Prof. A Rottura

13. Geochemical characteristics and isotopes as petrogenetic indicators: a review

Elementi in tracce e isotopi come indicatori petrogenetici

Further Readings: Wilson 1989, chapter Two; Rollinson 1993; Winter 2001.

"La Scienza come arte dell'approssimazione" (Luca Cavalli-Sforza)

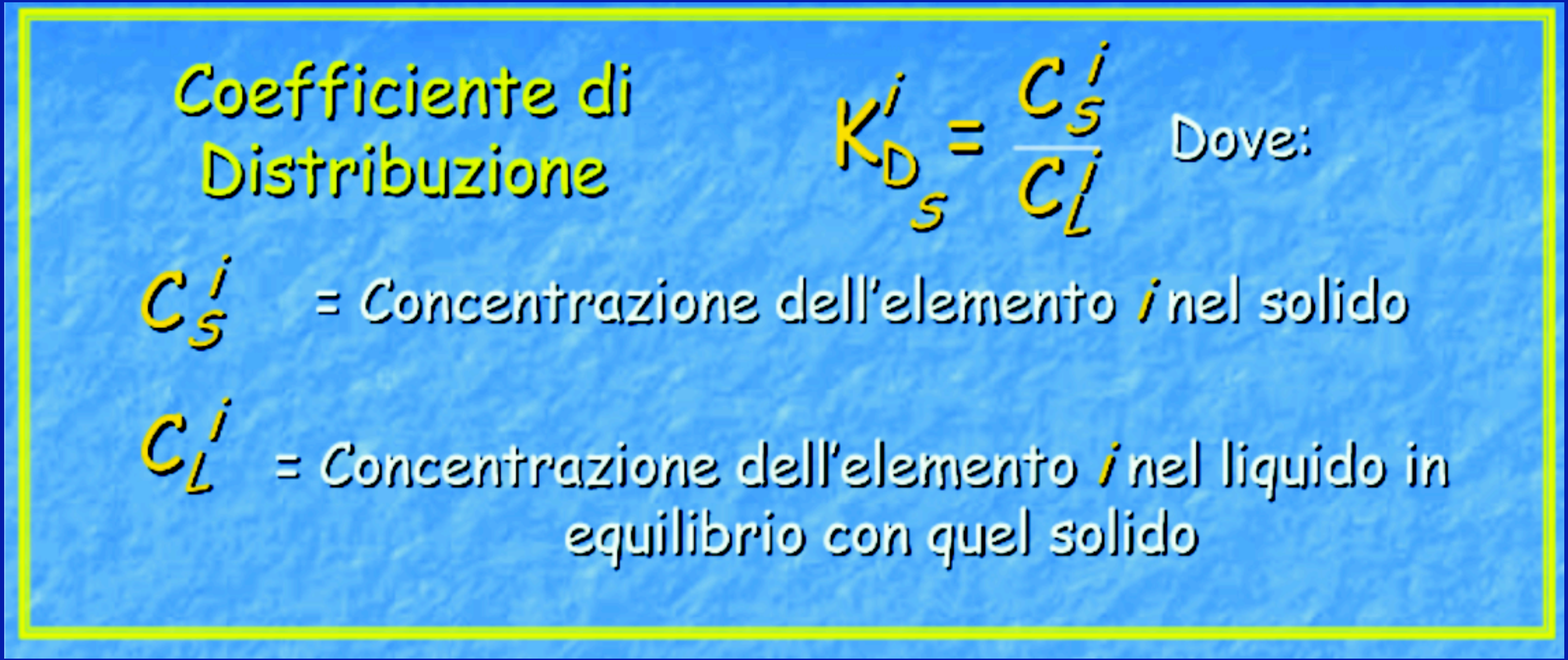
- Gli elementi in tracce (<0.1wt %; 1.000 ppm) sono *più sensibili degli elementi maggiori* ai processi di PM, FC, MIX

  - le loro concentrazioni possono variare di alcuni ordini grandezza

  - la loro *distribuzione* è regolata da *leggi matematiche* che rendono possibile un *approccio quantitativo* alla petrogenesi delle rocce (e.g. Gast, 1968)

Review of trace elements

Chemical Fractionation and Distribution Coefficient (K_D)



Coefficiente di Distribuzione

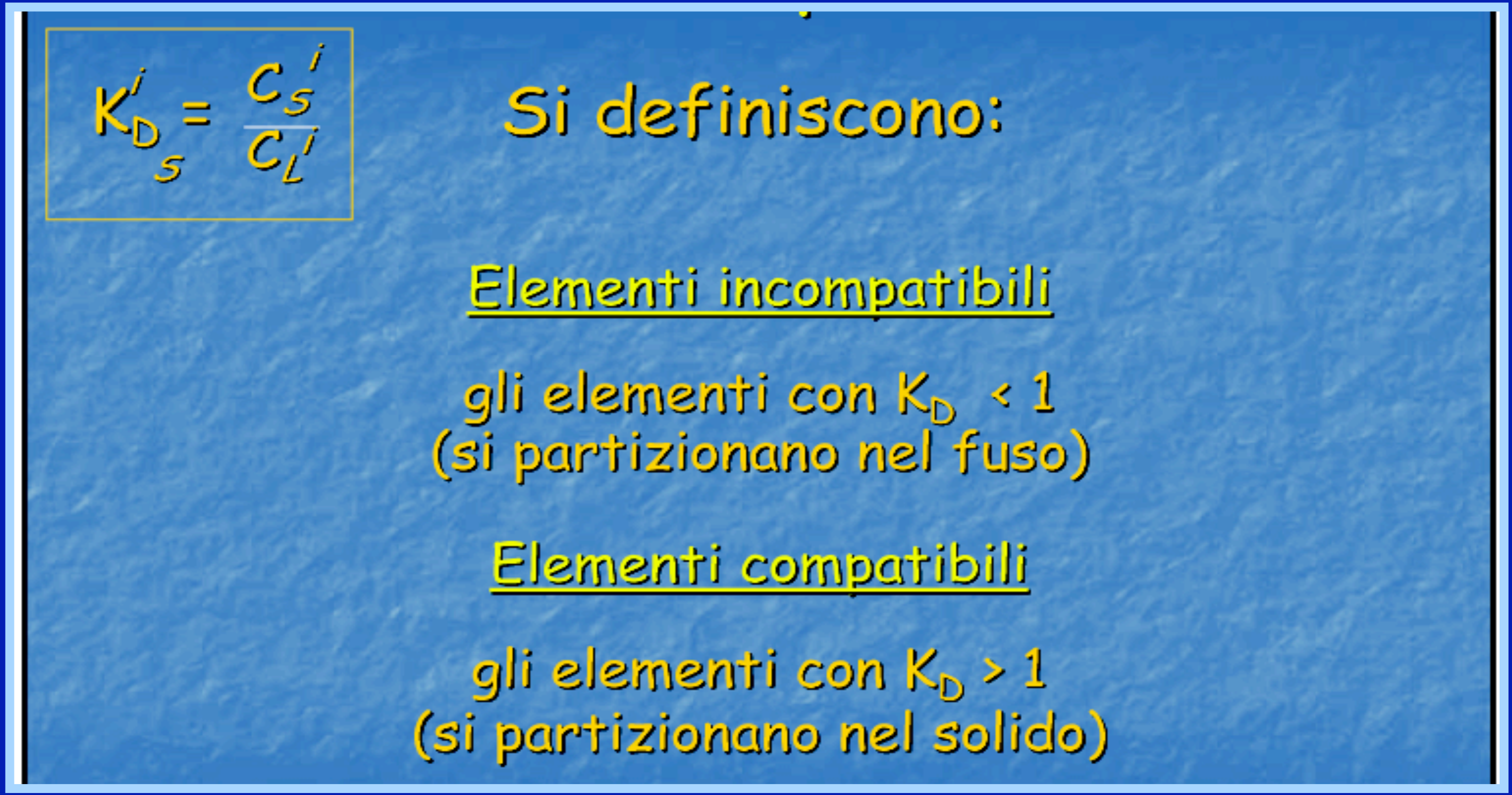
$$K^{i}_{D_S} = \frac{C^{i}_{S}}{C^{i}_{L}}$$

Dove:

C^{i}_{S} = Concentrazione dell'elemento *i* nel solido

C^{i}_{L} = Concentrazione dell'elemento *i* nel liquido in equilibrio con quel solido

Incompatible vs. Compatible element



$$K^{i}_{D_s} = \frac{C_s^{i}}{C_L^{i}}$$

Si definiscono:

Elementi incompatibili

gli elementi con $K_D < 1$
(si partizionano nel fuso)

Elementi compatibili

gli elementi con $K_D > 1$
(si partizionano nel solido)

- Incompatible elements have also been called hygromagmatophile (Treuil and Varet, 1973)

- Incompatible elements: 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

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

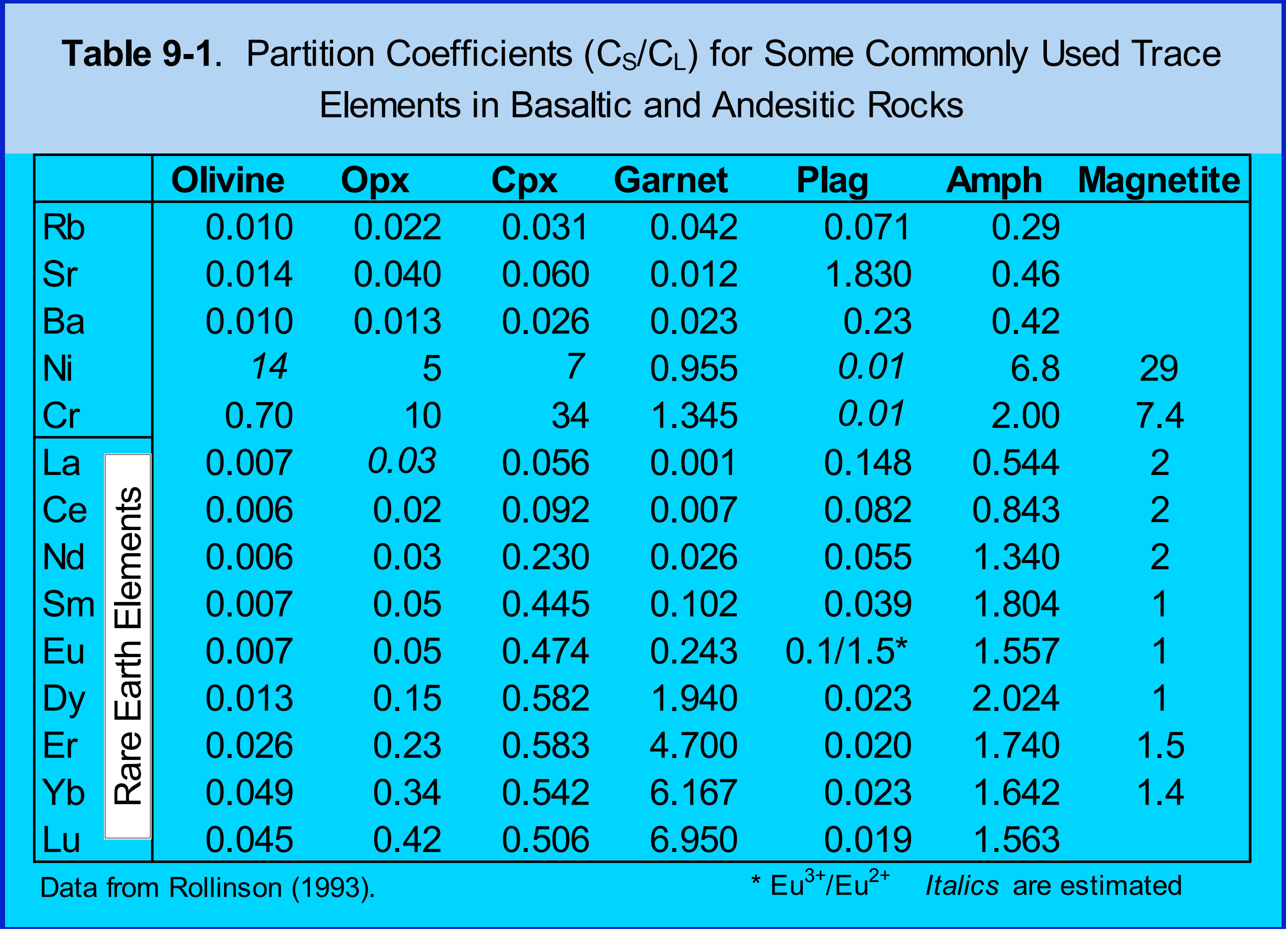


Table 9-1. Partition Coefficients (C_S/C_L) for Some Commonly Used Trace Elements in Basaltic and Andesitic Rocks

		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	*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	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).

* 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

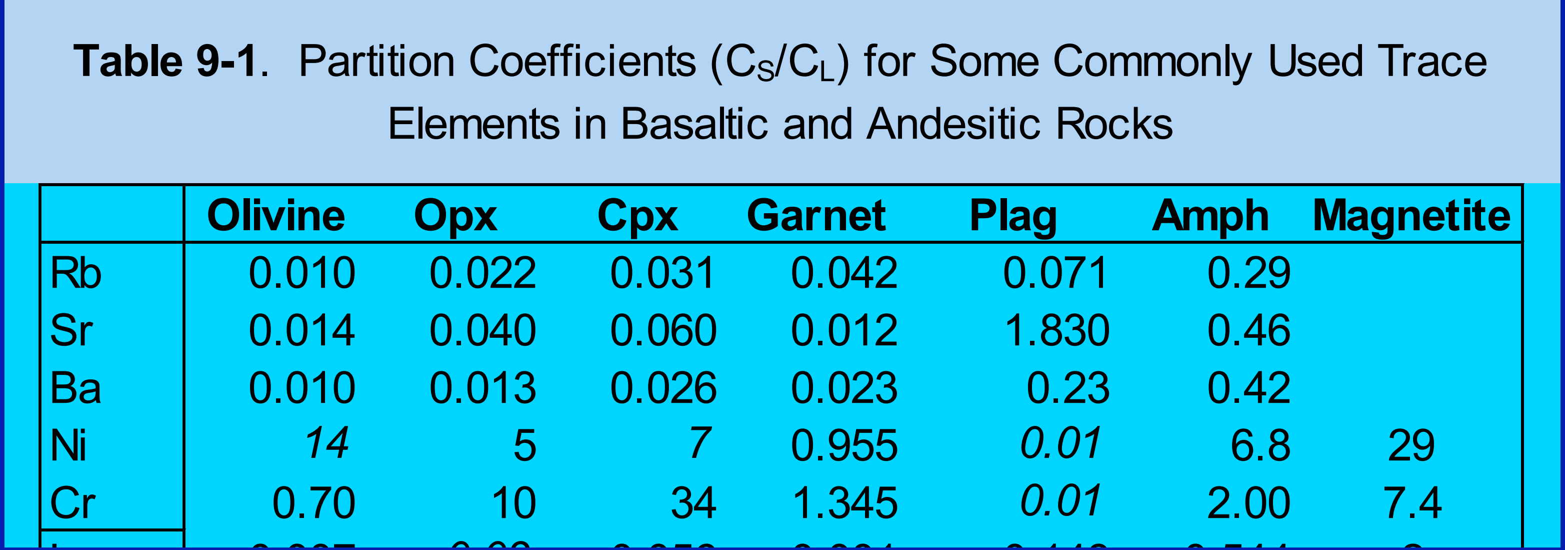


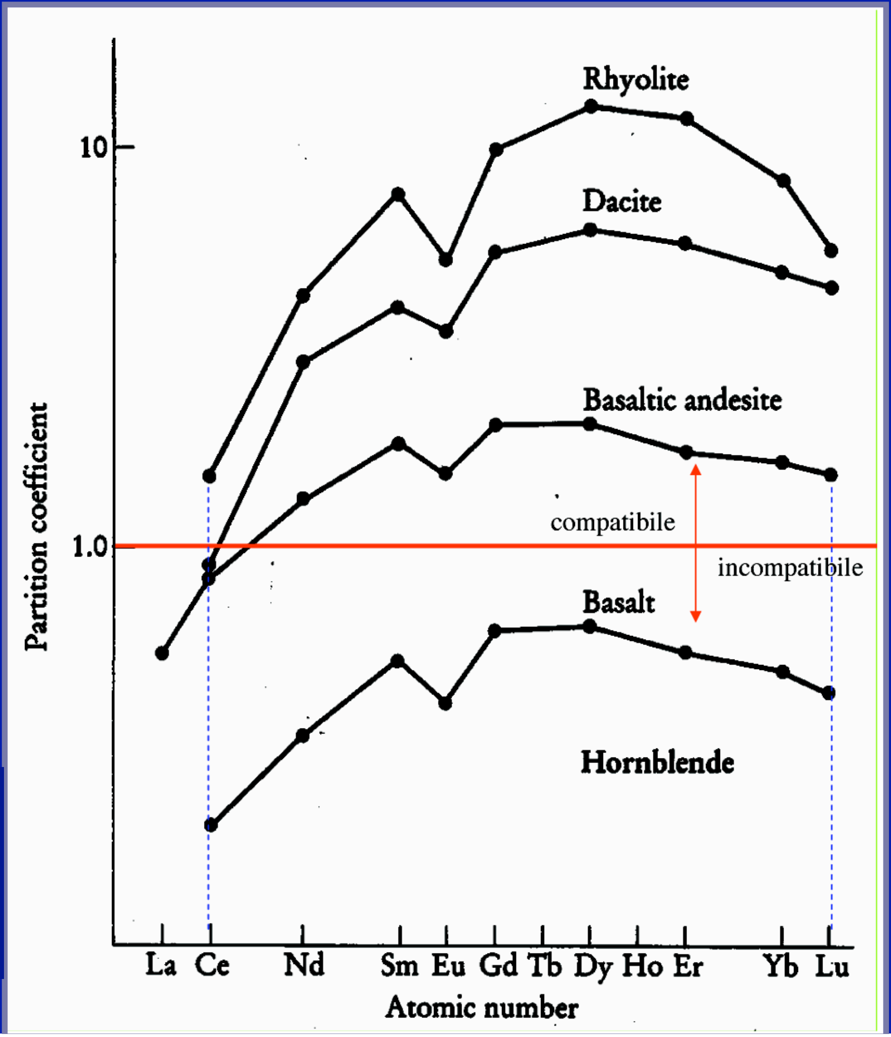
Table 9-1. Partition Coefficients (C_S/C_L) for Some Commonly Used Trace Elements in Basaltic and Andesitic Rocks

	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	*0.01*	6.8	29
Cr	0.70	10	34	1.345	*0.01*	2.00	7.4

See Table 9.6 in Appendix

● Incompatible vs. Compatible element

- Compatibility and incompatibility depend on minerals and melts involved



Partition coefficients for REE between hbl and basaltic to rhyolitic melts. After Rollinson, 1993)

- For a rock, determine the bulk distribution coefficient D for an element by calculating the contribution for each mineral

$$D_{i(bulk)} = \Sigma W_A D_{iA}$$

W_A = weight % of mineral A in the rock

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

Calcolo del *coefficiente di distribuzione globale* D

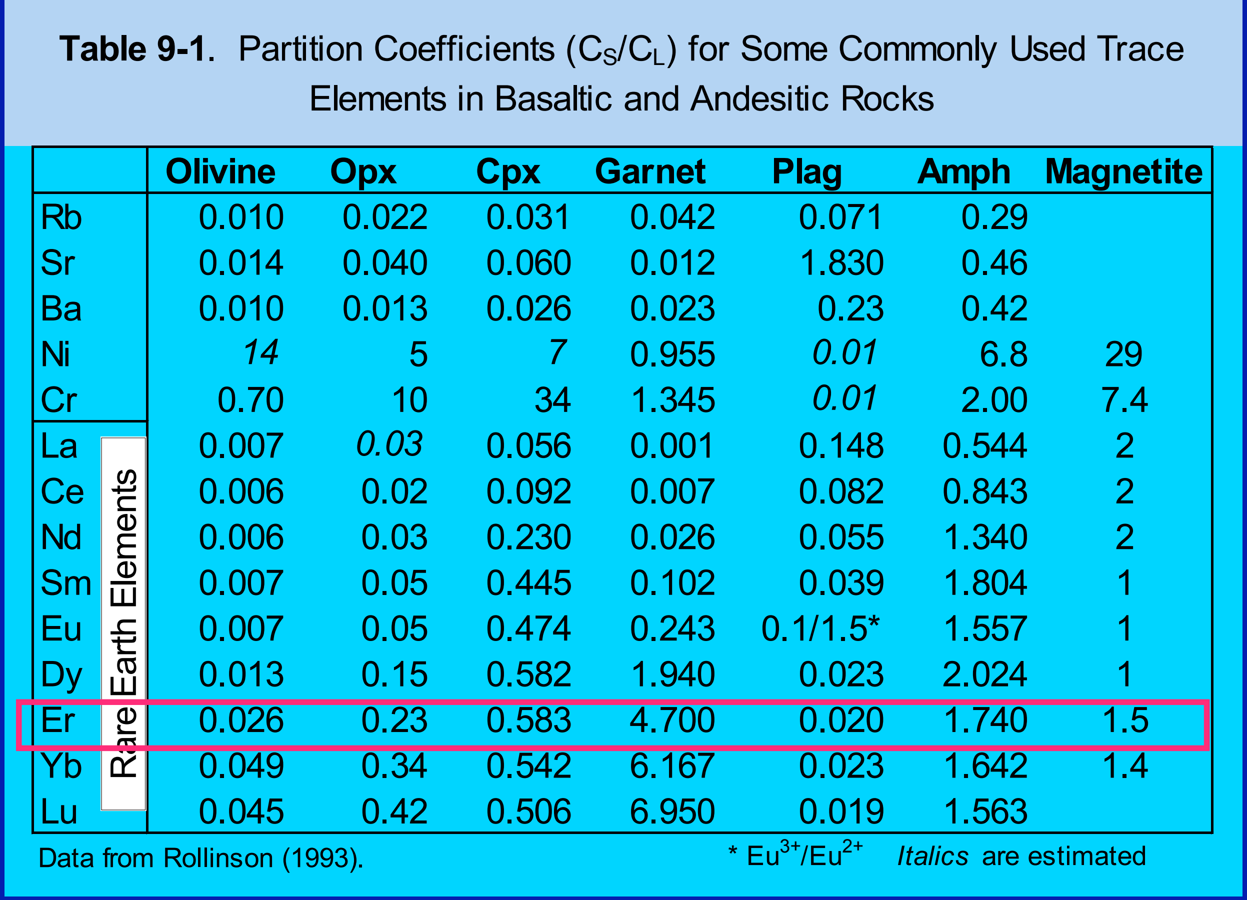


Table 9-1. Partition Coefficients (C_S/C_L) for Some Commonly Used Trace Elements in Basaltic and Andesitic Rocks

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

Esempio: calcolo di D^{Er}_{bulk} in una ipotetica lherzolite a grt costituita da: 60% ol, 25% opx, 10% cpx, e 5% grt, usando i dati di Tab.9.1

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

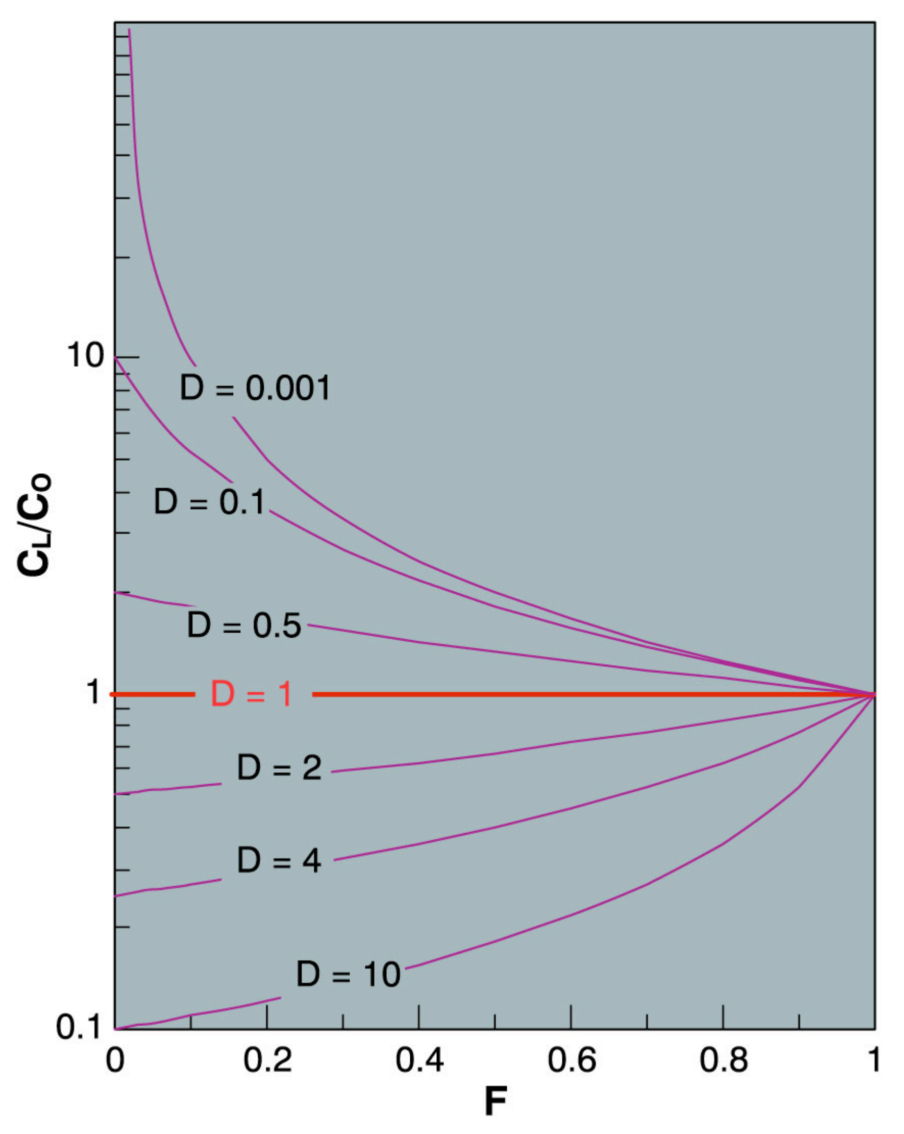
Models of Magma Evolution

1. Equilibrium Batch melting (EBM)

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

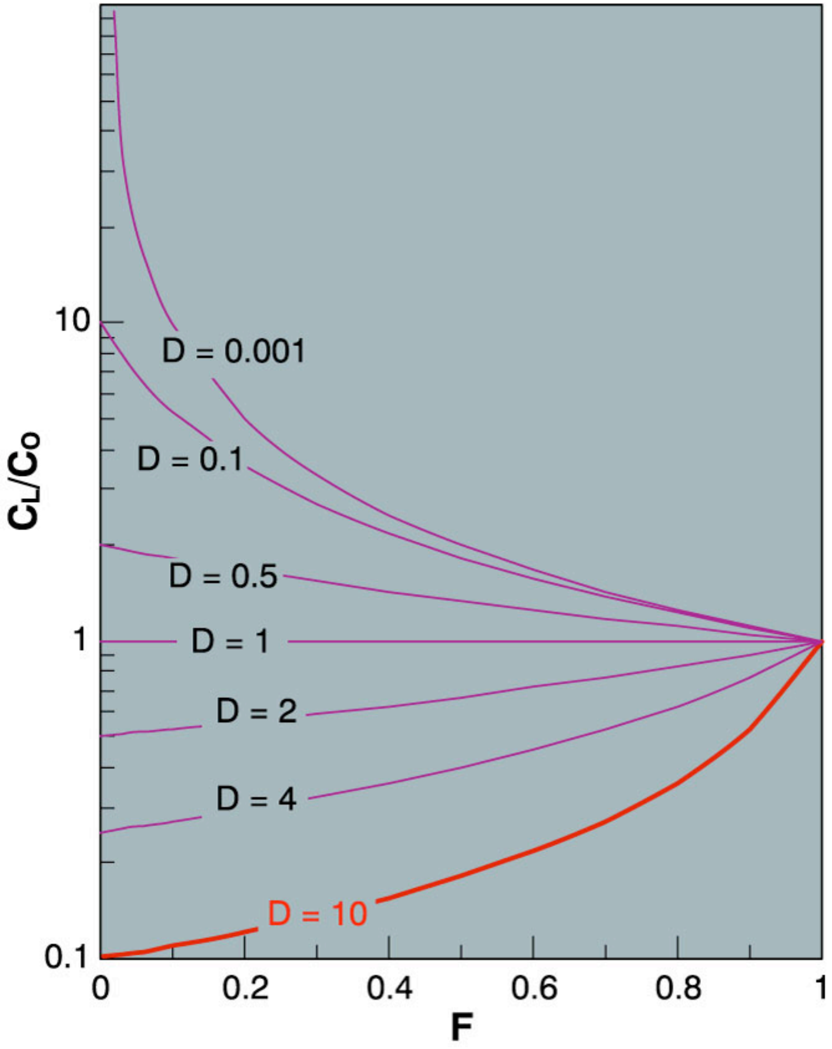
- ✦$D_i = 1.0$

Variation in the relative concentration of a trace element in a liquid vs. source rock as a fiunction of D and the fraction melted, using equation for equilibrium batch melting (after Winter, 2001)



D_i »1.0 (compatible element)

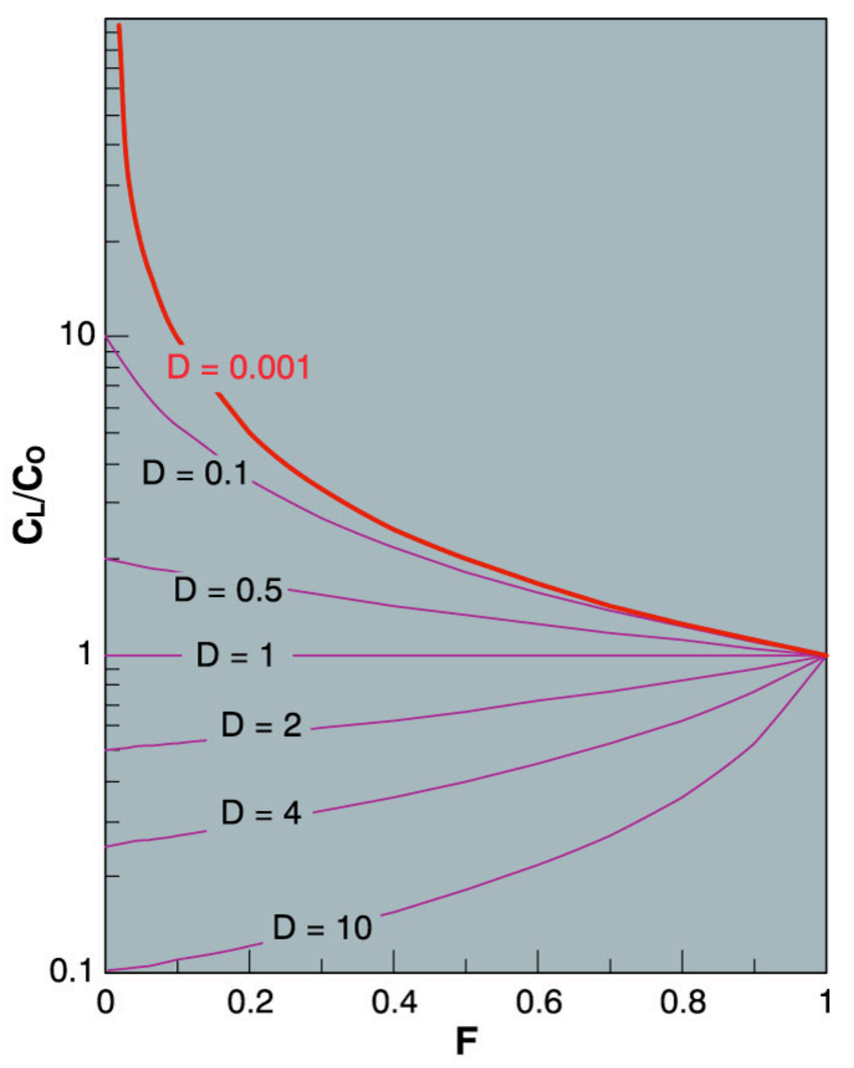
- Very low concentration in melt, especially for low % melting (low F)



Variation in the relative concentration of a trace element in a liquid vs. source rock as a fiunction of D and the fraction melted, using equation for equilibrium batch melting (after Winter, 2001)

Highly incompatible elements

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



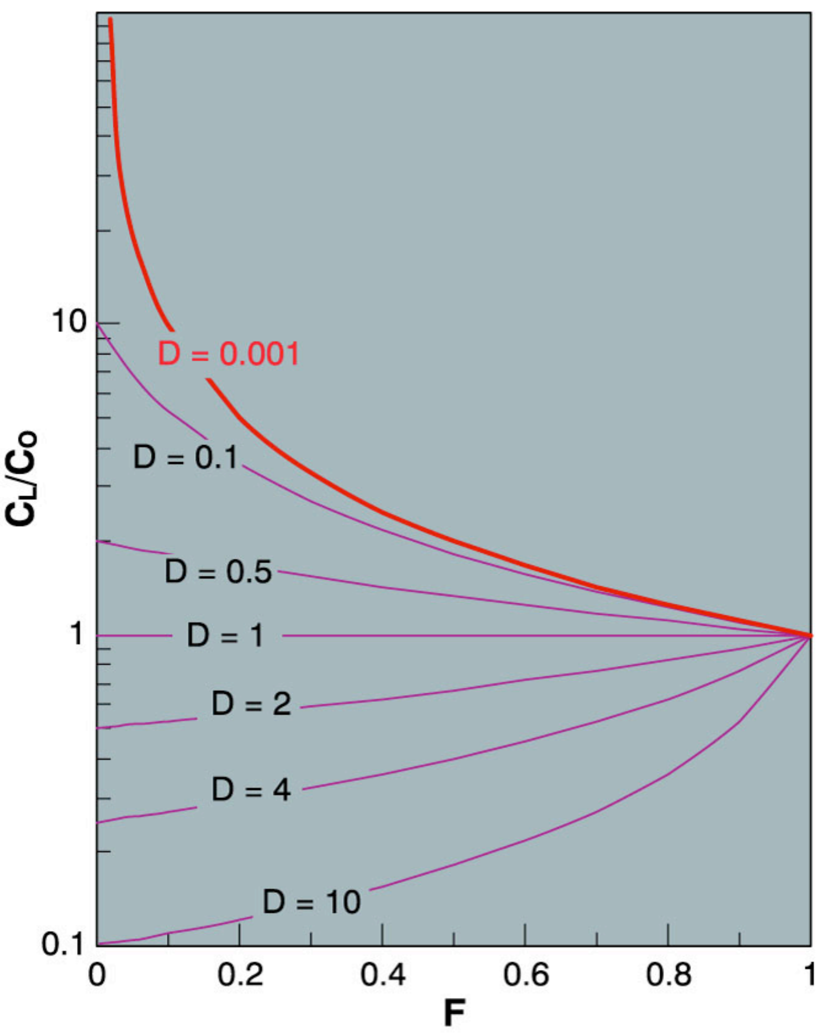
Variation in the relative concentration of a trace element in a liquid vs. source rock as a fiunction of D and the fraction melted, using equation for equilibrium batch melting. From Winter (2001)

Per ogni elemento fortemente incompatibile ($D_i \rightarrow 0$)

$$\frac{C_L}{C_0} = \frac{1}{D_i(1-F)+F} \quad \Longrightarrow \quad \frac{C_L}{C_0} = \frac{1}{F}$$

Nell'ipotesi di una fusione parziale di 1%, 3%, 5% (F=0.01/ 0.03/ 0.05) avremmo un fattore d'arricchimento:

C_L/C_0= 100/ 33/20



2. Fractional Crystallization (FC)

- Equilibrium Crystallization (EC)

  Crystals remain in equilibrium with each melt increment

- Rayleigh Fractionation (RFC)

  The other extreme: separation of each crystal as it formed=perfectly continuous fractional crystallization in a magma chamber

  - Concentration of some element in the *residual* liquid, C_L is modeled by the Rayleigh equation:

$$C_L/C_O = F^{(D-1)}$$ Rayleigh Fractionation

Partial Melting vs. Fractional Crystallization

Compatible vs. *incompatible* element plots

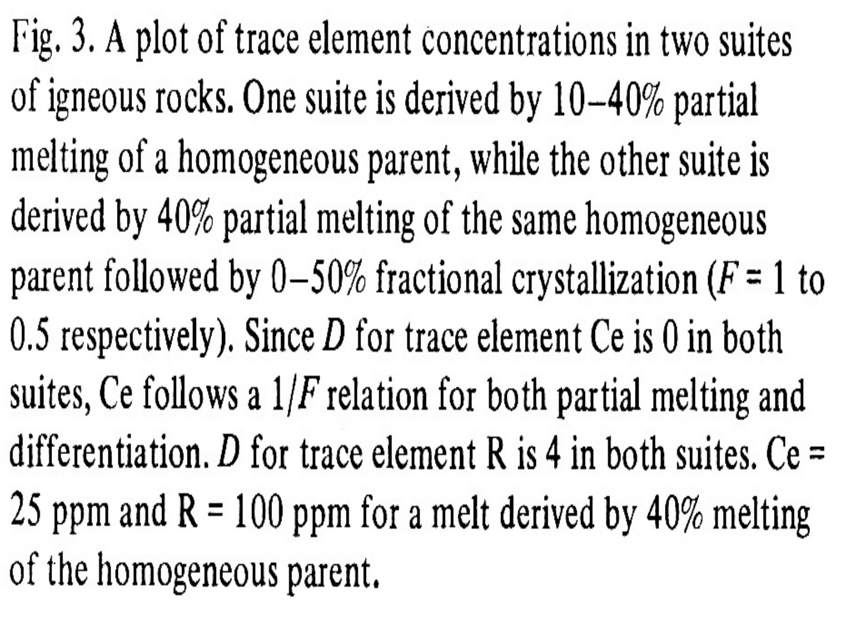
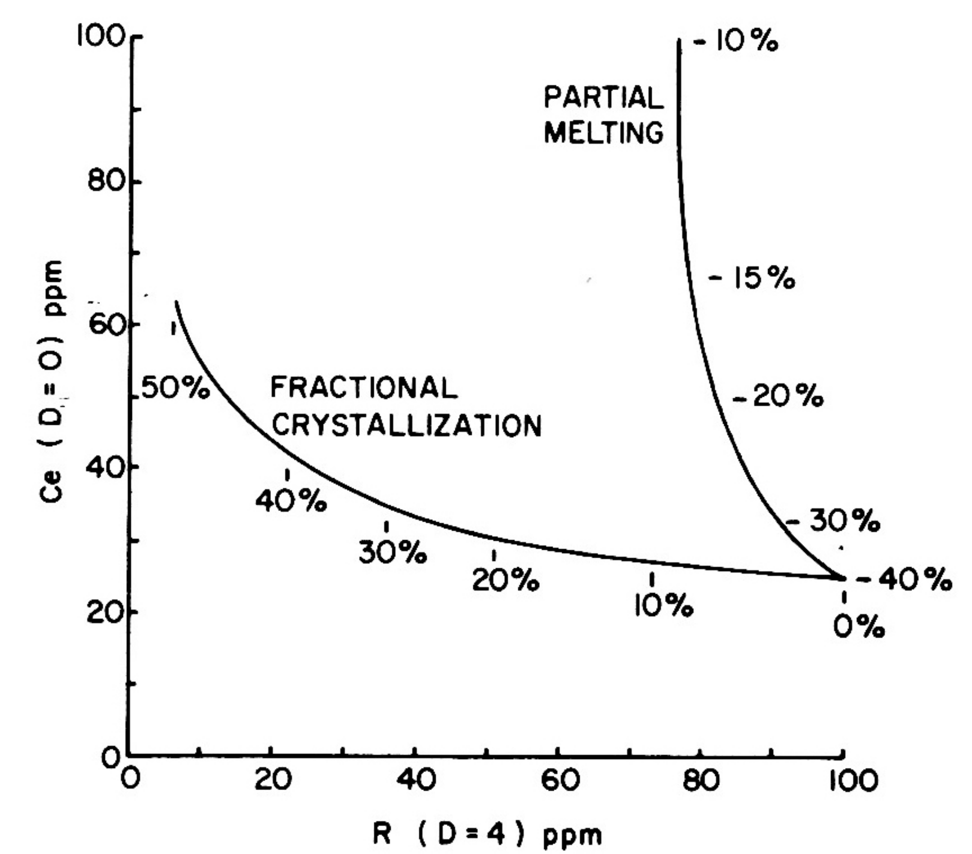


Fig. 3. A plot of trace element concentrations in two suites of igneous rocks. One suite is derived by 10–40% partial melting of a homogeneous parent, while the other suite is derived by 40% partial melting of the same homogeneous parent followed by 0–50% fractional crystallization ($F = 1$ to 0.5 respectively). Since D for trace element Ce is 0 in both suites, Ce follows a $1/F$ relation for both partial melting and differentiation. D for trace element R is 4 in both suites. Ce = 25 ppm and R = 100 ppm for a melt derived by 40% melting of the homogeneous parent.



(after Hanson, 1978. EPSL, 38, 26-43)

Other models are used to analyze

- AFC (Assimilation Fractional Crystallization)

  Tests

✓ AFC processes produce curved trends in both the trace element and isotopic concentrations

- However, AFC processes are difficult to recognize and require a strong contrast in trace element concentations between magma and wallrock before they can be detected (Powell, 1984)

Other models are used to analyze

- Mixing of magmas

Tests (*mixing equations*): mixing produces

✓ linear trends in el-el plots

✓ hyperbolic trends

in ratio-ratio/el plots

^{143}Nd/^{144}/Nd vs. ^{87}Sr/^{86}Sr

^{87}Sr/^{86}Sr vs. 1/Sr

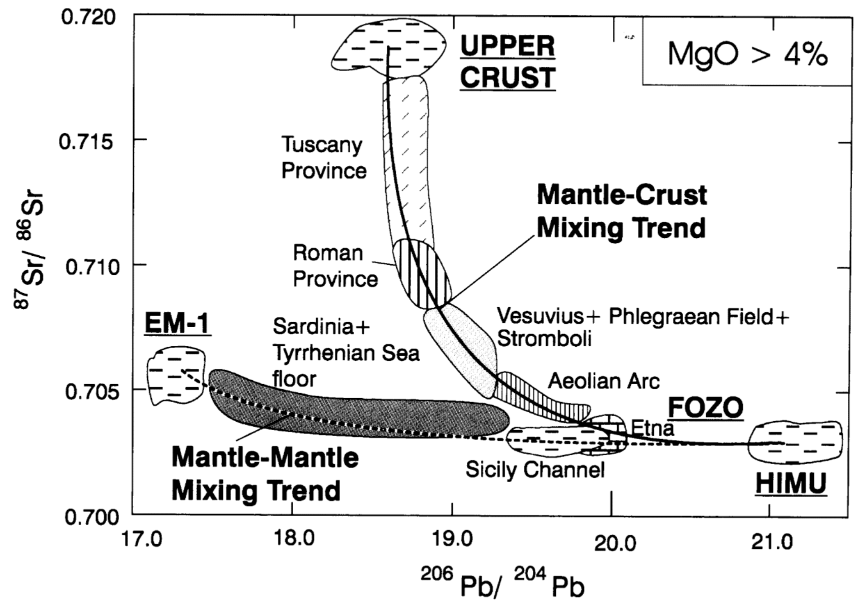
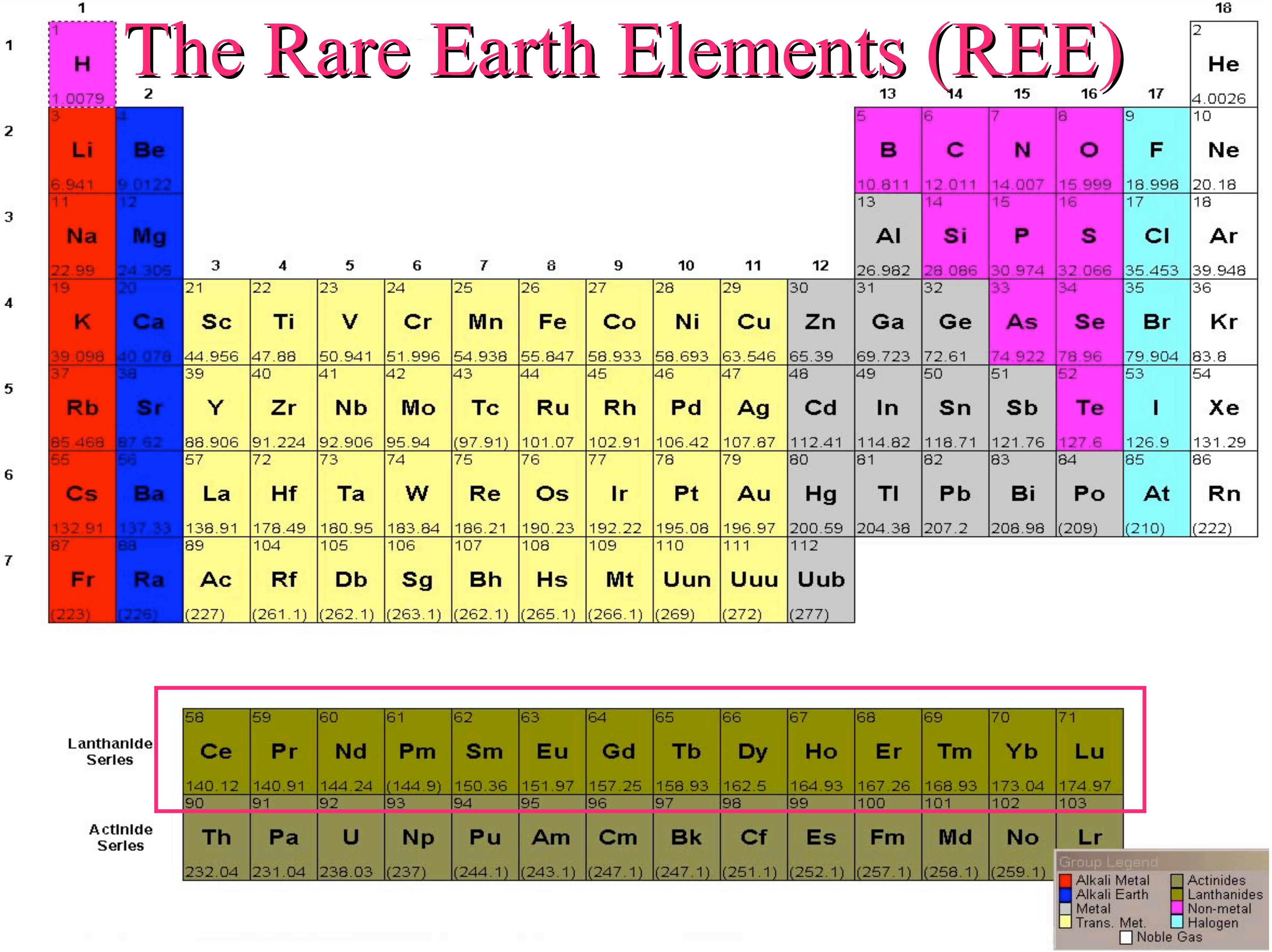


Figure 7 ^{87}Sr/^{86}Sr vs. ^{206}Pb/^{204}Pb variations of Plio-Quaternary Italian mafic rocks. Central Italy orogenic magmatism falls along a mantle-crust mixing trend involving HIMU-FOZO and Upper Crust. Sicily, Sicily Channel, Sardinia and some Tyrrhenian Sea seamounts (anorogenic magmatism) plot along a mantle-mantle mixing trend involving at least two end members (HIMU-EM1).

(after Peccerillo, 2003)

The Rare Earth Elements (REE)



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H 1.0079																	2 He 4.0026
2	3 Li 6.941	4 Be 9.0122											5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.18
3	11 Na 22.99	12 Mg 24.305											13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.066	17 Cl 35.453	18 Ar 39.948
4	19 K 39.098	20 Ca 40.078	21 Sc 44.956	22 Ti 47.88	23 V 50.941	24 Cr 51.996	25 Mn 54.938	26 Fe 55.847	27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.39	31 Ga 69.723	32 Ge 72.61	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.8
5	37 Rb 85.468	38 Sr 87.62	39 Y 88.906	40 Zr 91.224	41 Nb 92.906	42 Mo 95.94	43 Tc (97.91)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.76	52 Te 127.6	53 I 126.9	54 Xe 131.29
6	55 Cs 132.91	56 Ba 137.33	57 La 138.91	72 Hf 178.49	73 Ta 180.95	74 W 183.84	75 Re 186.21	76 Os 190.23	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po (209)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra (226)	89 Ac (227)	104 Rf (261.1)	105 Db (262.1)	106 Sg (263.1)	107 Bh (262.1)	108 Hs (265.1)	109 Mt (266.1)	110 Uun (269)	111 Uuu (272)	112 Uub (277)						

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

Group Legend

🟥 Alkali Metal	🟫 Actinides
🟦 Alkali Earth	🟩 Lanthanides
▨ Metal	🟪 Non-metal
🟨 Trans. Met.	▧ Halogen
☐ Noble Gas	

- Le REE hanno proprietà chimiche e fisiche molto simili. Nondimeno, a causa della Δri (*contrazione dei lantanidi*) hanno la capacità di frazionarsi selettivamente nei processi di PM e FC.

Contrasts and similarities in the D values:

Also Note:

HREE are less incompatible especially in garnet

Eu can → 2+ which conc. in plagioclase

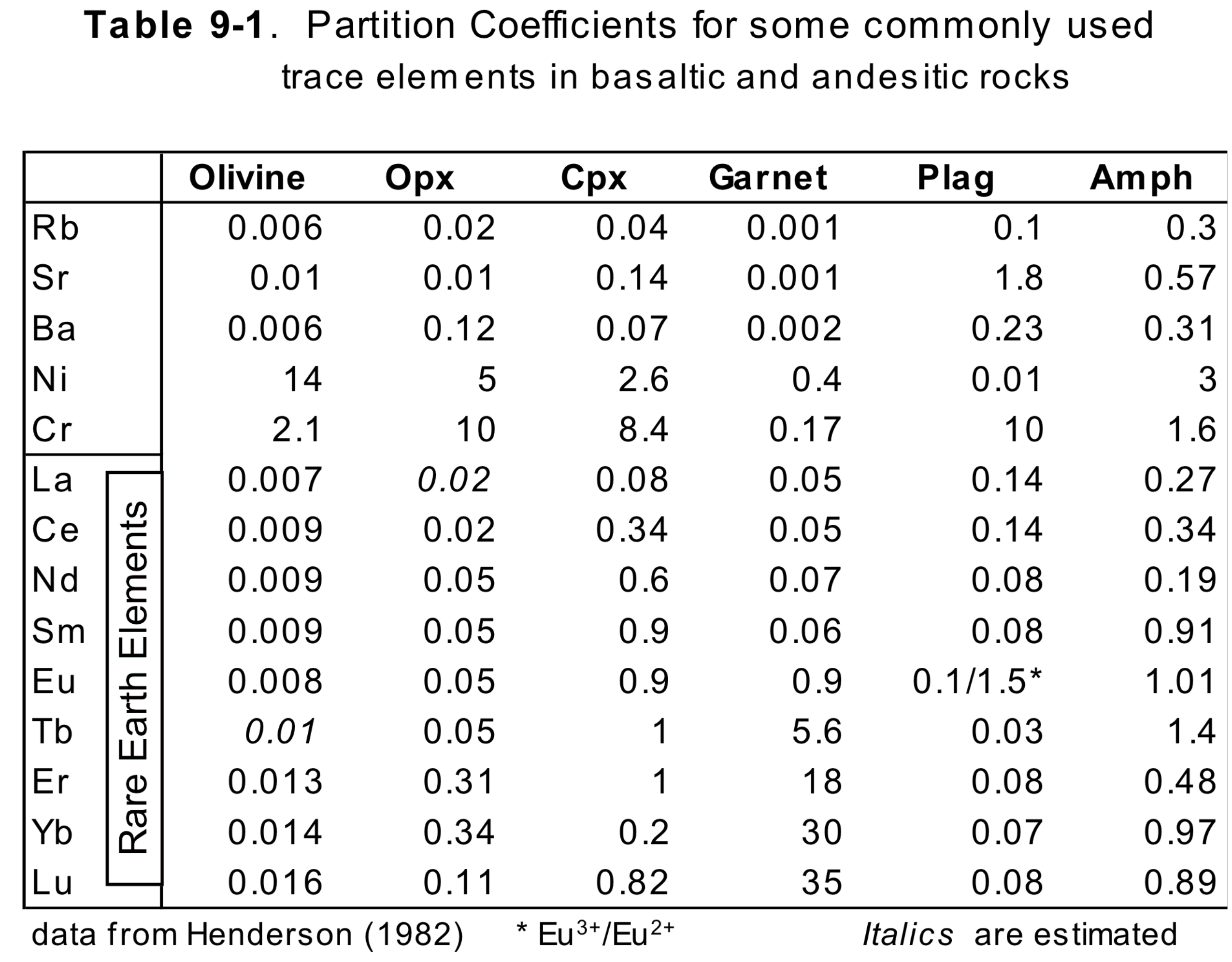


Table 9-1. Partition Coefficients for some commonly used trace elements in basaltic and andesitic rocks

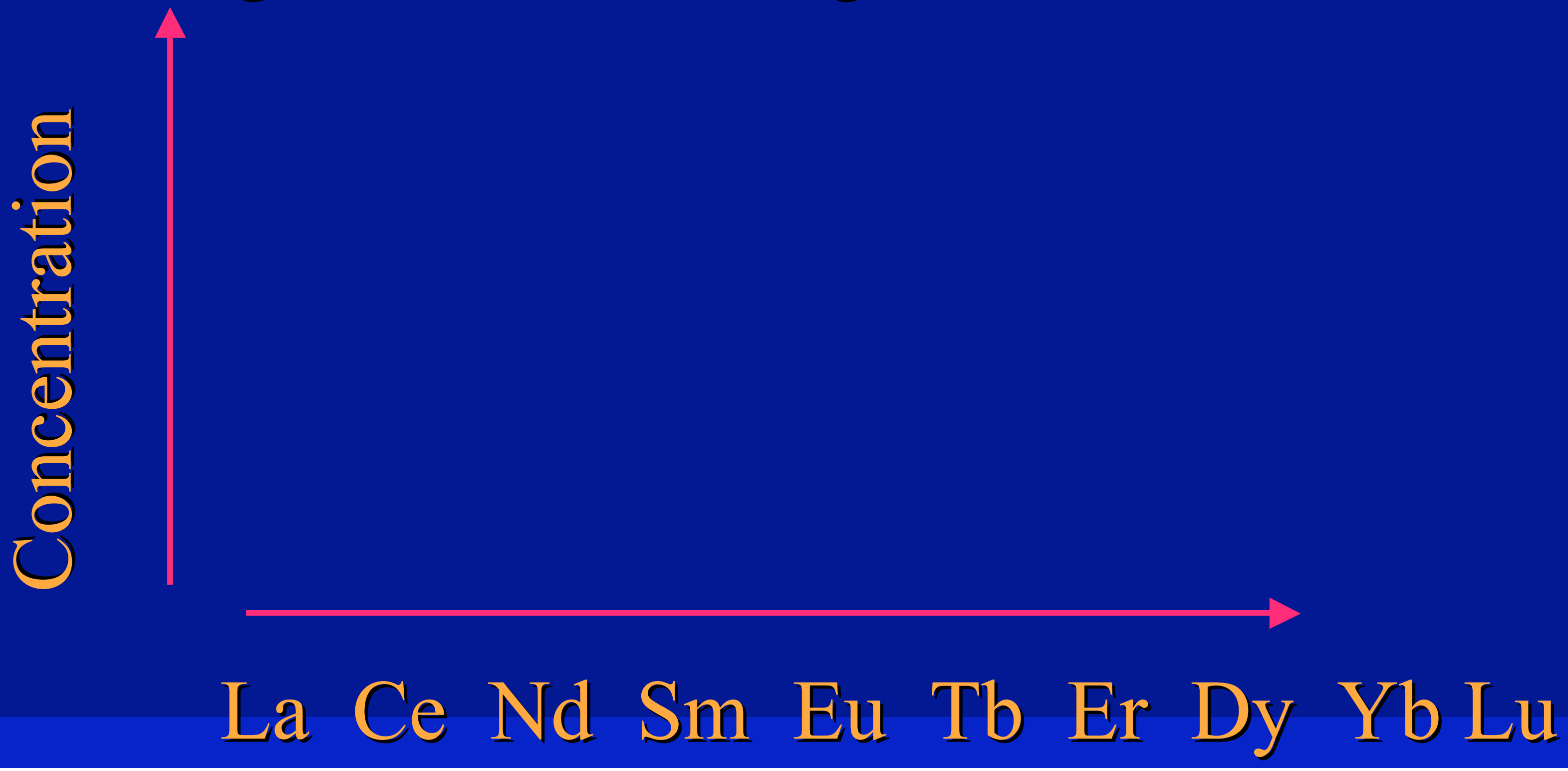
		Olivine	Opx	Cpx	Garnet	Plag	Amph
Rb		0.006	0.02	0.04	0.001	0.1	0.3
Sr		0.01	0.01	0.14	0.001	1.8	0.57
Ba		0.006	0.12	0.07	0.002	0.23	0.31
Ni		14	5	2.6	0.4	0.01	3
Cr		2.1	10	8.4	0.17	10	1.6
La	Rare Earth Elements	0.007	*0.02*	0.08	0.05	0.14	0.27
Ce		0.009	0.02	0.34	0.05	0.14	0.34
Nd		0.009	0.05	0.6	0.07	0.08	0.19
Sm		0.009	0.05	0.9	0.06	0.08	0.91
Eu		0.008	0.05	0.9	0.9	0.1/1.5*	1.01
Tb		*0.01*	0.05	1	5.6	0.03	1.4
Er		0.013	0.31	1	18	0.08	0.48
Yb		0.014	0.34	0.2	30	0.07	0.97
Lu		0.016	0.11	0.82	35	0.08	0.89

data from Henderson (1982) * Eu^{3+}/Eu^{2+} *Italics* are estimated

REE Diagrams

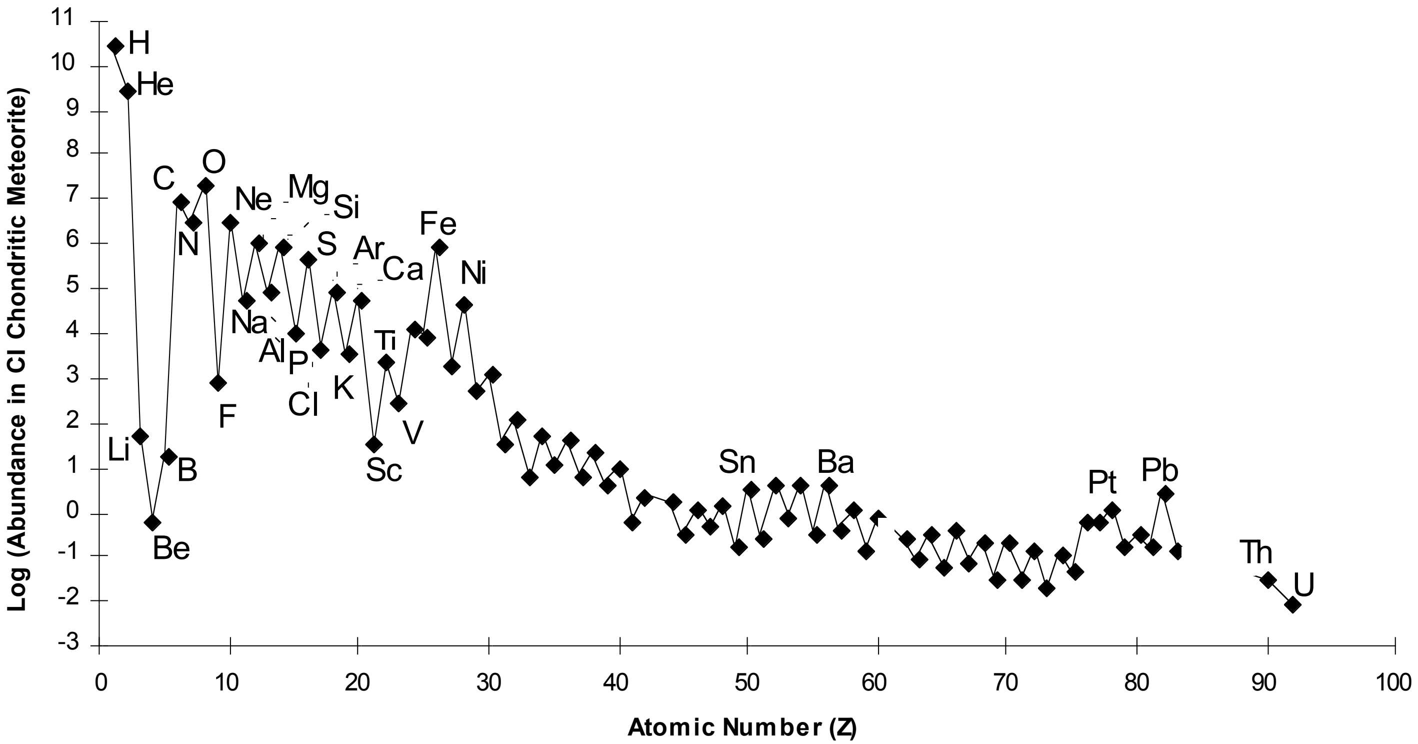
Plots of concentration as the ordinate (y-axis) against increasing atomic number

- Degree of compatibility increases from left to right across the diagram



Concentration

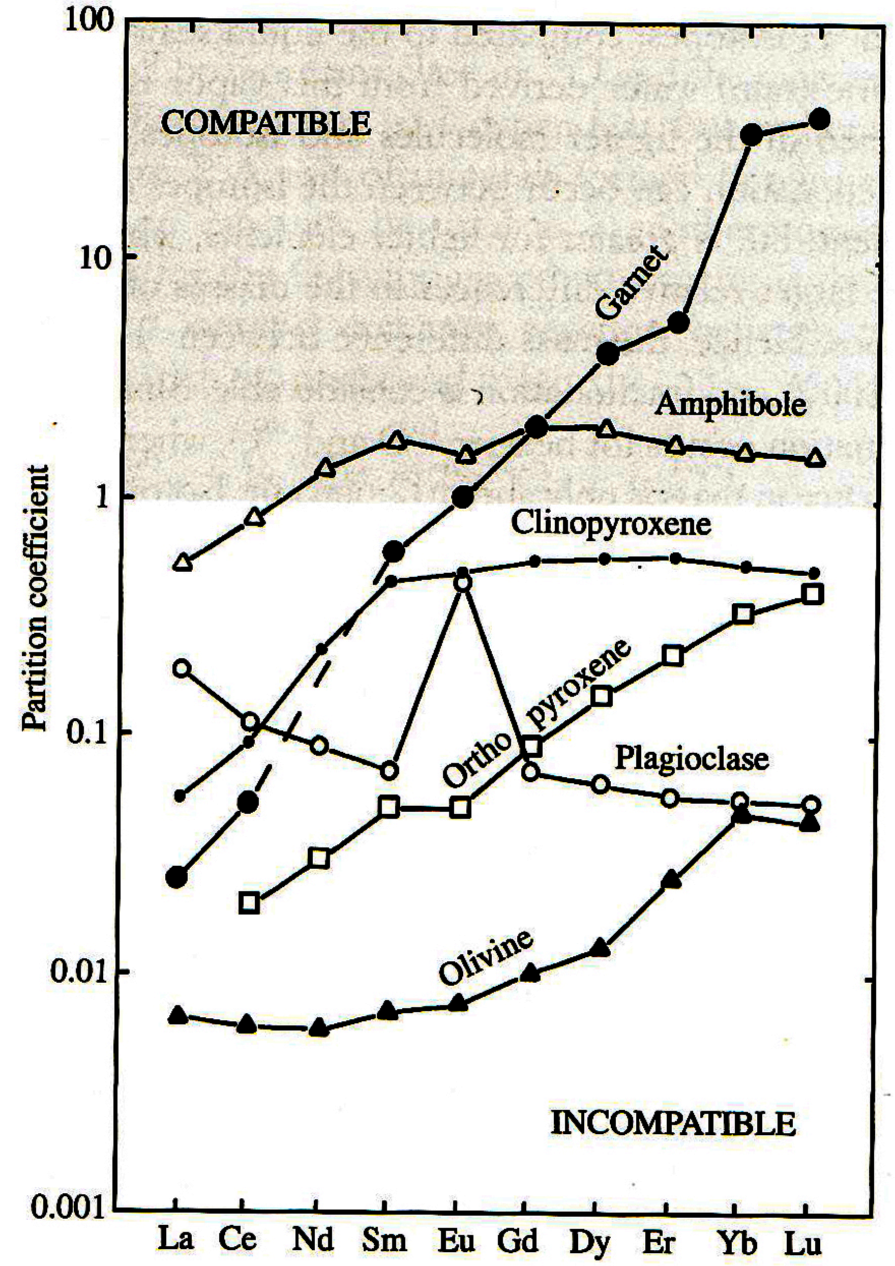
La Ce Nd Sm Eu Tb Er Dy Yb Lu



- Eliminate “saw-tooth” Oddo-Harkins effect and make y-scale more functional by normalizing to a standard (see Rollinson,1993, pp142-148)
  - estimates of primordial mantle REE (ca. 2xchondrites)
  - chondrite meteorite concentrations (Recommended values in Boynton, 1984)

- 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 negative slope in REE and HREE*

- Negative Europium anomaly develops when plagioclase is a fractionating phenocryst or a residual solid in source



2.22 Partition coefficients for REEs between minerals and basaltic melt. Garnet and plagioclase are the principal aluminous phases in basaltic magmas, but the former is stable at pressures above which plagioclase is stable. Note the striking contrast in their pattern of coefficients. Amphibole is another aluminous phase stable in hydrous systems. (Redrawn from Rollinson, 1993.)

(after Best, 2003)

✓ Schematic chondrite-normalized REE patterns for basaltic rocks

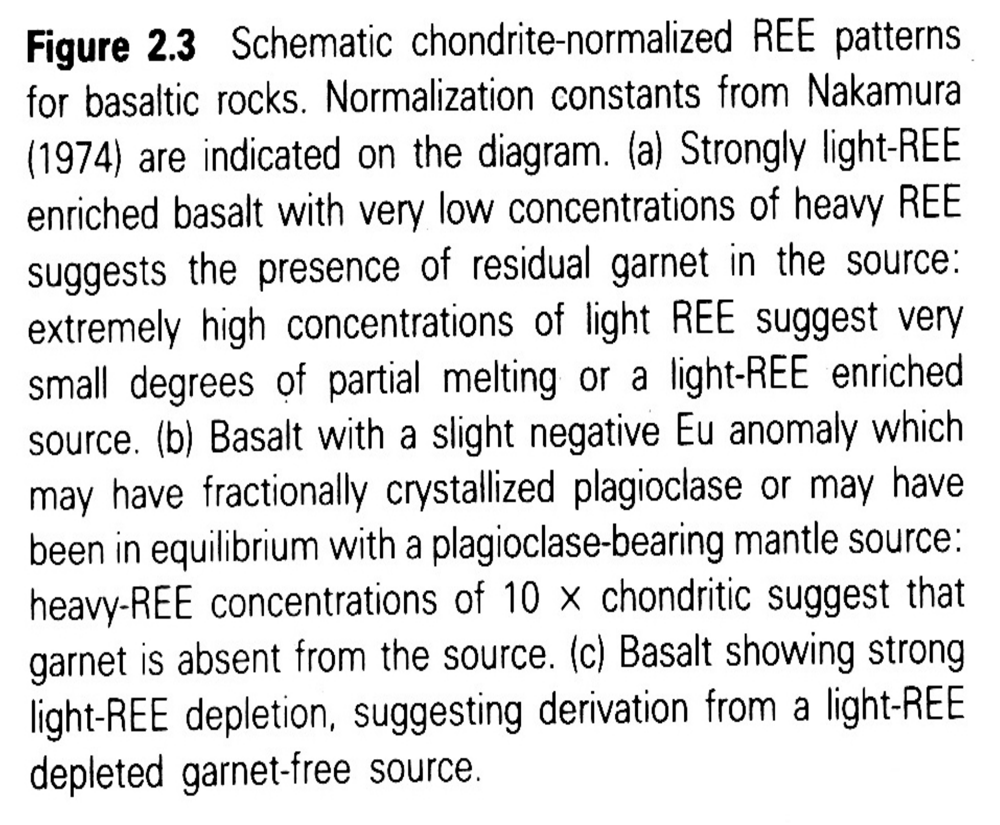
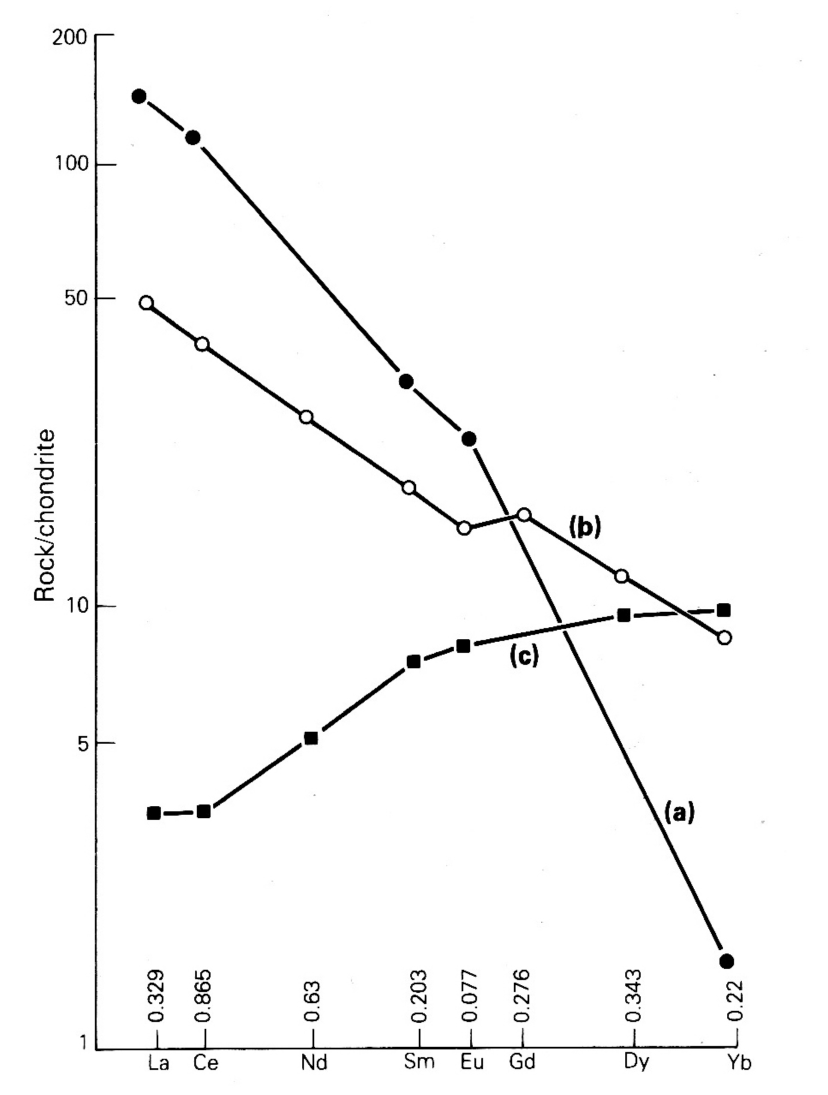


Figure 2.3 Schematic chondrite-normalized REE patterns for basaltic rocks. Normalization constants from Nakamura (1974) are indicated on the diagram. (a) Strongly light-REE enriched basalt with very low concentrations of heavy REE suggests the presence of residual garnet in the source: extremely high concentrations of light REE suggest very small degrees of partial melting or a light-REE enriched source. (b) Basalt with a slight negative Eu anomaly which may have fractionally crystallized plagioclase or may have been in equilibrium with a plagioclase-bearing mantle source: heavy-REE concentrations of 10 × chondritic suggest that garnet is absent from the source. (c) Basalt showing strong light-REE depletion, suggesting derivation from a light-REE depleted garnet-free source.



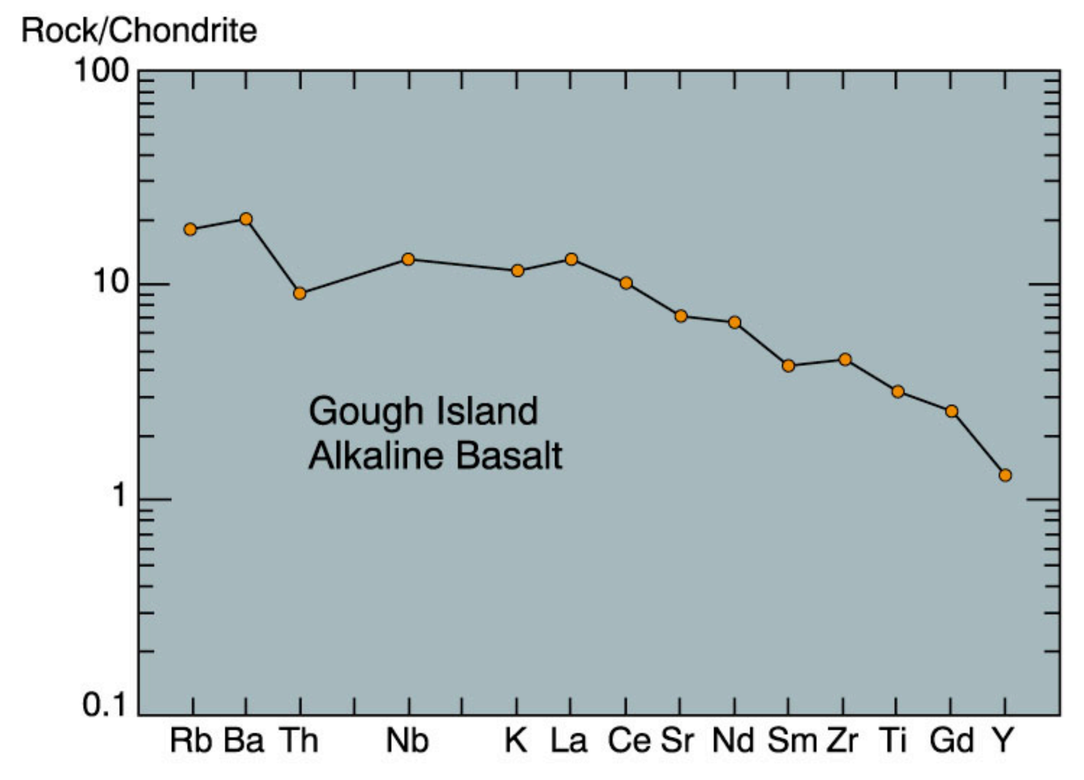
(after Wilson, 1989)

Spider Diagrams

An extension of the normalized REE technique to a broader spectrum of elements (multi-element diagrams)

Chondrite-normalized spider diagrams are commonly organized by *increasing incompatibility* Left ← Right

The order of the elements along the abscissa may vary slightly with different authors (Wood et al., 1979; Sun, 1980; Thompson, 1982, etc.)



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. (after Winter, 2001)

Spider diagram come *indicatori petrogenetici*

✓I pattern non vengono modificati in maniera significativa dai processi di FC e dal grado di PM e quindi riflettono le caratteristiche della sorgente (Pearce, 1983)

⇩

Conseguentemente, i magmi basaltici dei principali ambienti geottettonici (MORB, OIB, CFB, IAB) hanno pattern caratteristici

Spider Diagrams

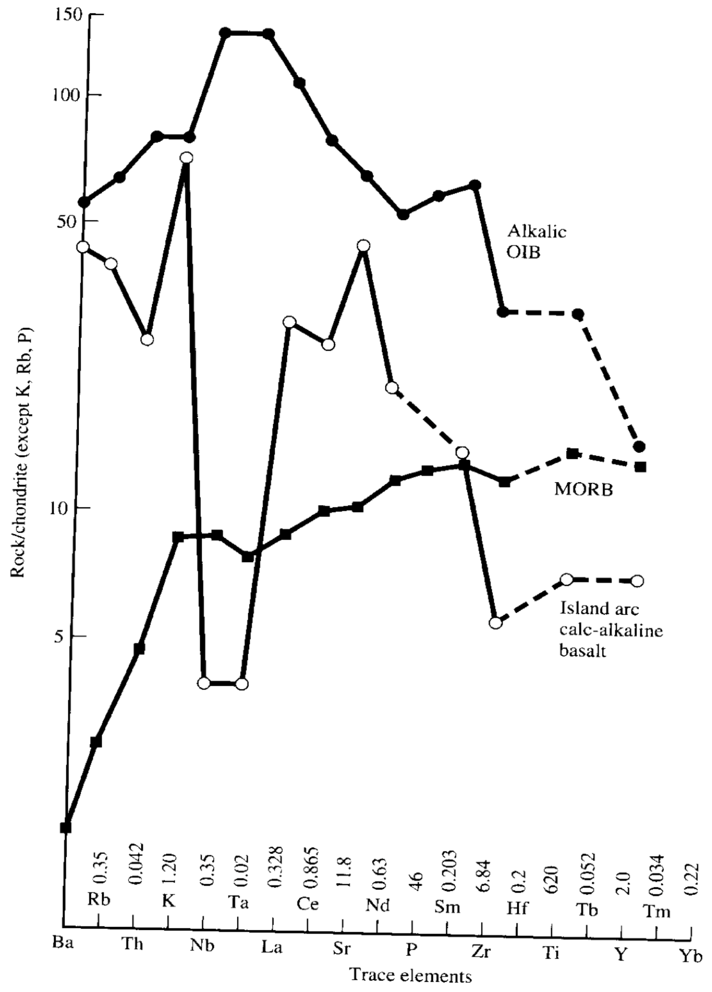


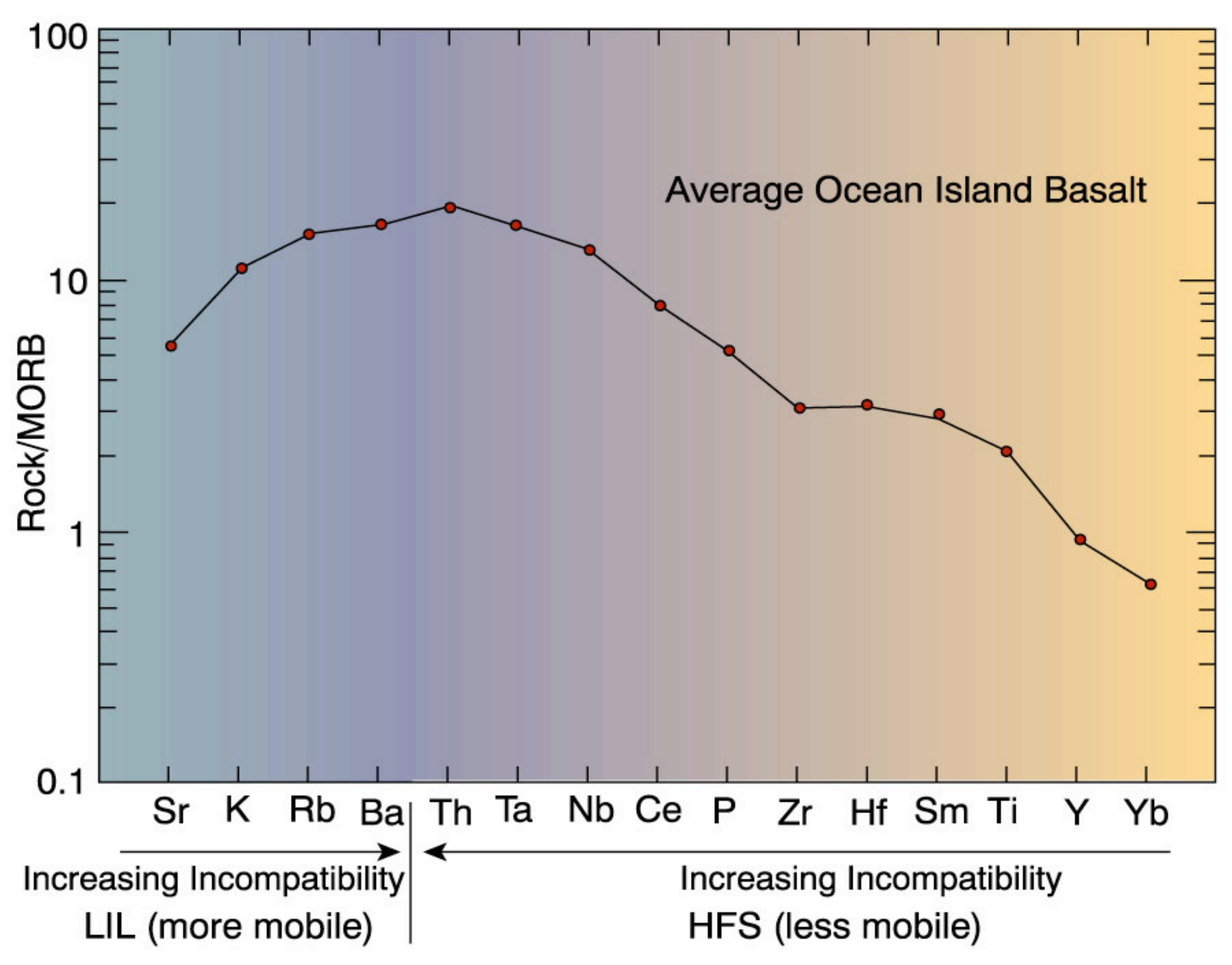
FIGURE 3-8

A typical spider diagram pattern for mid-ocean ridge (MORB), ocean island (OIB), and island arc basalts. The ordinate scale is element abundance normalized to abundance in chonditic meteorites (see text). Normalization constants along the abscissa relate to estimates of abundances of each element in the primordial earth. [From M. Wilson, 1989, *Igneous Petrogenesis: A Global Tectonic Approach* (New York: Chapman & Hall), Fig. 2.4(a).]

Typical spider diagram for MORB, OIB and IAB normalized according to Thompson et al (1984). After Wilson (989).

MORB-normalized Spider

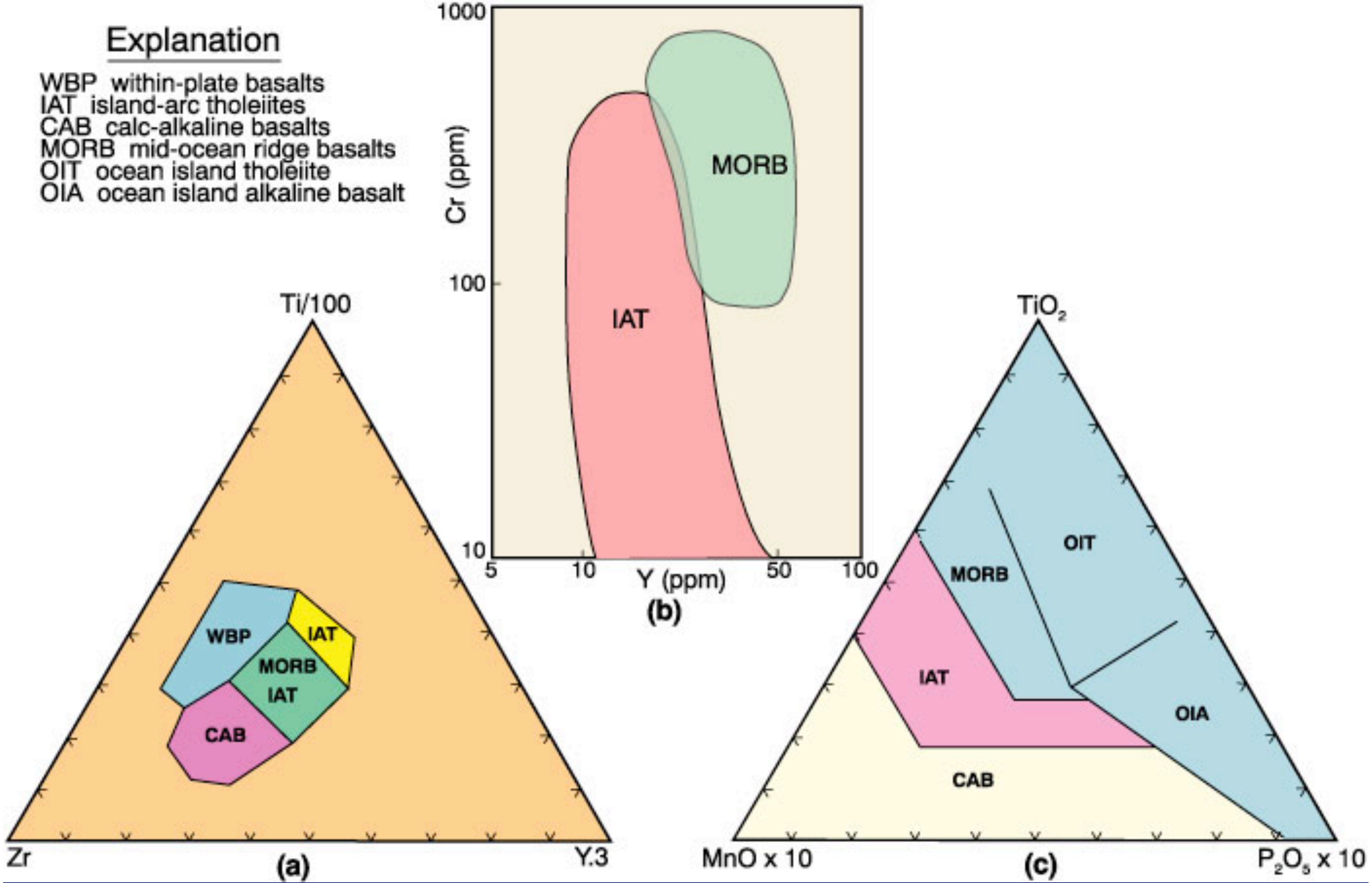
Separates LIL and HFS



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)

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



(a) after Pearce and Cann (1973), Earth Planet, Sci. Lett., **19**, 290-300. (b) after Pearce (1982) in Thorpe (ed.), Andesites: Orogenic andesites and related rocks. Wiley. Chichester. pp. 525-548, Coish et al. (1986), Amer. J. Sci., **286**, 1-28. (c) after Mullen (1983), Earth Planet. Sci. Lett., **62**, 53-62 (after Winter, 2001).

✓Isotopi come indicatori petrogenetici

L’uso degli isotopi come indicatori petrogenetici si basa su due assunti:

1. I rapporti isotopici in un magma rispecchiano quelli della sorgente (EBM process)*

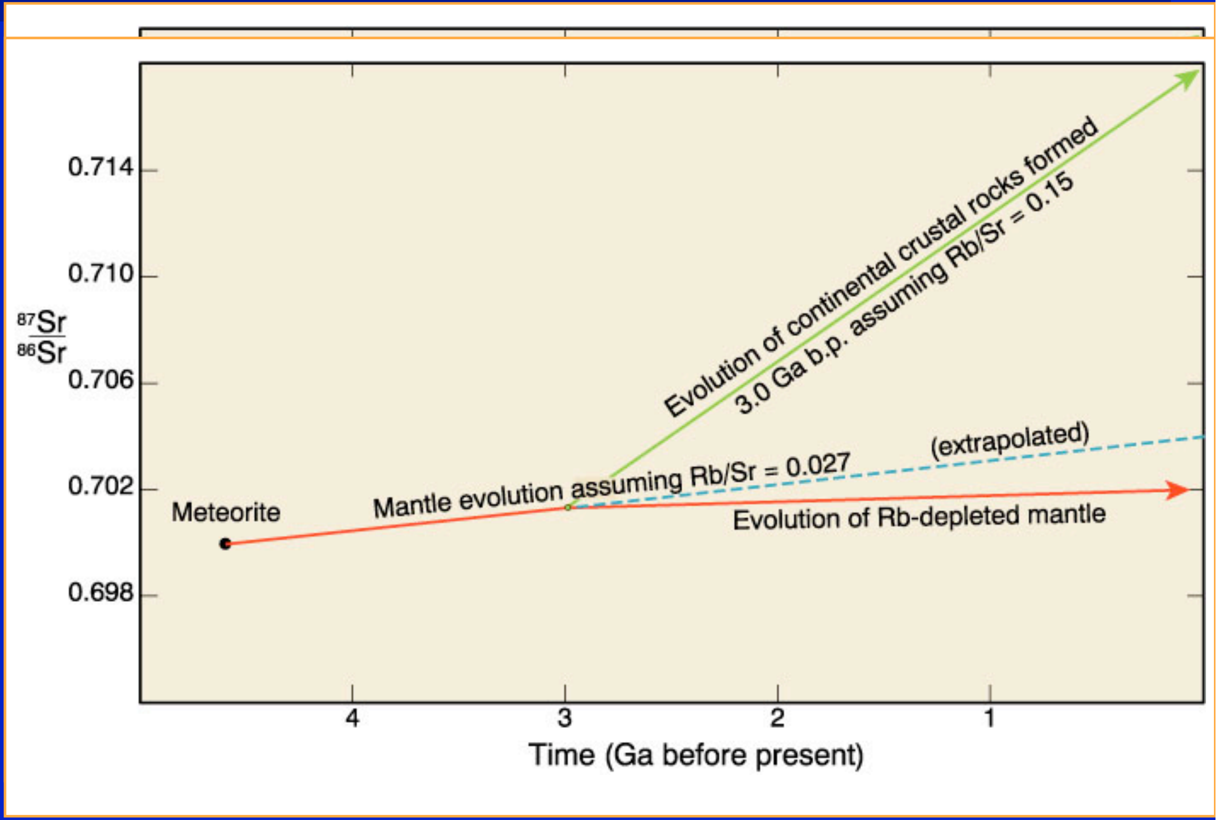
* Non vale nel caso di *fusione in disequilibrio*:la Xisotopica del fuso è f delle fasi che fondono

2. Tali rapporti non vengono modificati dai processi di frazionamento**

** Vale per elementi con massa atomica >40 (Sr, Nd, Pb, etc). Elementi più leggeri (H, C, O,N, S) si frazionano (v. Appendix)

The Rb-Sr System: Review of Sr isotopes

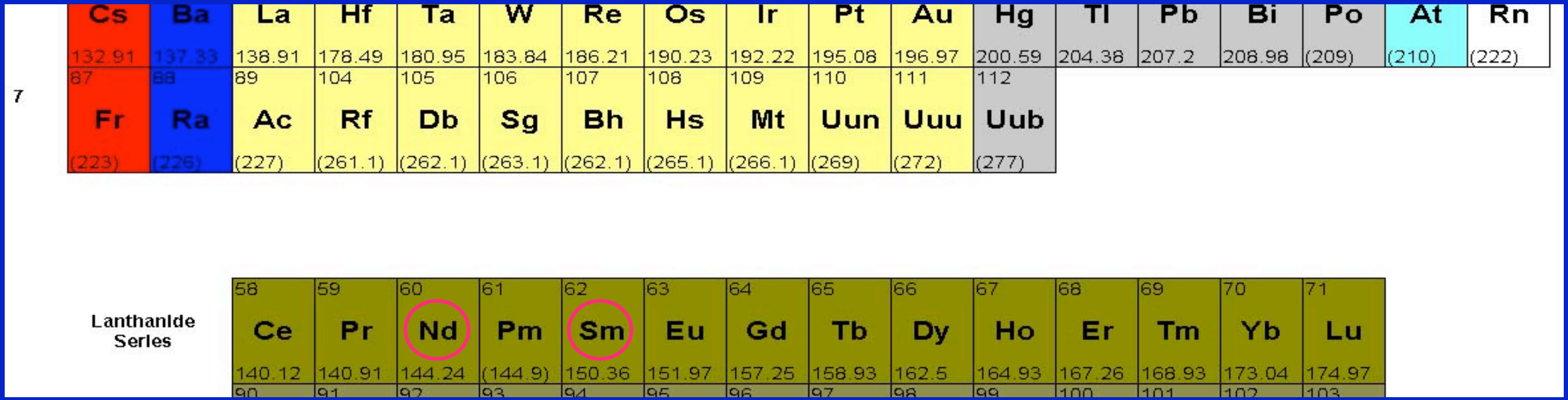
- ^{87}Rb → ^{87}Sr (decay constant λ = 1.42 x 10^{-11} a)
- Rb (parent) conc. in enriched reservoir (incompatible)
  - Enriched reservoir *develops more ^{87}Sr over time*
- Depleted reservoir (less Rb) *develops less ^{87}Sr over time*



After Wilson (1989). Igneous Petrogenesis. Unwin Hyman/Kluwer, in Winter 2001)

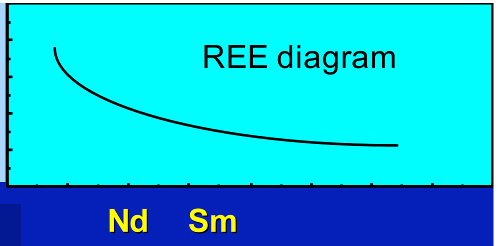
The Sm-Nd System

- Both Sm and Nd are LREE
  - Nd > incompatible than Sm
  - Sm/Nd ratio lower in partial melts than source

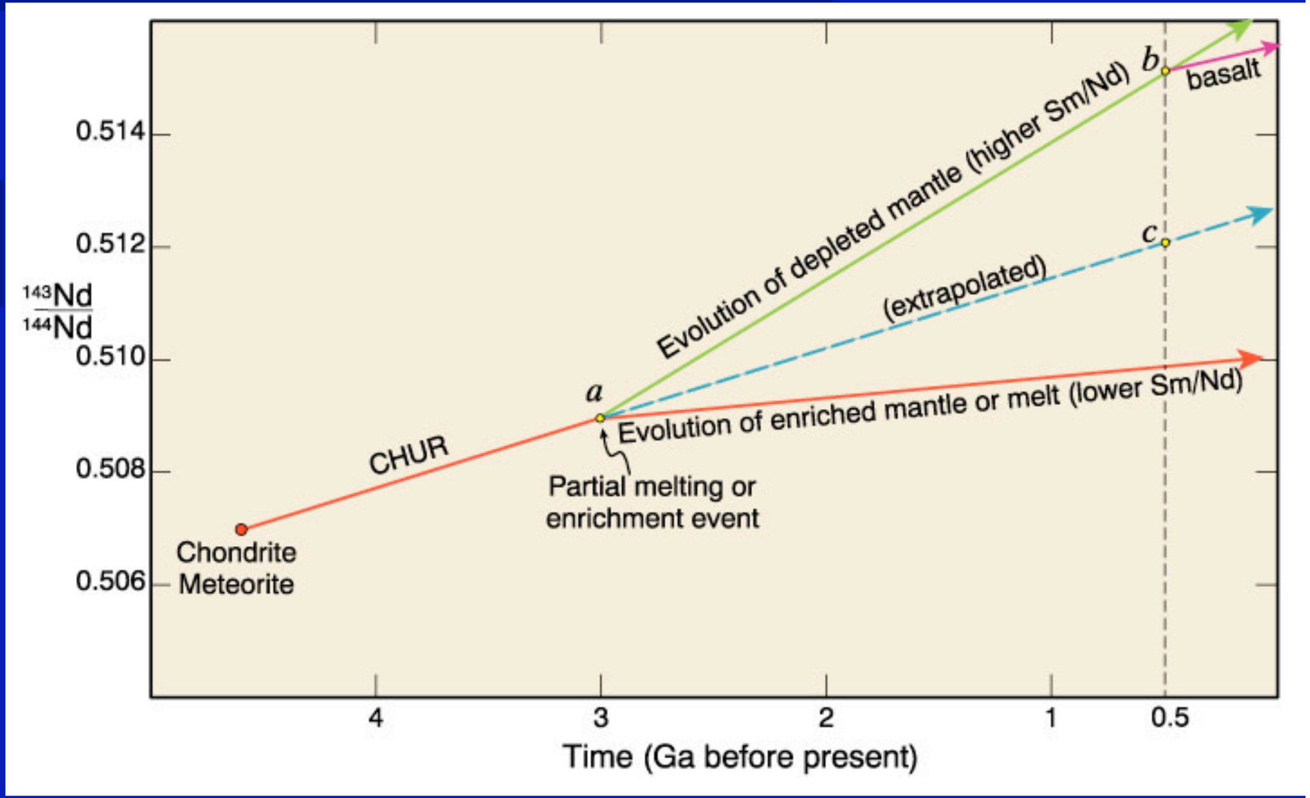


	Cs 132.91	Ba 137.33	La 138.91	Hf 178.49	Ta 180.95	W 183.84	Re 186.21	Os 190.23	Ir 192.22	Pt 195.08	Au 196.97	Hg 200.59	Tl 204.38	Pb 207.2	Bi 208.98	Po (209)	At (210)	Rn (222)
7	87 Fr (223)	88 Ra (226)	89 Ac (227)	104 Rf (261.1)	105 Db (262.1)	106 Sg (263.1)	107 Bh (262.1)	108 Hs (265.1)	109 Mt (266.1)	110 Uun (269)	111 Uuu (272)	112 Uub (277)						
Lanthanide Series			58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (144.9)	62 Sm 150.36	63 Eu 151.97	64 Gd 157.25	65 Tb 158.93	66 Dy 162.5	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97		
			90	91	92	93	94	95	96	97	98	99	100	101	102	103		

Review of Nd isotopes

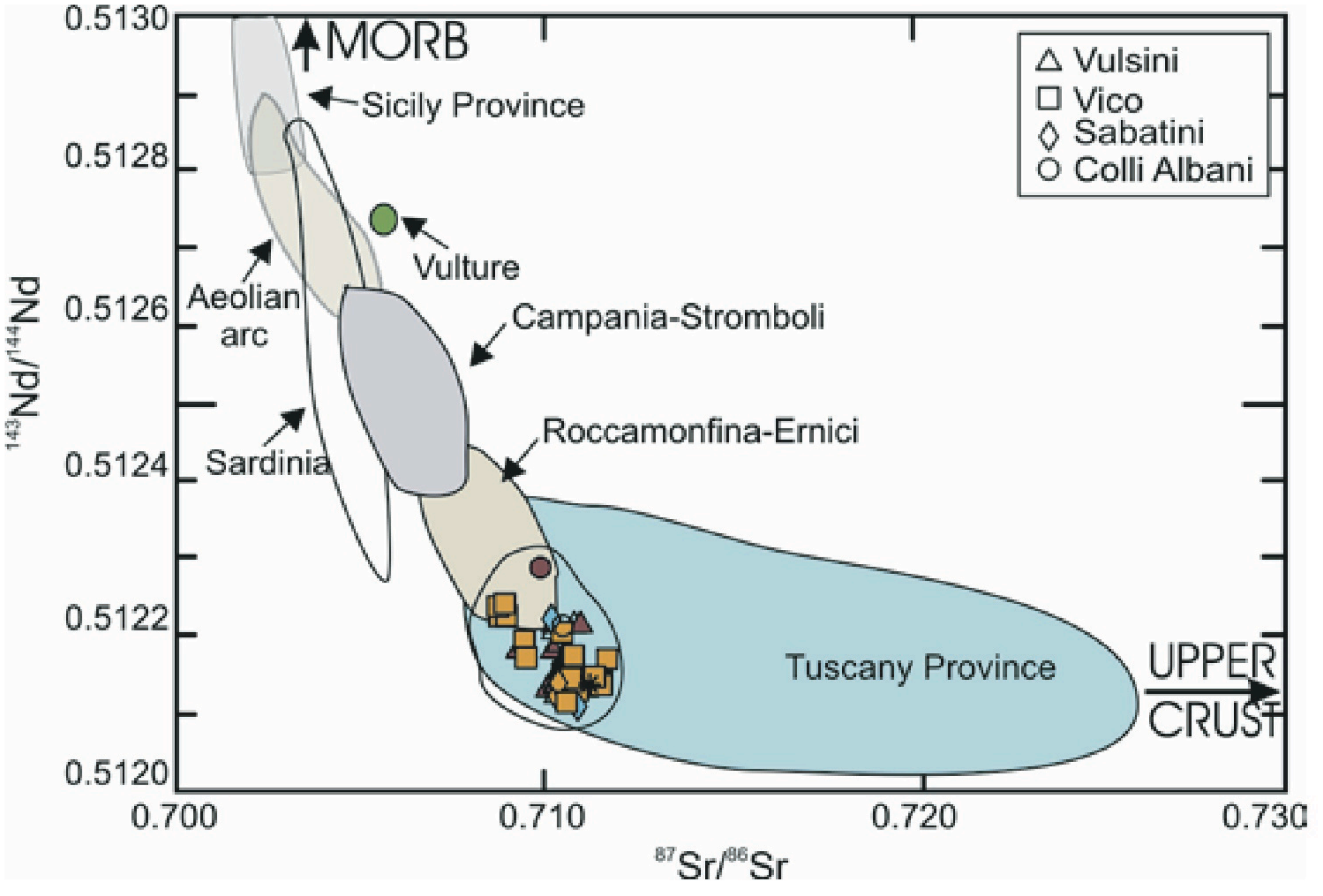


- $^{147}Sm \rightarrow {}^{143}Nd$ (decay constant $\lambda = 6.54 \times 10^{-12}$ a)
- Nd (daughter) enriched reservoir > Sm
  - Enriched reservoir develops *less* *^{143}Nd over time*
  - Depleted res. (higher Sm/Nd) develops *higher* *$^{143}Nd/^{144}Nd$ over time*



After Wilson (1989). Igneous Petrogenesis. Unwin Hyman/Kluwer, in Winter 2001)

Isotope Correlation Diagram: Mixing between two sources



(after Peccerillo, 2007)

Appendix

Review of trace elements
Chemical Fractionation and Distribution Coefficient (D)

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

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

$$K = a^{i\ \text{solid}}/a^{i\ \text{liquid}} = \gamma X^{i\ \text{solid}}/\gamma\, {}^{i}X^{\ \text{liquid}}$$

K = equilibrium constant

✓ For dilute solutions can substitute D for K_D:

$$D = C_S/C_L$$

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.
V, Ti	Both show strong fractionation into Fe-Ti oxides (ilmenite or titanomagnetite). If they behave differently, Ti probably fractionates into an accessory phase, such as sphene or rutile.
Zr, Hf	Very incompatible elements that do not substitute into major silicate phases (although they may replace Ti in sphene or rutile).
Ba, Rb	Incompatible element that substitutes for K in K-feldspar, micas, or hornblende. Rb substitutes less readily in hornblende than K-spar and micas, such that the K/Ba ratio may distinguish these phases.
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 at higher pressure where plagioclase is no longer stable.
REE	Garnet accommodates the HREE more than the LREE, and orthopyroxene and hornblende do so to a lesser degree. Sphene and plagioclase accommodates more LREE. Eu^{2+} is strongly partitioned into plagioclase.
Y	Commonly incompatible (like HREE). Strongly partitioned into garnet and amphibole. Sphene and apatite also concentrate Y, so the presence of these as accessories could have a significant effect.

Table 9-6. After Green (1980). Tectonophys., **63**, 367-385. From Winter (2001)

Stable Isotopes

- Stable: last ~ forever
- Chemical fractionation is impossible
- Mass fractionation is the only type possible

Example: Oxygen Isotopes

^{16}O	99.756%	of natural oxygen
^{17}O	0.039%	“
^{18}O	0.205%	“

Concentrations expressed by reference to a standard

International standard for O isotopes = standard mean ocean water (SMOW)

^{18}O and ^{16}O are the commonly used isotopes and their ratio is expressed as d:

d $(^{18}O/^{16}O) =$

$$\frac{(^{18}O/^{16}O)_{\mathrm{sample}} - (^{18}O/^{16}O)_{\mathrm{SMOW}}}{(^{18}O/^{16}O)_{\mathrm{SMOW}}} \times 1000$$

result expressed in per mille (‰)

$\delta^{18}O$ vs. $^{87}Sr/^{86}Sr$

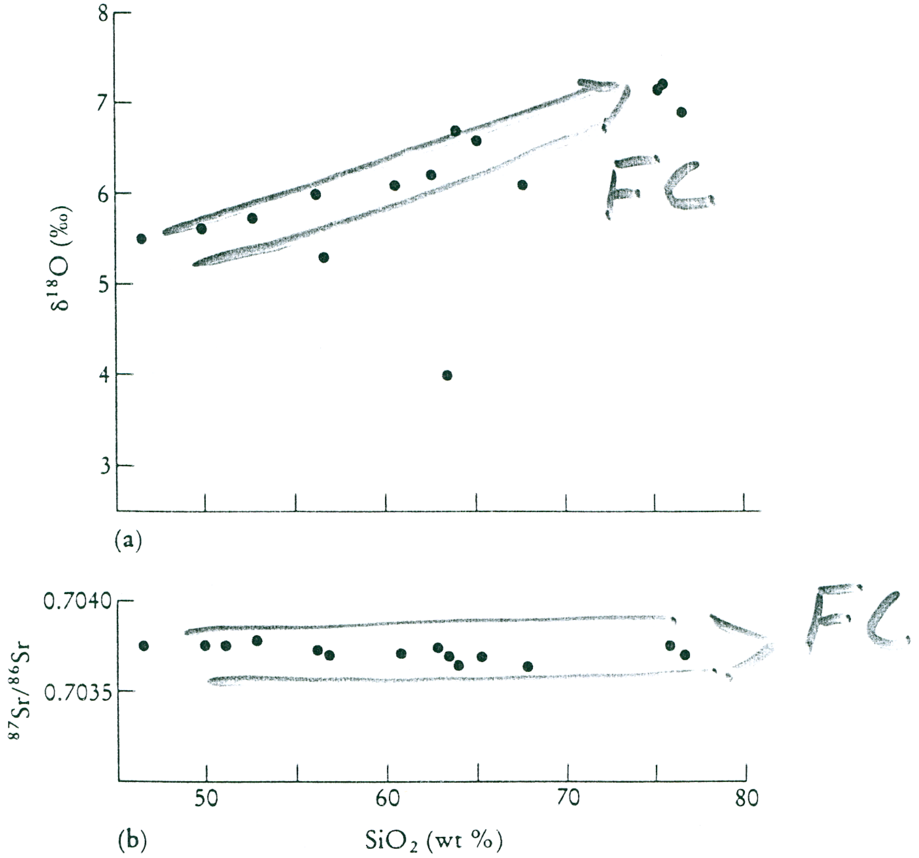


Figure 7.10 (a) Plot showing a positive correlation between $\delta^{18}O$ and SiO_2 for a fractional crystallization-related calc–alkaline gabbro–diorite–tonalite–trondhjemite suite from an oceanic-arc plutonic complex in the Solomon Islands. (b) The same suite of rocks shows no correlation between $^{87}Sr/^{86}Sr$ and SiO_2. (Data from Chivas *et al.*, 1982.)

(after Rollinson, 1993)