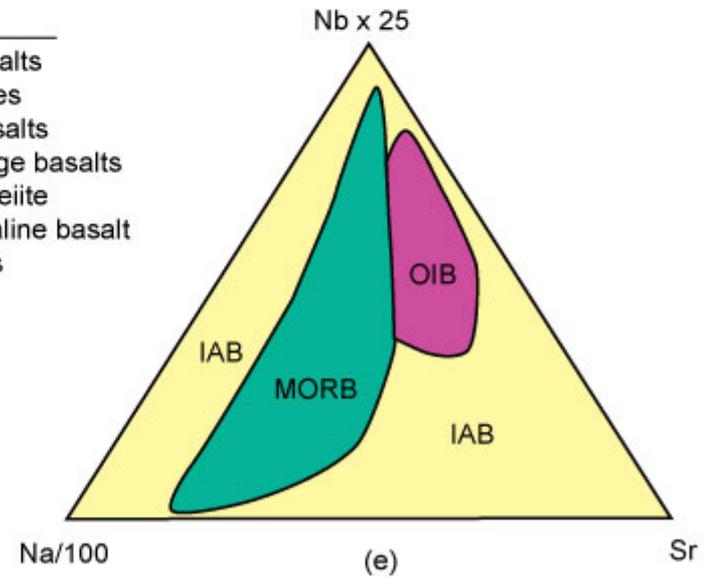


Figure 9.8 Examples of discrimination diagrams used to infer tectonic setting of ancient (meta)volcanics. **(a)** after Pearce and Cann (1973), **(b)** after Pearce (1982), Coish et al. (1986). Reprinted by permission of the American Journal of Science, **(c)** after Mullen (1983) Copyright © with permission from Elsevier Science, **(d)** and **(e)** after Vermeesch (2005) © AGU with permission.