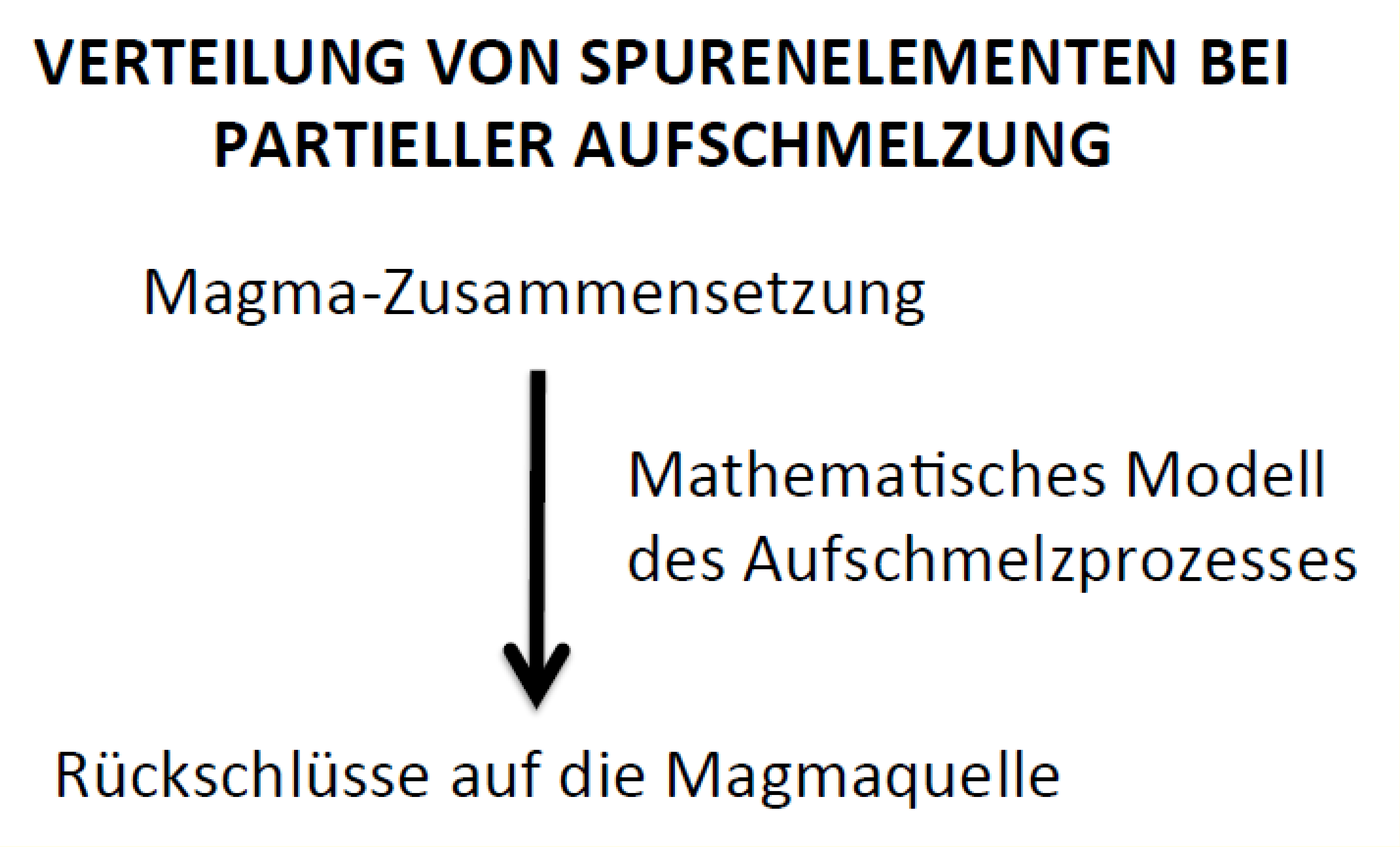
Spurenelemente in magmatischen Prozessen



VERTEILUNG VON SPURENELEMENTEN BEI PARTIELLER AUFSCHMELZUNG

Magma-Zusammensetzung

↓ Mathematisches Modell des Aufschmelzprozesses

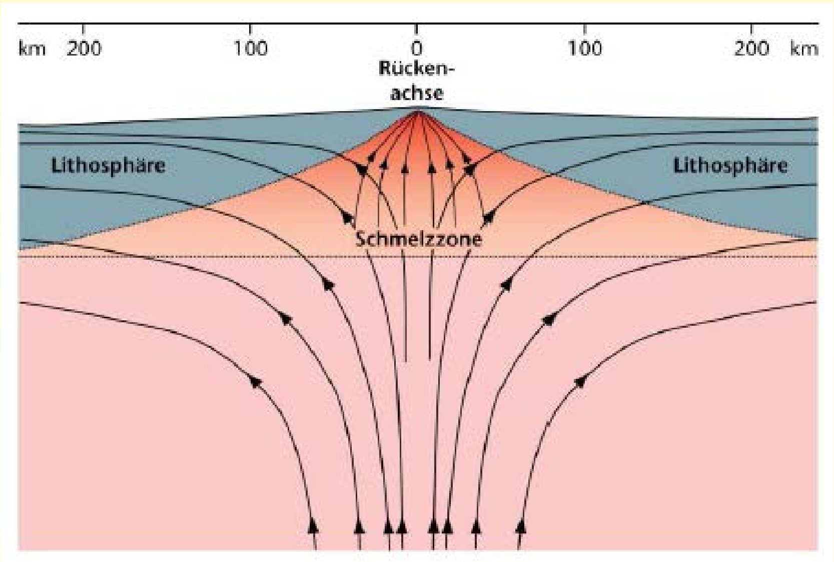
Rückschlüsse auf die Magmaquelle

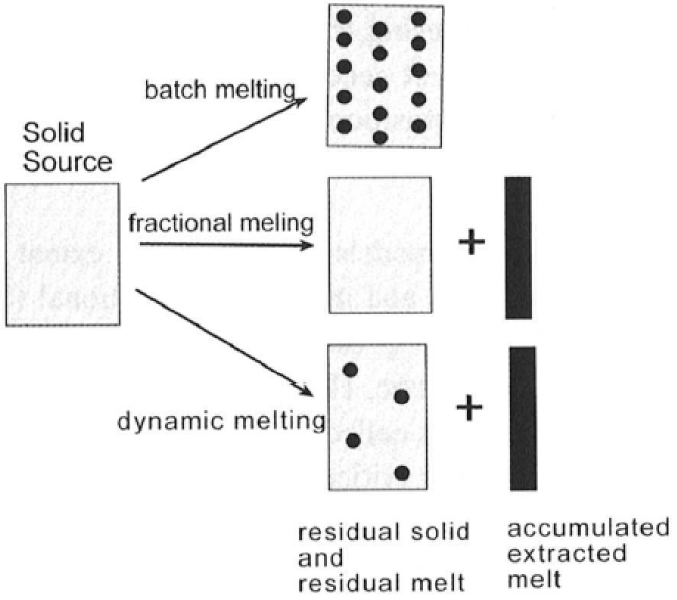
Modelle der Schmelzbildung

- Gleichgewichtsschmelzen = Batch (equilibrium) melting: Eine bestimmte Menge an Schmelze equilibriert mit dem Residualgestein

- Fraktionierte Aufschmelzung = Fractional melting: Die Schmelze wird sofort nach ihrer Bildung extrahiert

- Kontinuierliche Aufschmelzung = Continuous melting: Die Schmelze wird kontinuierlich extrahiert, aber ein Teil der Schmelze bleibt im System um die Porenräume zu füllen





Modelle der Schmelzbildung

Was für ein Schmelzbildungsprozess hat hier stattgefunden?

Modelle der Schmelzbildung

- Modal

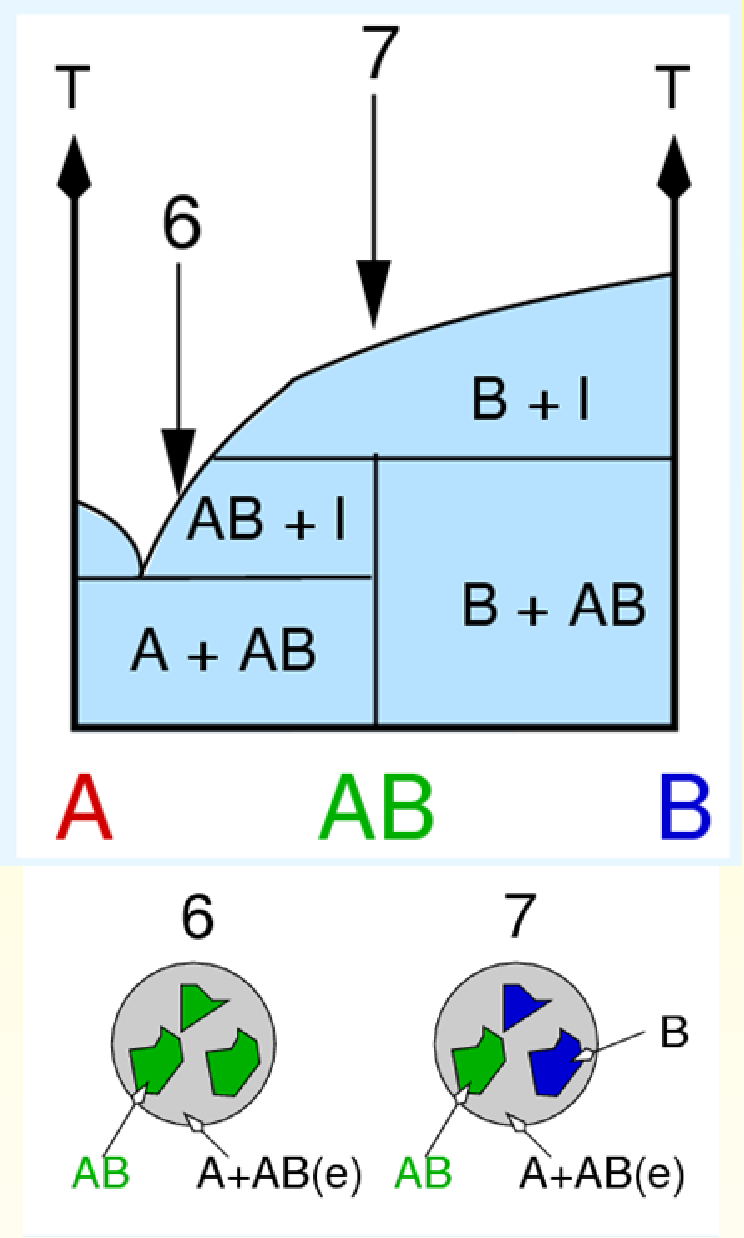
  Ausgangsgestein und Schmelze haben gleiche modale Zusammensetzung

- Nicht modal (eutektisch)

  Ausgangsgestein und Schmelze haben unterschiedliche modale Zusammensetzung

- Inkongruent (peritektisch)

  die feste Phase reagiert mit der Schmelze. Bildung neuer Mineralphasen



Modelle der Schmelzbildung

- Schmelzbildung von Gesteinen ist oft komplexer als durch die bisherigen Gleichungen beschrieben
  - Verläuft typischerweise inkongruent
  - Minerale → Minerale + Schmelze → Schmelze

  z.B. A ol + B cpx → C opx + D liquid

Inkongruentes Schmelzen

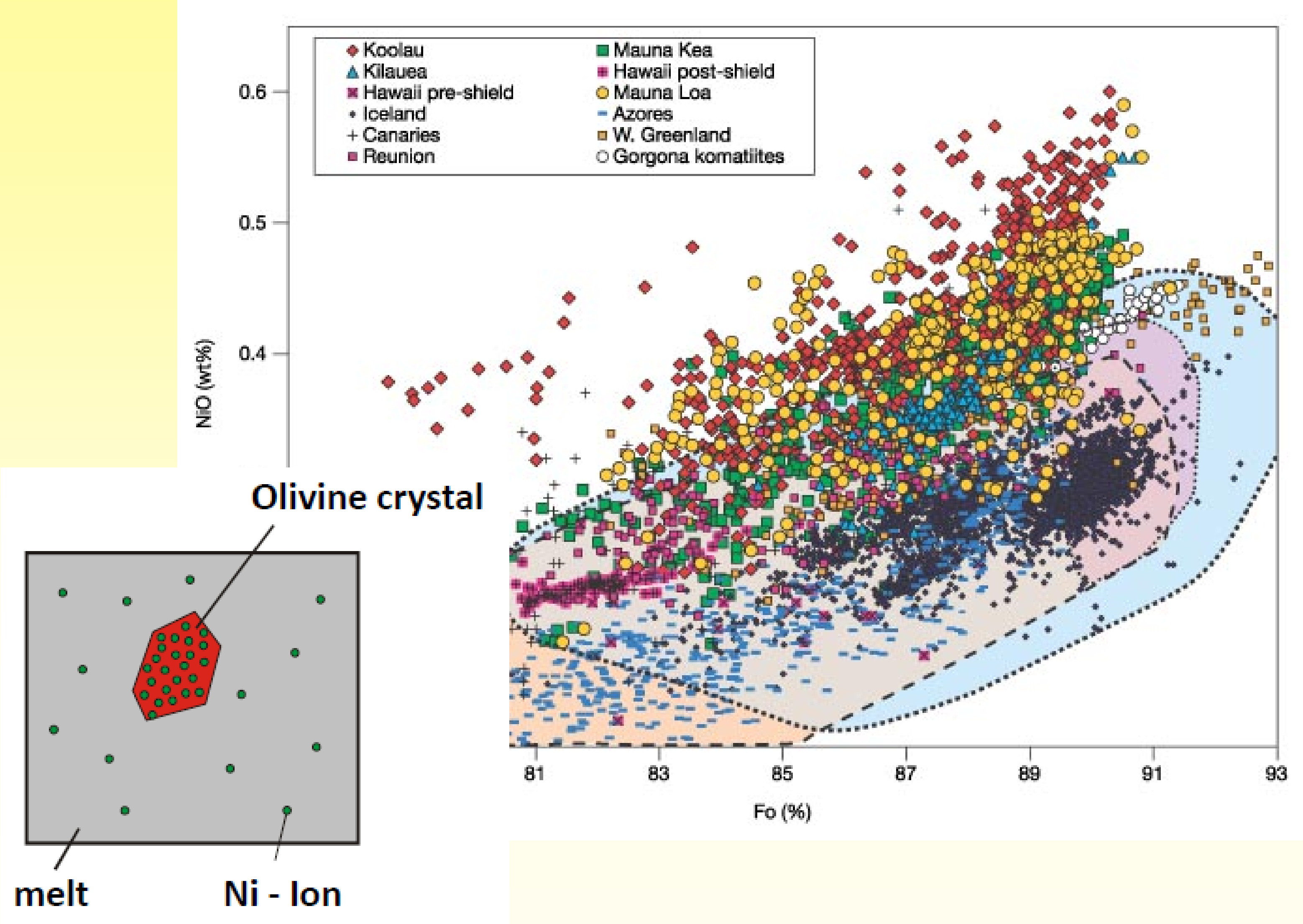
(non-modal melting)

- komplexer aber realistischer

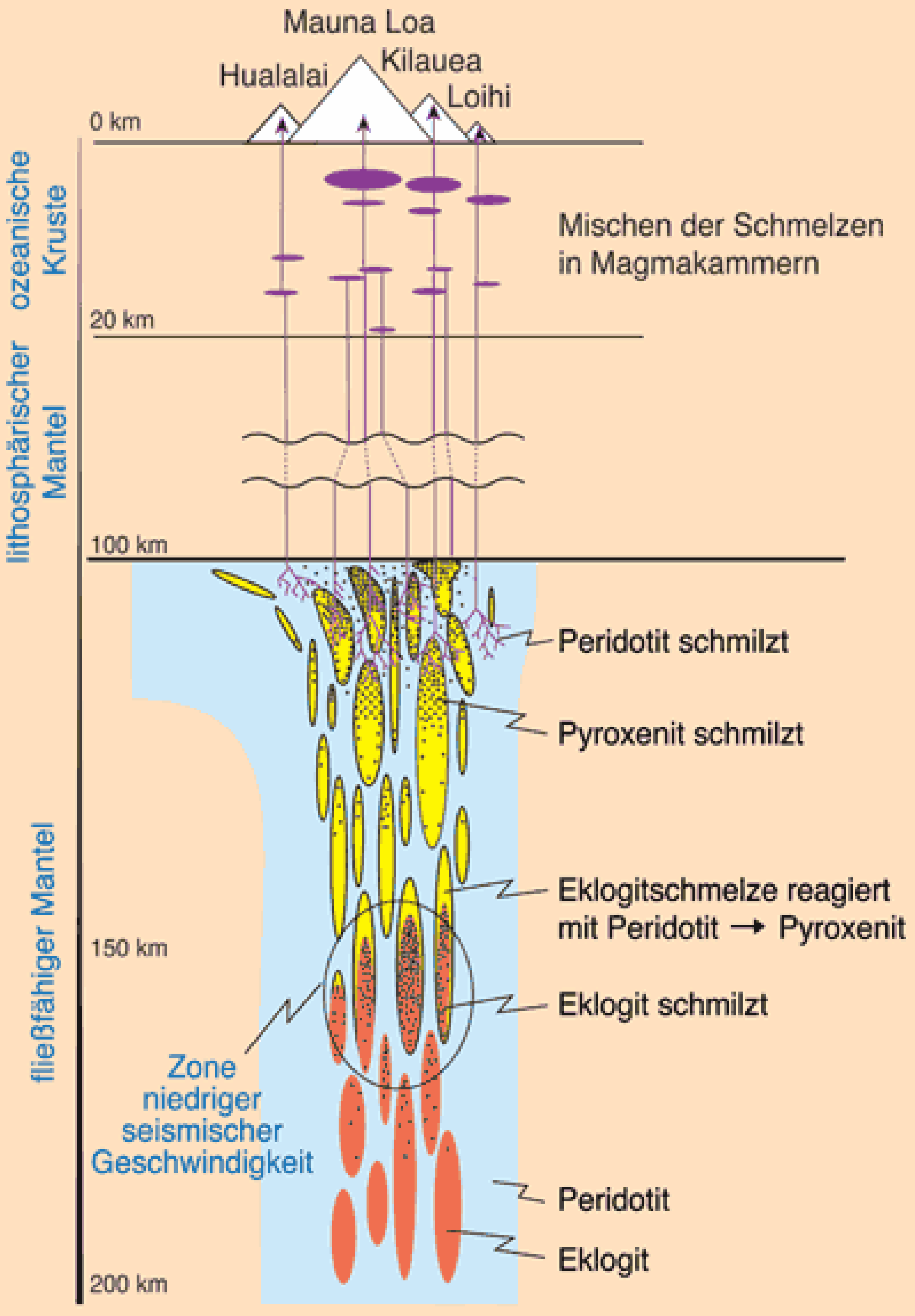
- setzt Kenntnisse über Schmelzbildungsreaktionen voraus

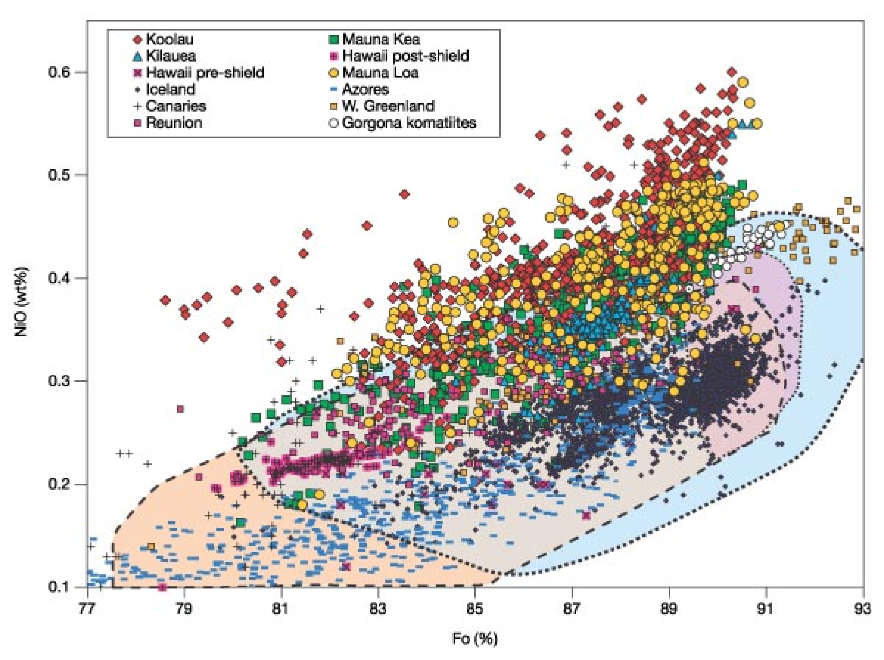
feste Phase reagiert mit der Schmelze. Die resultierende Schmelze hat danach einen anderen Chemismus als die feste Ausgangsphase

Hawaii – hohe Ni-Gehalte in OIBs



Sobolev et al. Nature 2005, vol. 434, p. 590



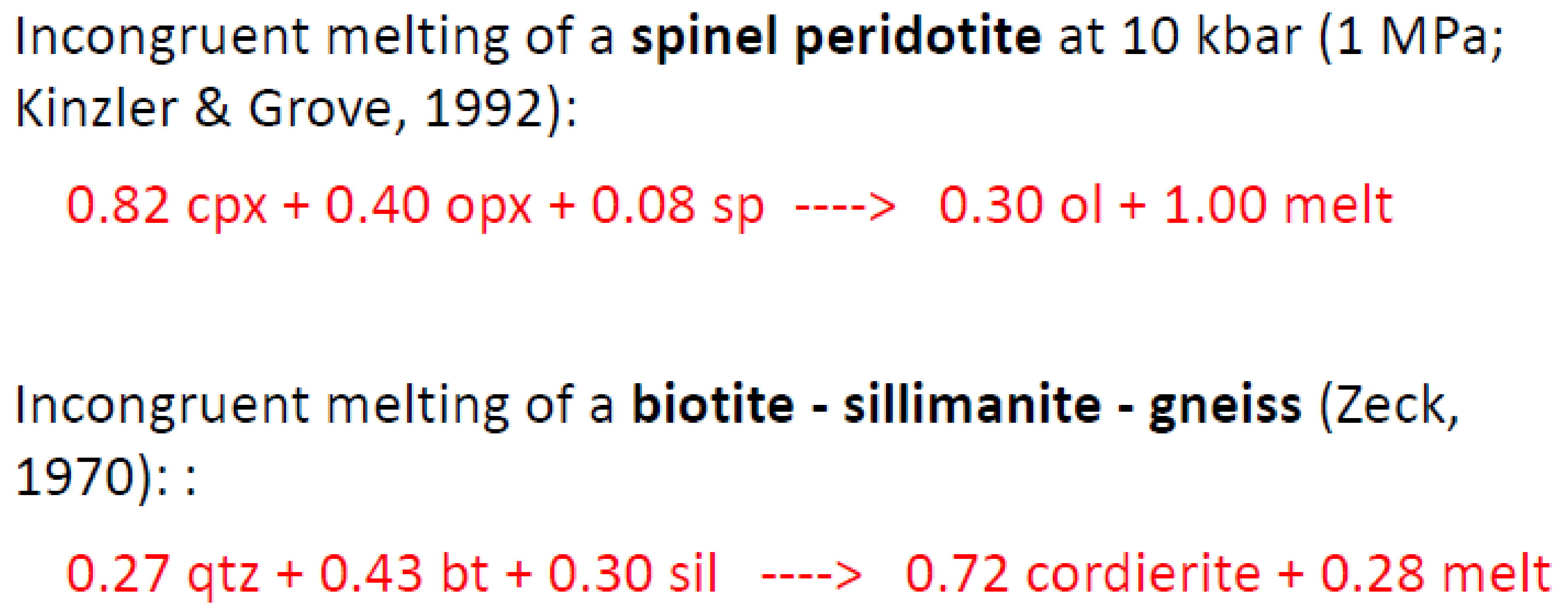


Sobolev et al. Nature 2005, vol. 434, p. 590

Modelle der Schmelzbildung

Inkongruentes Schmelzen

Beispiele:



Incongruent melting of a **spinel peridotite** at 10 kbar (1 MPa; Kinzler & Grove, 1992):

0.82 cpx + 0.40 opx + 0.08 sp ----> 0.30 ol + 1.00 melt

Incongruent melting of a **biotite - sillimanite - gneiss** (Zeck, 1970): :

0.27 qtz + 0.43 bt + 0.30 sil ----> 0.72 cordierite + 0.28 melt

Modelle der Schmelzbildung

Nicht-modale Aufschmelzung (Non-modal melting):

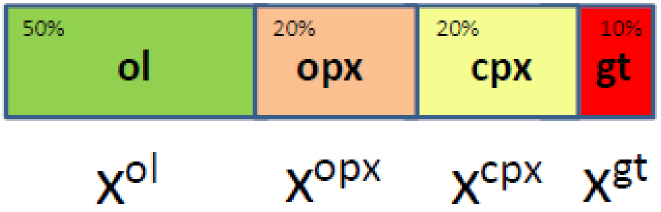
Minerale bilden die Schmelzphase nicht in den gleichen Verhältnissen, in denen sie im Gestein vorliegen

→ Verhältnisse, in denen die Minerale an der Schmelzbildung beteiligt sind, müssen bei der Berechnung berücksichtigt werden

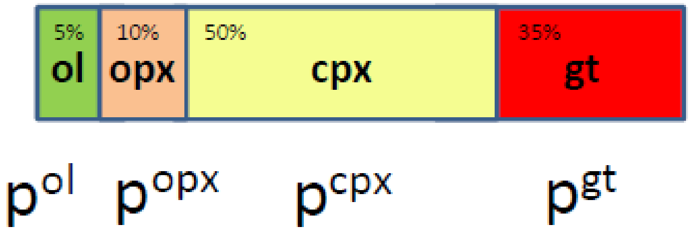
$$\boxed{P_i = \sum_{\phi} p_{\phi} D_i^{\phi/l}}$$

p = Anteil, in denen ein Mineral an der Schmelzbildung beteiligt ist

D_i^{ϕ} = Verteilungskoeffizient von Phase ϕ



Modal composition of the **solid**
(here: Lherzolite, "Pyrolite")



"**Modal composition**" of the **melt**
(i.e. eutectic composition,
here: basaltic melt)

Non modal melting

Non-modal batch melting

$$\boxed{\frac{C_i^l}{C_i^o} = \frac{1}{F(1-P_i)+D_i^o}}$$

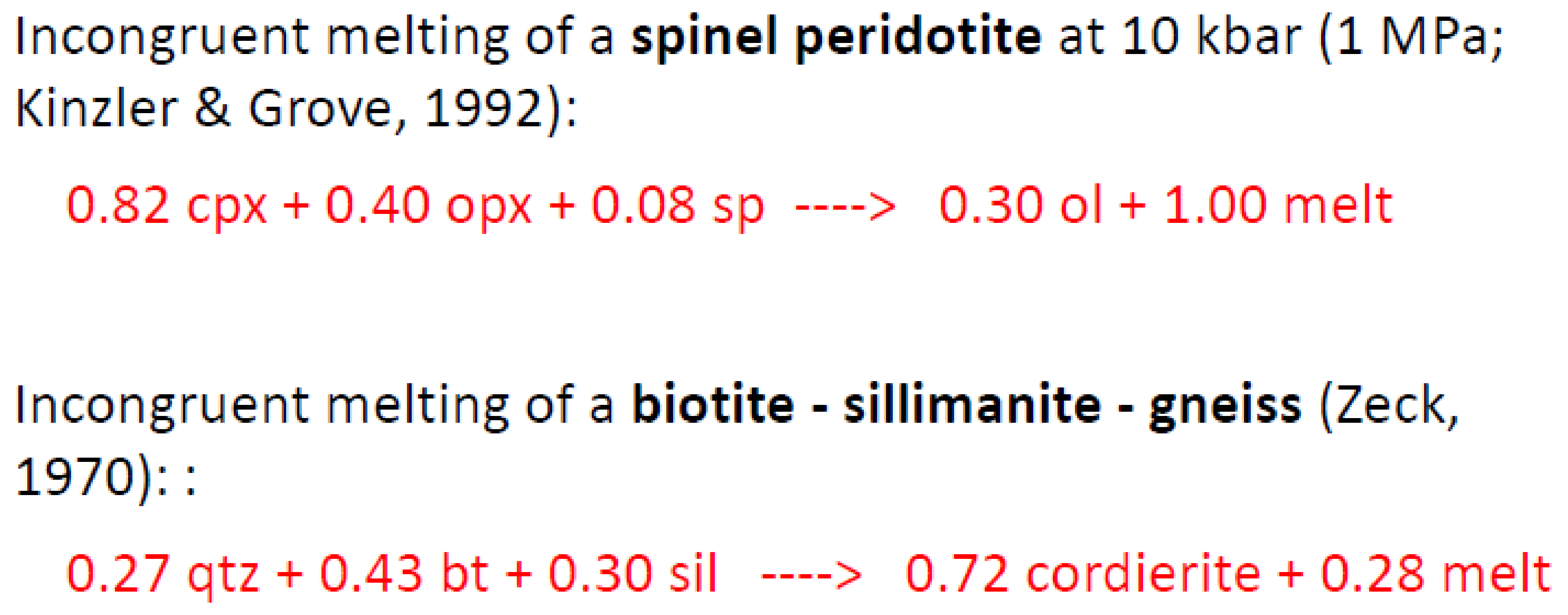
Non-modal fractional melting

$$\boxed{\frac{C_i^l}{C_i^o} = \frac{1}{D_i^o}\left(1-\left(1-\frac{P_iF}{D_i^o}\right)^{1/P_i}\right)}$$

Modelle der Schmelzbildung

Inkongruentes Schmelzen

Beispiele:



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0.27 qtz + 0.43 bt + 0.30 sil ----> 0.72 cordierite + 0.28 melt

Spurenelemente in magmatischen Prozessen

Verteilungskoeffizient: $$Kd = \frac{C_i^{\text{min}}}{C_i^{\text{Schmelze}}}$$

Gesamtverteilungskoeffizient D

$$D_i = x_1 Kd_i^{\text{min1}} + x_2 Kd_i^{\text{min2}} + x_3 Kd_i^{\text{min3}}$$

Massenbilanz: $$C_i^o = C_i^s (1 - F) + C_i^l F$$

i = Element

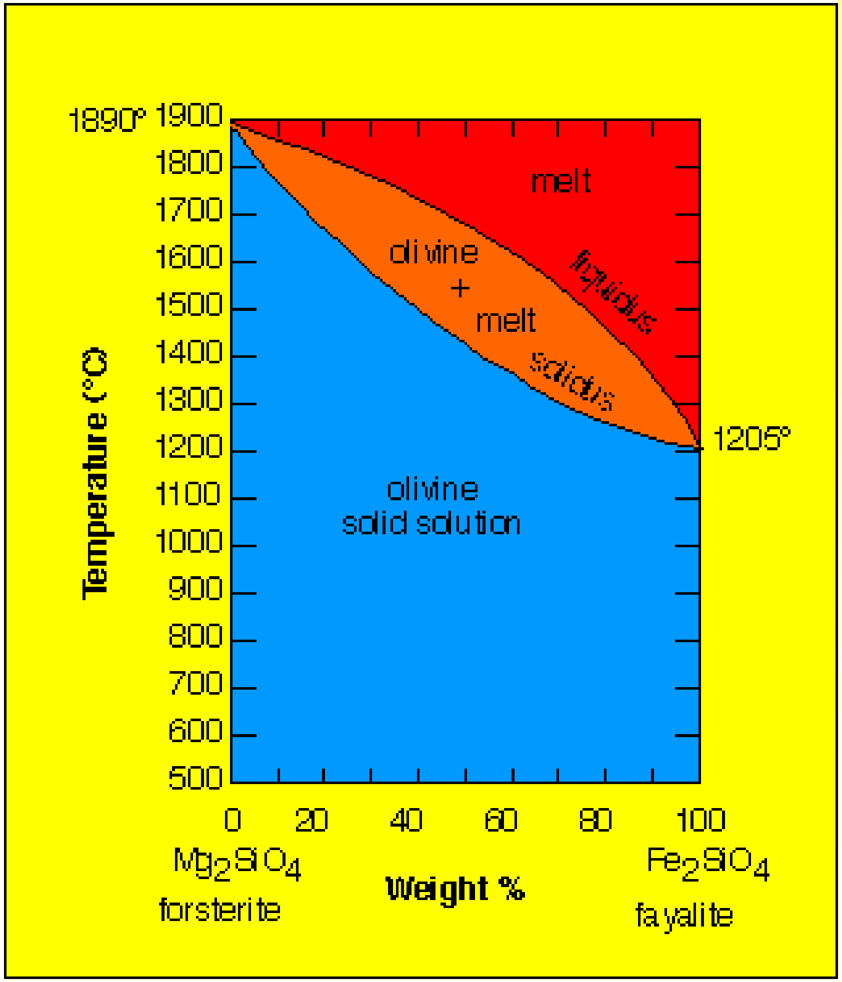
C^o = Ursprüngliche Konzentration in den festen Phasen

C^l = Konzentration in der Schmelze

C^s = Konzentration in den residualen festen Phasen nach der Aufschmelzung

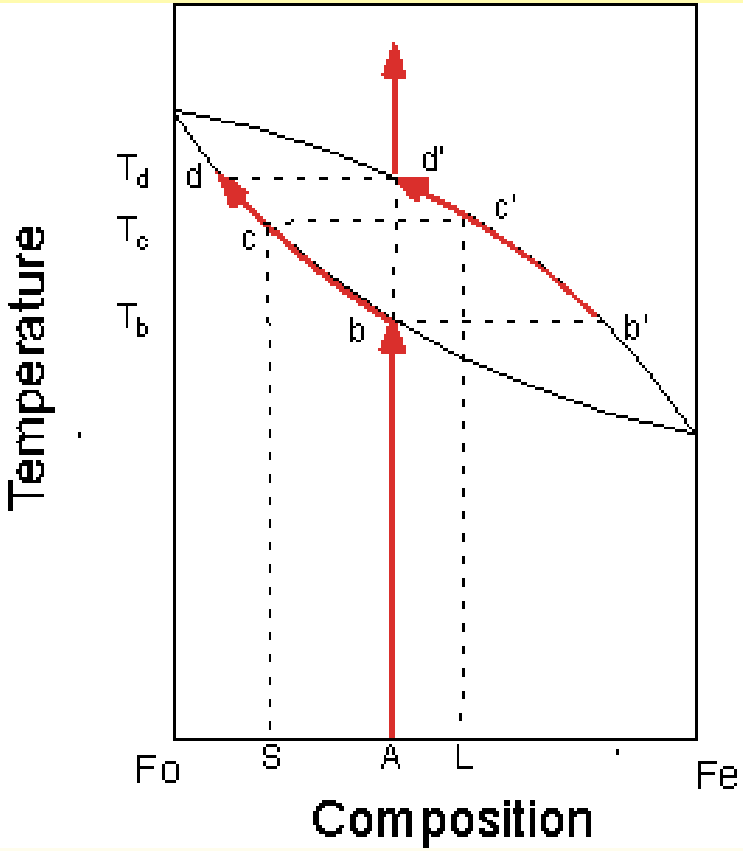
F = Aufschmelzgrad

Gleichgewichtsschmelzbildung
Batch melting bzw. equilibrium melting

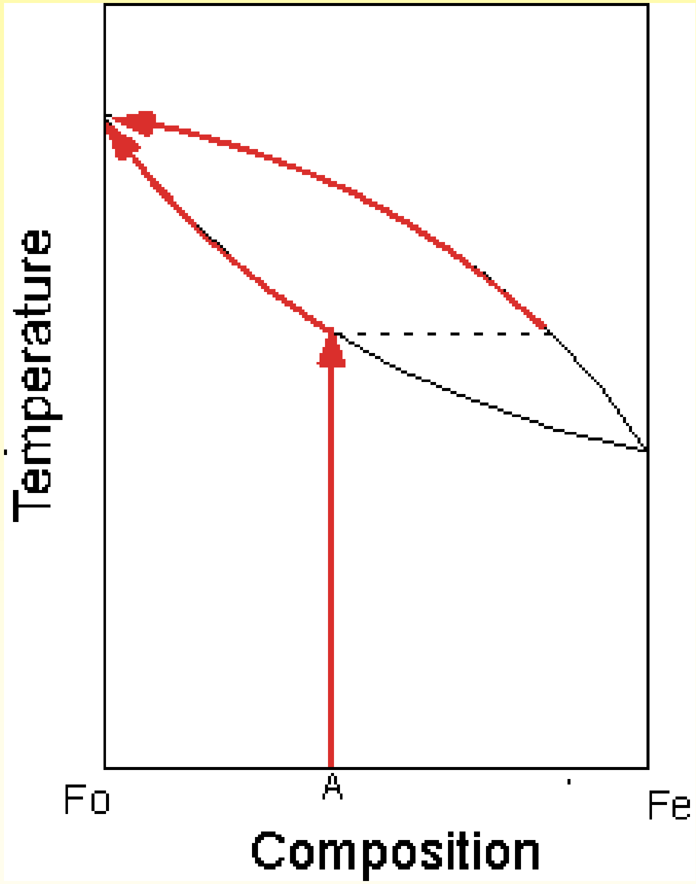


Fraktionierte Aufschmelzung

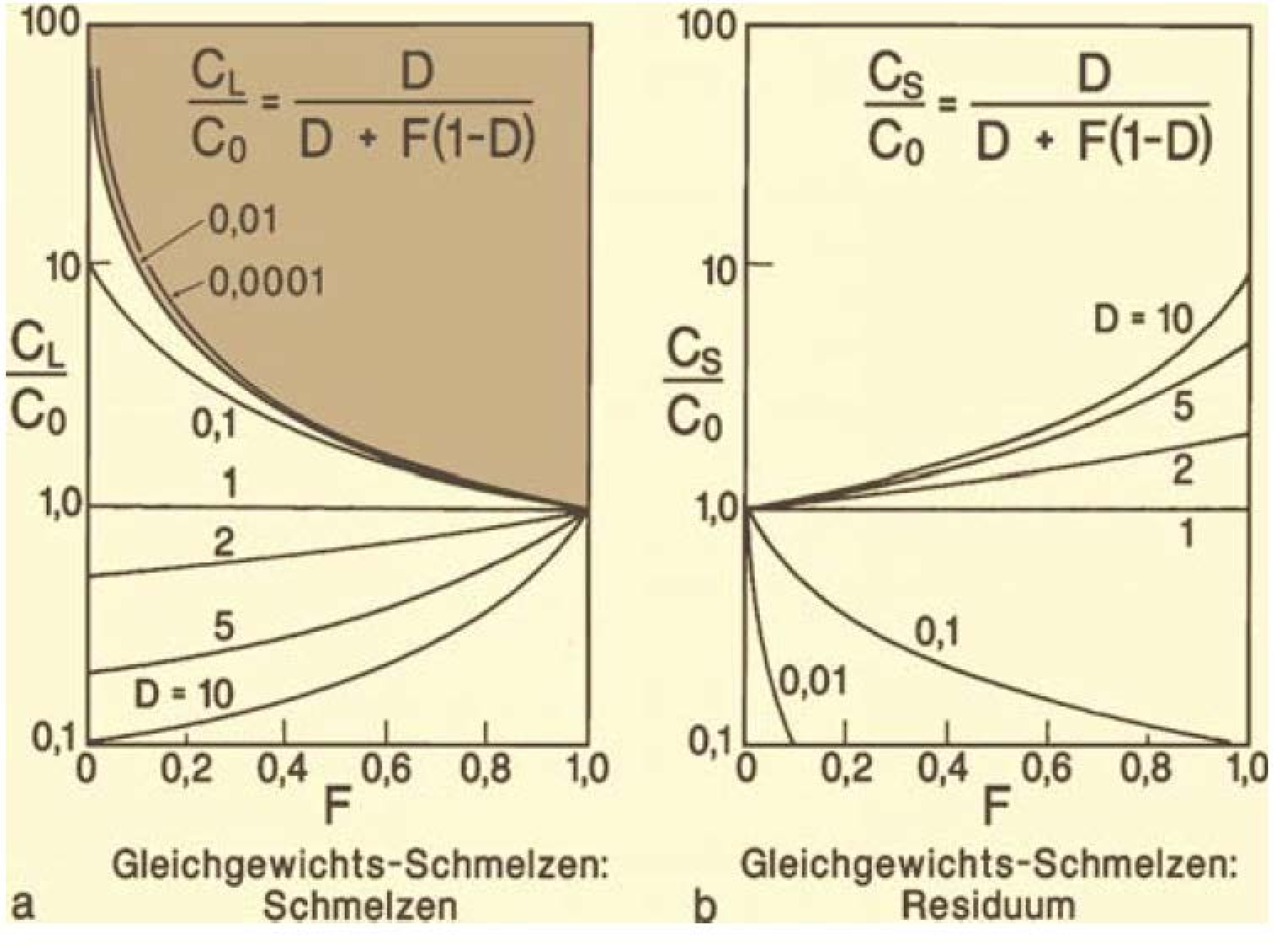
Gleichgewichts-Schmelzbildung



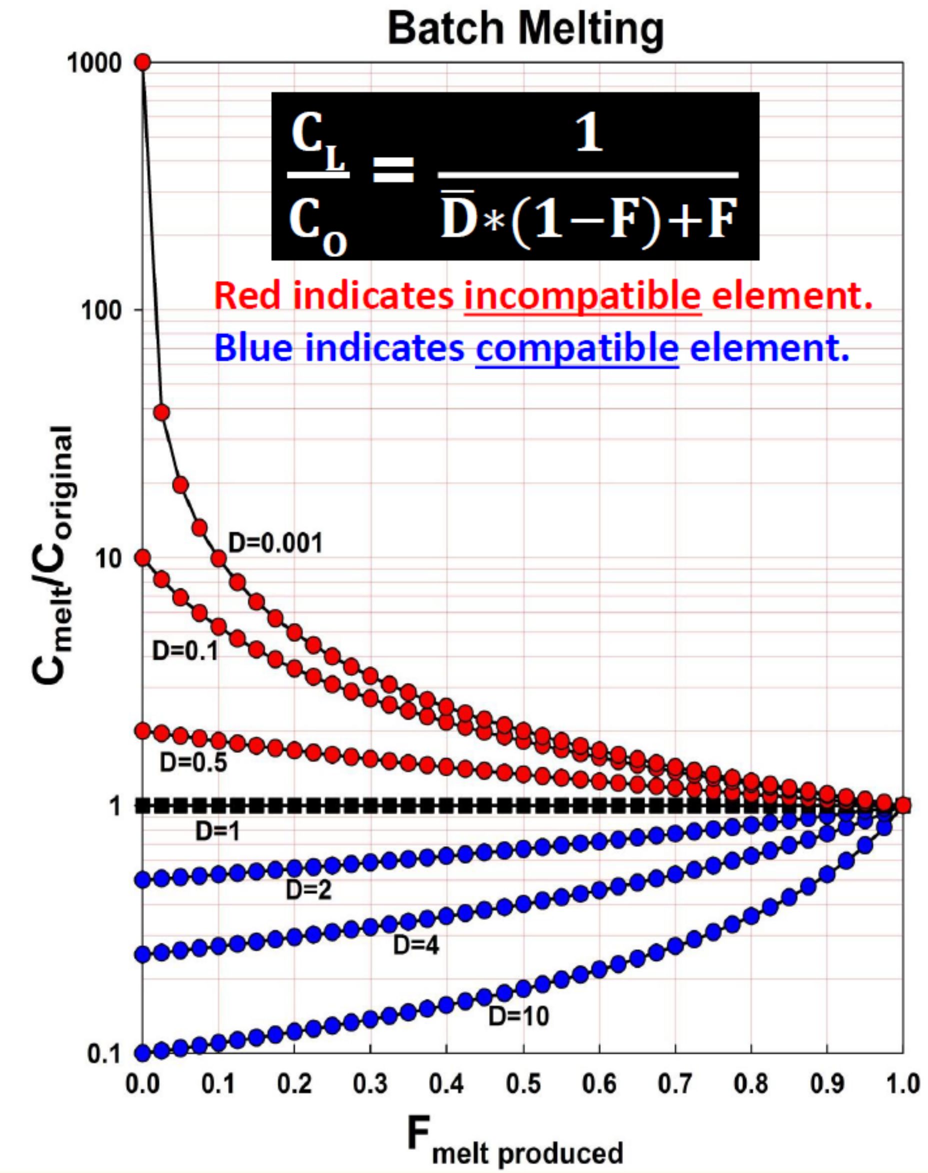
Fraktionierte Aufschmelzung



Gleichgewichtsschmelzbildung
Batch melting bzw. equilibrium melting



“Batch melting modeling”



$C_{melt}/C_{original}$

$F_{melt\ produced}$

$$\frac{C_L}{C_o} = \frac{1}{\bar{D} * (1 - F) + F}$$

Red indicates incompatible element.

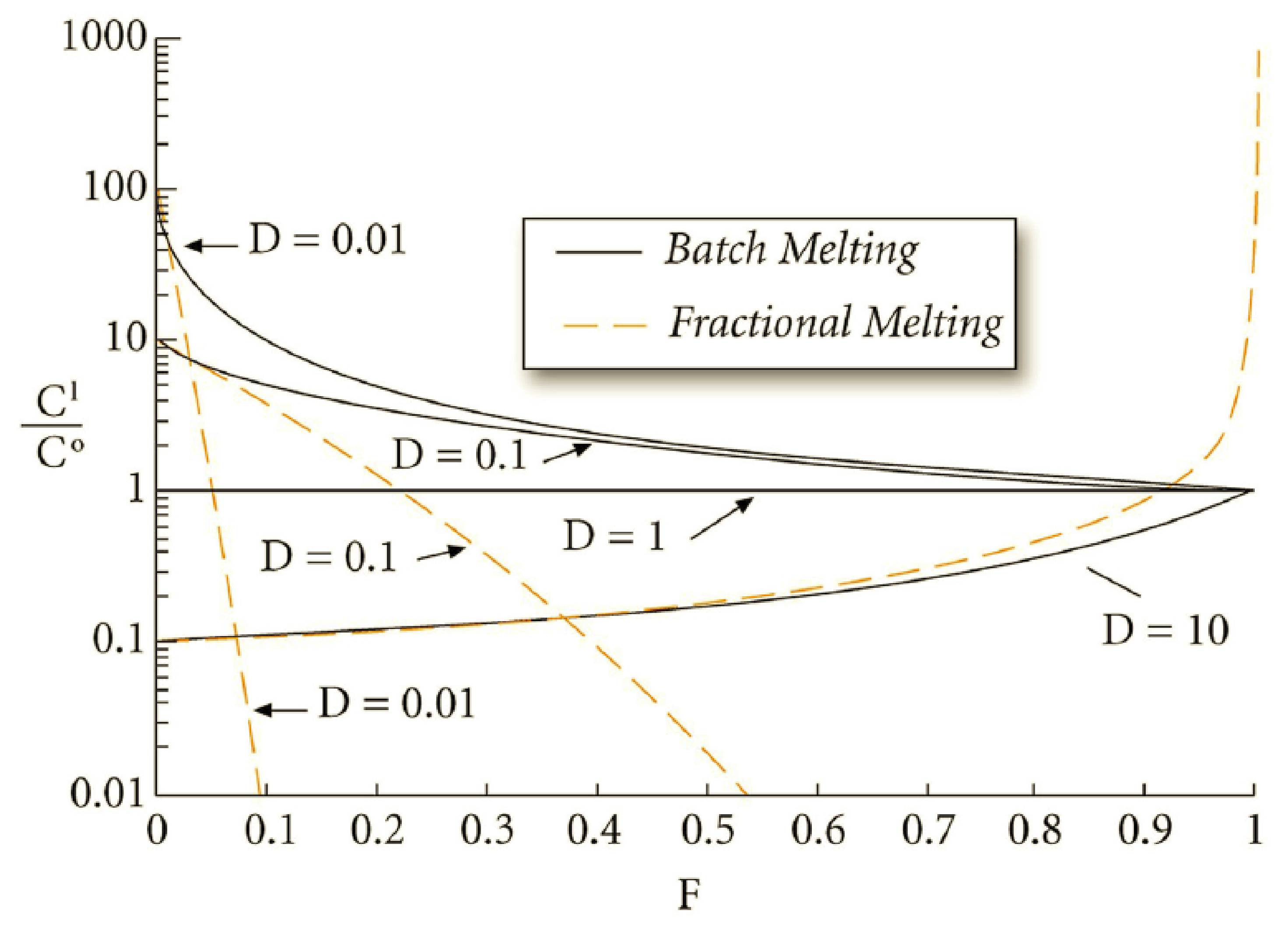
Blue indicates compatible element.

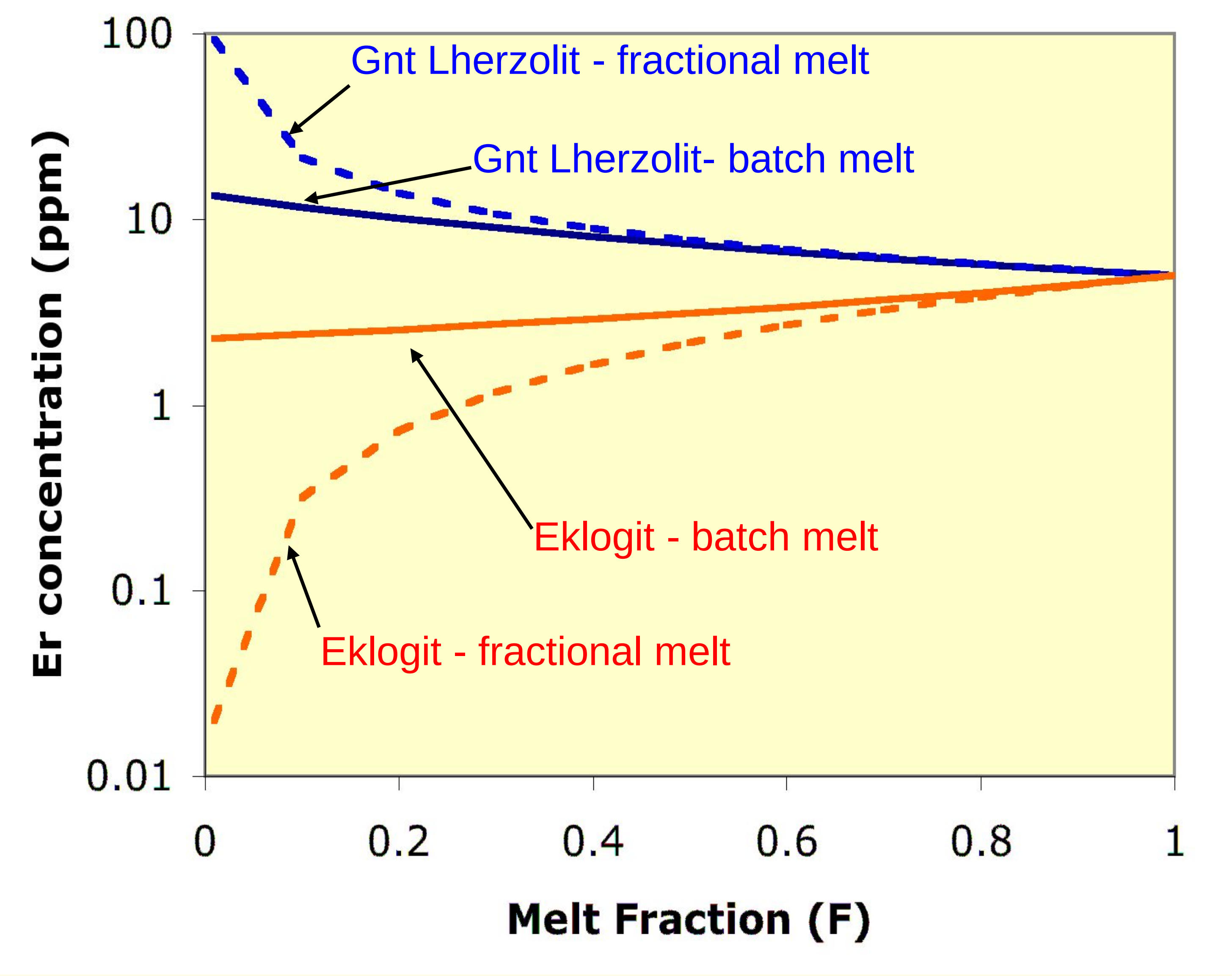
Batch melting

$$\frac{C_L}{C_0} = \frac{1}{D_{RS} + F(1 - D_{RS})}$$

Fractional melting

$$\frac{C_L}{C_0} = \frac{1}{D_0}(1 - F)^{(1/D_0 - 1)}$$





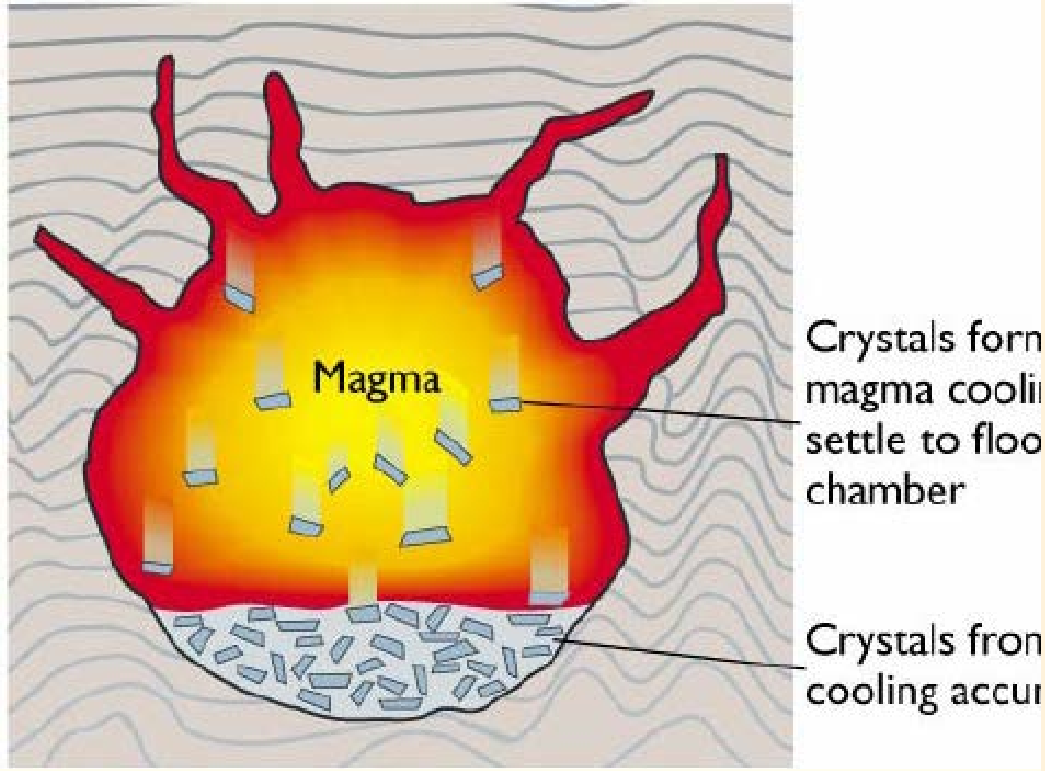
Fraktionierte Schmelzbildung führt zu extremeren Zusammensetzungen bei niedrigen Aufschmelzungsraten (F < 0.2)

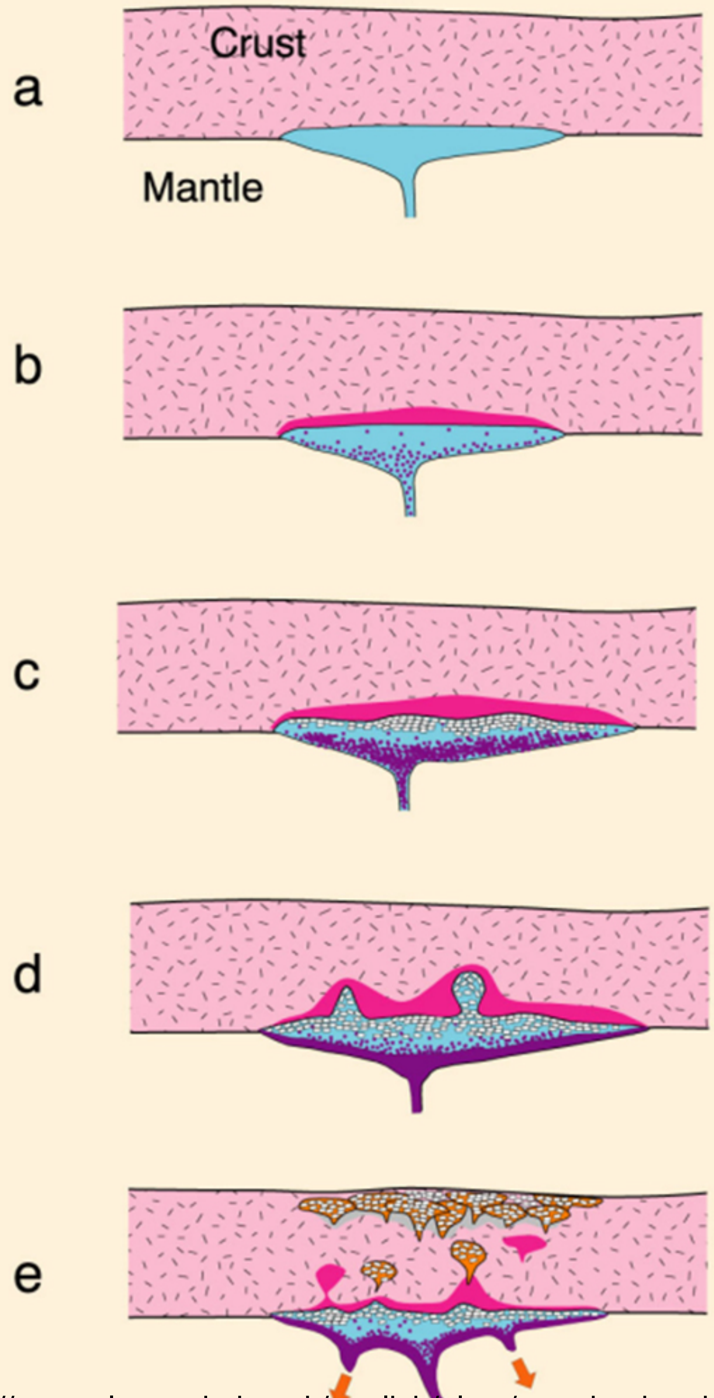
Kristallisationsm

Fraktionierte Kristallisation bzw. R

Trennung zwischen Kristallen und S

durch gravitatives Absinken oder Flo

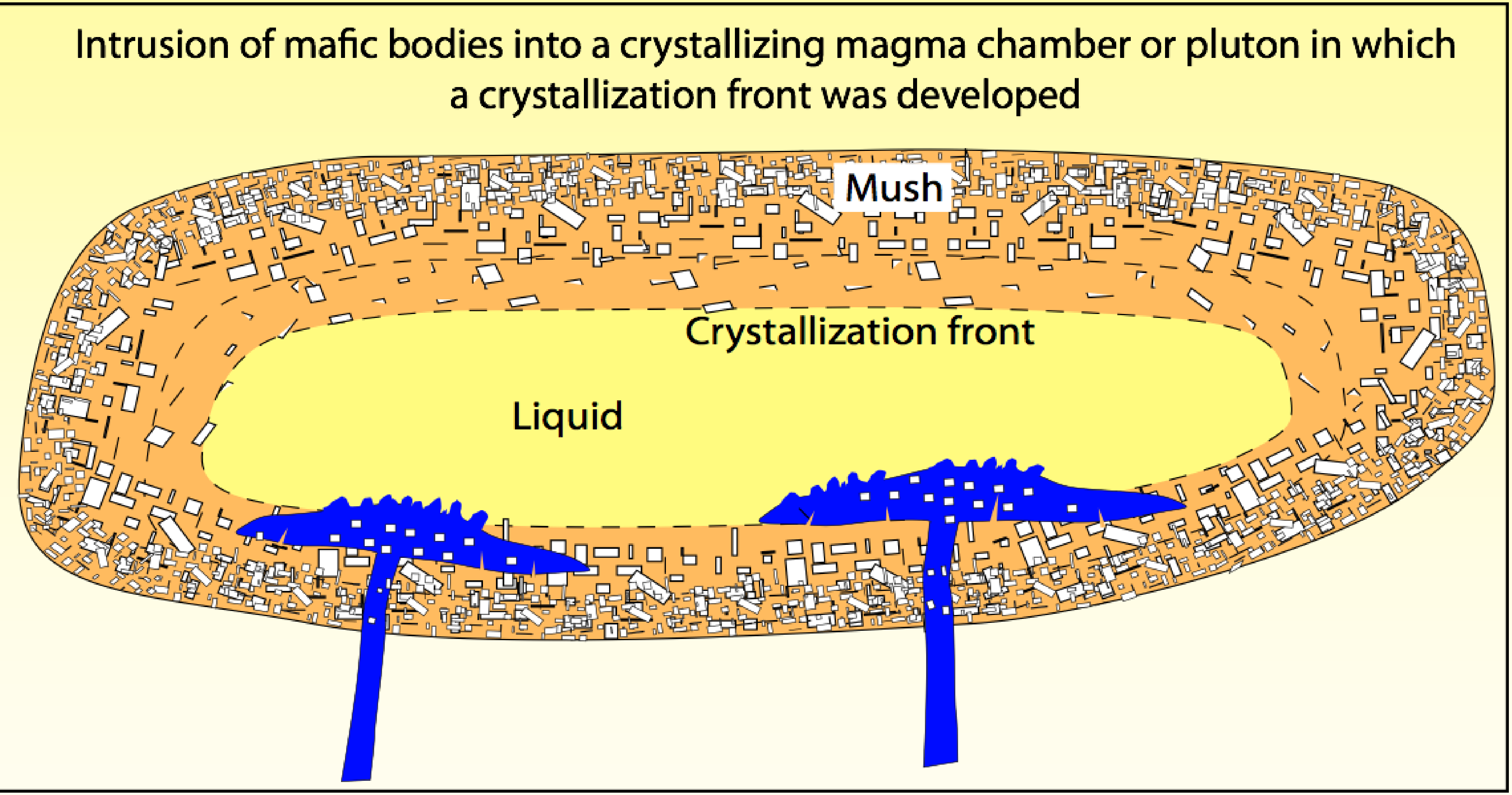




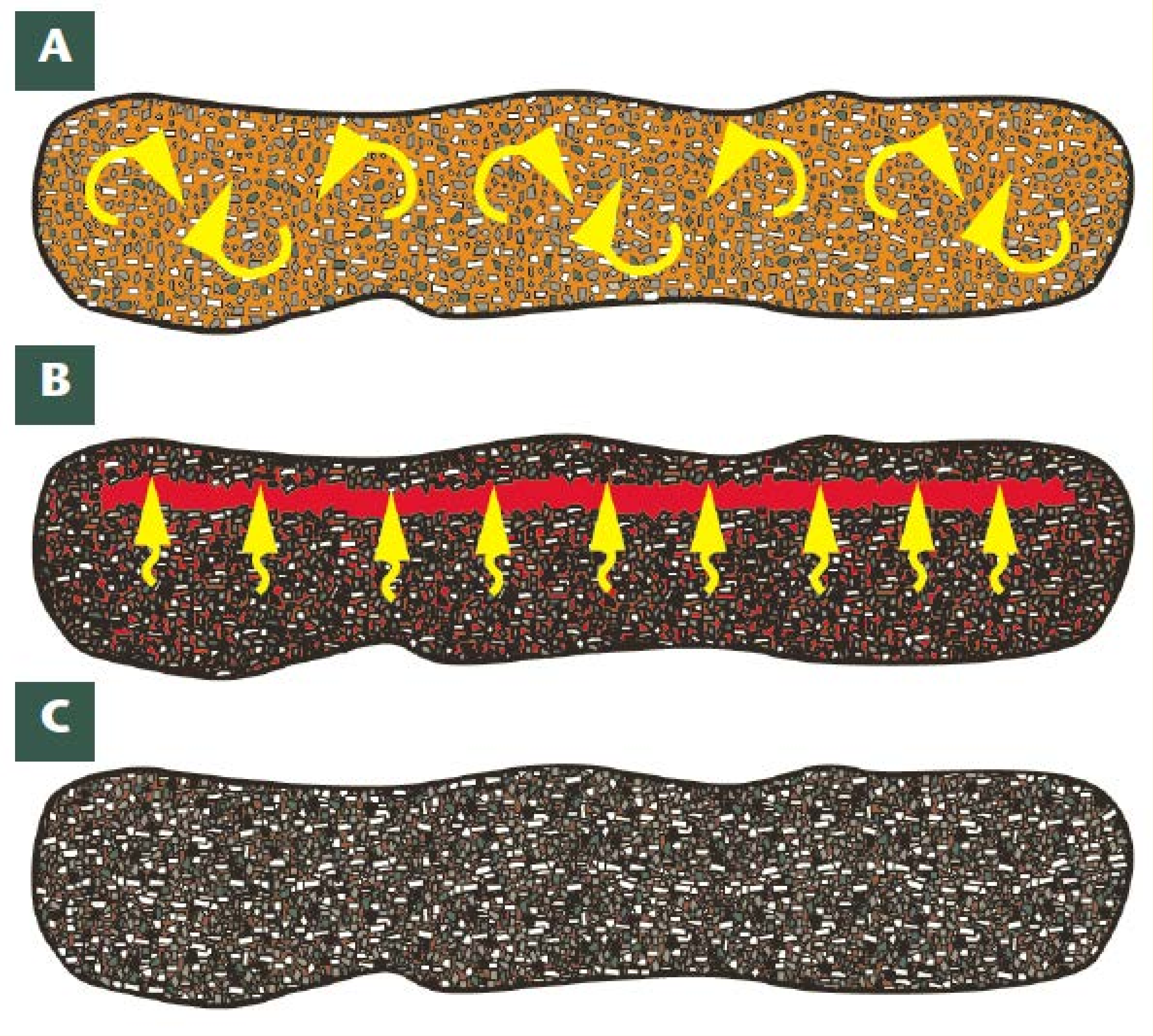
http://www.alexstrekeisen.it/english/pluto/anorthosite.php

Kristallisationsmodelle

Kristallisation vom Rand zur Mitte (Kristallisationsfront)



Kristallisationsmodelle



(<45 vol% Kristalle
Kristallbrei, Suspension

(45-60 vol% Kristalle
Trennung von Kristallen
und Schmelze

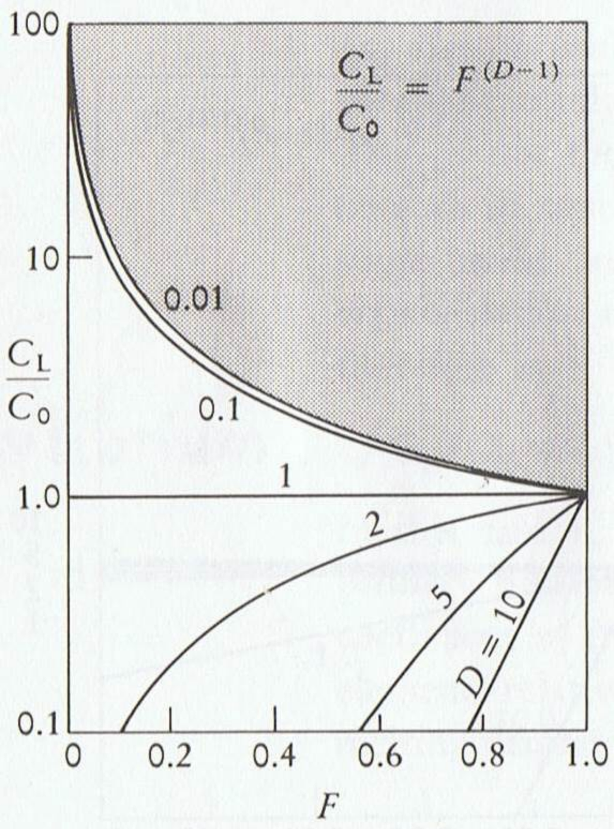
(> 60 vol% Kristalle
hohe Viskosität
geringe Permeabilität

Bachmann & Bergantz (2008) Elements

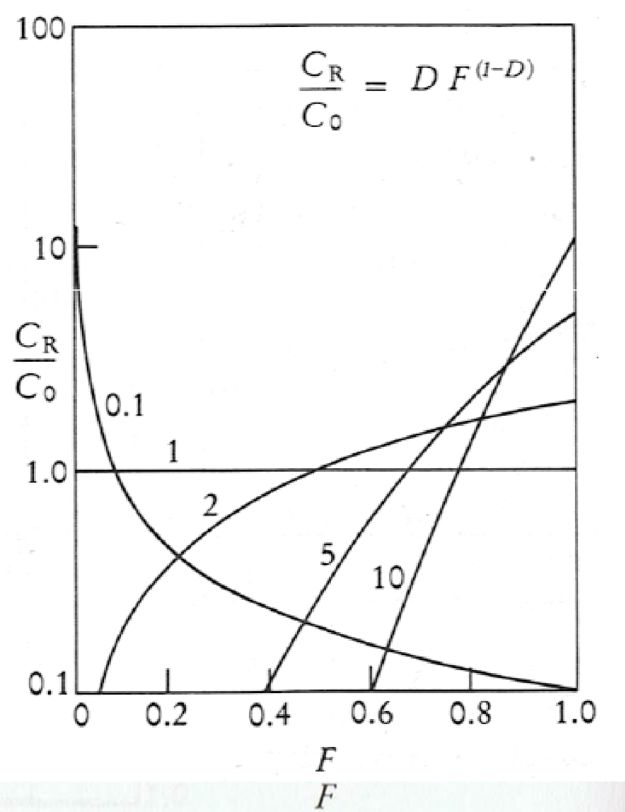
Fraktionierte Kristallisation
Fractional crystallization bzw. Rayleigh fractionation

$$\frac{C_L}{C_0} = F^{(D-1)}$$

$$\frac{C_R}{C_O} = DF^{(1-D)}$$



(a) Rayleigh fractionation — liquids

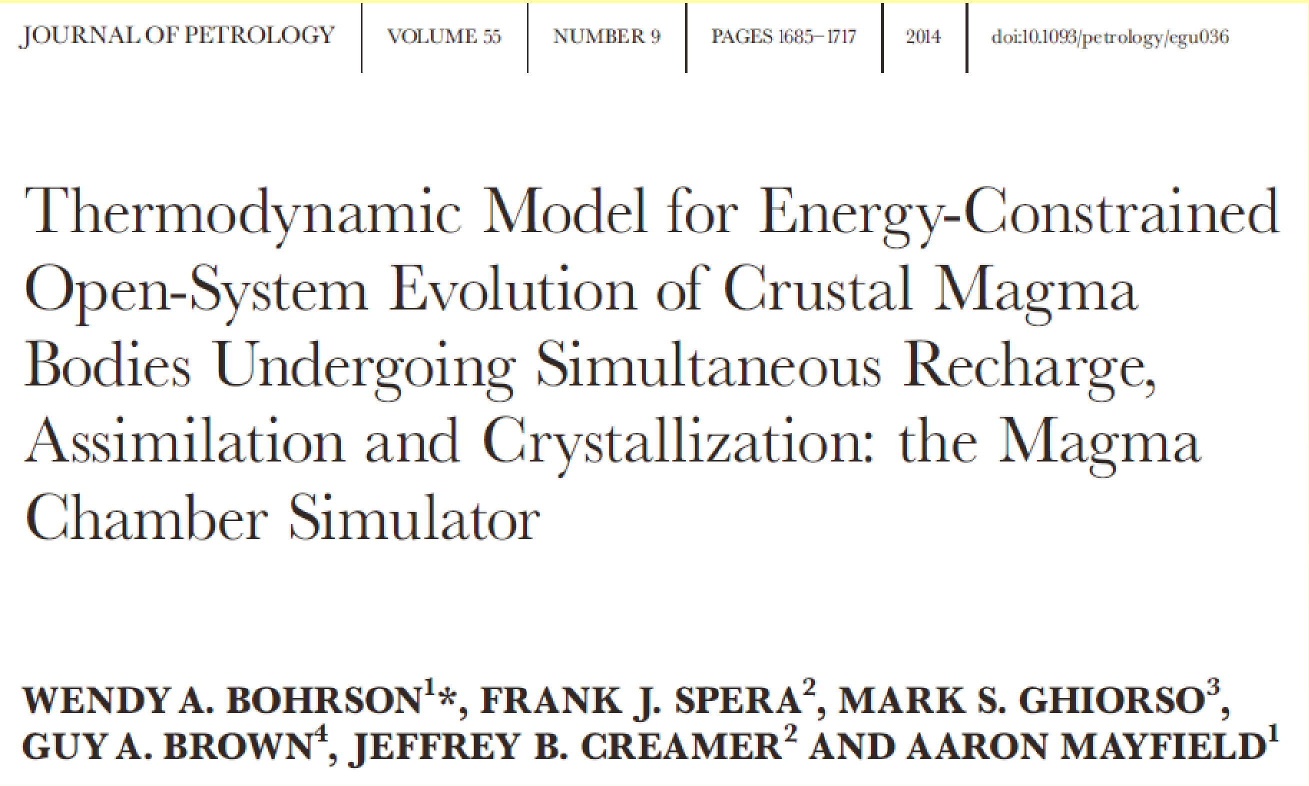


(c) Rayleigh fractionation — residue.

instantaneous solid

Komplexe Magmakammer

Magmakammer Simulator



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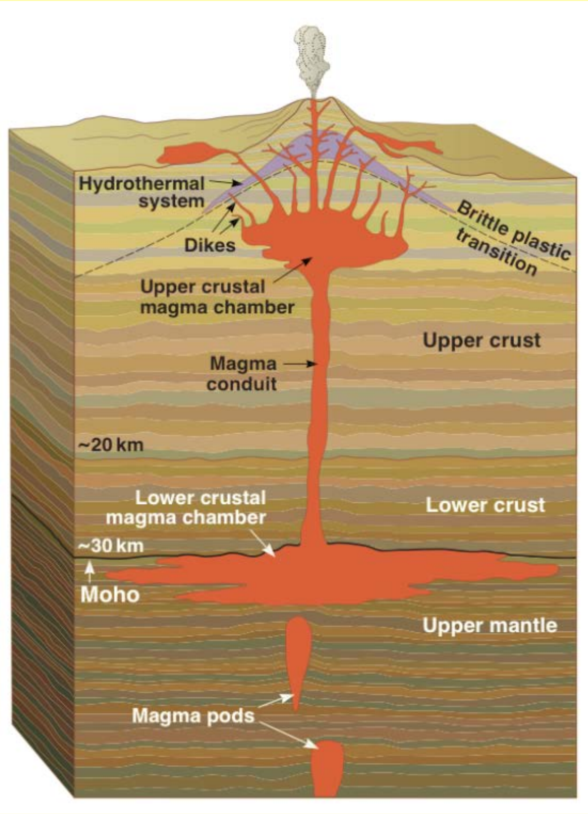
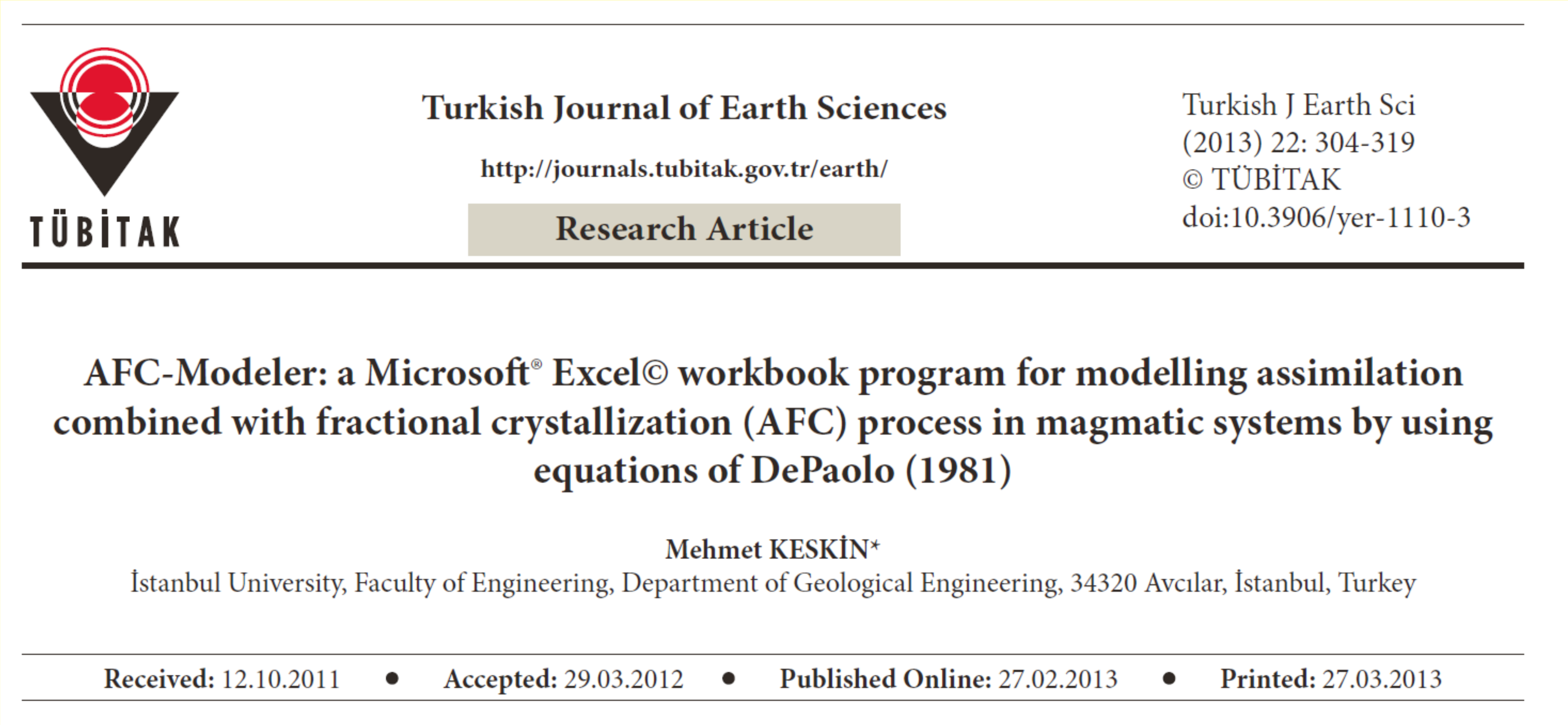
Thermodynamic Model for Energy-Constrained Open-System Evolution of Crustal Magma Bodies Undergoing Simultaneous Recharge, Assimilation and Crystallization: the Magma Chamber Simulator

WENDY A. BOHRSON[1]*, FRANK J. SPERA[2], MARK S. GHIORSO[3], GUY A. BROWN[4], JEFFREY B. CREAMER[2] AND AARON MAYFIELD[1]



Komplexe Magmakammer



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Research Article

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(2013) 22: 304-319
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doi:10.3906/yer-1110-3

AFC-Modeler: a Microsoft® Excel© workbook program for modelling assimilation combined with fractional crystallization (AFC) process in magmatic systems by using equations of DePaolo (1981)

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Wallrock (assimilant)

Elemental concentration in wallrock

C_a

Isotope ratio in the wallrock

ε_a

Bulk solid/liquid partition coefficient of an element between crystallizing phases and magma

D

The difference between stable isotopic ratios of crystals and magma

Δ

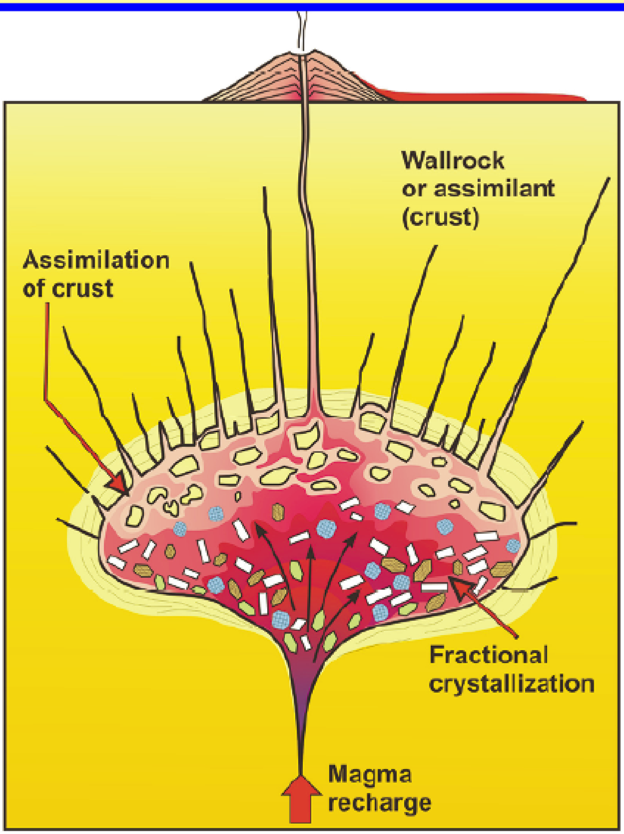
$$\Delta = \delta_{crystals} - \delta_{magma}$$

$$\approx 1000 \ln \alpha$$

Where α is the fractionation factor.

Initial stable isotope ratio in the wallrock (assimilant)

δ_a



Mass assimilation rate (mass/unit time): $\dot{M}_a$

Fractional crystallization rate : $\dot{M}_c$

Ratio of mass assimilation rate to fractional crystallization rate: $r = \dfrac{\dot{M}_a}{\dot{M}_c}$

$$z = \frac{r + D - 1}{r - 1}$$

Magma

Mass of magma

M_m

Initial mass of magma

M_m^0

The fraction of magma remaining

$$F = \frac{M_m}{M_m^0}$$

Elemental concentration in magma

C_m

Initial elemental concentration in magma

C_m^0

Elemental concentration in crystallizing phases

DC_m

Isotope ratio in magma

ε_m

Initial isotope ratio in magma

ε_m^0

Stable isotopic ratio in magma

δ_m

Initial stable isotope ratio in magma

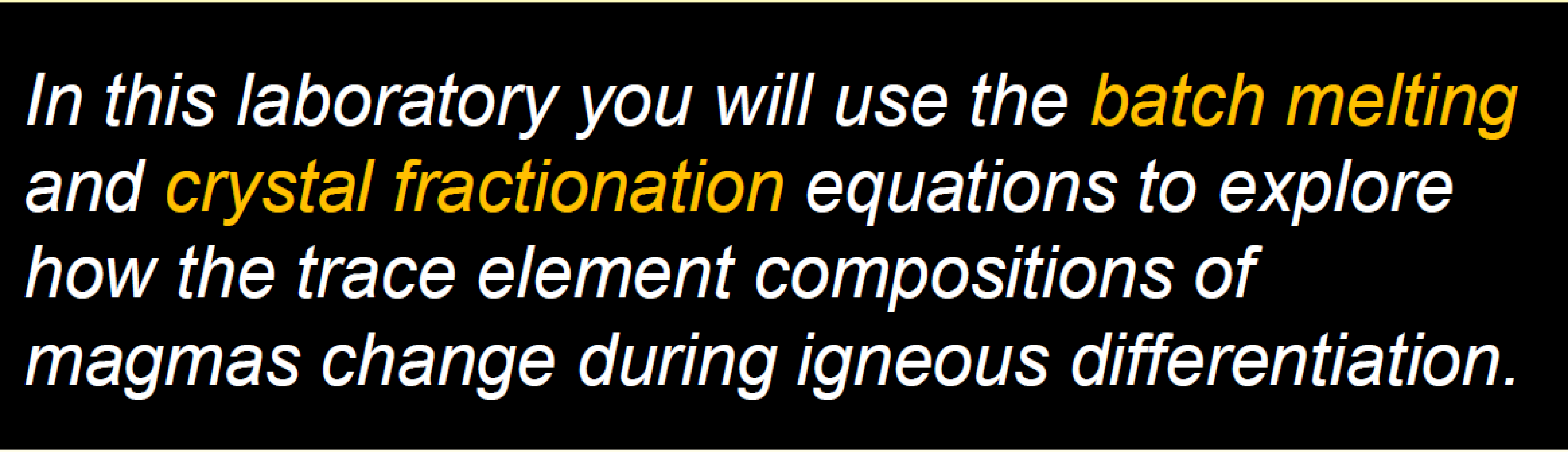
δ_m^0

Minerals

Olivine Plagioclase Pyroxene Amphibole

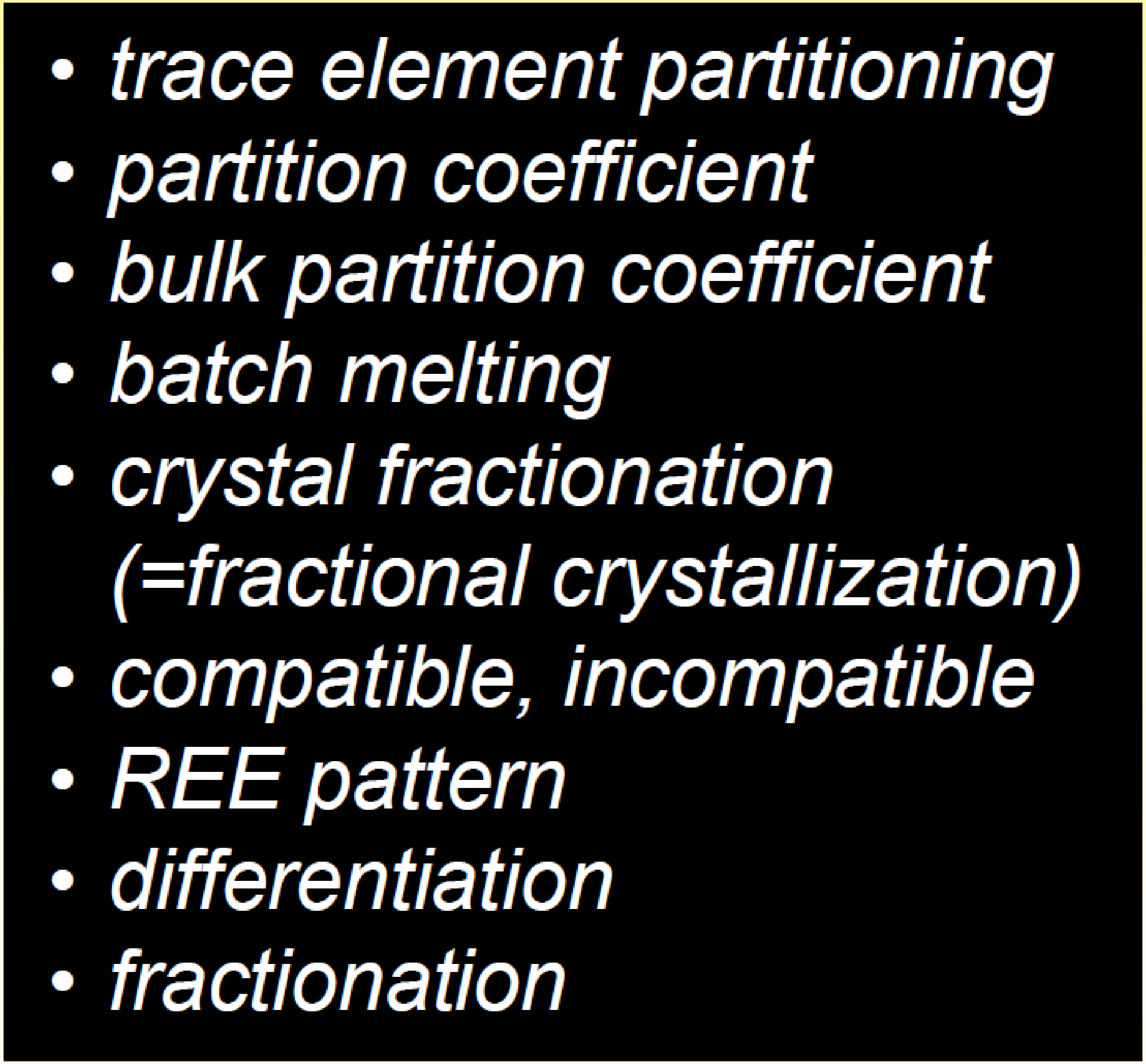
Übung: Elementverteilung bei magmatischen Prozessen

Zielsetzung



In this laboratory you will use the batch melting and crystal fractionation equations to explore how the trace element compositions of magmas change during igneous differentiation.

Terminologie



- *trace element partitioning*
- *partition coefficient*
- *bulk partition coefficient*
- *batch melting*
- *crystal fractionation (=fractional crystallization)*
- *compatible, incompatible*
- *REE pattern*
- *differentiation*
- *fractionation*

Verteilungskoeffizienten

$$D = C_S / C_L$$

D = partition coefficient

C_S = concentration of the element in the solid (i.e. residuals)

C_L = concentration of the element in the liquid (i.e. melt)

Distribution Coefficients are determined:

1) Experimentally

2) Natural Systems (phenocryst/glass)

Compatible element: $D > 1$

Incompatible element: $D < 1$

Gesamt-Verteilungskoeffizient (Bulk Partition Coefficient)

$$\bar{D}_i = \sum X_A D_i^A$$

$\bar{D}_i$ = *bulk partition coefficient for element i*
X_A = *weight fraction of mineral A in the rock*
D_i^A = *partition coefficient for element i in mineral A*

$X_{plag}=0.5$ $X_{cpx}=0.5$ $D^{plag/L}=4$ $D^{cpx/L}=0.2$

Bulk Partition Coefficient D

$$= \sum X \cdot D = 0.5 \times 4 + 0.5 \times 0.2 = 2 + 0.1 = 2.1$$

Übung: “Batch melting modeling”

Batch Melting is the melting process whereby the liquid remains in equilibrium with the residue until the liquid is removed.

$C_L/C_0 = 1/[D_S + F(1 - D_S]$ bzw. $\dfrac{C_L}{C_o} = \dfrac{1}{\bar{D}*(1-F)+F}$

$C_S/C_0 = D_S/[D_S + F(1 – D_S)]$

C_o = concentration of the element in the starting material (in the case of mantle melting, the concentration in the original mantle).

C_S = concentration of the element in the solid (i.e. residuals)

C_L = concentration of the element in the liquid (i.e. melt)

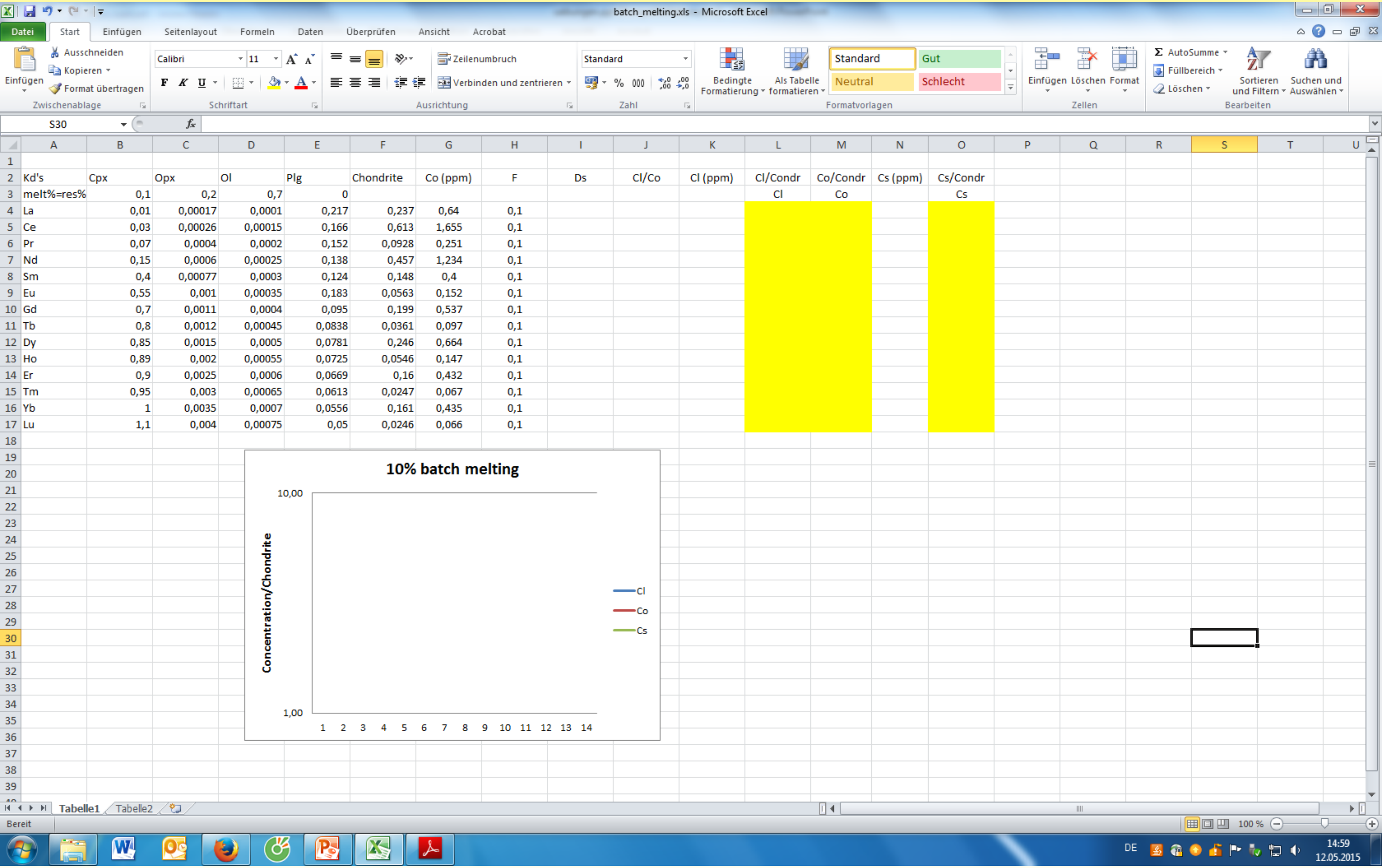
D_S = bulk partition coefficient for the residual mantle

F = weight fraction of melt produced [= melt/(melt + rock)]

Datensatz “Batch melting modeling”

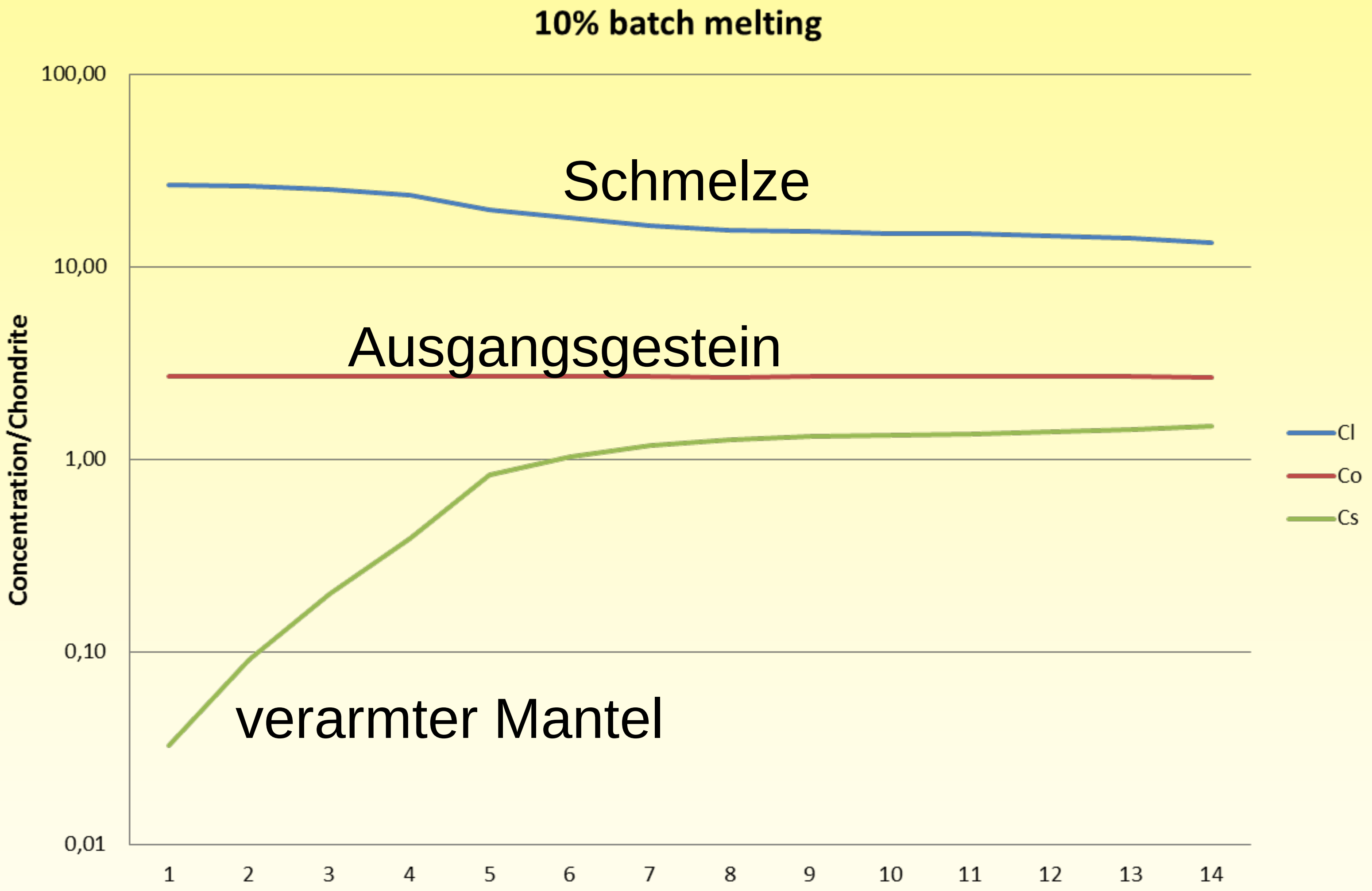
D-values	Cpx	Opx	Ol	Plag	Chondrite	Co
Residue Proportion	10%	20%	70%		ppm	ppm
La	0.01	0.00017	0.0001	0.217	0.237	0.640
Ce	0.03	0.00026	0.00015	0.166	0.613	1.655
Pr	0.07	0.0004	0.0002	0.152	0.0928	0.251
Nd	0.15	0.0006	0.00025	0.138	0.457	1.234
Pm						
Sm	0.4	0.00077	0.0003	0.124	0.148	0.400
Eu	0.55	0.001	0.00035	0.183	0.0563	0.152
Gd	0.7	0.0011	0.0004	0.095	0.199	0.537
Tb	0.8	0.0012	0.00045	0.0838	0.0361	0.097
Dy	0.85	0.0015	0.0005	0.0781	0.246	0.664
Ho	0.89	0.002	0.00055	0.0725	0.0546	0.147
Er	0.9	0.0025	0.0006	0.0669	0.16	0.432
Tm	0.95	0.003	0.00065	0.0613	0.0247	0.067
Yb	1	0.0035	0.0007	0.0556	0.161	0.435
Lu	1.1	0.004	0.00075	0.05	0.0246	0.066

Berechnen Sie C_l, C_o, C_s



Kd's	Cpx	Opx	Ol	Plg	Chondrite	Co (ppm)	F	Ds	Cl/Co	Cl (ppm)	Cl/Condr	Co/Condr	Cs (ppm)	Cs/Condr
melt%=res%	0,1	0,2	0,7	0							Cl	Co		Cs
La	0,01	0,00017	0,0001	0,217	0,237	0,64	0,1							
Ce	0,03	0,00026	0,00015	0,166	0,613	1,655	0,1							
Pr	0,07	0,0004	0,0002	0,152	0,0928	0,251	0,1							
Nd	0,15	0,0006	0,00025	0,138	0,457	1,234	0,1							
Sm	0,4	0,00077	0,0003	0,124	0,148	0,4	0,1							
Eu	0,55	0,001	0,00035	0,183	0,0563	0,152	0,1							
Gd	0,7	0,0011	0,0004	0,095	0,199	0,537	0,1							
Tb	0,8	0,0012	0,00045	0,0838	0,0361	0,097	0,1							
Dy	0,85	0,0015	0,0005	0,0781	0,246	0,664	0,1							
Ho	0,89	0,002	0,00055	0,0725	0,0546	0,147	0,1							
Er	0,9	0,0025	0,0006	0,0669	0,16	0,432	0,1							
Tm	0,95	0,003	0,00065	0,0613	0,0247	0,067	0,1							
Yb	1	0,0035	0,0007	0,0556	0,161	0,435	0,1							
Lu	1,1	0,004	0,00075	0,05	0,0246	0,066	0,1							

Übung: Schmelzbildung im Erdmantel



LSSE -- SSEE

Datierungsmethoden und Schließungstemperatur

Closure Temp: the temperature at which a cooling mineral can no longer exchange isotopes with it's surroundings

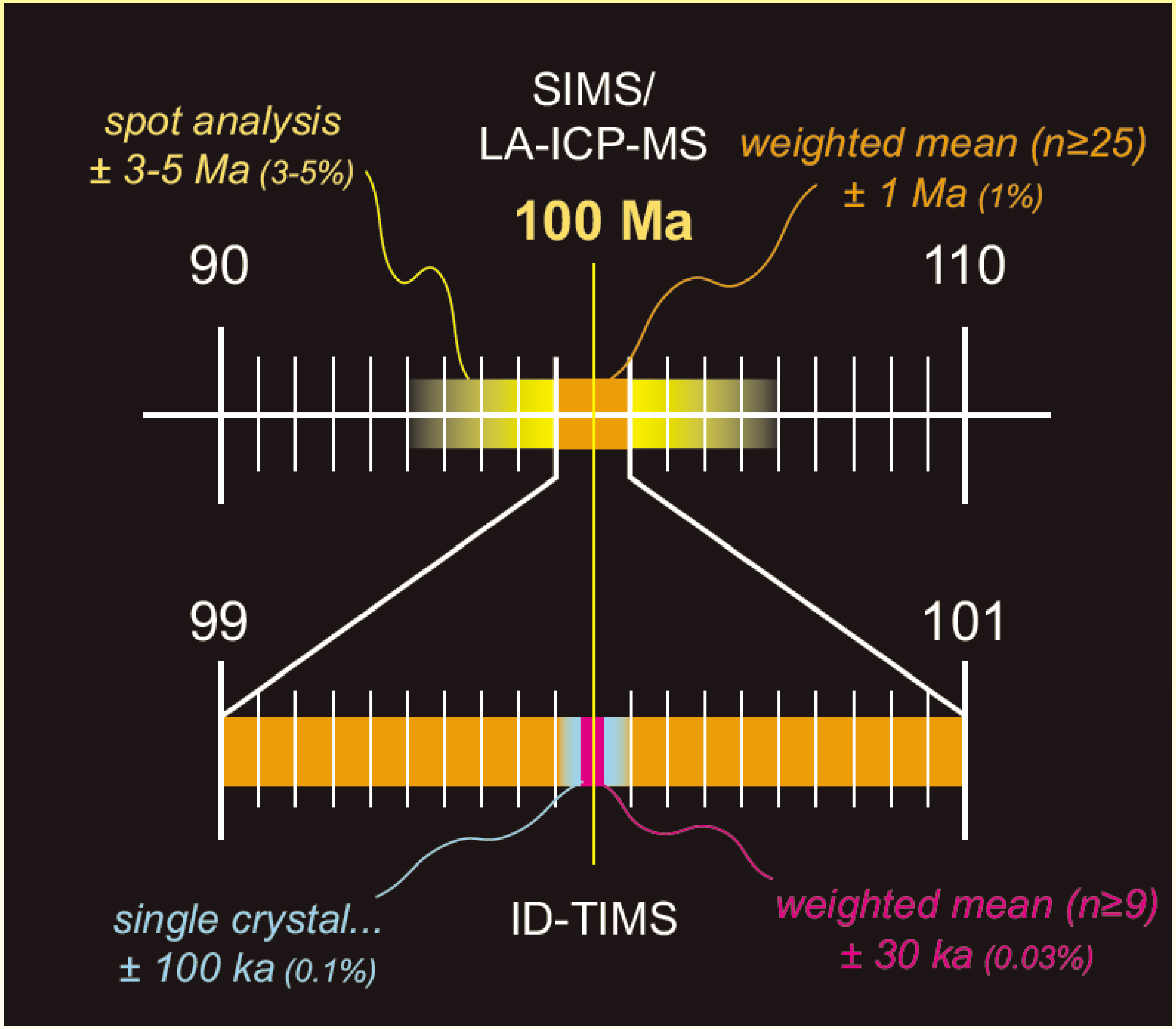
Mineral	**Method**	**T (°C)**
Zircon	U-Pb	>800
Monazite	U-Pb	>800
Titanite (Sphene)	U-Pb	600
Garnet	Sm-Nd	>550
Hornblende	K-Ar	500
Muscovite	Rb-Sr	500
Muscovite	K-Ar	350
Apatite	U-Pb	350
Biotite	Rb-Sr	300
Biotite	K-Ar	280
K-Feldspar	K-Ar	200
Apatite	Fission Track	120

Closure temperatures for common minerals for different isotopic systems. Note that closure temperatures for different systems in the same minerals can vary.

Unsicherheiten

The uncertainty of a date (age) is as important as the data (age) itself
(Ken Ludwig)

Meßgenauigkeit



Statistische Grundlagen

Mittelwert:

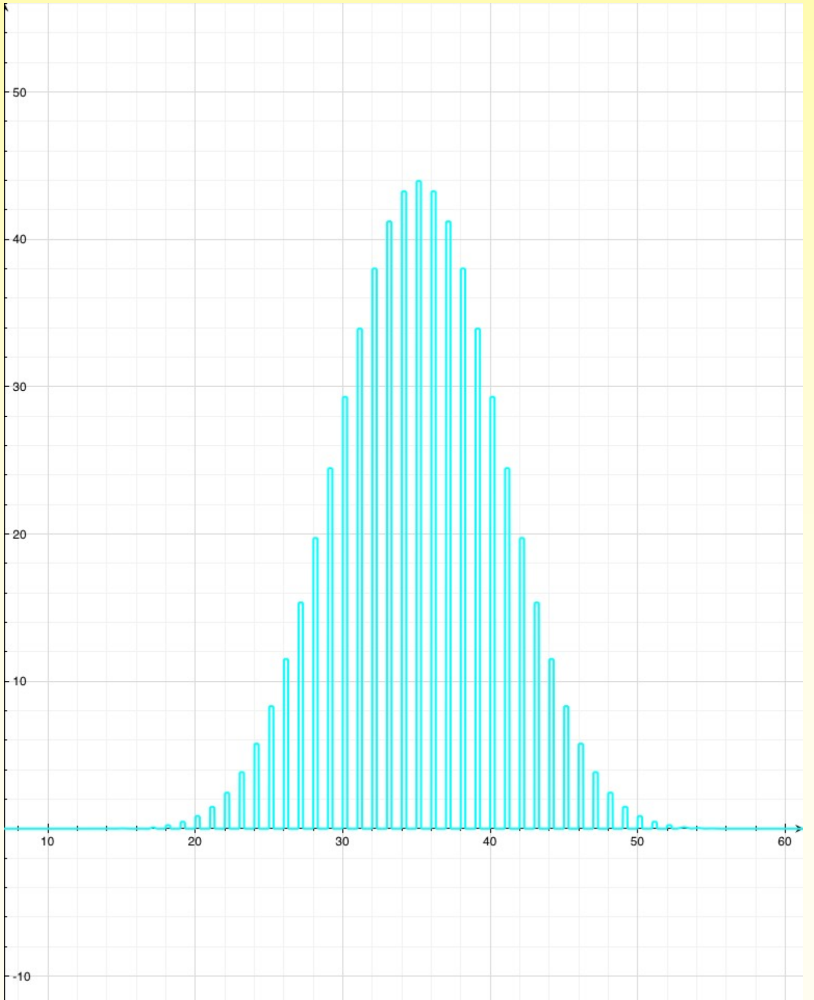
$$\bar{x} = \frac{X_1 + X_2 + X_3 \ldots\ldots\ldots + X_N}{N}$$

Summe der quadrierten Abweichungen:

$$V_x = \sum_{i}^{N} (x_i - \bar{x})^2$$

Varianz:

$$V_x = \frac{\sum_i^N (x_i - \bar{x})^2}{(N-1)}$$



Statistische Grundlagen

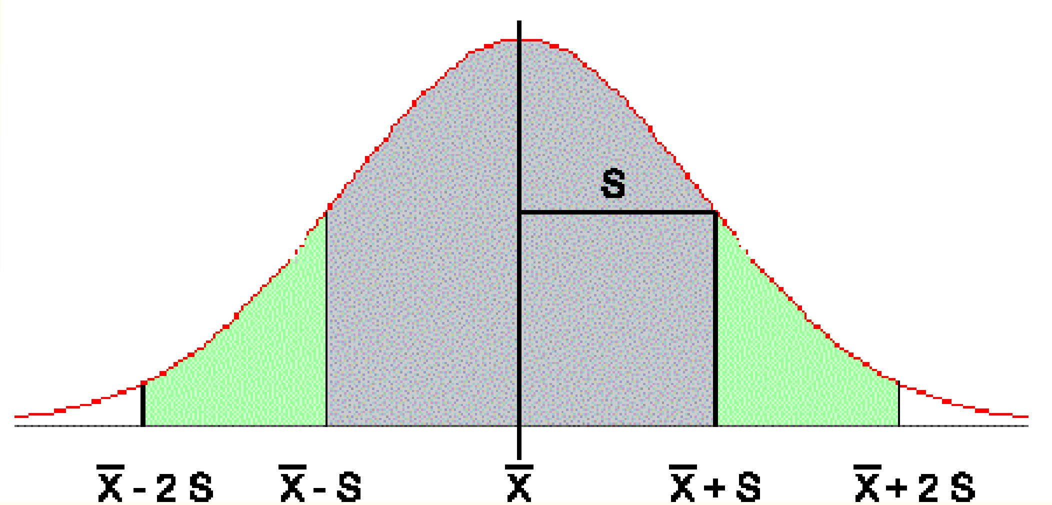
Standardabweichung: Streuung der Meßwerte um den Mittelwert:

$$\sigma_x = \sqrt{V_x} = \sqrt{\frac{\sum_i (x_i - \bar{x})^2}{(N-1)}}$$

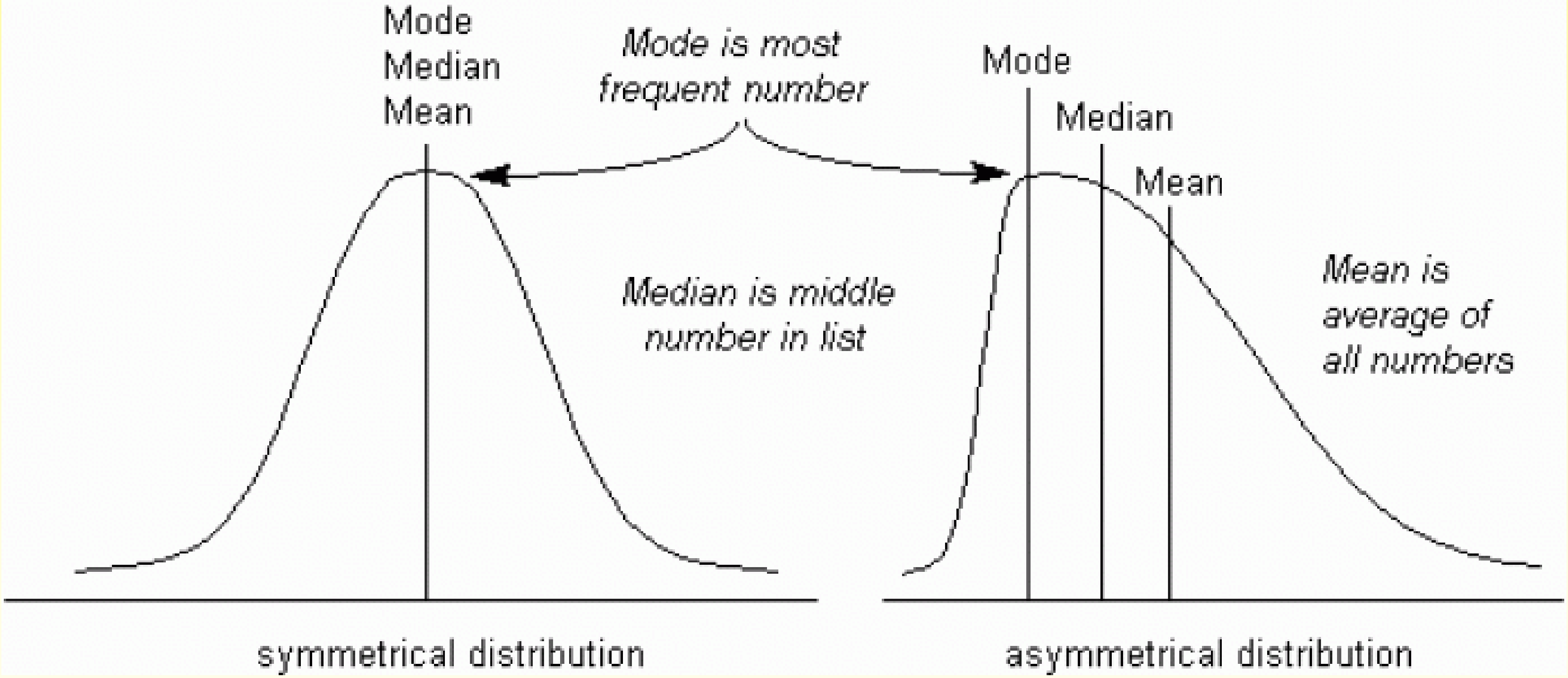
Die Abweichung des wahren Wertes vom Mittelwert sollte mit zunehmender Zahl der Messungen kleiner werden:

Fehler/Unsicherheit:

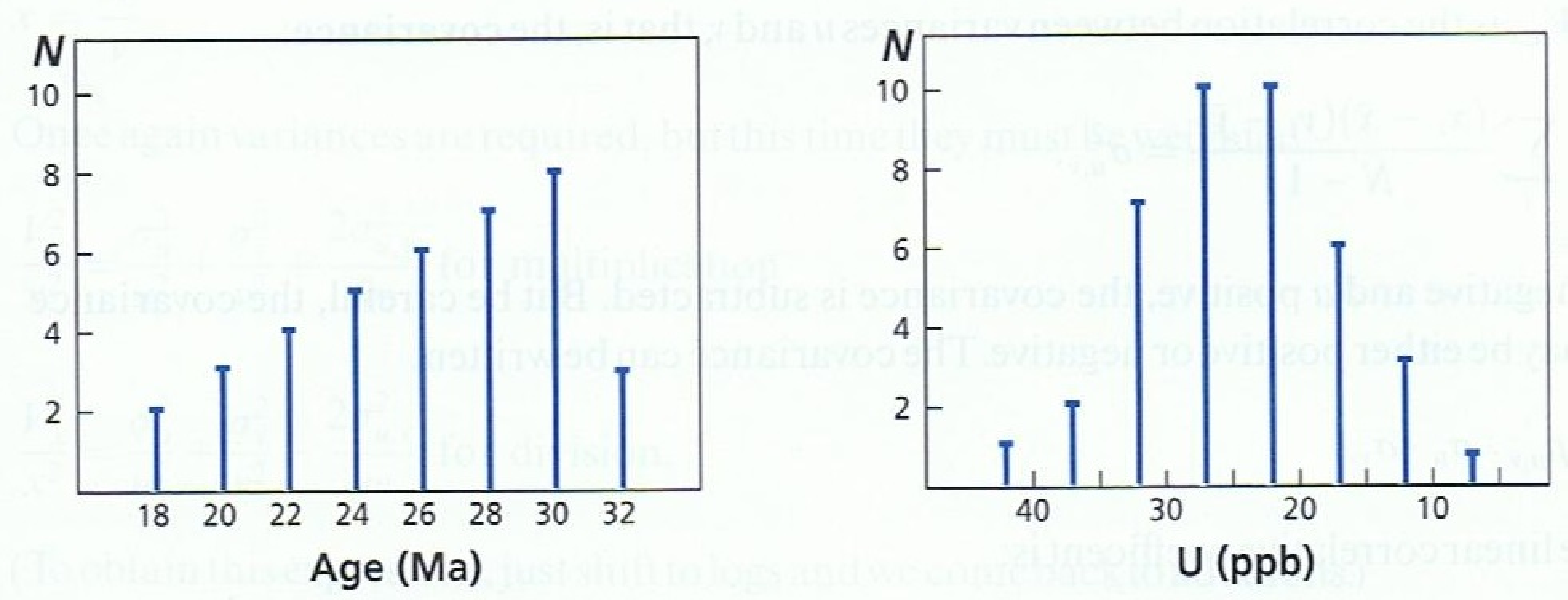
$$\Delta x = \left(\frac{\sigma_x}{\sqrt{N}}\right)$$



Modalwert (Mode), Zentralwert (Median) und arithmetisches Mittel (Mean)

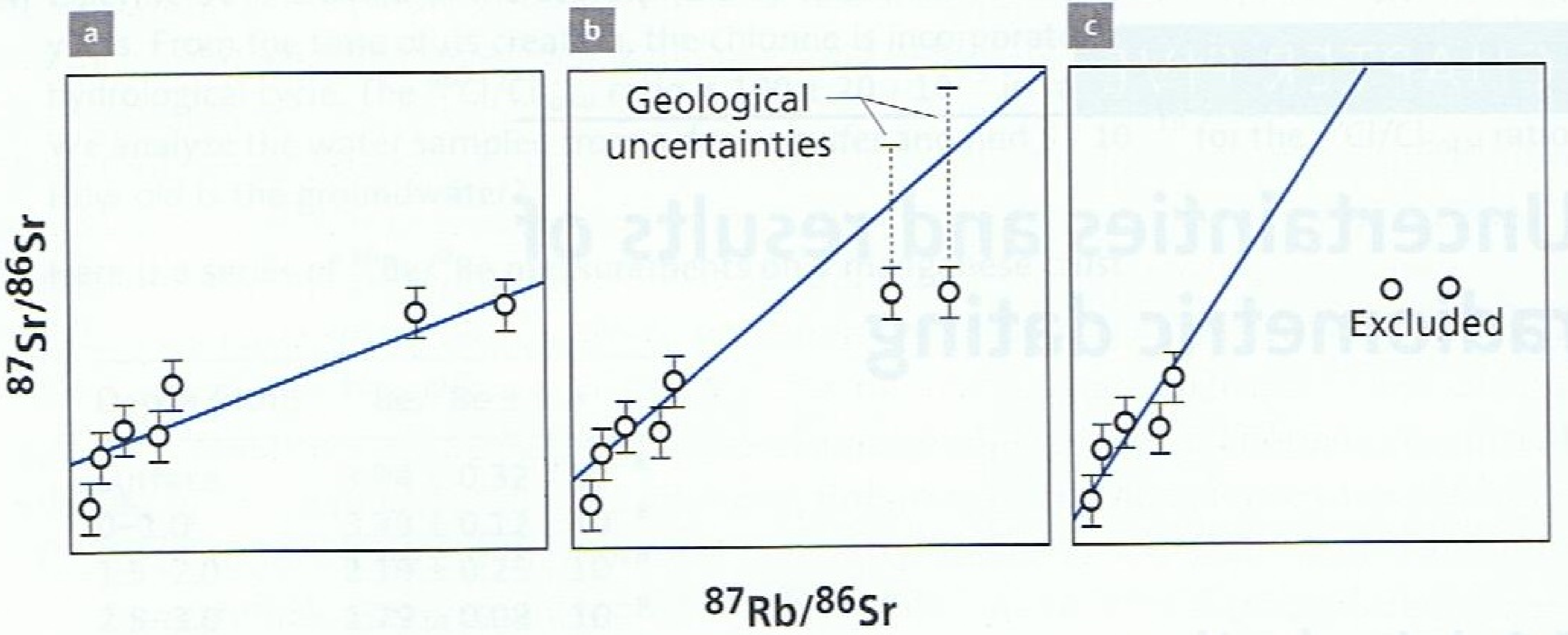


Beispiel: U—He Altersbestimmung an Magnetiten



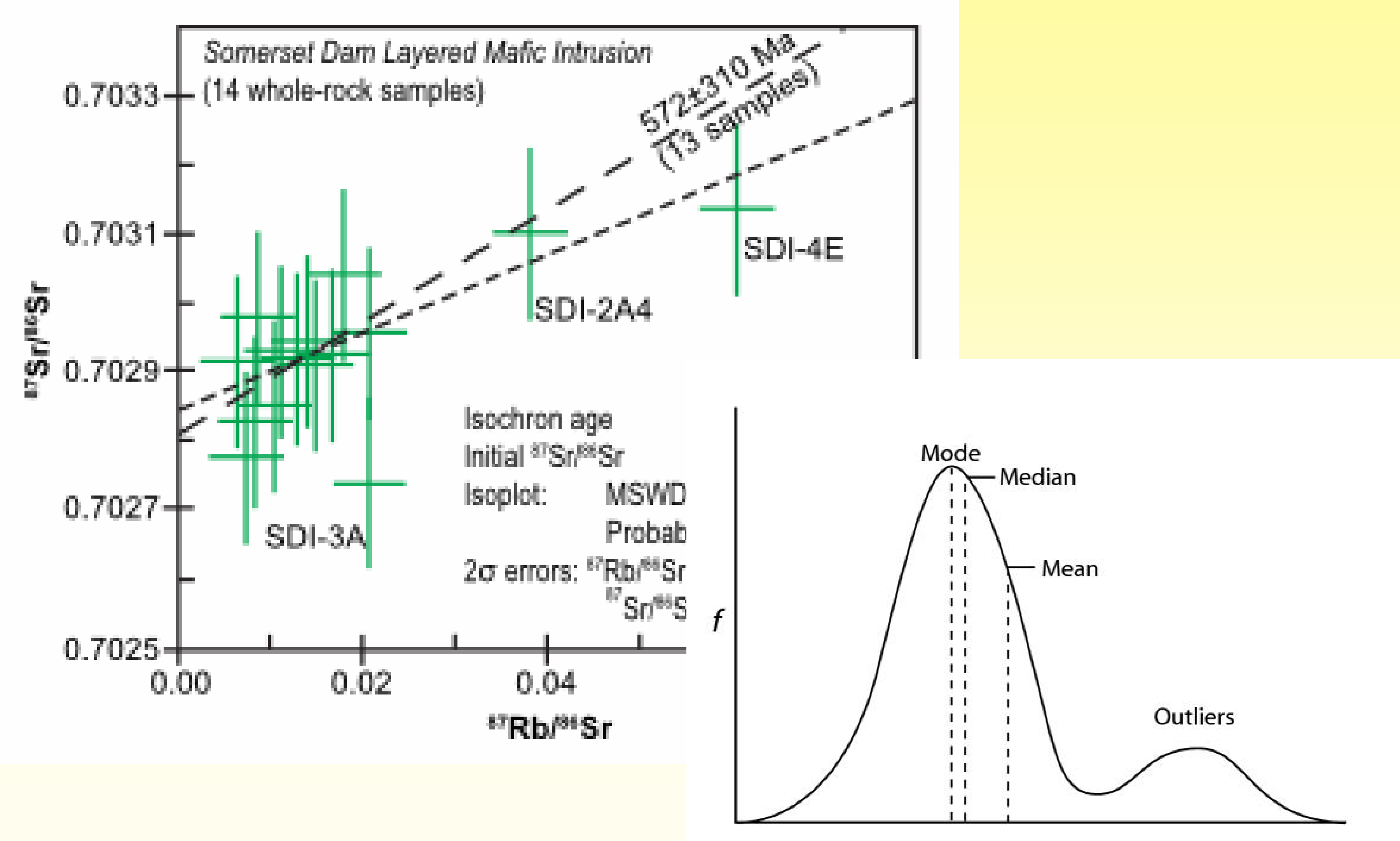
Geologische Unsicherheit

… oder das Erkennen von Ausreißern



Geologische Unsicherheit

… oder das Erkennen von Ausreißern

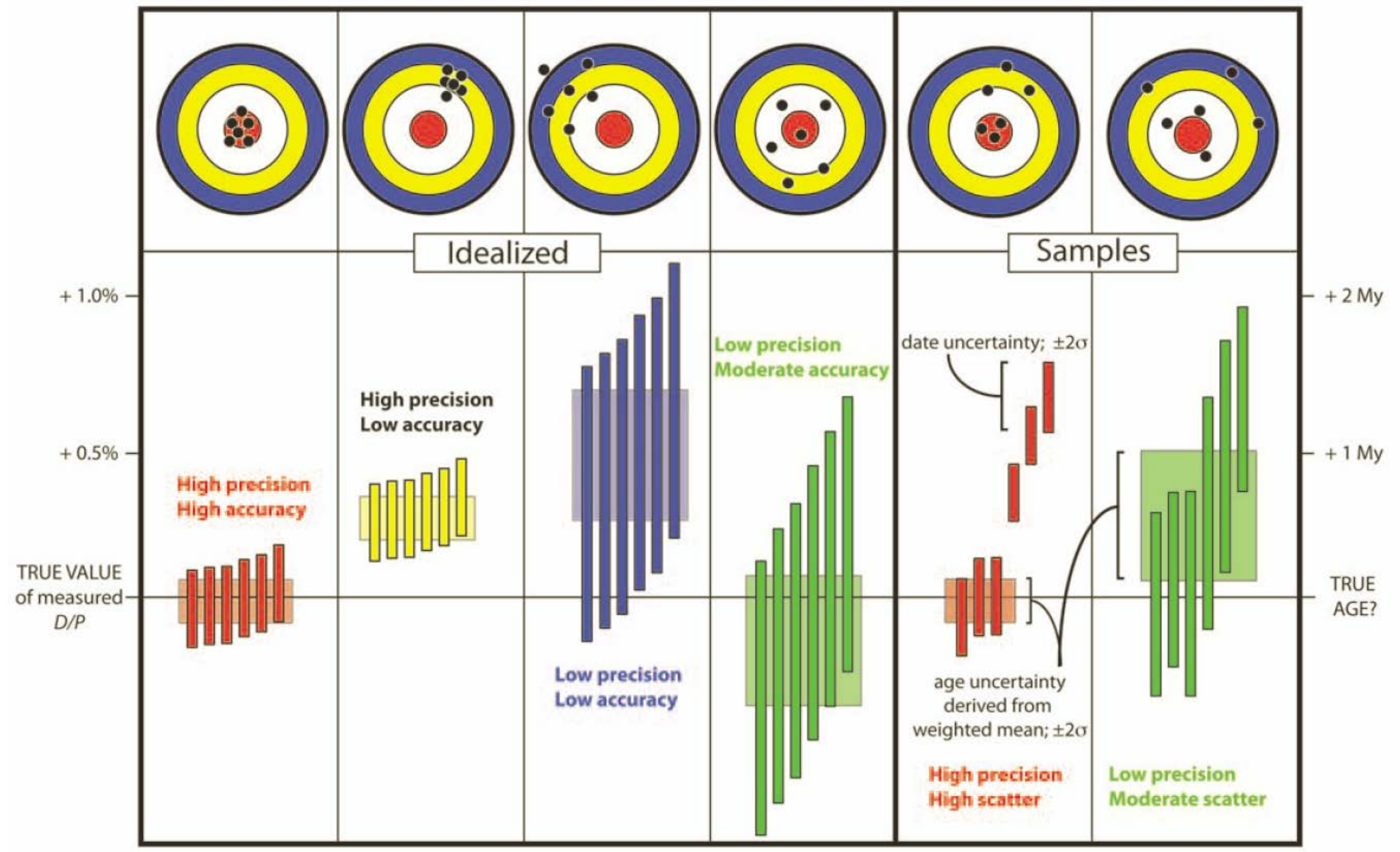


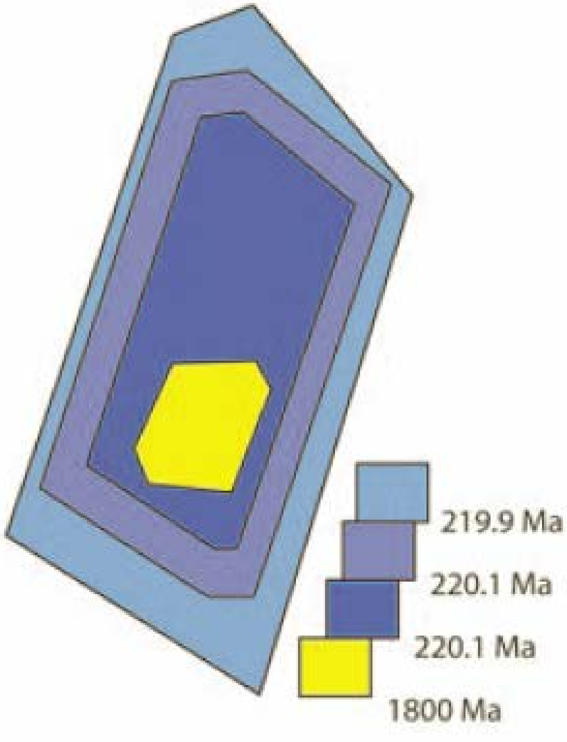
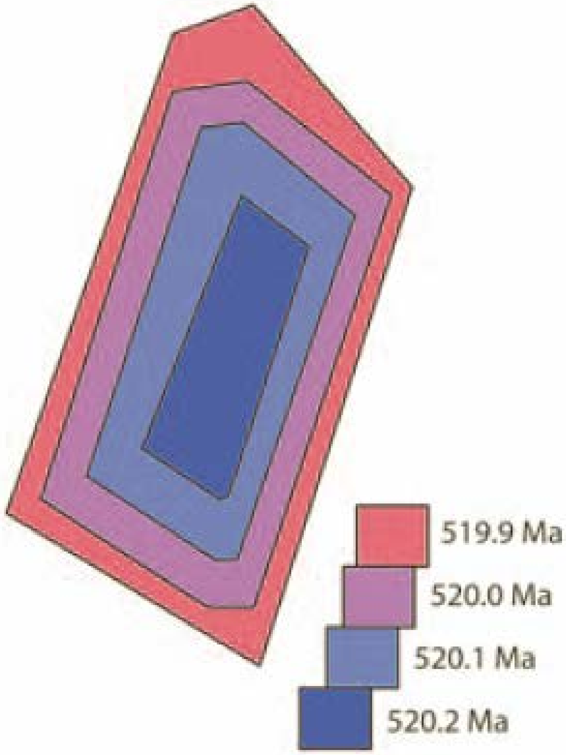
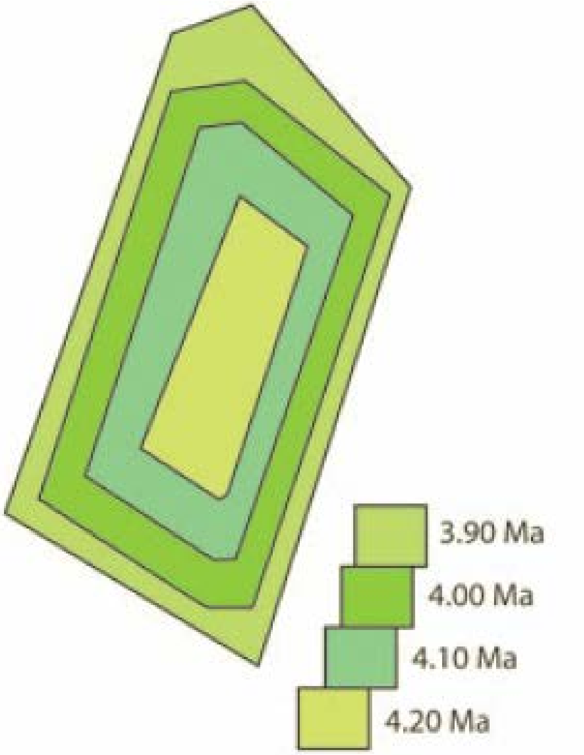
Snelling (2010) a Creationists view

Unterschied zwischen Präzision (bzw. Reproduzierbarkeit) und Genauigkeit (accuracy)

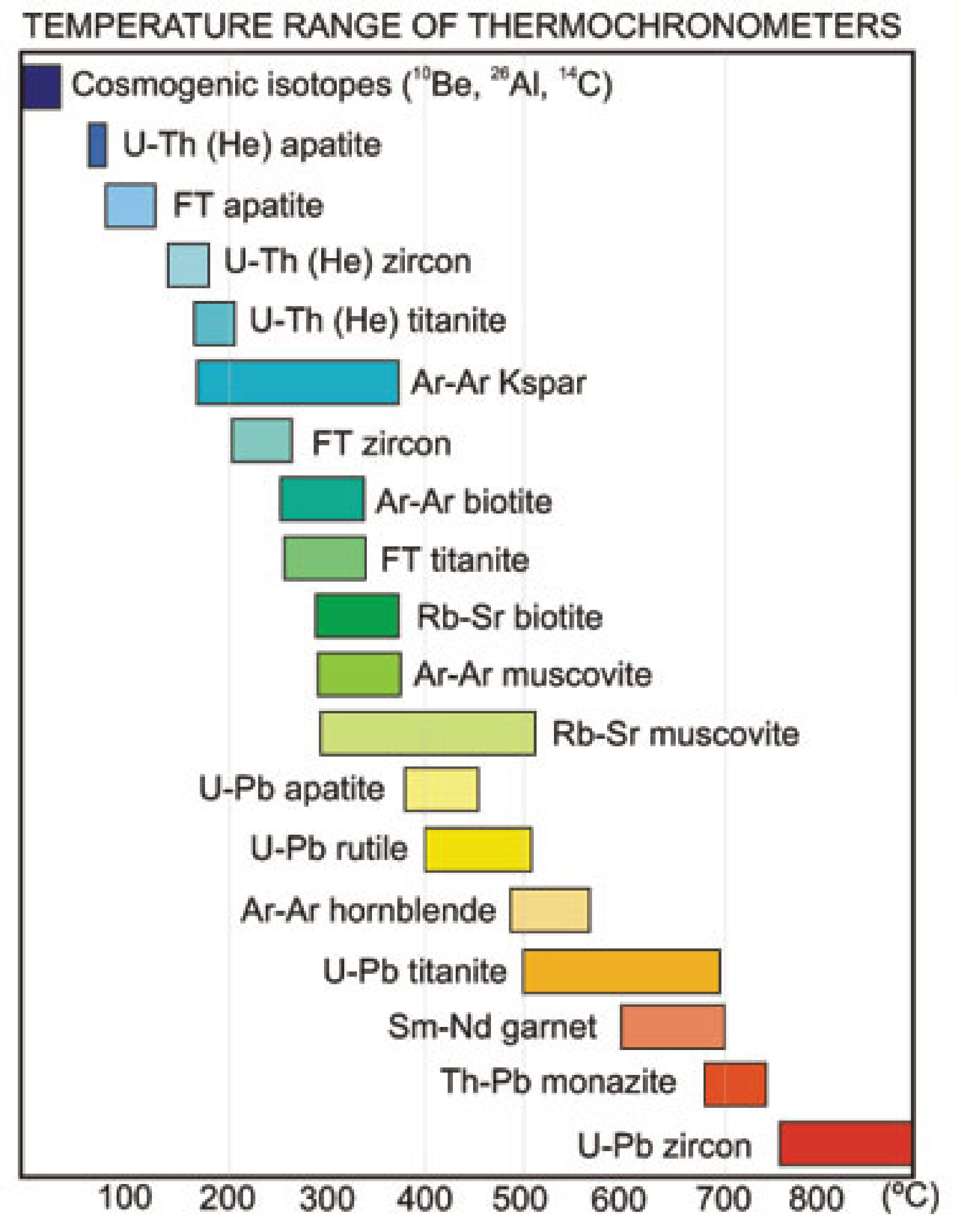
Ideale Welt

Reale Welt



1800 Ma core with a 220 Ma overgrowth	520 Ma crystal, 300 ky (0.06%) crystallization history	~4 Ma crystal, 300 ky (7.5%) crystallization history
		
Intracrystal age variation larger than analytical precision of microbeam and ID methods: *In situ or microsampling required*	Intracrystal age variation unresolvable: *whole crystal or in situ sample dates are accurate; weighted mean ages may not be*	Intracrystal age variation exceeds analytical precision of microbeam and ID methods: *In situ or microsampling can resolve growth history*

Datierungsmethoden und Schließungstemperatur



Welche Art von Alter?

Bildungsalter (Entstehungsalter)

oder ererbtes (inherited) Alter?

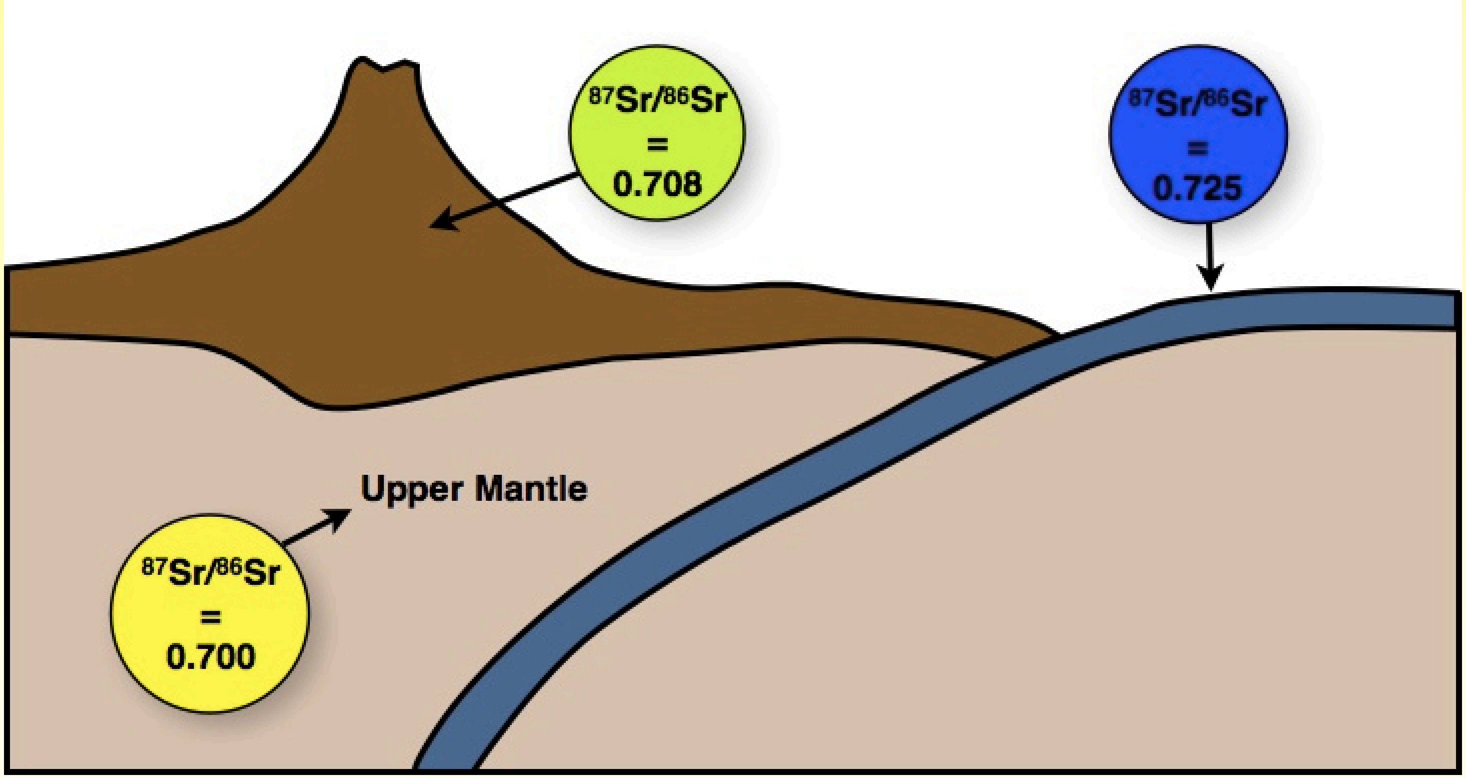
Abkühlungsalter (Abkühlalter) oder

Metamorphosealter (Aufheizungsalter)?

Hebungsalter (bei Spaltspuren)

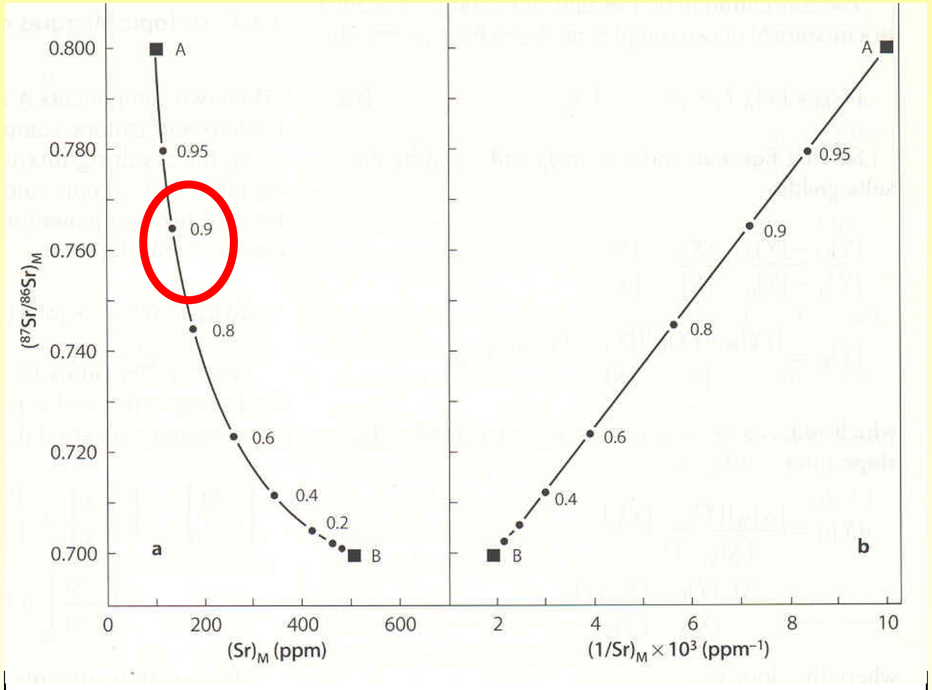
Welches Mineral oder Gestein wurde mit welcher Methode datiert?

Element- und Isotopenmischung

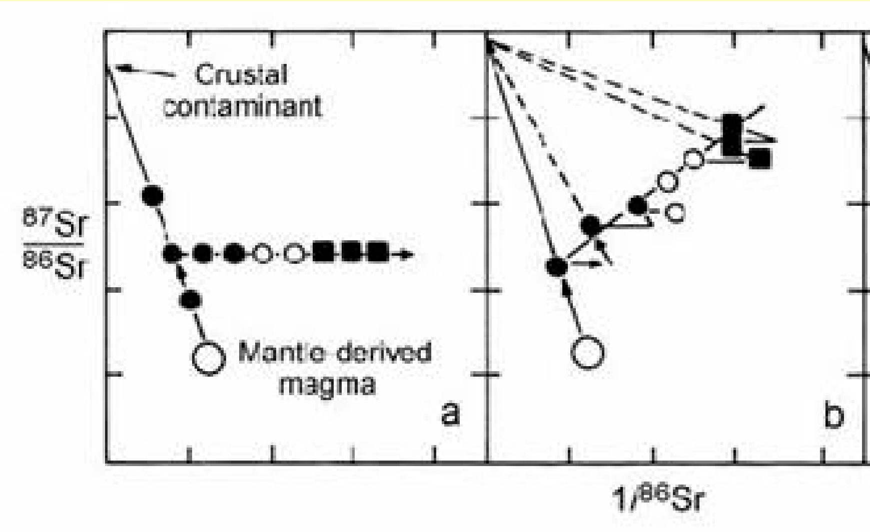


Binäre Mischungen

	Component A	Component B
Sr	100 ppm	500 ppm
$^{87}Sr/^{86}Sr$	0.800	0.700



$$\left(\frac{^{87}Sr}{^{86}Sr}\right)_M = \frac{0.8\times 100\times 0.9 + 0.7\times 500(1-0.9)}{100\times 0.9 + 500(1-0.9)} = 0.764$$

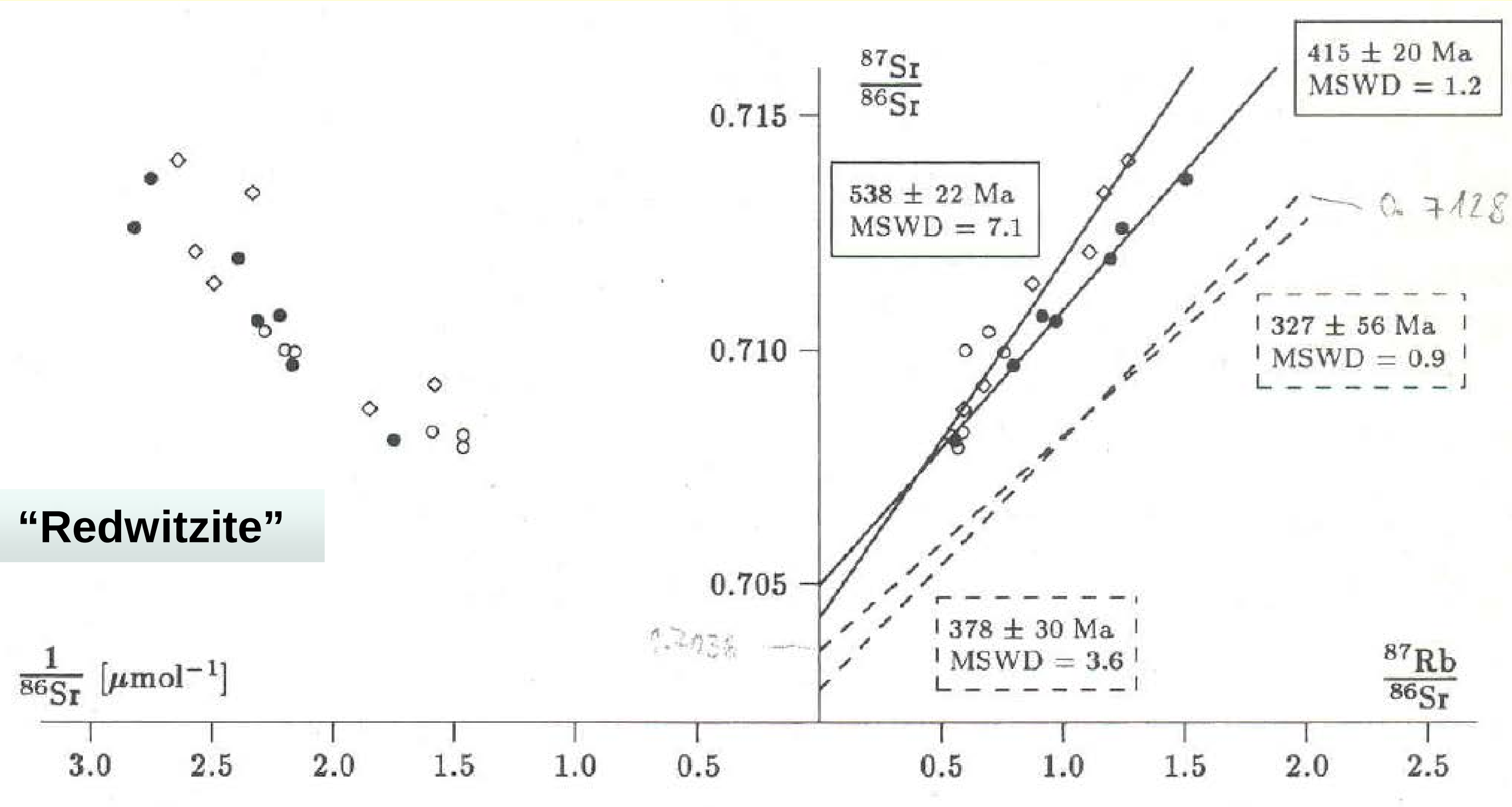


Briquet & Lancelot 1979

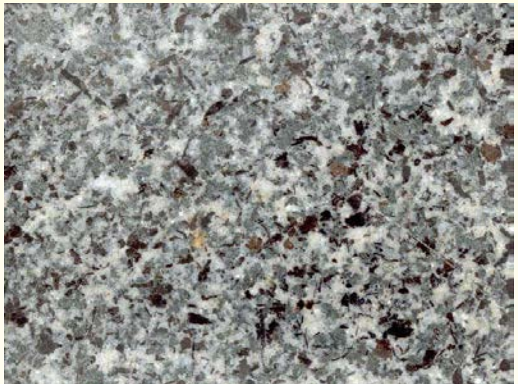
$$\left(\frac{^{87}Sr}{^{86}Sr}\right)_M = \left(\frac{^{87}Sr}{^{86}Sr}\right)_A \times f_A\left(\frac{Sr_A}{Sr_M}\right) + \left(\frac{^{87}Sr}{^{86}Sr}\right)_B \times (1-f_A)\left(\frac{Sr_B}{Sr_M}\right)$$

G. Faure, 1986, 2001

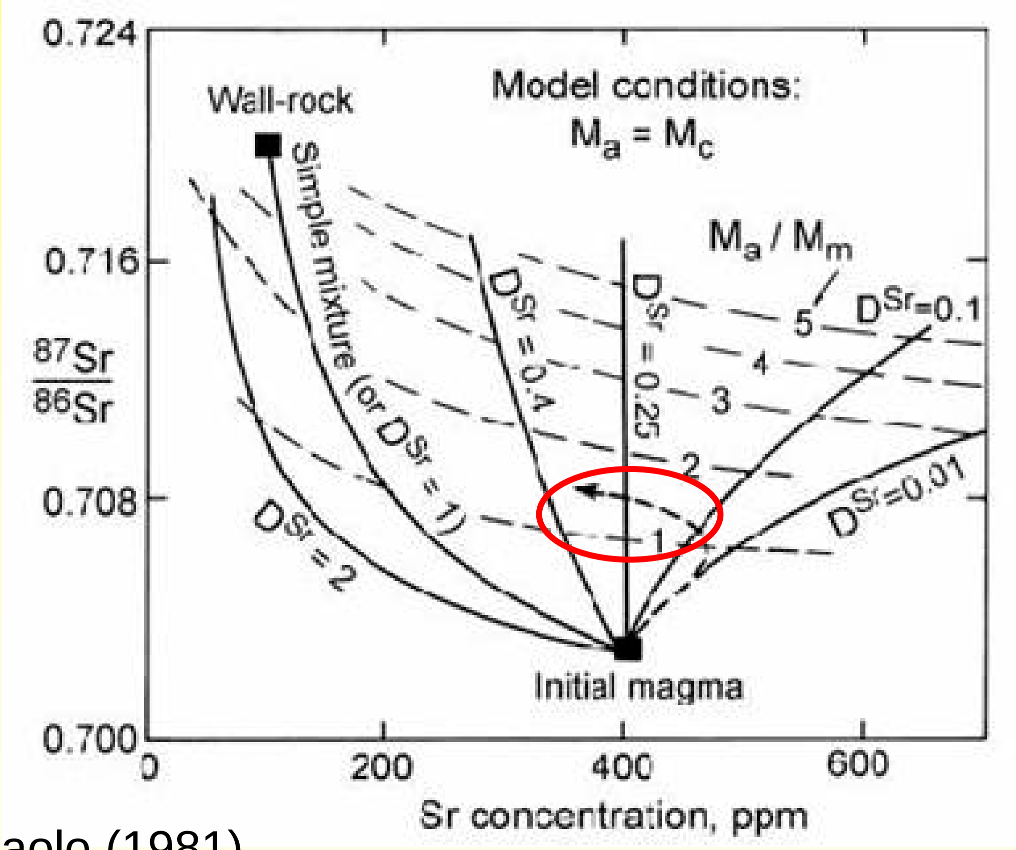
Isochrone oder Mischungslinie?



“Redwitzite”

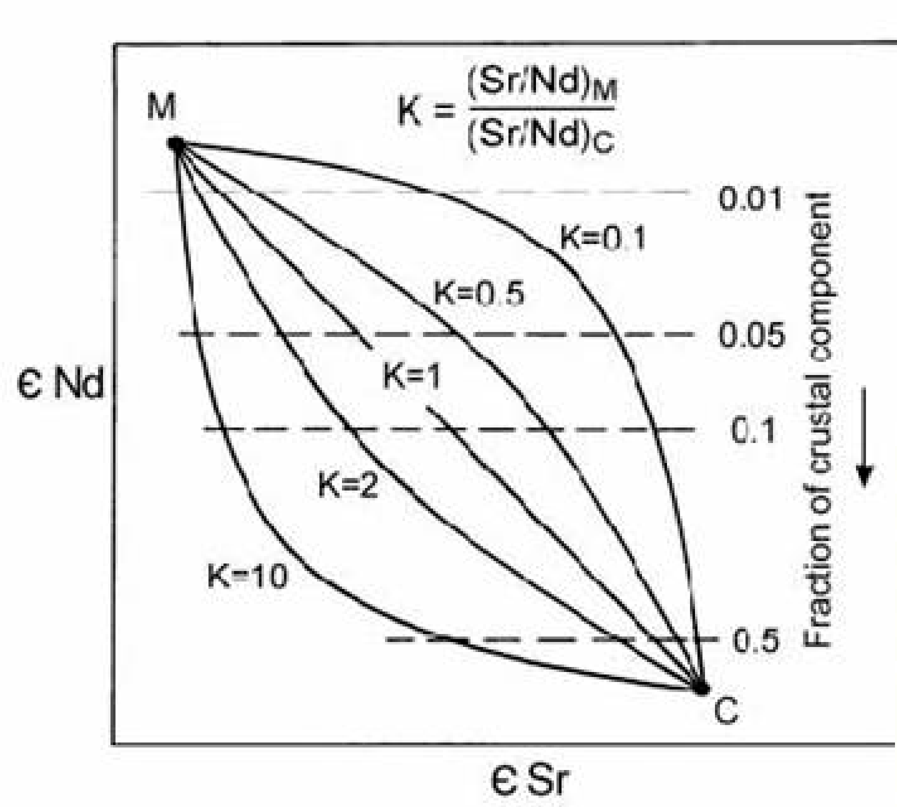


AFC - Prozesse

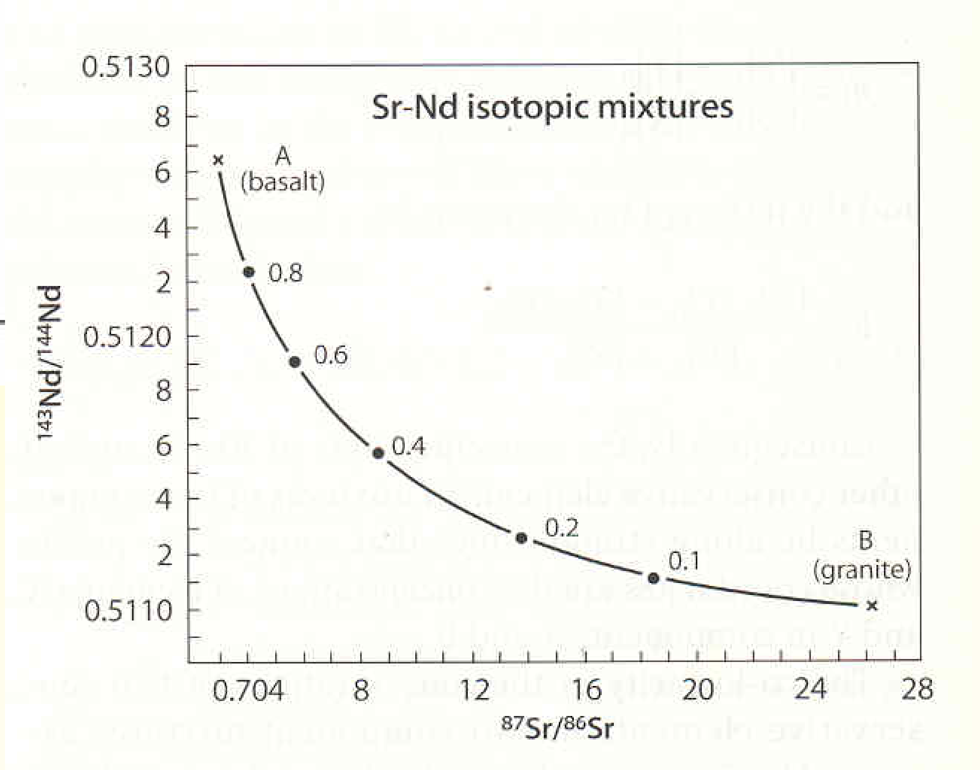


DePaolo (1981)

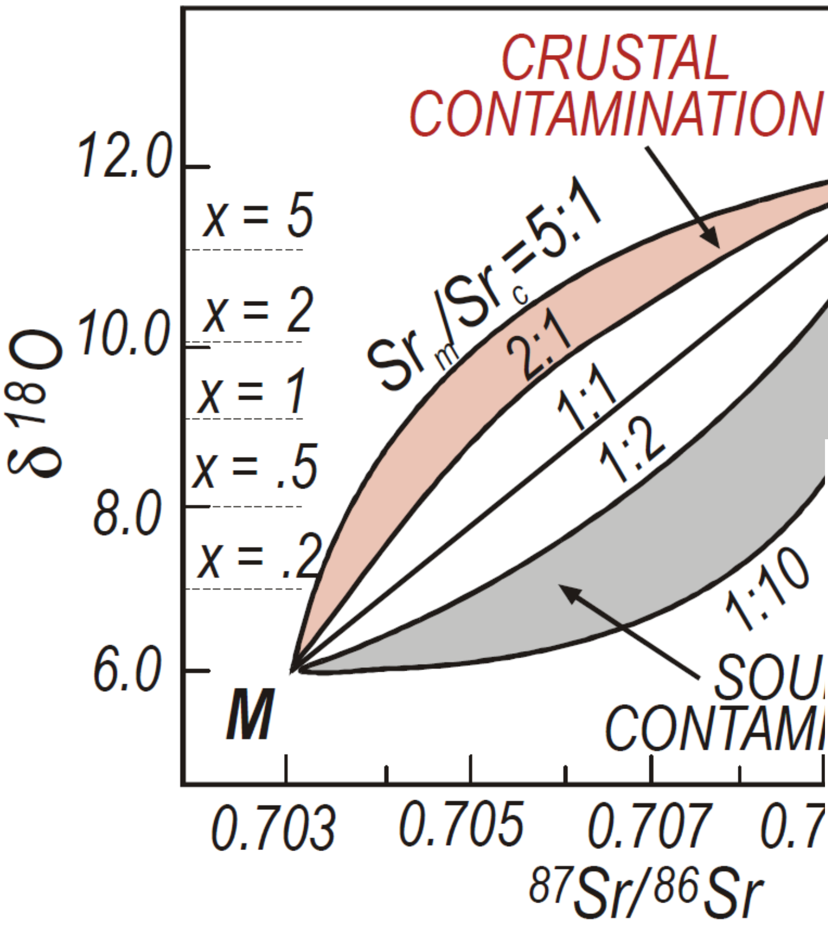
Krustenkontaminationmodelle



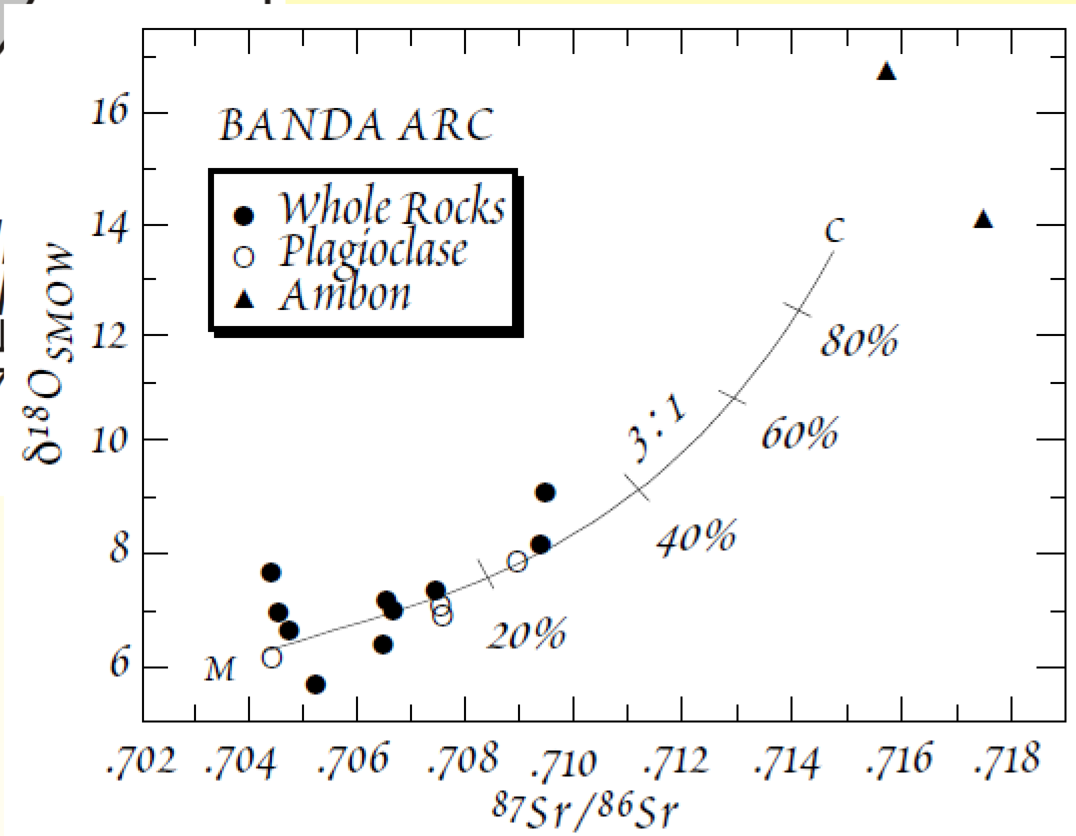
DePaolo & Wasserburg (1979)



Quell- oder Krustenkontamination



White:
Geochemistry
Lec. 31



Magaritz et al. (1978) EPSL 40: 220-230
James (1981) J. Geol Soc Lond 141:823-830