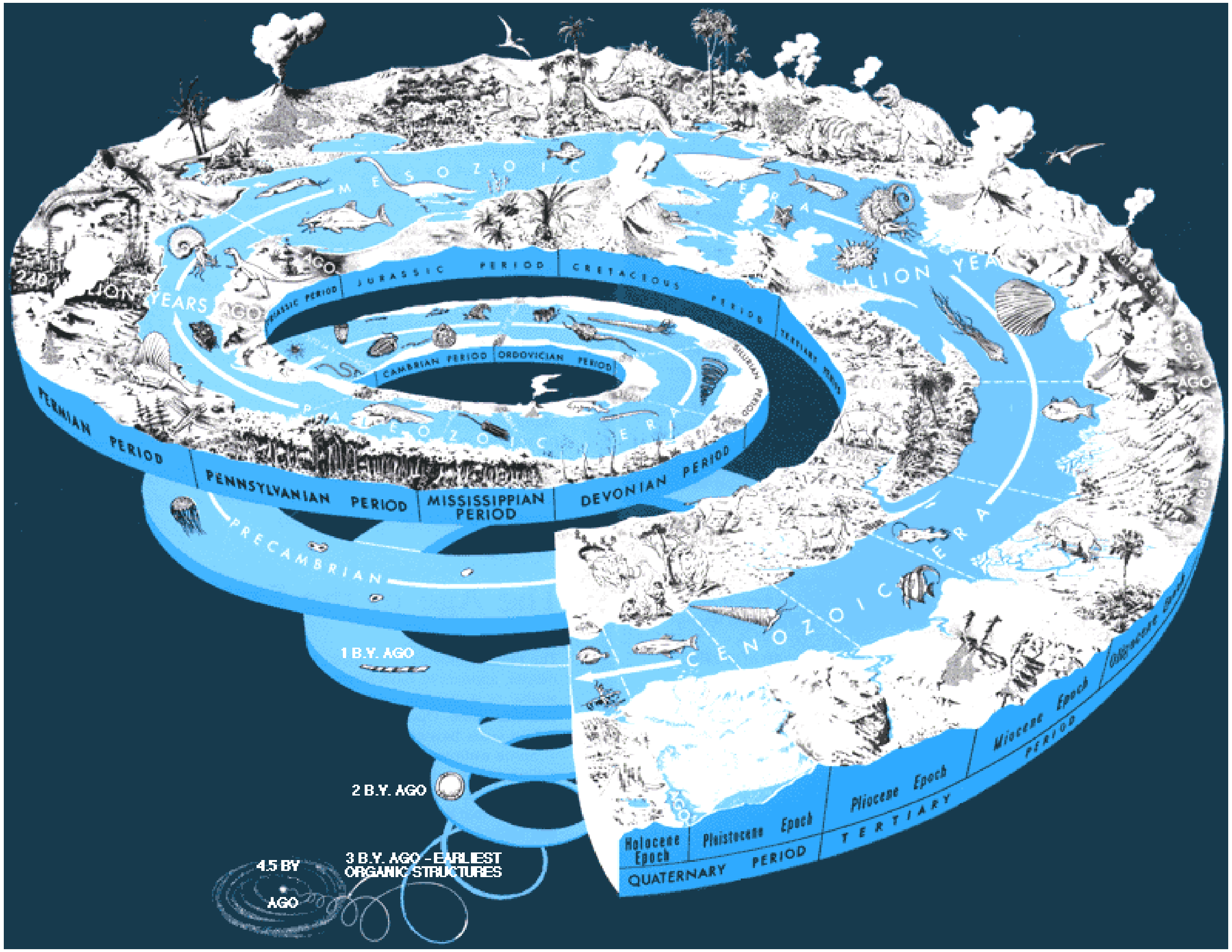
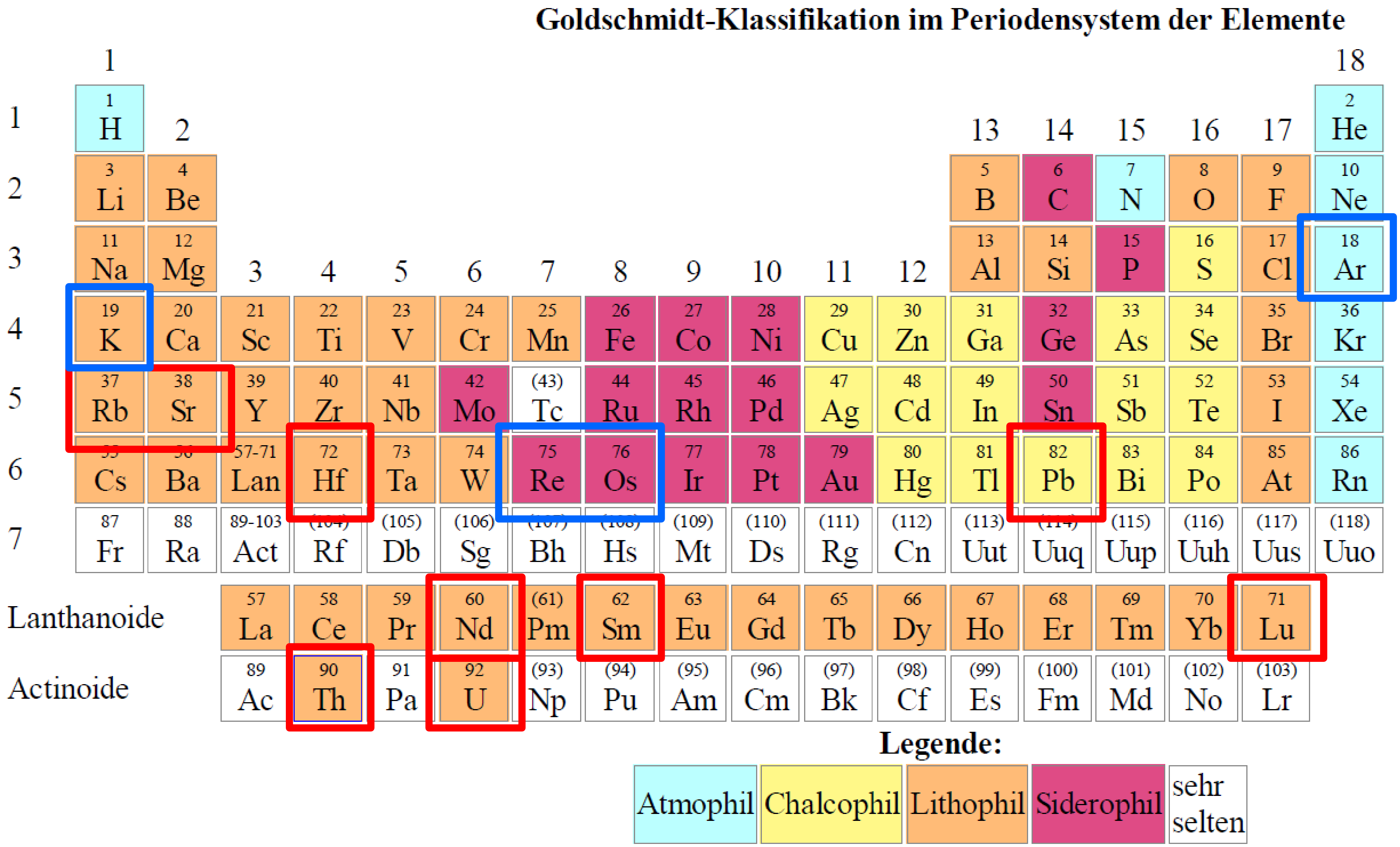
Isotopengeochemie
Geochronologie



Radiogene Isotopensysteme



Goldschmidt-Klassifikation im Periodensystem der Elemente

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	(43) Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57-71 Lan	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89-103 Act	(104) Rf	(105) Db	(106) Sg	(107) Bh	(108) Hs	(109) Mt	(110) Ds	(111) Rg	(112) Cn	(113) Uut	(114) Uuq	(115) Uup	(116) Uuh	(117) Uus	(118) Uuo
Lanthanoide			57 La	58 Ce	59 Pr	60 Nd	(61) Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
Actinoide			89 Ac	90 Th	91 Pa	92 U	(93) Np	(94) Pu	(95) Am	(96) Cm	(97) Bk	(98) Cf	(99) Es	(100) Fm	(101) Md	(102) No	(103) Lr	

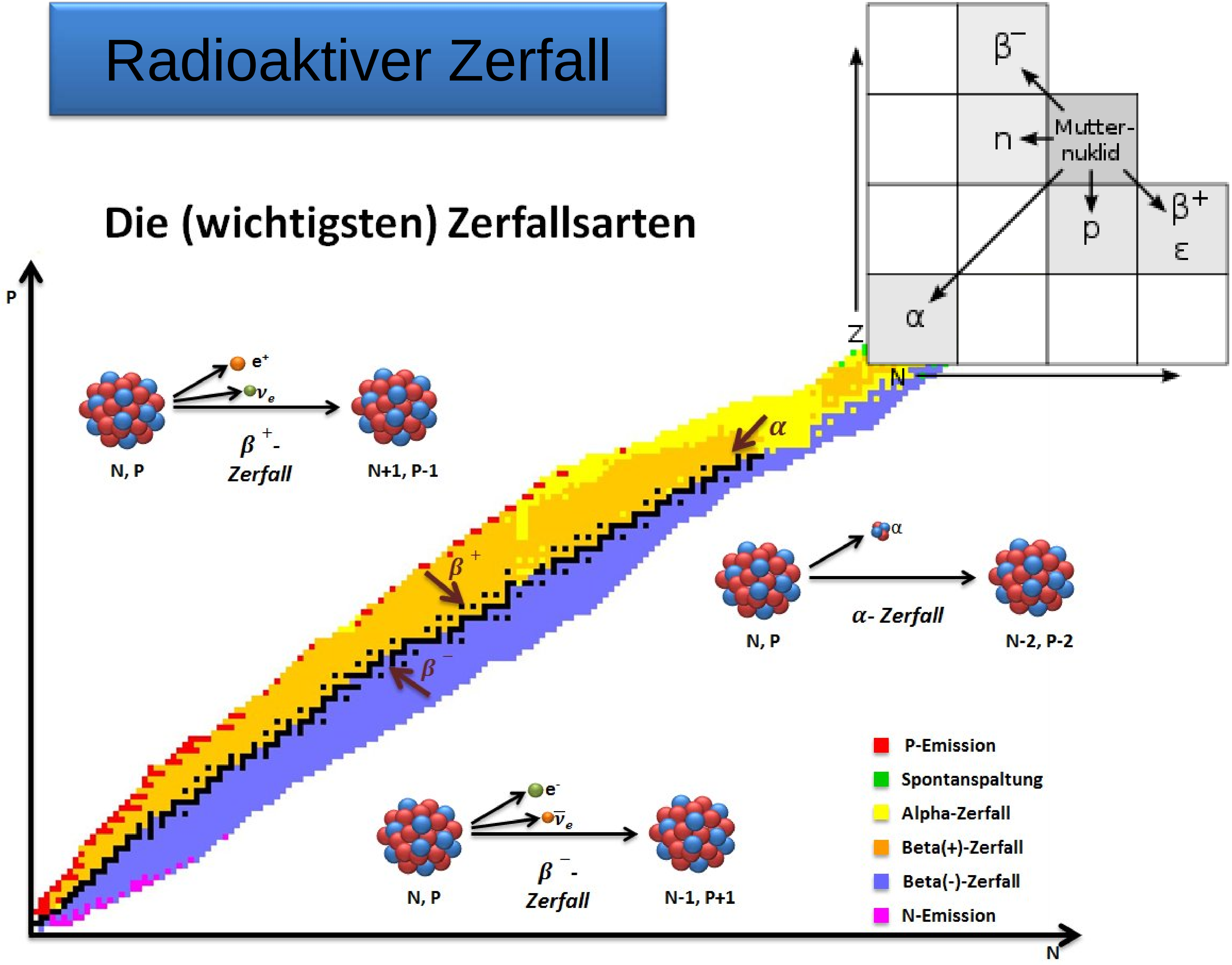
Legende:

Atmophil	Chalcophil	Lithophil	Siderophil	sehr selten

Grafik von: *http://de.wikipedia.org/wiki/Goldschmidt-Klassifikation*

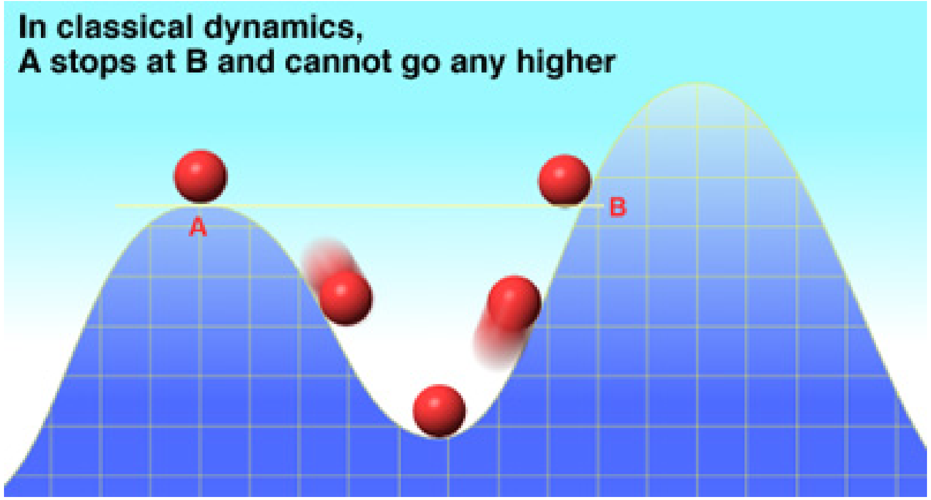
Radioaktiver Zerfall

Die (wichtigsten) Zerfallsarten

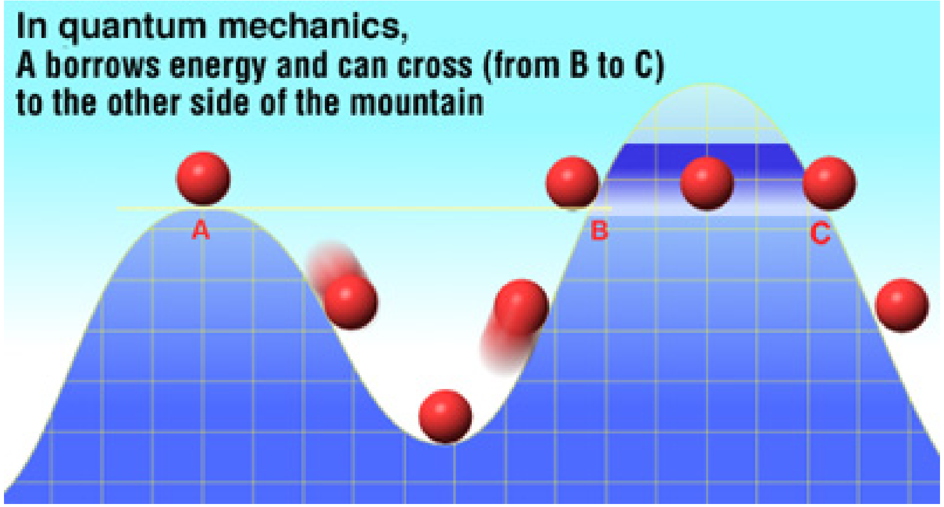


Alpha (α) Zerfall

Tunnel Effekt

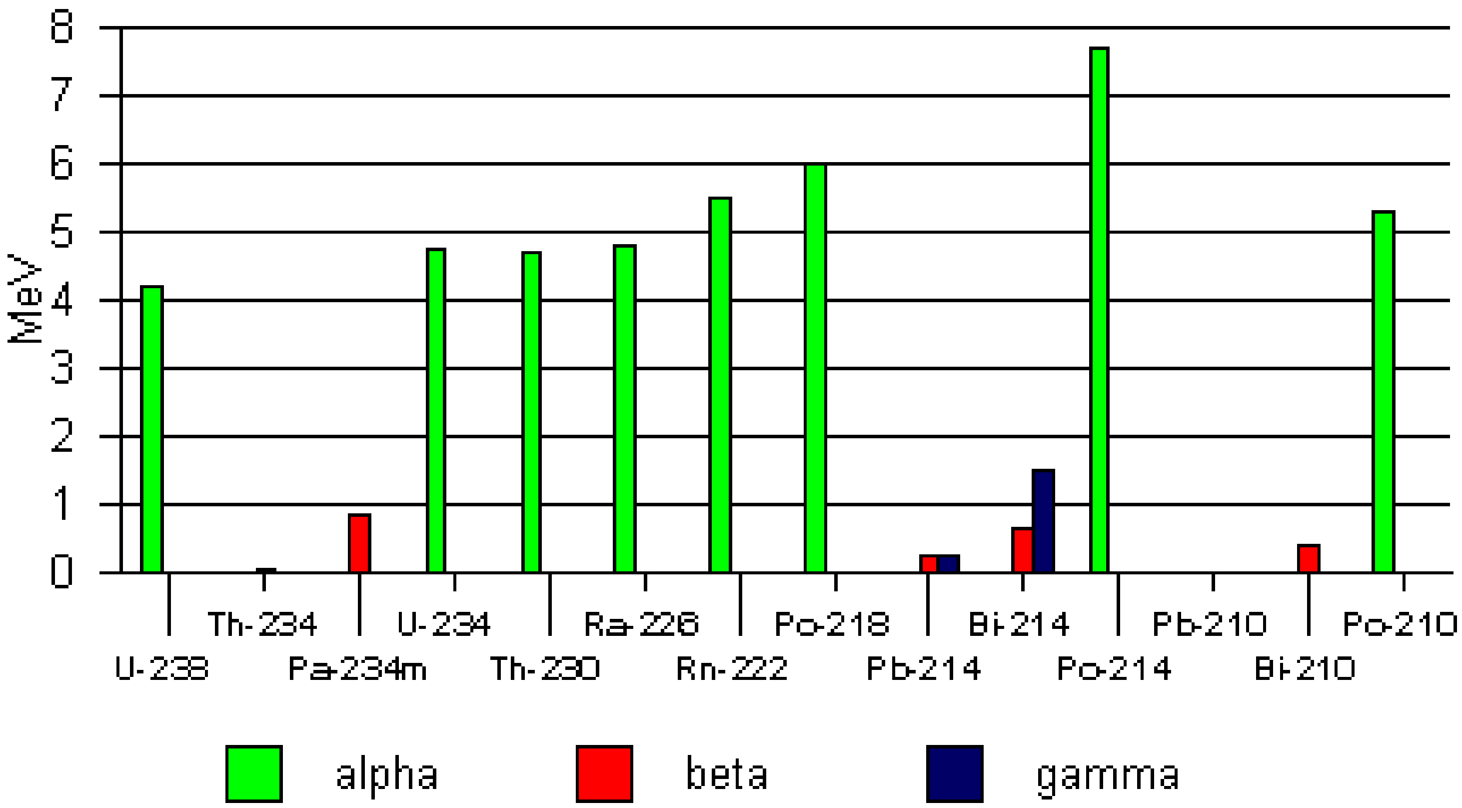


In classical dynamics,
A stops at B and cannot go any higher



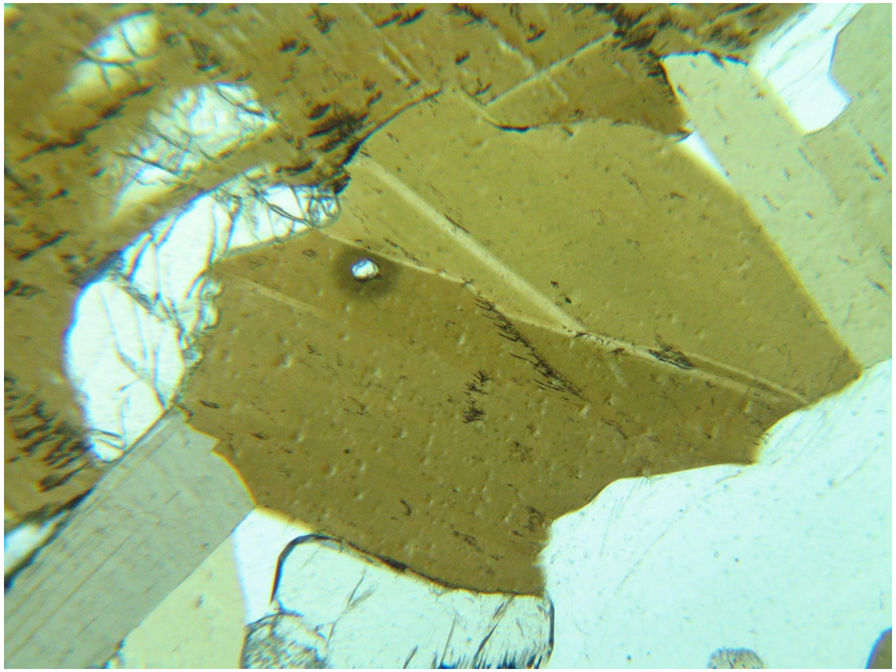
In quantum mechanics,
A borrows energy and can cross (from B to C)
to the other side of the mountain

Zerfallsenergien: U-238 Serie



Alpha (α) Zerfall - Kristallgitterschäden

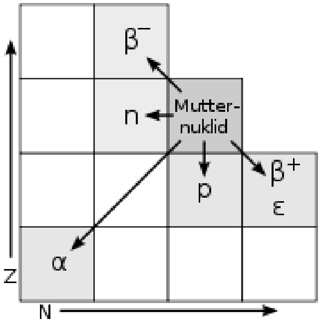
Biotite with a halo around a zircon inclusion



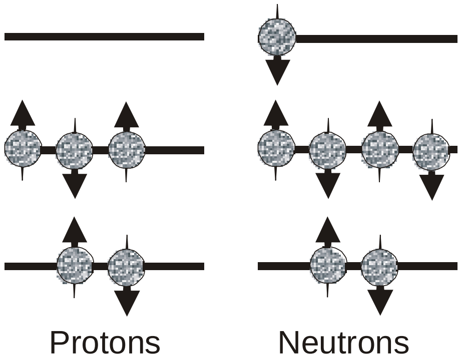
The field of view is about 2 mm

ß-Zerfall

Kernschalenmodell

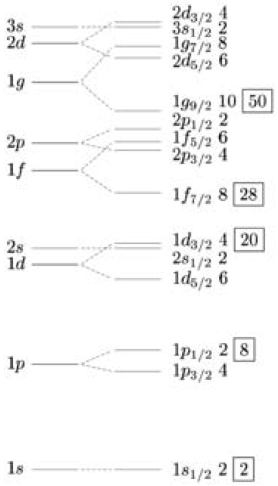


$^{12}_{5}\mathrm{B}$

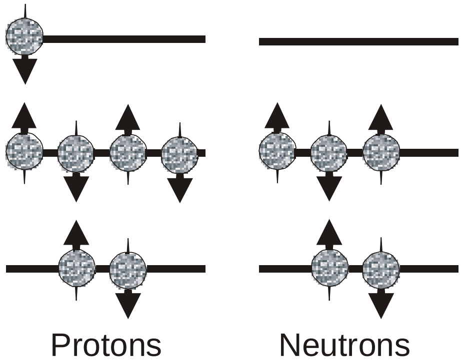


$${}^{1}_{0}\mathrm{n} \rightarrow {}^{1}_{1}\mathrm{p} + \mathrm{e}^{-} + \overline{\nu}_{\mathrm{e}}$$

Beta Minus Decay



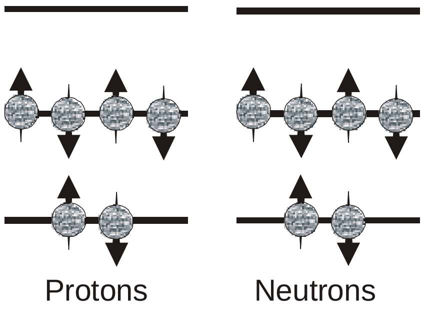
$^{12}_{7}\mathrm{N}$



$${}^{1}_{1}\mathrm{p} \rightarrow {}^{1}_{0}\mathrm{n} + \mathrm{e}^{+} + \nu_{\mathrm{e}}$$

Beta Plus Decay

$^{12}_{6}\mathrm{C}$



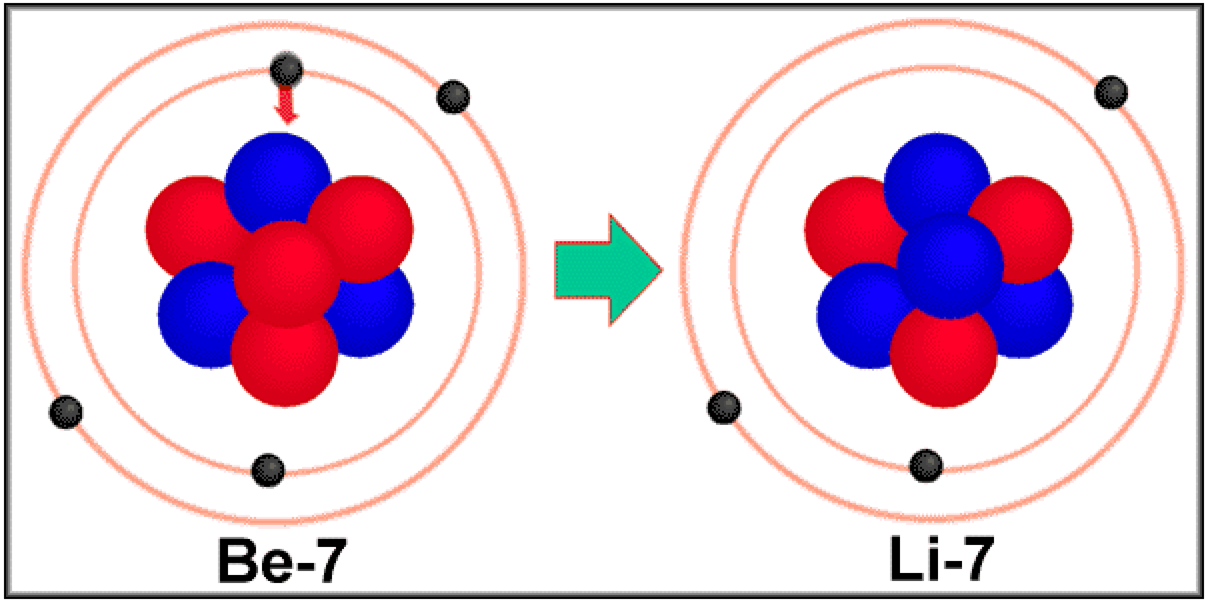
$${}^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z+1}\mathrm{Y} + \mathrm{e}^{-} + \overline{\nu}_{\mathrm{e}}$$

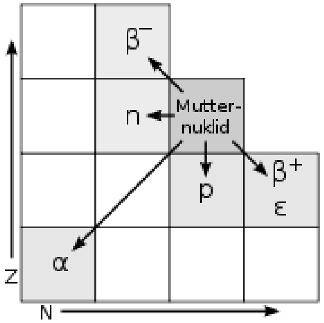
$${}^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z-1}\mathrm{Y} + \mathrm{e}^{+} + \nu_{\mathrm{e}}$$

Elektroneneinfang

A parent nucleus may capture one of its orbital electrons and emit a neutrino

Most commonly, it is a K-shell electron which is captured, and this is referred to as K-capture



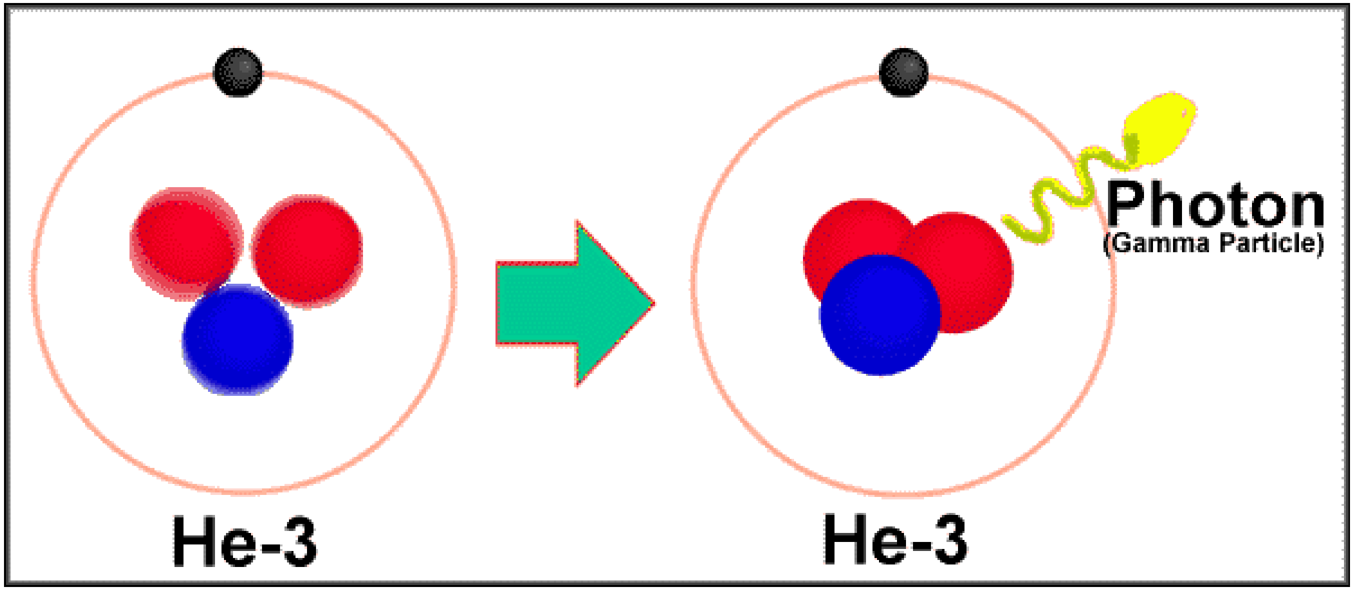


$${}^{7}_{4}\mathrm{Be} + {}^{0}_{-1}\mathrm{e} \text{ --> } {}^{7}_{3}\mathrm{Li} + \nu$$

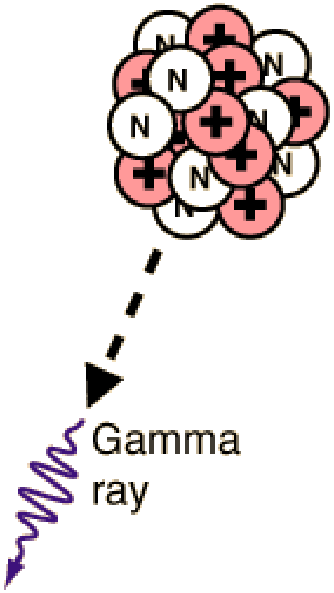
Gamma(γ) Strahlung

Gamma radioactivity is composed of electromagnetic rays.

It is distinguished from x-rays by the fact that it comes from the nucleus.



He-3 produced by Tritium



Elements

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An International Magazine of Mineralogy, Geochemistry, and Petrology

One Hundred Years of Geochronology

DANIEL J. CONDON and MARK D. SCHMITZ, Guest Editors

...and Counting

Precision and Accuracy in Geochronology

High-Precision Geochronology

High-Spatial-Resolution Geochronology

Dating the Oldest Rocks in the Solar System

Time Constraints in the Quaternary Period

100 Years of U–Pb Geochronology

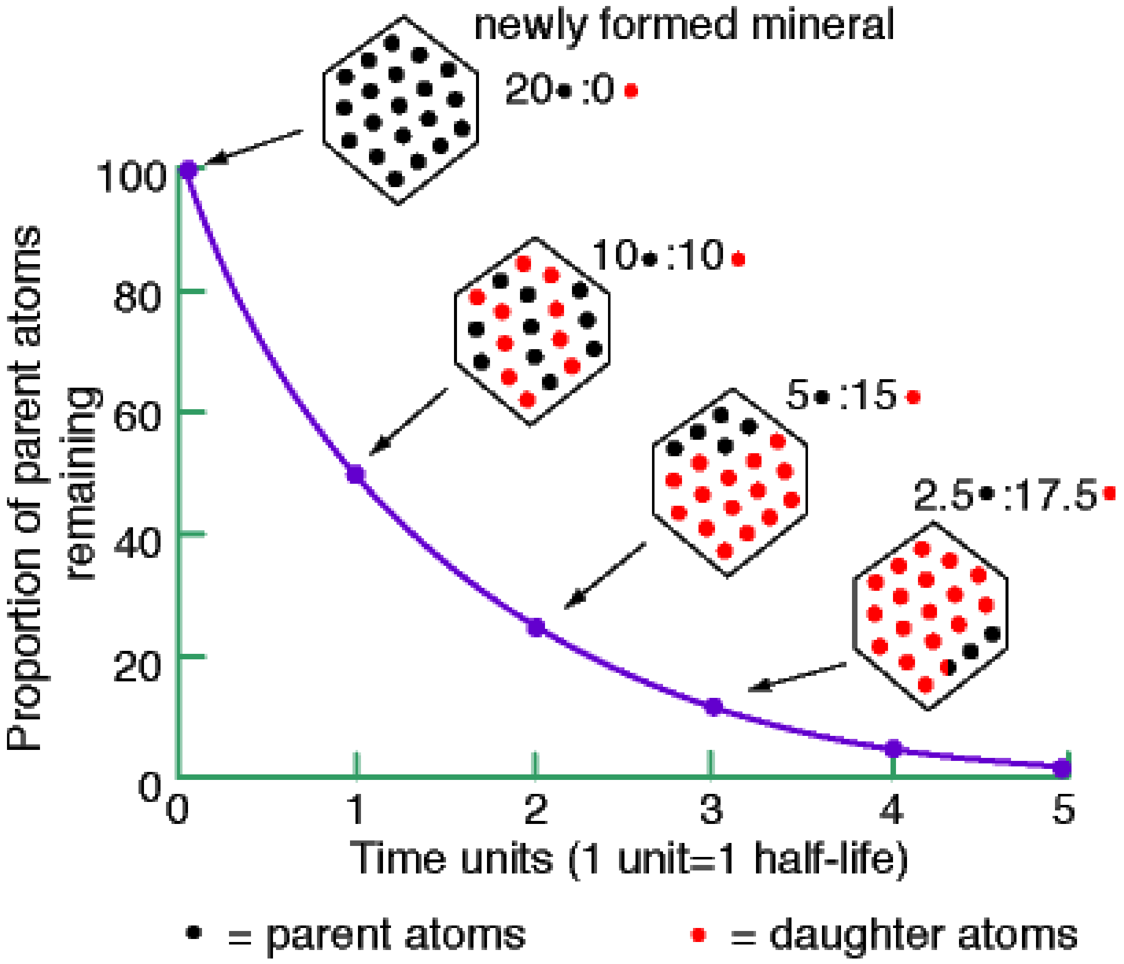
Arthur Holmes 1913:
The age of the Earth

Relative Ereignisabfolge?

Jutulhogget, Antarctica

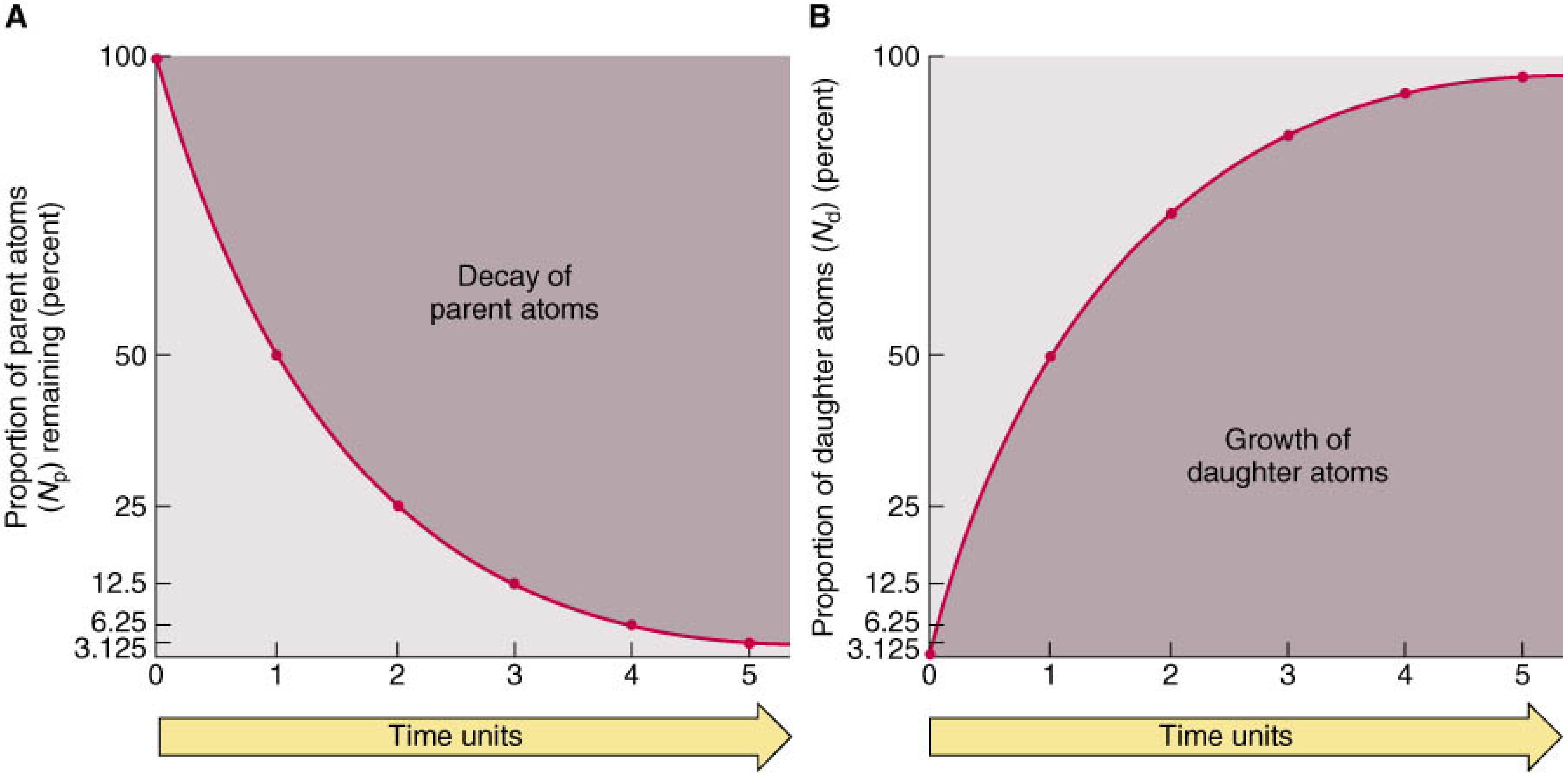
Radioaktiver Zerfall

Halbwertszeiten, $T_{1/2}$



- if it is possible to determine the ratio of the PARENT and DAUGHTER atoms, it is then possible to determine how long ago the decay process started → age determination

Mutter – Tochter System



Radioaktiver Zerfall

- Rate of decay is proportional to the number of decaying nuclei

$$\frac{dN}{dt} = -\lambda N$$

- Integrate to find the change in N with time

$$\frac{dN}{N} = -\lambda \cdot dt$$

λ = decay constant

Radioaktiver Zerfall

- Integrieren:

$$\int_{N_o}^{N(t)} \frac{1}{N}\, dN = -\int_0^t \lambda\, dt$$

- Resultat N(t):

$$\boxed{N = N_0\, e^{-\lambda t}}$$

Mutter-Tochter System:

$$\boxed{D = D_0 + N(e^{\lambda t} - 1)}$$

Radioaktiver Zerfall

$$A = -\frac{\mathrm{d}N}{\mathrm{d}t} \qquad \text{mit } A = \lambda \cdot N$$

$$-\lambda \cdot N = \frac{\mathrm{d}N}{\mathrm{d}t}$$

$$-\lambda \cdot \mathrm{d}t = \frac{1}{N} \cdot \mathrm{d}N$$

$$\int_0^t -\lambda \cdot \mathrm{d}t' = \int_{N_0}^{N} \frac{1}{N'} \cdot \mathrm{d}N'$$

$$-\lambda t - (-\lambda \cdot 0) = \ln(N) - \ln(N_0)$$

$$-\lambda t = \ln\left(\frac{N}{N_0}\right)$$

$$\mathrm{e}^{-\lambda t} = \frac{N}{N_0}$$

$$N(t) = N_0 \cdot \mathrm{e}^{-\lambda t}$$

Radioaktiver Zerfall

- Integrieren:

$$\int_{N_o}^{N(t)} \frac{1}{N}\, dN = -\int_0^t \lambda\, dt$$

- Resultat N(t):

$$\boxed{N = N_0\, e^{-\lambda t}}$$

Mutter-Tochter System:

$$\boxed{D = D_0 + N(e^{\lambda t} - 1)}$$

Radioaktiver Zerfall und Altersgleichung

Parent—daughter system:

$D = N_0 - N$

D – Number of daughter atoms, today

N – Number of parent atoms, today

N_0 – Number of parent atoms, initially present

$$N = N_o \cdot e^{-\lambda \cdot t} \quad \text{or} \quad N_O = N \frac{1}{e^{-\lambda t}} = Ne^{\lambda t}$$

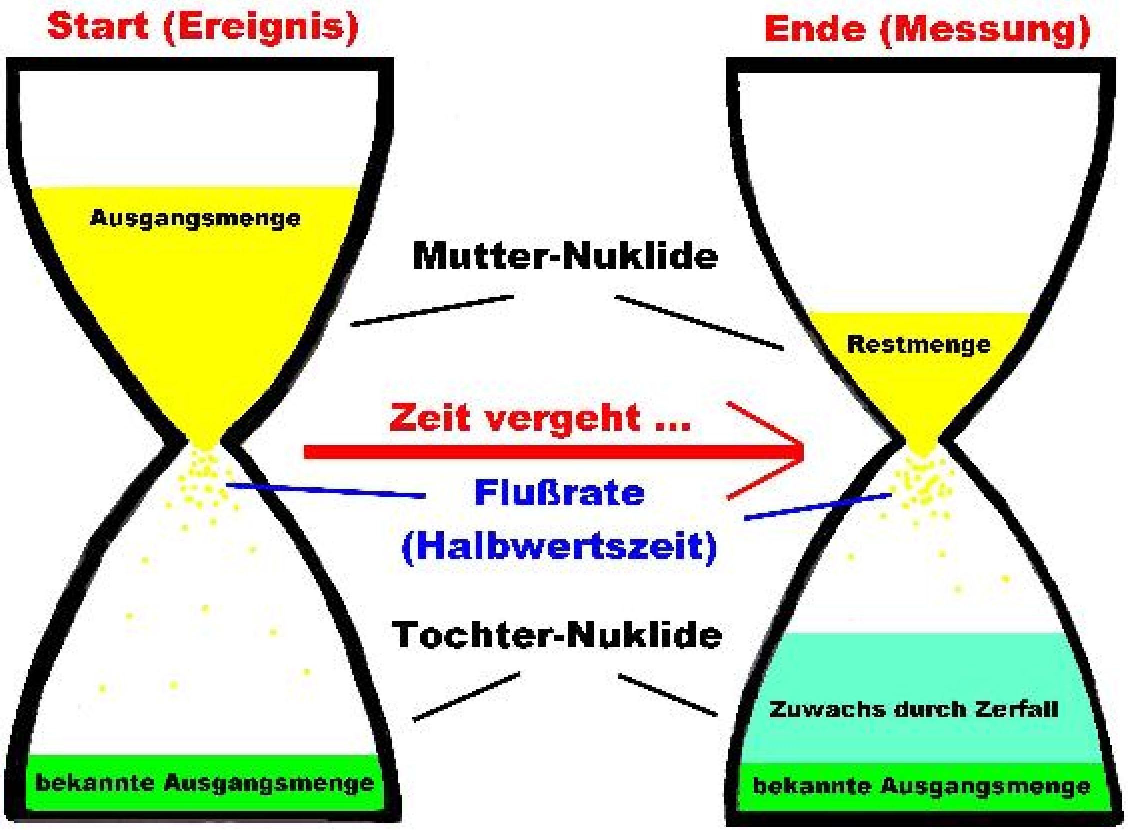
$N_0 = D + N$, hence: $D + N = Ne^{\lambda t}$, or $D = N\,e^{\lambda t} - N$, or $D = N(e^{\lambda t} - 1)$

$$t = \frac{1}{\lambda} \ln\left(1 + \frac{D}{N}\right)$$

This is the mathematical expression that relates radioactive decay to geologic time!

If some daughter nuclides, D_0, are there initially: $D = D_0 + N(e^{\lambda t} - 1)$

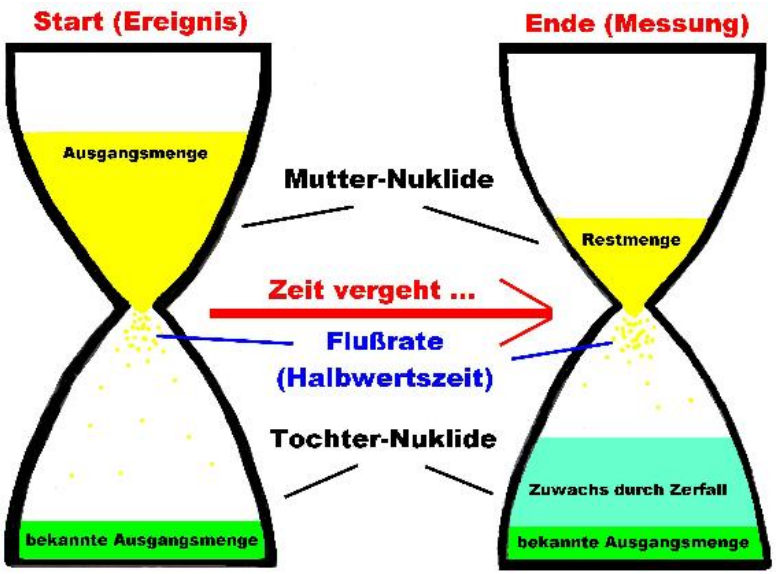
Radiometrische Datierung



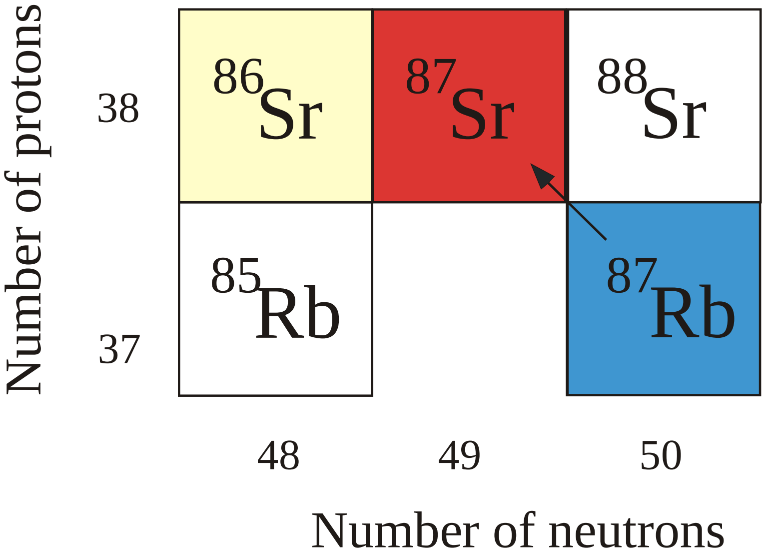
Radiometrische Datierung

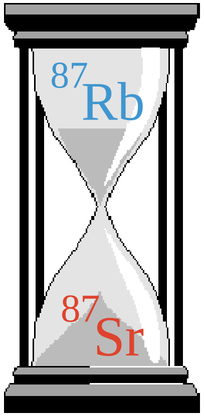
Method is restricted to minerals which:

- Still contain some of the parent nuclei
- Allowed for no gain or loss of D or P as time passed
- Initially contained no D (or D_0 must be known)

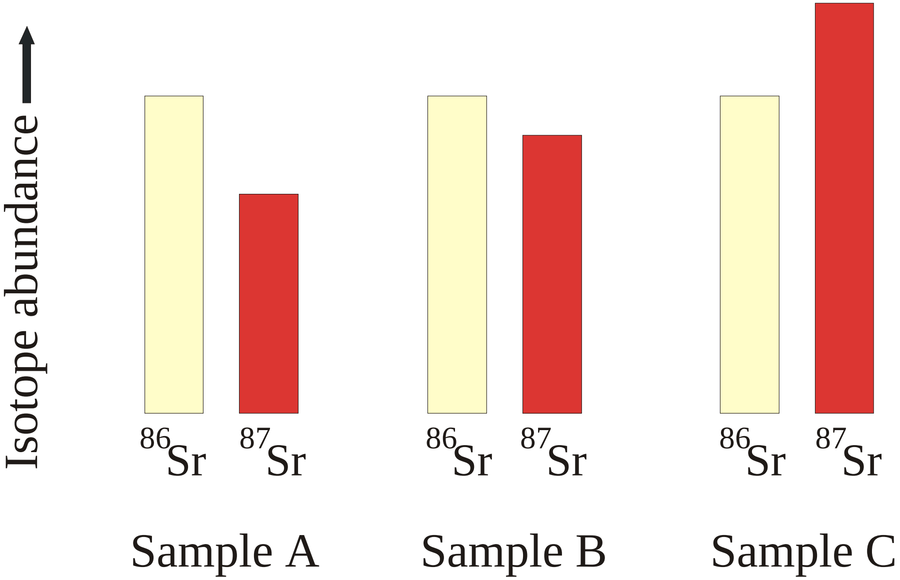


Rb–Sr System

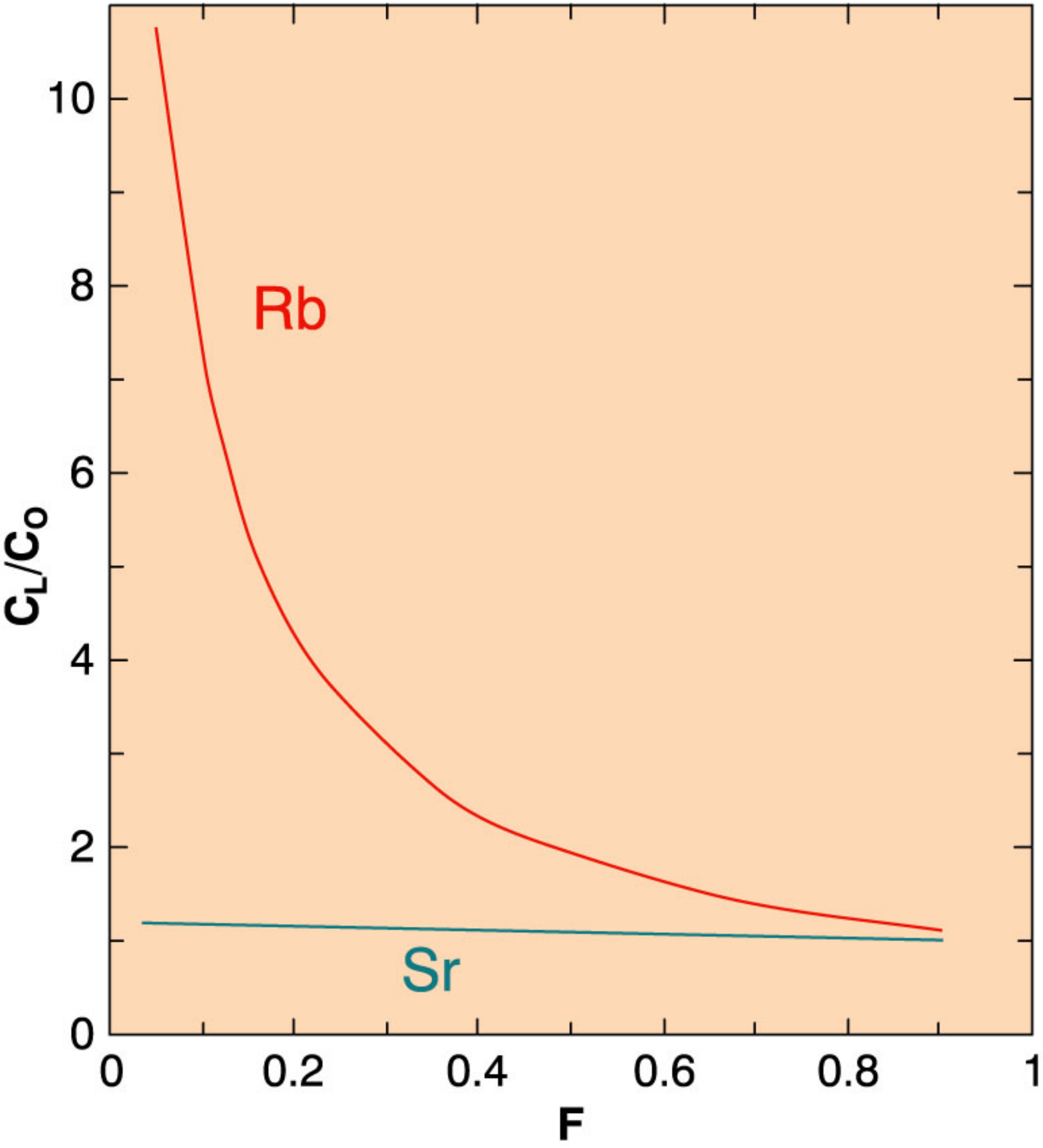




$T_{1/2} = 4.8 \times 10^{10}$ years

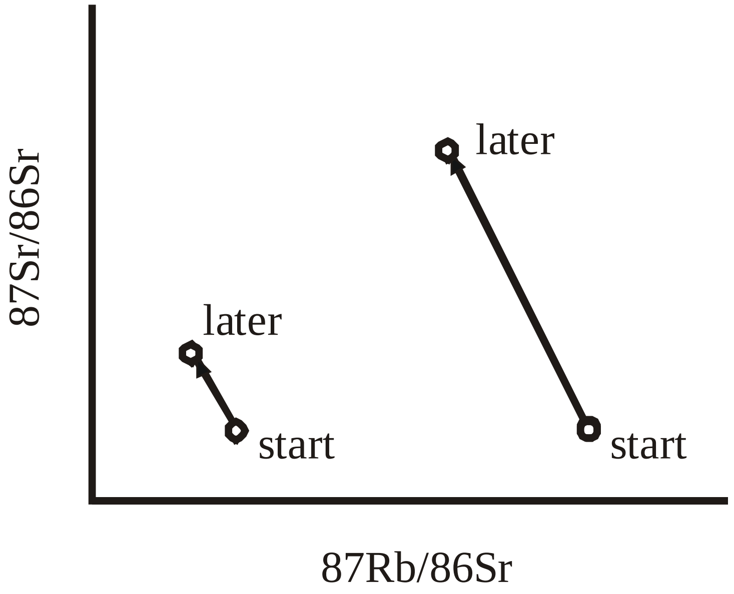


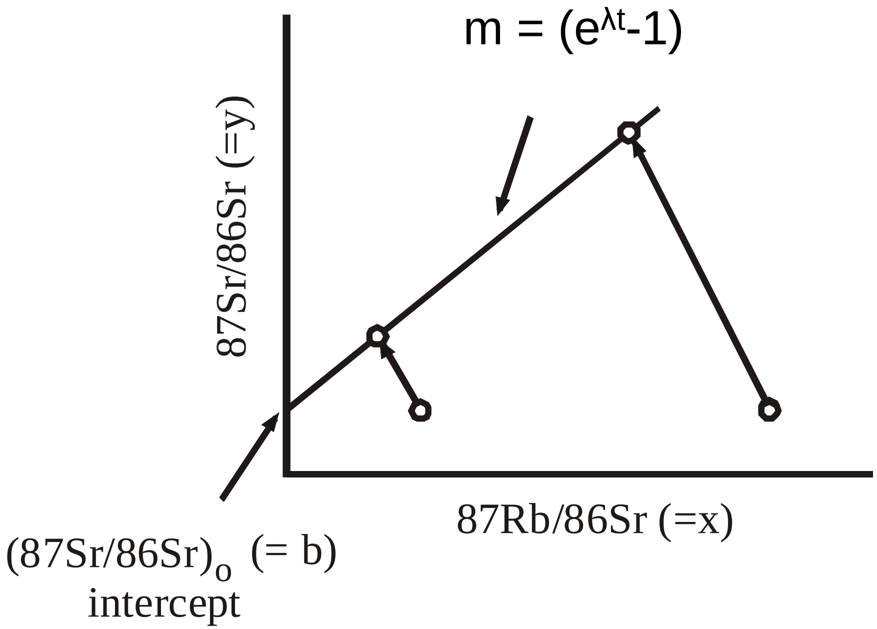
Geochemische Diagramme



Veränderung der Rb und Sr Konzentrationen in der Schmelze mit steigendem Aufschmelzungsgrad. Basaltisches Ausgangsgestein (Plagioklas, Augit, Olivin).

Rb–Sr System – Nicolaysen Diagramm





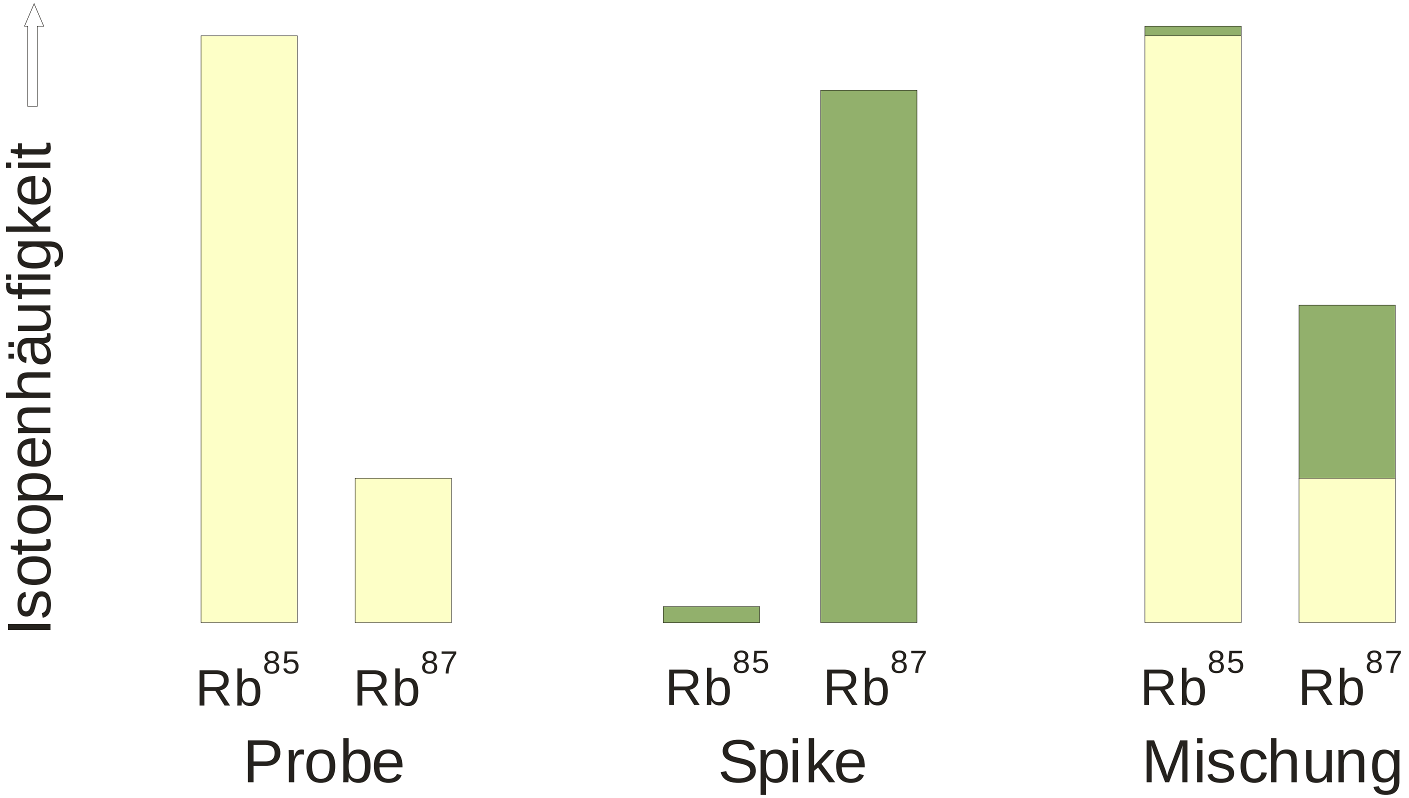
$$^{87}\mathrm{Sr}/^{86}\mathrm{Sr} = (^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_0 + {}^{87}\mathrm{Rb}/^{86}\mathrm{Sr}\,(e^{\lambda t}-1)$$

$$y \quad = \quad b \quad + \quad x \quad m$$

$$m = (e^{\lambda t}-1)$$

$$T = \ln(m + 1)/\lambda$$

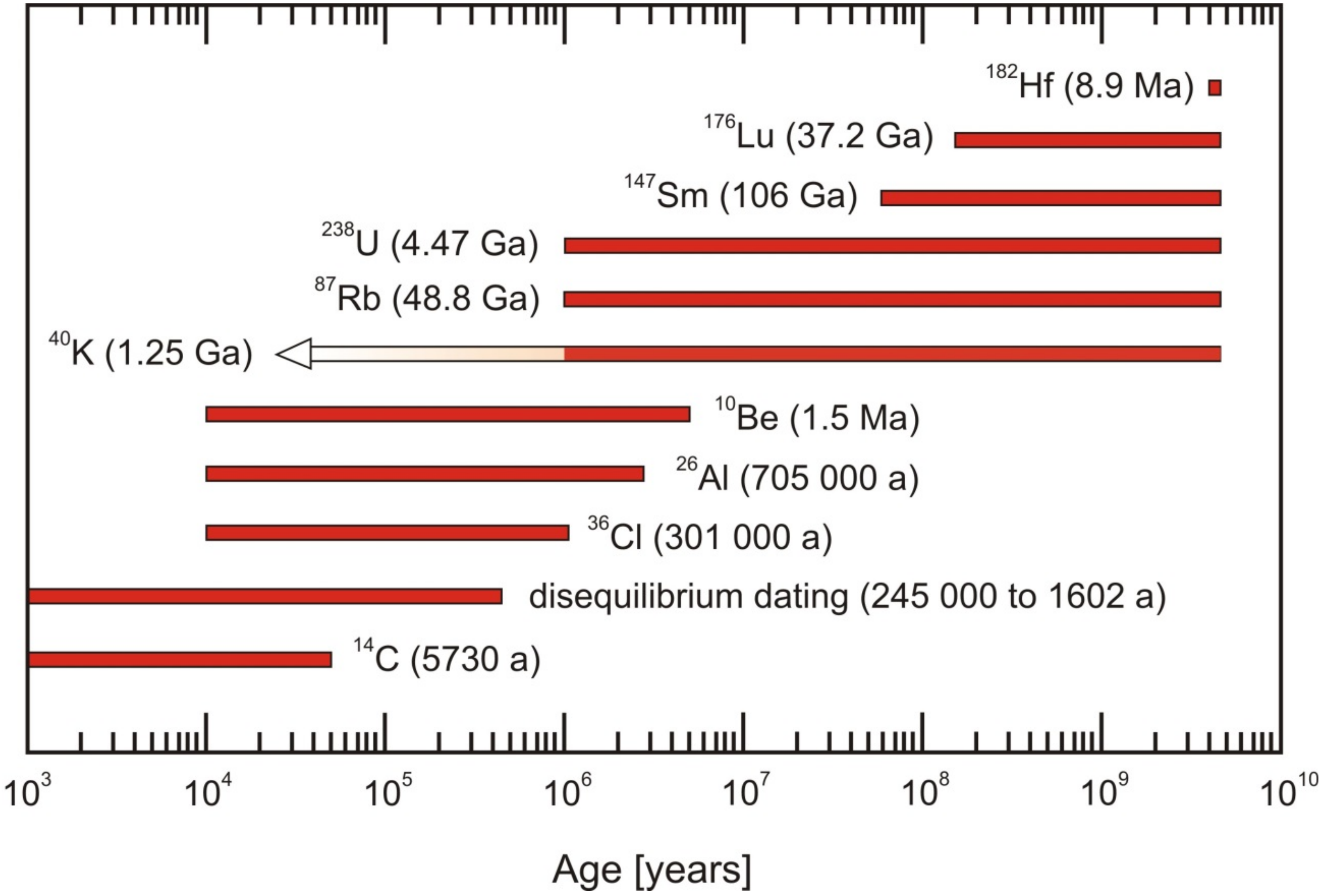
Isotopenverdünnungsanalyse



Isotopenverdünnungsanalyse

- Zusatz des gleichen Elements mit anderer Isotopenzusammensetzung (Spike)
- Mischung von Probe und Isotopenstandard
- Abtrennung des Elements (keine quantitative Ausbeute notwenig!)
- Bestimmung des Verhältnis der Isotope
- Berechnung der Konzentration

Datierungssysteme

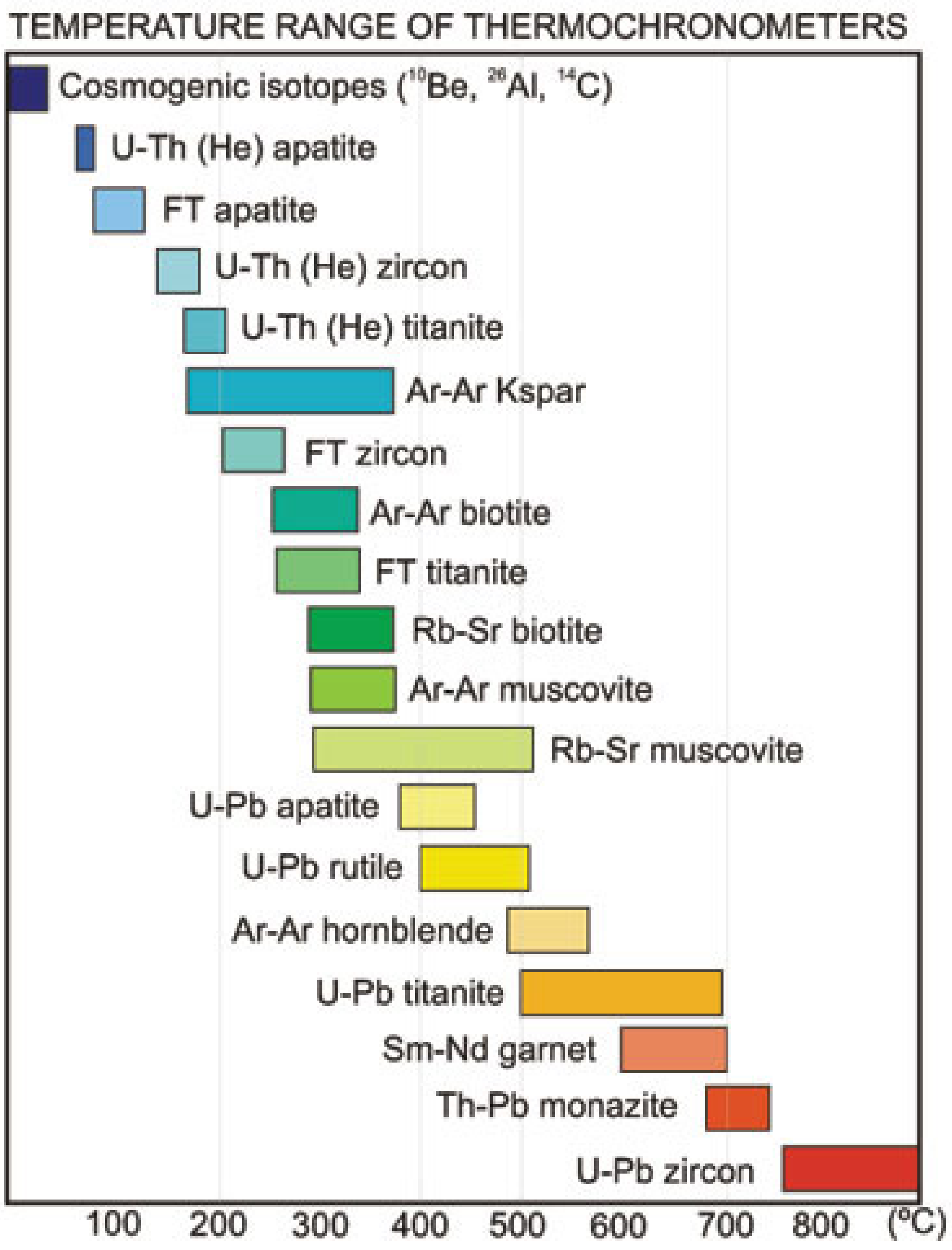


Datierungsmethoden und Schließungstemperatur

Schließungstemperatur: Temperatur unterhalb der keine signifikante Diffusion mehr stattfindet und die geochronologische Uhr zu ticken beginnt

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

Datierungsmethoden und Schließungstemperatur



Welche Art von Alter?

Bildungsalter (Entstehungsalter)

oder ererbtes Alter?

Abkühlungsalter (Abkühlalter) oder

Metamorphosealter (Aufheizungsalter)?

Hebungsalter (bei Spaltspuren)

Welches Mineral oder Gestein wurde mit welcher Methode datiert?

Isochronenmethode

Beispiel Rb-Sr:

$$^{87}_{37}Rb \rightarrow {}^{87}_{38}Sr + \beta^-$$

Halbwertszeit: $T_{1/2}$ = 48.8 Ga

Zerfallskonstante: $\lambda = \ln 2/T_{1/2}$ = $0.693/T_{1/2}$

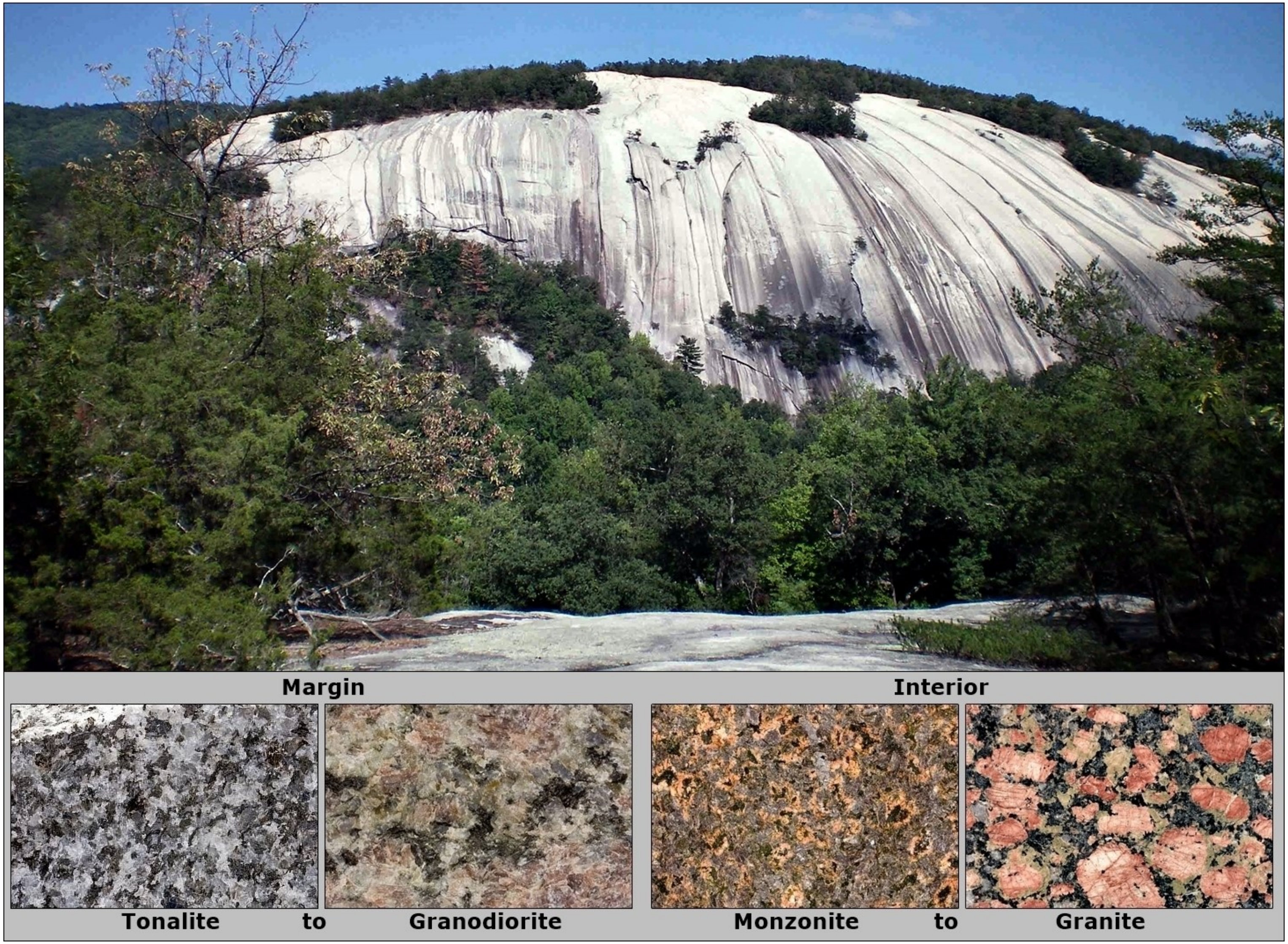
Altersgleichung:

$$\boxed{\frac{^{87}Sr}{^{86}Sr} = \left(\frac{^{87}Sr}{^{86}Sr}\right)_0 + \frac{^{87}Rb}{^{86}Sr}(e^{\lambda t} - 1)}$$

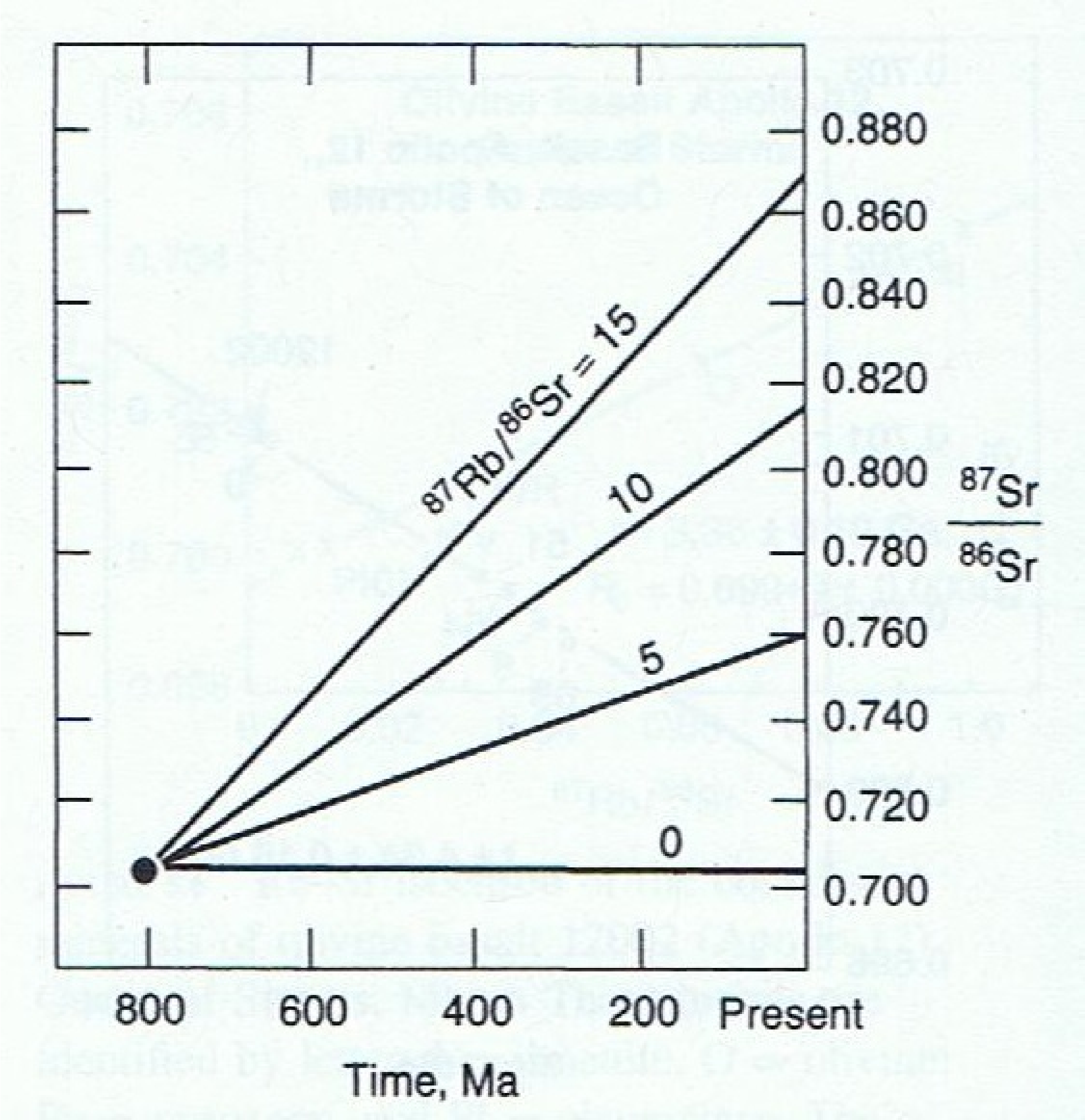
Rb-Sr Isochronendiagram

M_1, M_2 = cogenetische Minerale

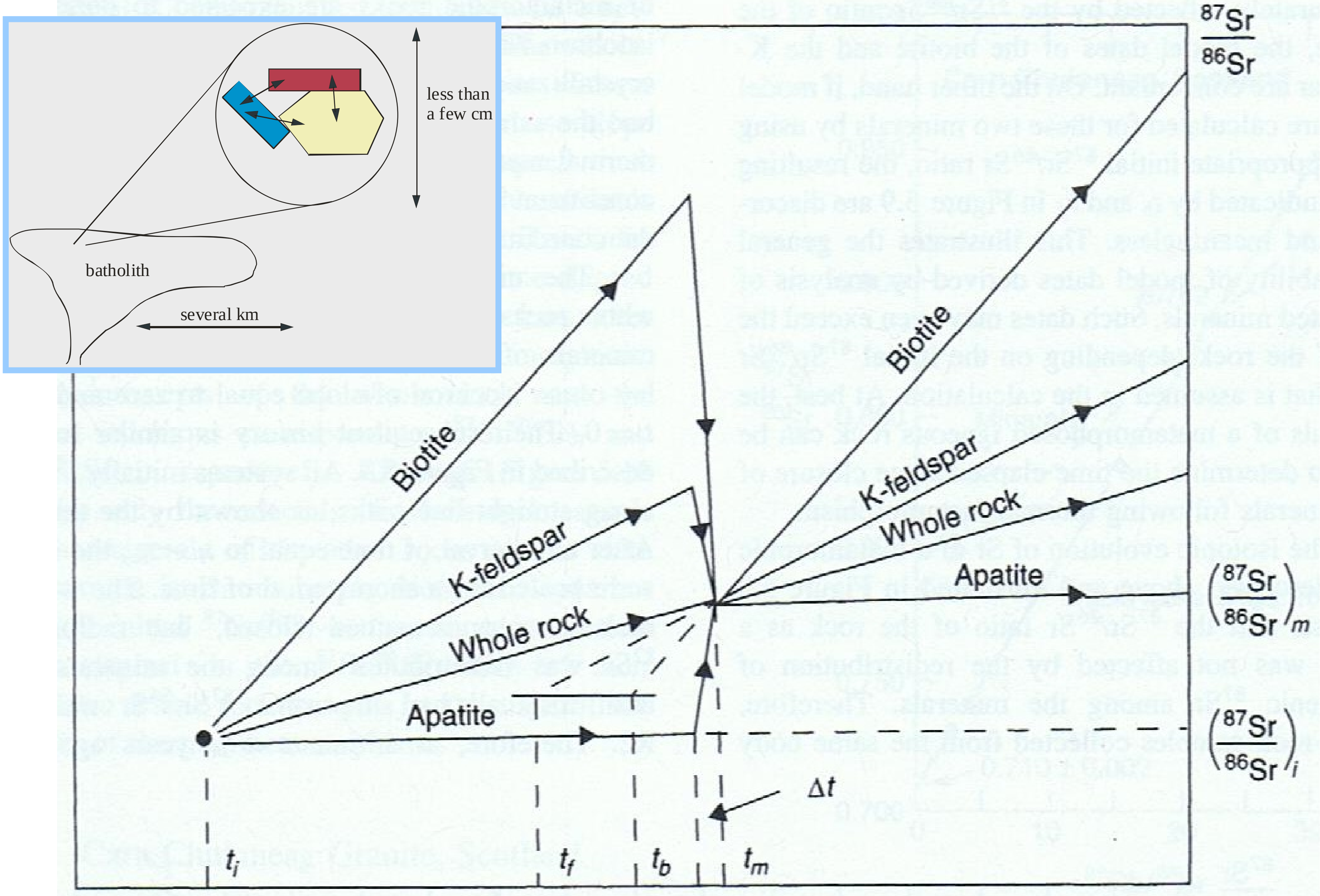
R_1, R_2 cogenetische Gesamtgesteine mit unterschiedlichen Rb/Sr Verhältnissen



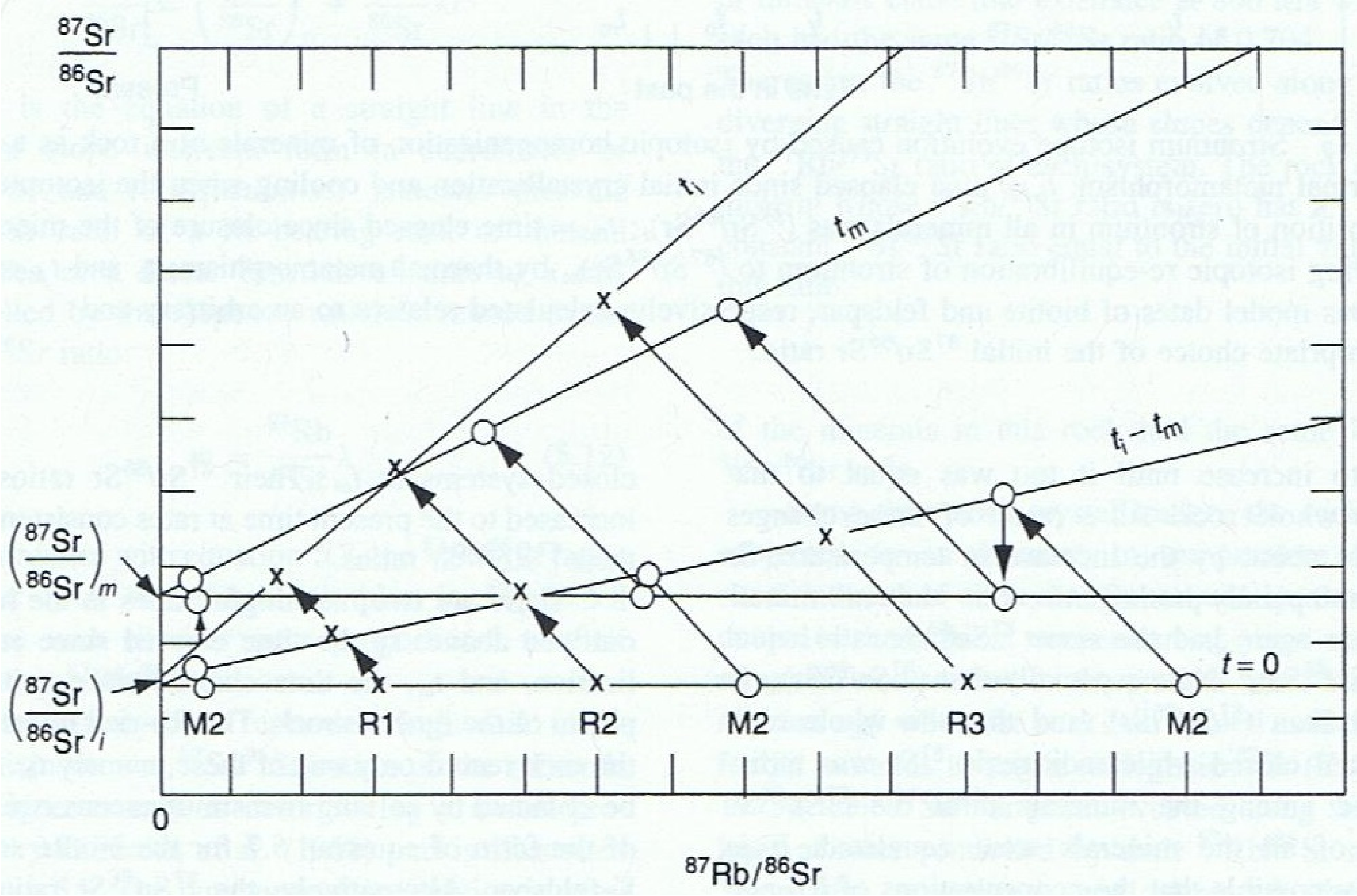
Compston-Jeffery Diagramm



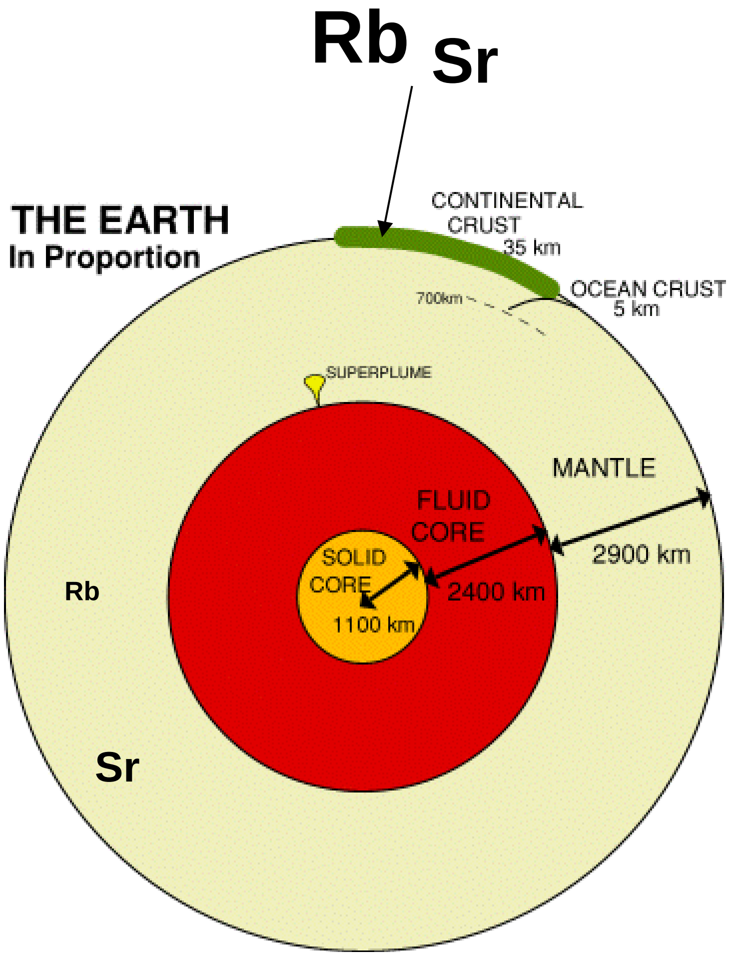
Rb/Sr-System während einer Metamorphose



Rb/Sr-System während einer Metamorphose



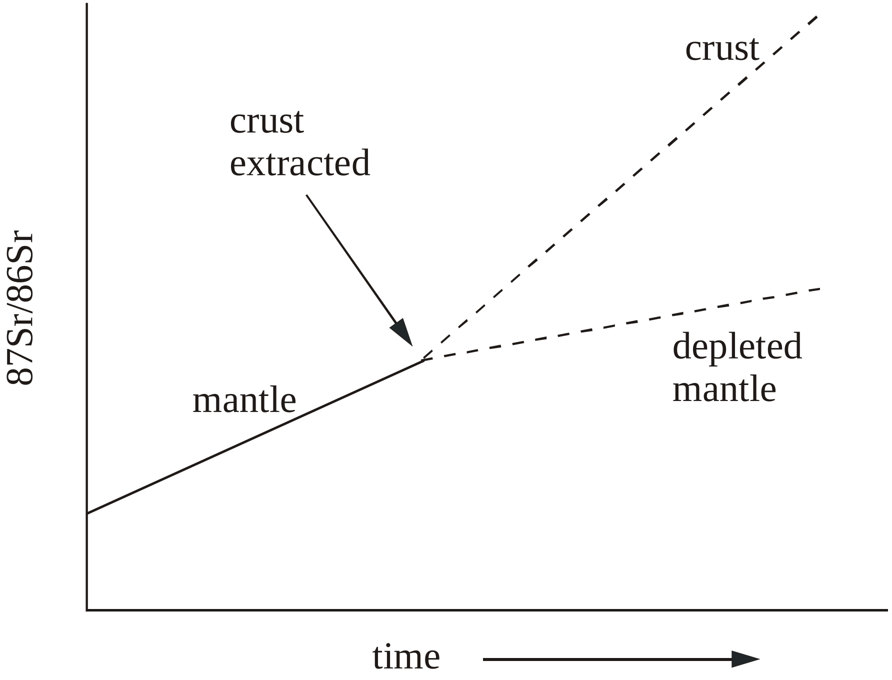
Die Sr-Isotopenentwicklung der Erde



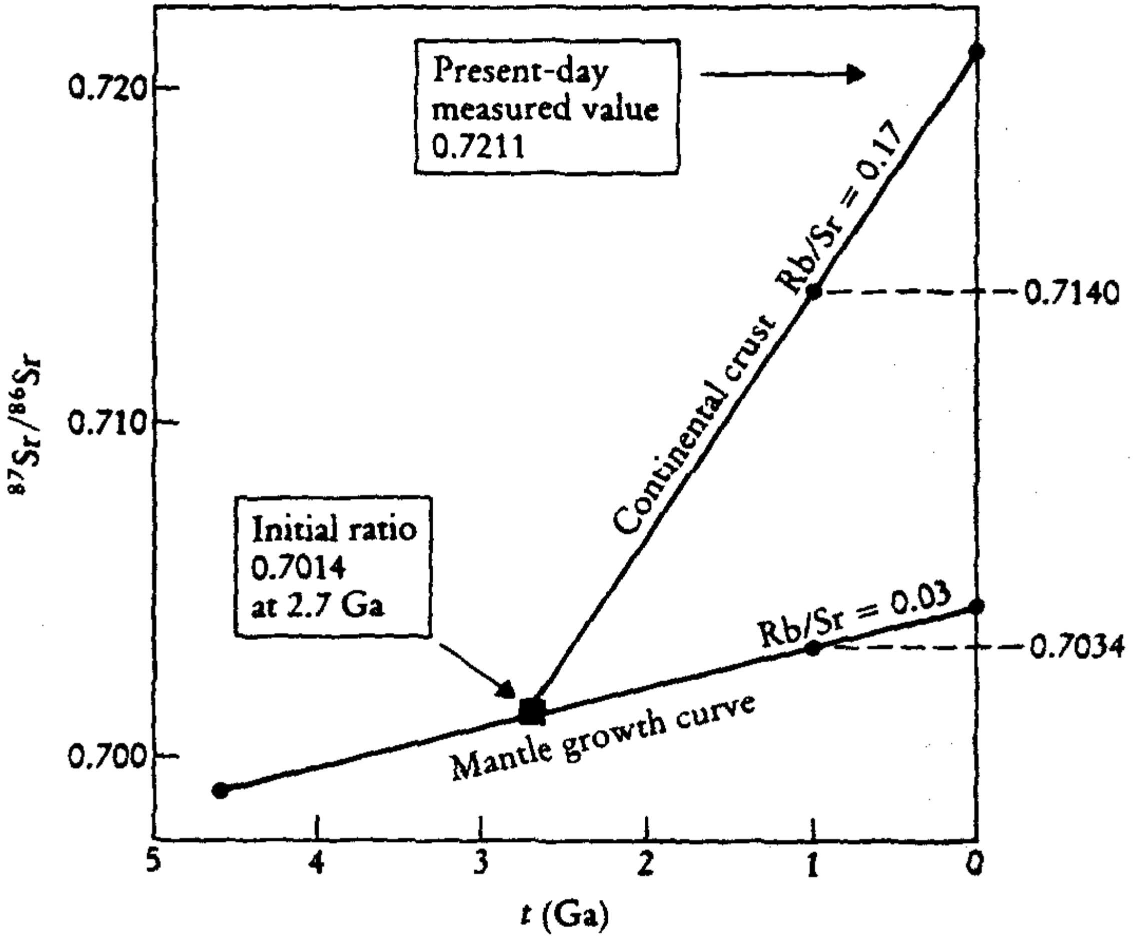
Continental crust: 32-78 ppm Rb, 260-333 ppm Sr
Depleted Mantle: 0.6 ppm Rb, 19.9 ppm Sr

Mehr Rb in der Kruste als im Erdmantel

Dadurch höhere $^{87}Sr/^{86}Sr$ Verhältnisse in der Kruste als im Mantel

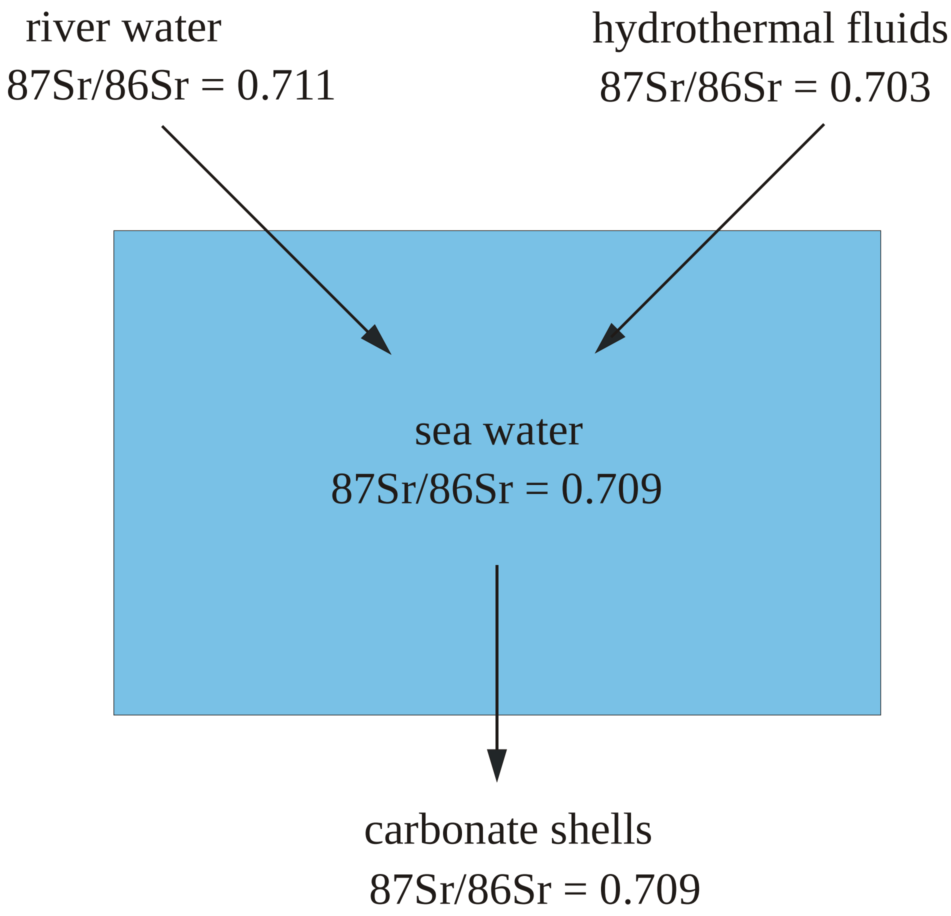


$^{87}Sr/^{86}Sr$ Isotopenentwicklung in Kruste und Mantel



Sr-Isotopie der Ozeane

Sr isotope composition of the oceans is determined by the relative contributions of Sr from river waters and hydrothermal sources



river water

87Sr/86Sr = 0.711

hydrothermal fluids

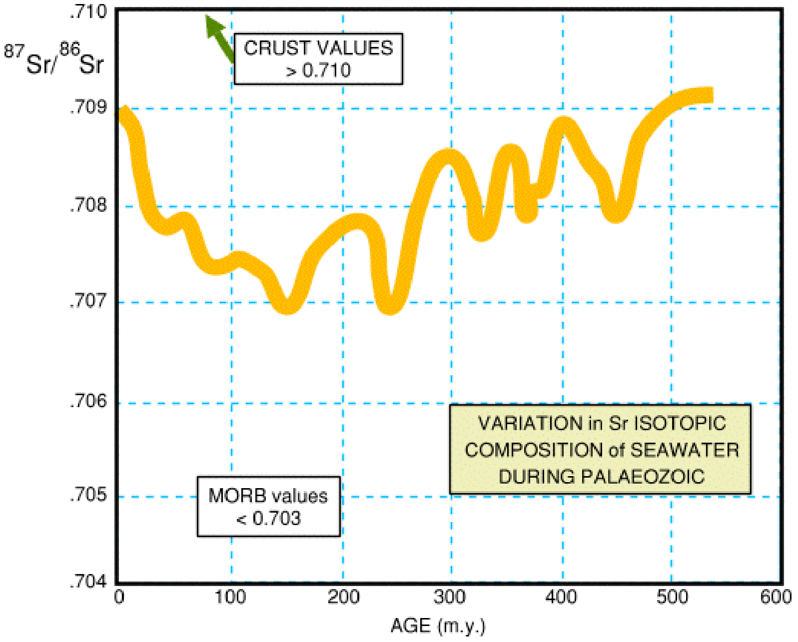
87Sr/86Sr = 0.703

sea water

87Sr/86Sr = 0.709

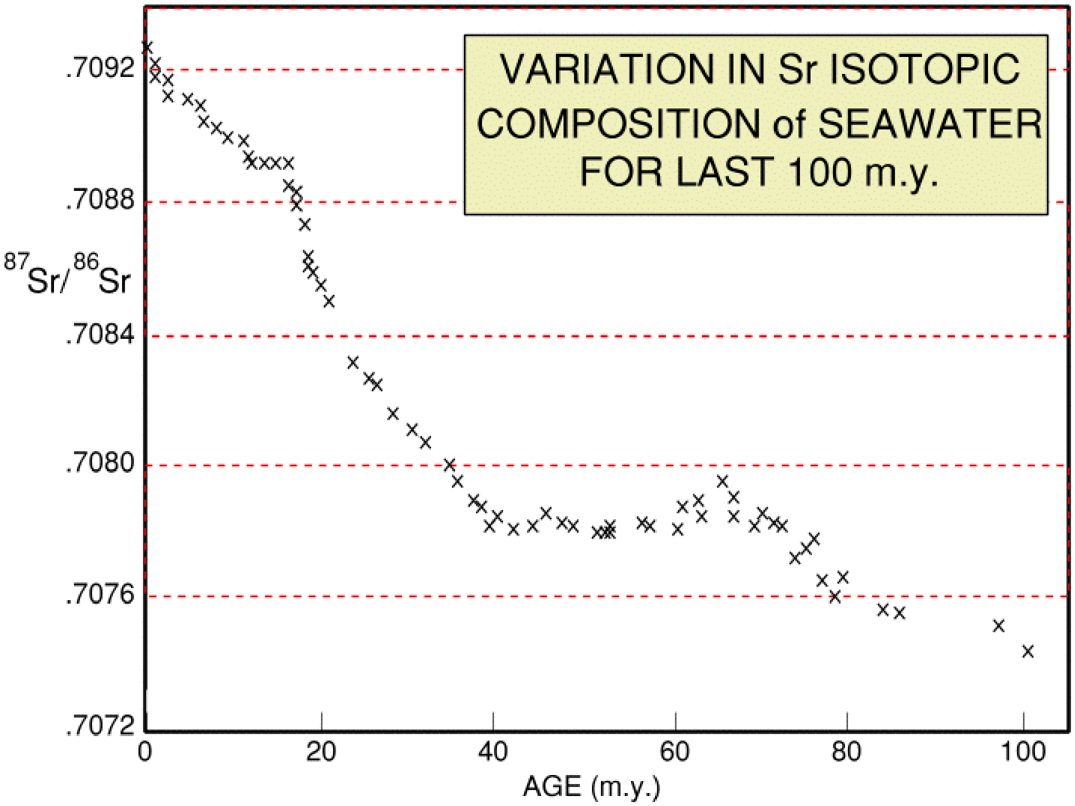
carbonate shells

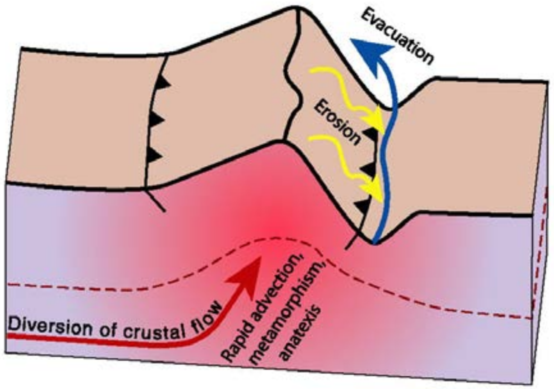
87Sr/86Sr = 0.709



Sr-Isotopie der Ozeane

Increase in the global ocean $^{87}Sr/^{86}Sr$ ratio since India-Asia collision





Die U-Th-Pb Methoden

Basiert auf drei verschiedenen Zerfallsreaktionen:

$^{238}U \rightarrow {}^{206}Pb \quad T_{1/2} = 4.468$ Ga

$^{235}U \rightarrow {}^{207}Pb \quad T_{1/2} = 0.704$ Ga

$^{232}Th \rightarrow {}^{208}Pb \quad T_{1/2} = 14.01$ Ga

^{204}Pb ist ein nicht radiogen, stabiles Isotop. Daher gilt:

$$\boxed{\frac{^{206}Pb}{^{204}Pb} = \left(\frac{^{206}Pb}{^{204}Pb}\right)_0 + \frac{^{238}U}{^{204}Pb}(e^{\lambda_1 t} - 1)}$$

$$\boxed{\frac{^{207}Pb}{^{204}Pb} = \left(\frac{^{207}Pb}{^{204}Pb}\right)_0 + \frac{^{235}U}{^{204}Pb}(e^{\lambda_2 t} - 1)}$$

$$\boxed{\frac{^{208}Pb}{^{204}Pb} = \left(\frac{^{208}Pb}{^{204}Pb}\right)_0 + \frac{^{232}Th}{^{204}Pb}(e^{\lambda_3 t} - 1)}$$

Die U-Th-Pb Methoden

Diese drei Gleichungen liefern drei voneinander unabhängige Alter von Th und U-haltigen Gesteinen oder Mineralen

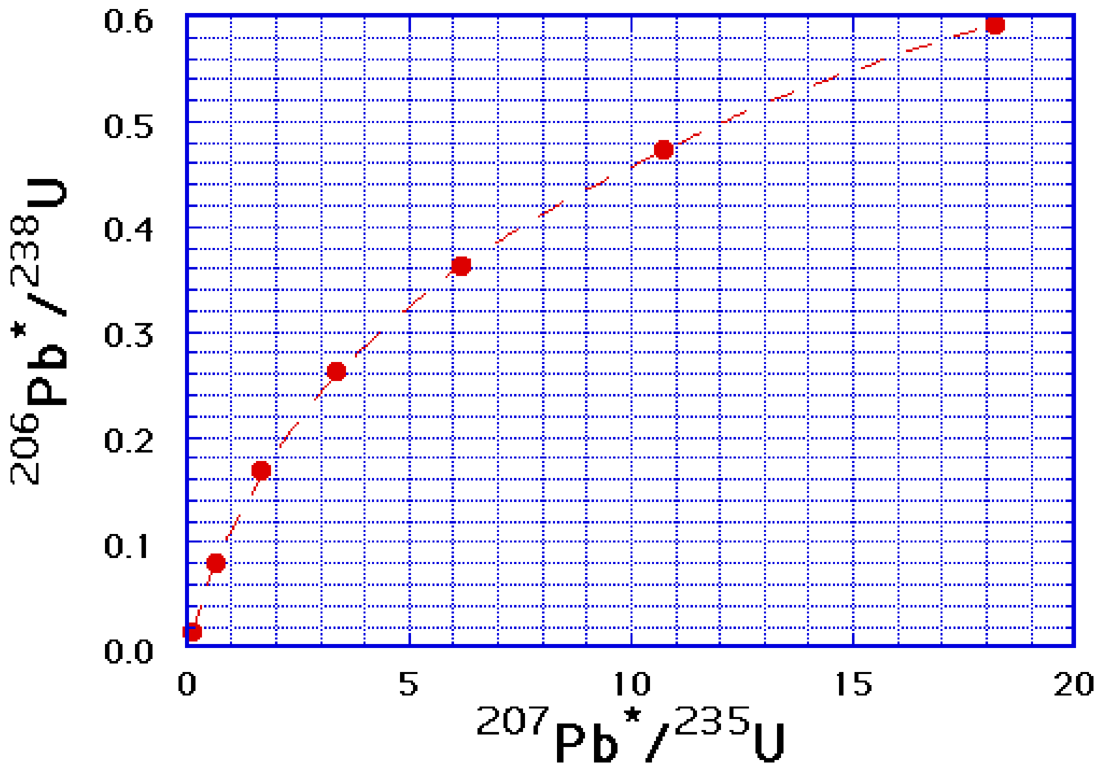
Wenn kein Austausch von U, Th oder Pb stattgefunden hat (geschlossenes System) sollten diese Alter identisch sein

Wenn die drei Alter übereinstimmen, sind sie konkordant, sind sie unterschiedlich sind, sind sie diskordant

Eine häufige Ursache für diskordante Altersdaten ist Bleiverlust

U-Pb Concordia Diagramm

$^{206}Pb^*/^{238}U = (e^{\lambda t1}-1)$, $^{207}Pb^*/^{235}U = (e^{\lambda t2}-1)$



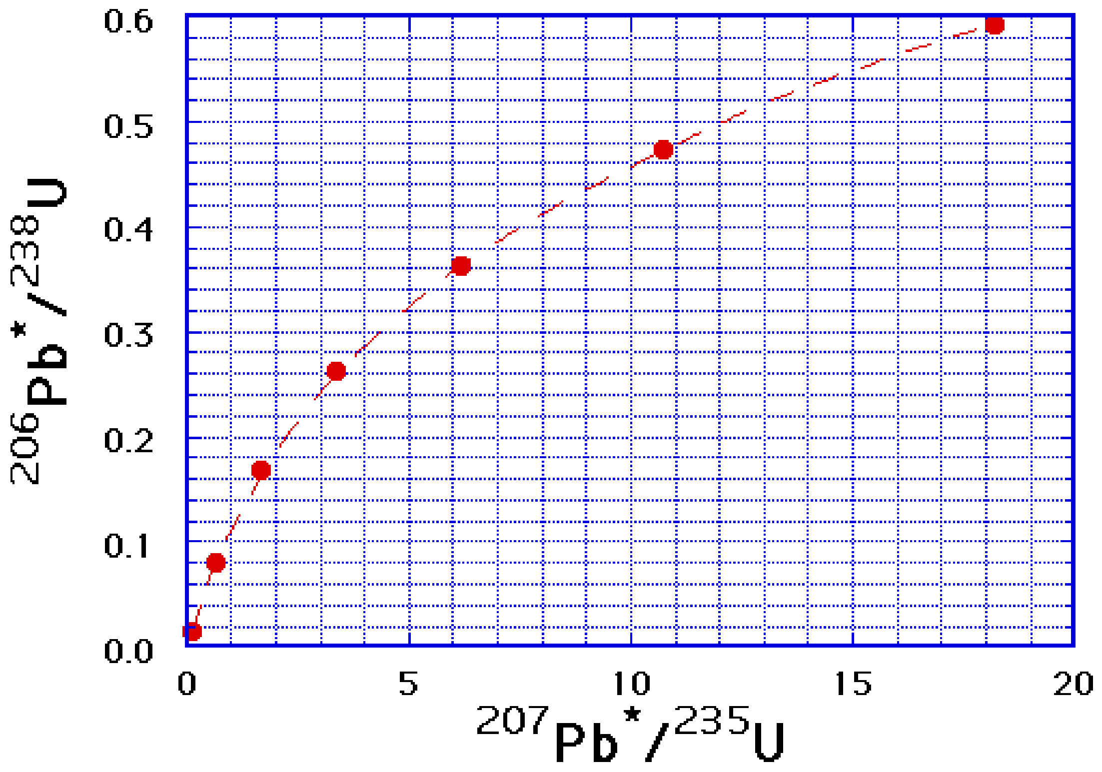
U-Pb Concordia Diagramm

Numerical values of $e^{\lambda_1 t} - 1$, $e^{\lambda_2 t} - 1$, and of the radiogenic $^{207}Pb/^{206}Pb$ ratio as a function of age (t)

Ga	$e^{\lambda_1 t} - 1$	$e^{\lambda_2 t} - 1$	$\left(\frac{^{207}Pb}{^{206}Pb}\right)^*$	Ga	$e^{\lambda_1 t} - 1$	$e^{\lambda_2 t} - 1$	$\left(\frac{^{207}Pb}{^{206}Pb}\right)^*$
0	0.0000	0.0000	0.04607	2.4	0.4511	9.6296	0.15492
0.2	0.0315	0.2177	0.05014	2.6	0.4968	11.9437	0.17447
0.4	0.0640	0.4828	0.05473	2.8	0.5440	14.7617	0.19693
0.6	0.0975	0.8056	0.05994	3.0	0.5926	18.1931	0.22279
0.8	0.1321	1.1987	0.06584	3.2	0.6428	22.3716	0.25257
1.0	0.1678	1.6774	0.07254	3.4	0.6946	27.4597	0.28690
1.2	0.2046	2.2603	0.08017	3.6	0.7480	33.6556	0.32653
1.4	0.2426	2.9701	0.08886	3.8	0.8030	41.2004	0.37232
1.6	0.2817	3.8344	0.09877	4.0	0.8599	50.3878	0.42525
1.8	0.3221	4.8869	0.11010	4.2	0.9185	63.5753	0.48951
2.0	0.3638	6.1685	0.12306	4.4	0.9789	75.1984	0.55746
2.2	0.4067	7.7291	0.13790	4.6	1.0413	91.7873	0.63969

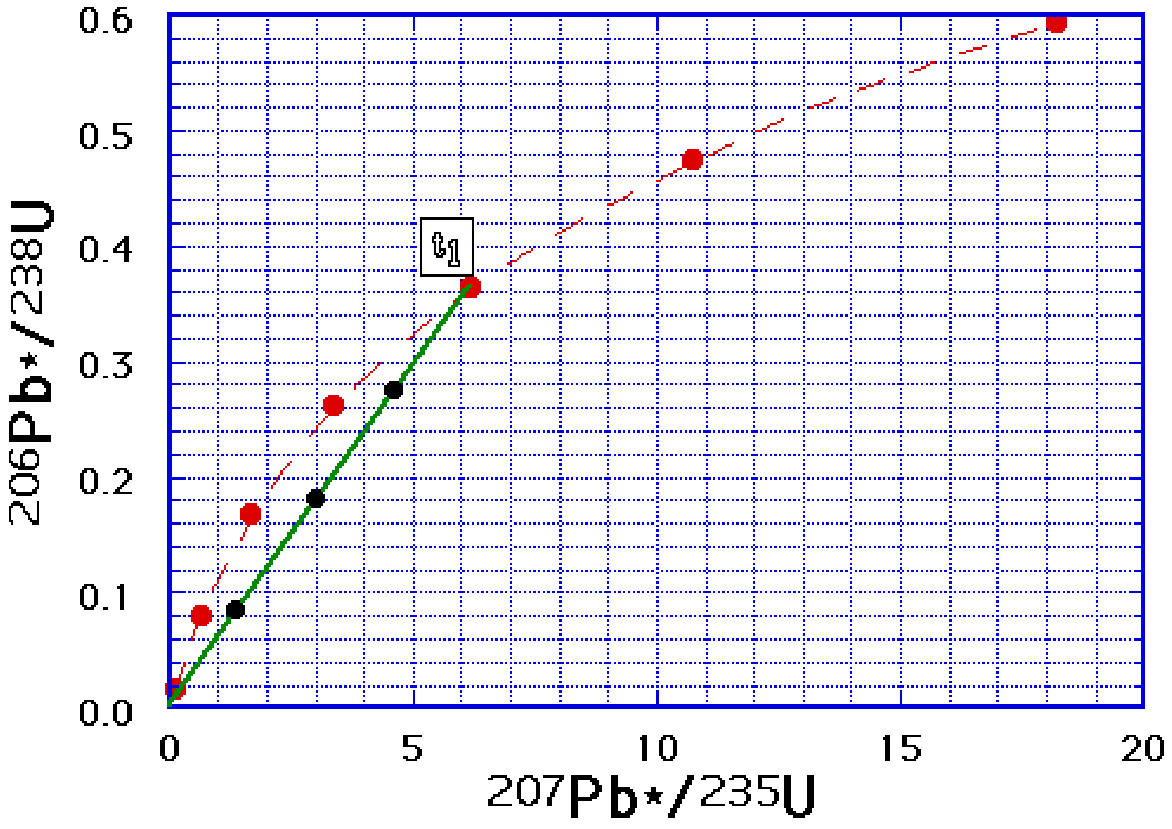
U-Pb Concordia Diagramm

$^{206}Pb^*/^{238}U = (e^{\lambda t1}-1)$, $^{207}Pb^*/^{235}U = (e^{\lambda t2}-1)$

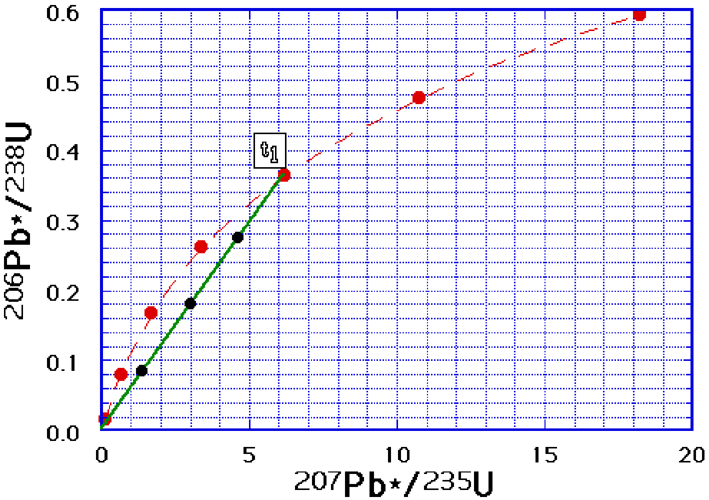


U-Pb Datierung

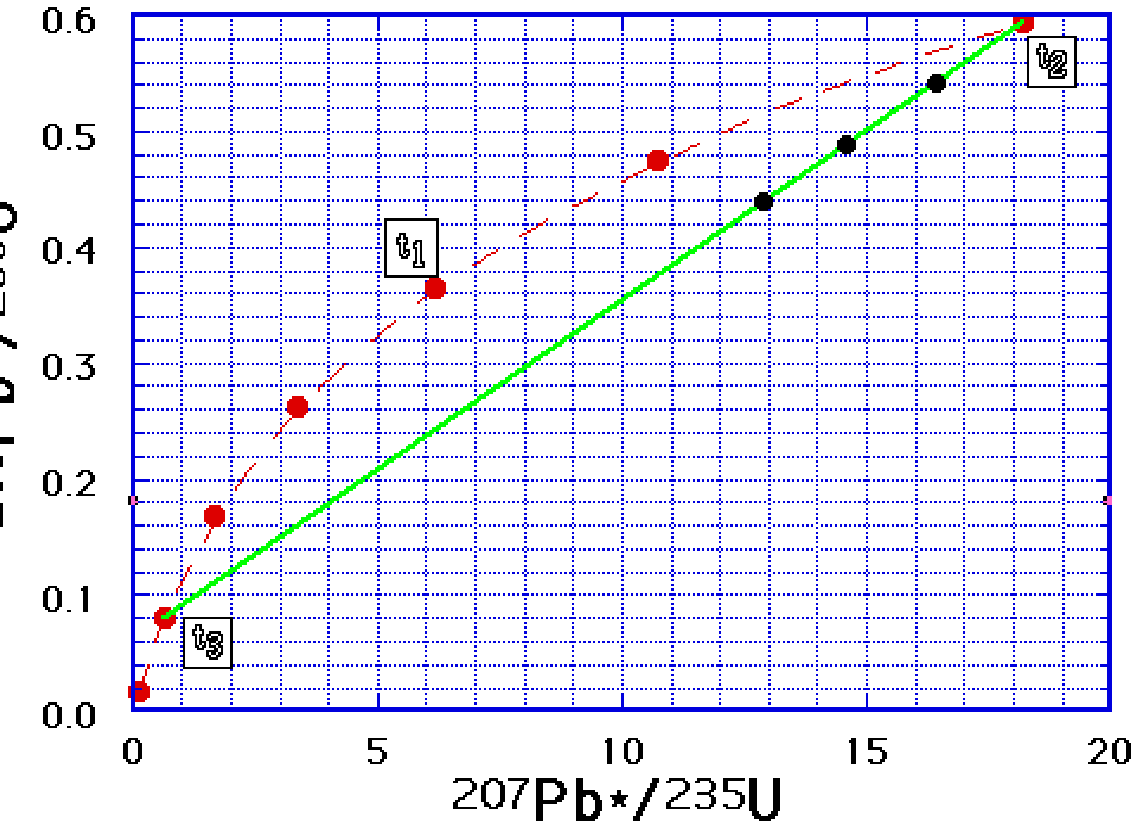
$^{206}Pb^*/^{238}U = (e^{\lambda t_1}-1)$, $^{207}Pb^*/^{235}U = (e^{\lambda t_2}-1)$



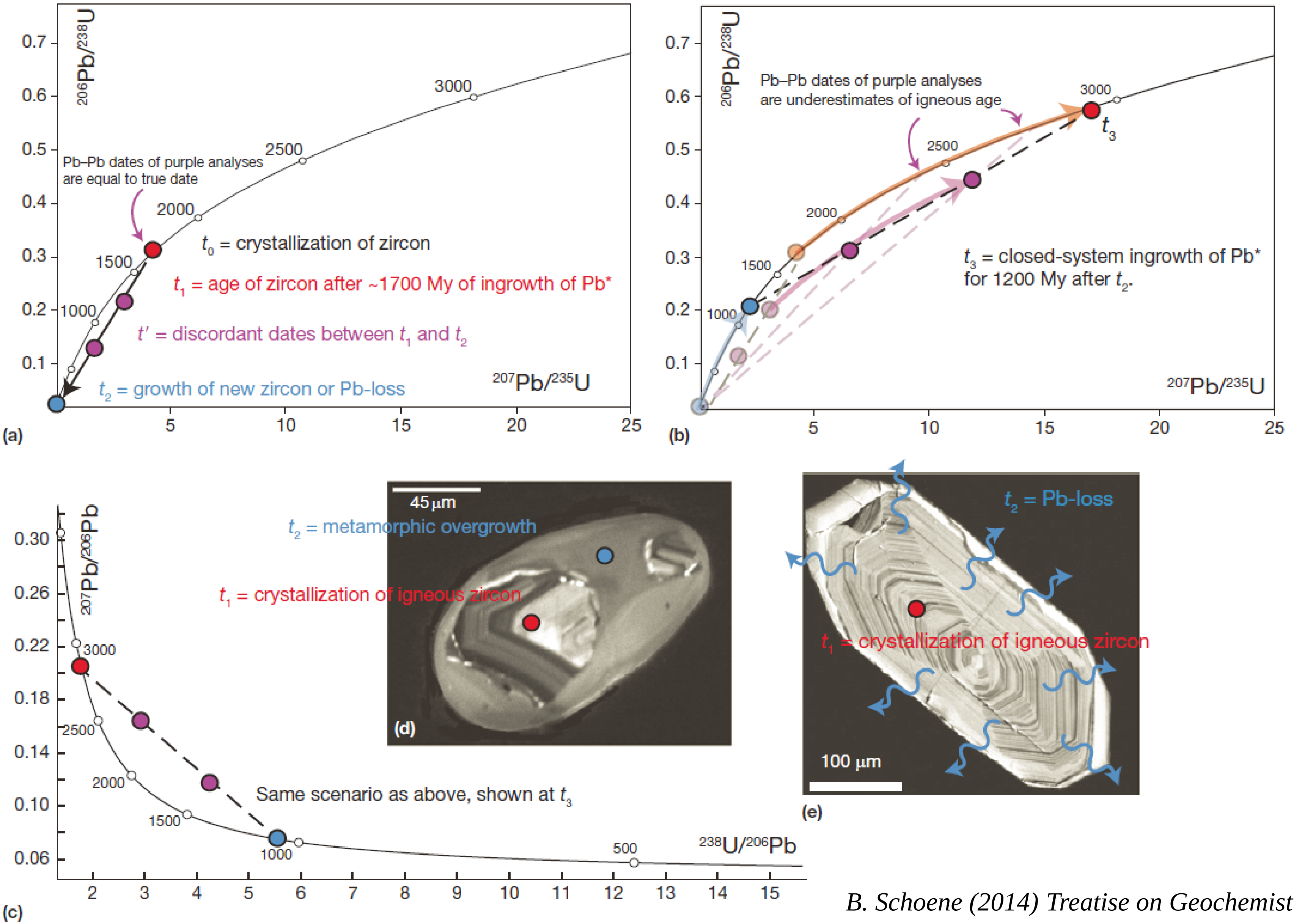
U-Pb Datierung



$$^{206}Pb^*/^{238}U = (e^{\lambda t1}-1),$$
$$^{207}Pb^*/^{235}U = (e^{\lambda t2}-1)$$



Wetherill & Tera-Wasserburg concordia

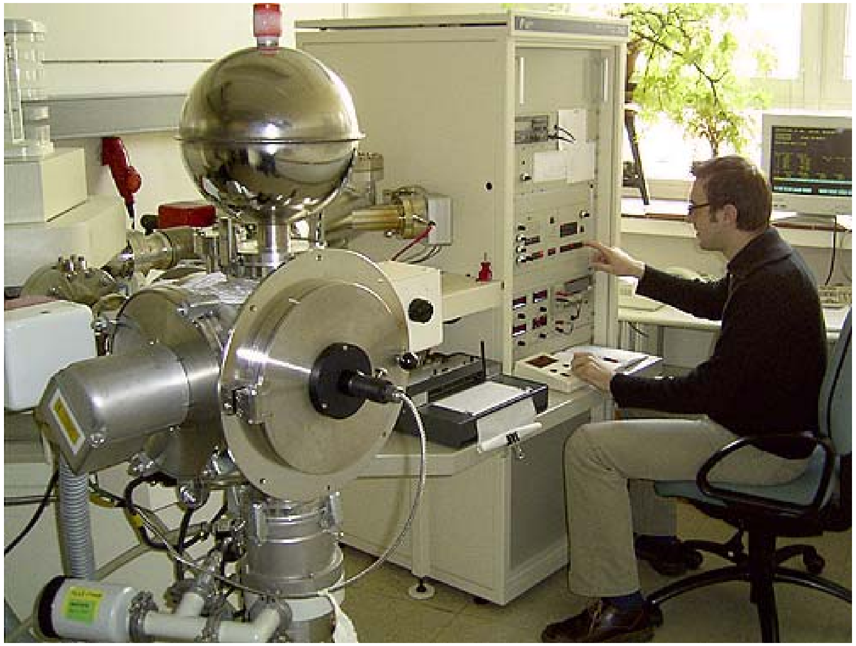


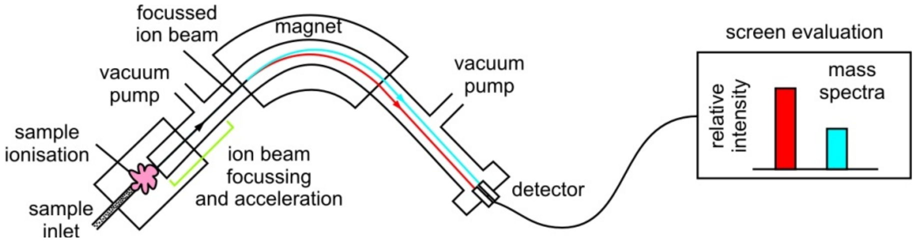
B. Schoene (2014) Treatise on Geochemistry

U-Pb Datierung

Reinraumlabor

Massenspektrometer





Stabile Isotope

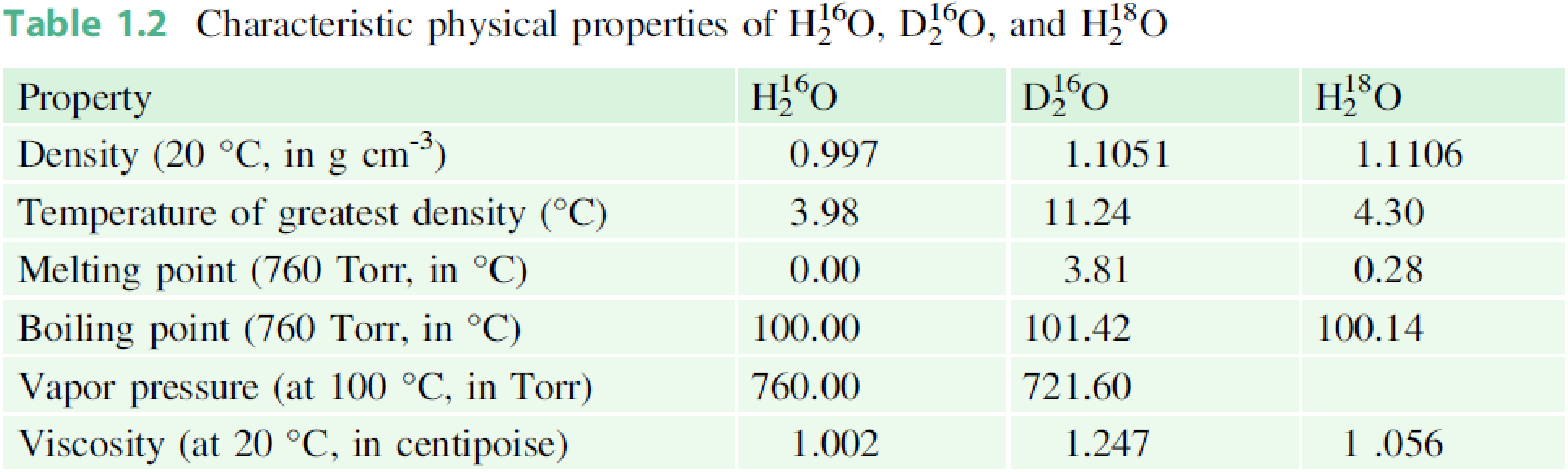


Table 1.2 Characteristic physical properties of $H_2^{16}O$, $D_2^{16}O$, and $H_2^{18}O$

Property	$H_2^{16}O$	$D_2^{16}O$	$H_2^{18}O$
Density (20 °C, in g cm^{-3})	0.997	1.1051	1.1106
Temperature of greatest density (°C)	3.98	11.24	4.30
Melting point (760 Torr, in °C)	0.00	3.81	0.28
Boiling point (760 Torr, in °C)	100.00	101.42	100.14
Vapor pressure (at 100 °C, in Torr)	760.00	721.60	
Viscosity (at 20 °C, in centipoise)	1.002	1.247	1 .056

“isotope effects”:
Differences in chemical and physical properties arising from variations in atomic mass of an element or molecule

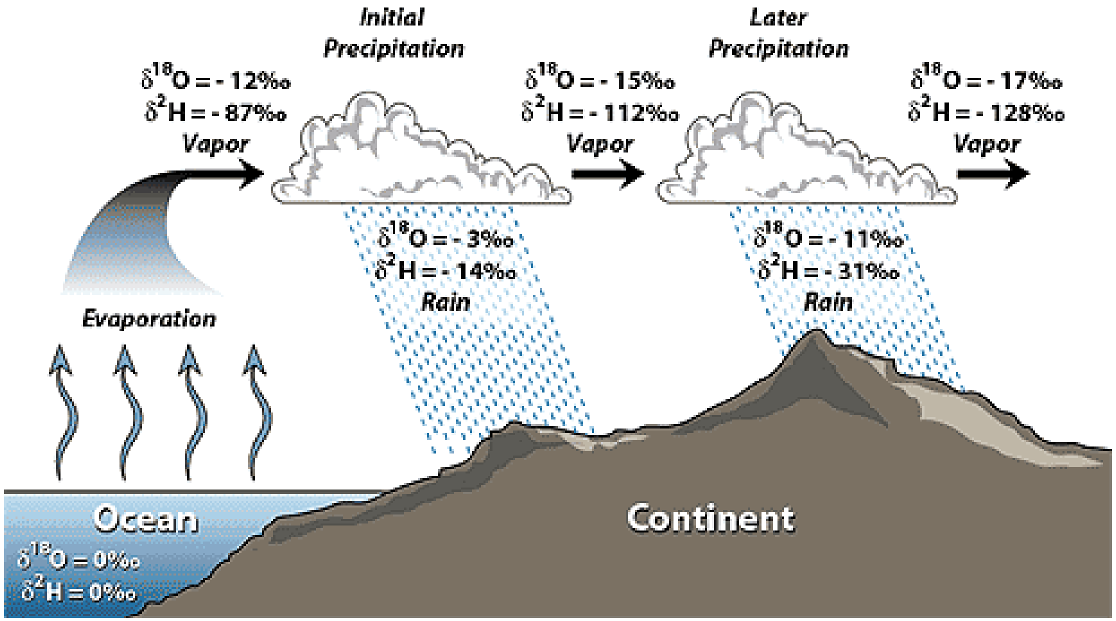
Jochen Hoefs (Stable Isotopes)

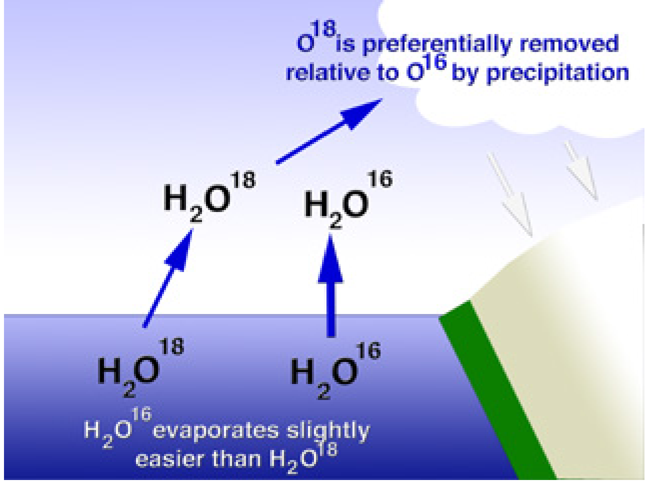
Stabile Isotope

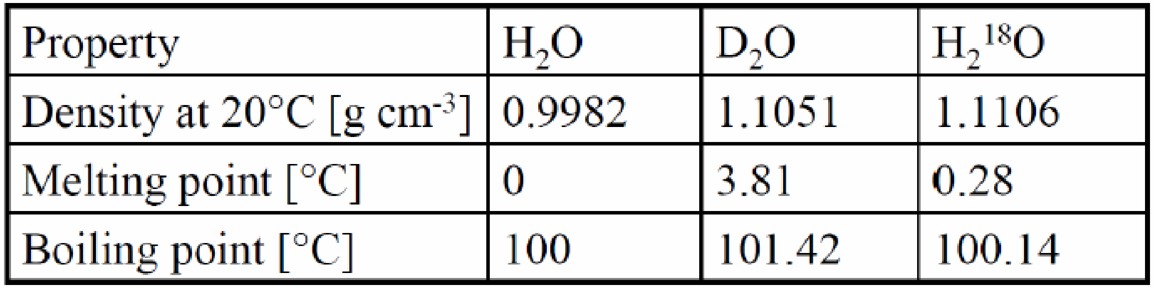
Evaporation/precipitation

The lighter isotopes evaporate more easily

Heavyer isotopes enriched in remaining liquid phase

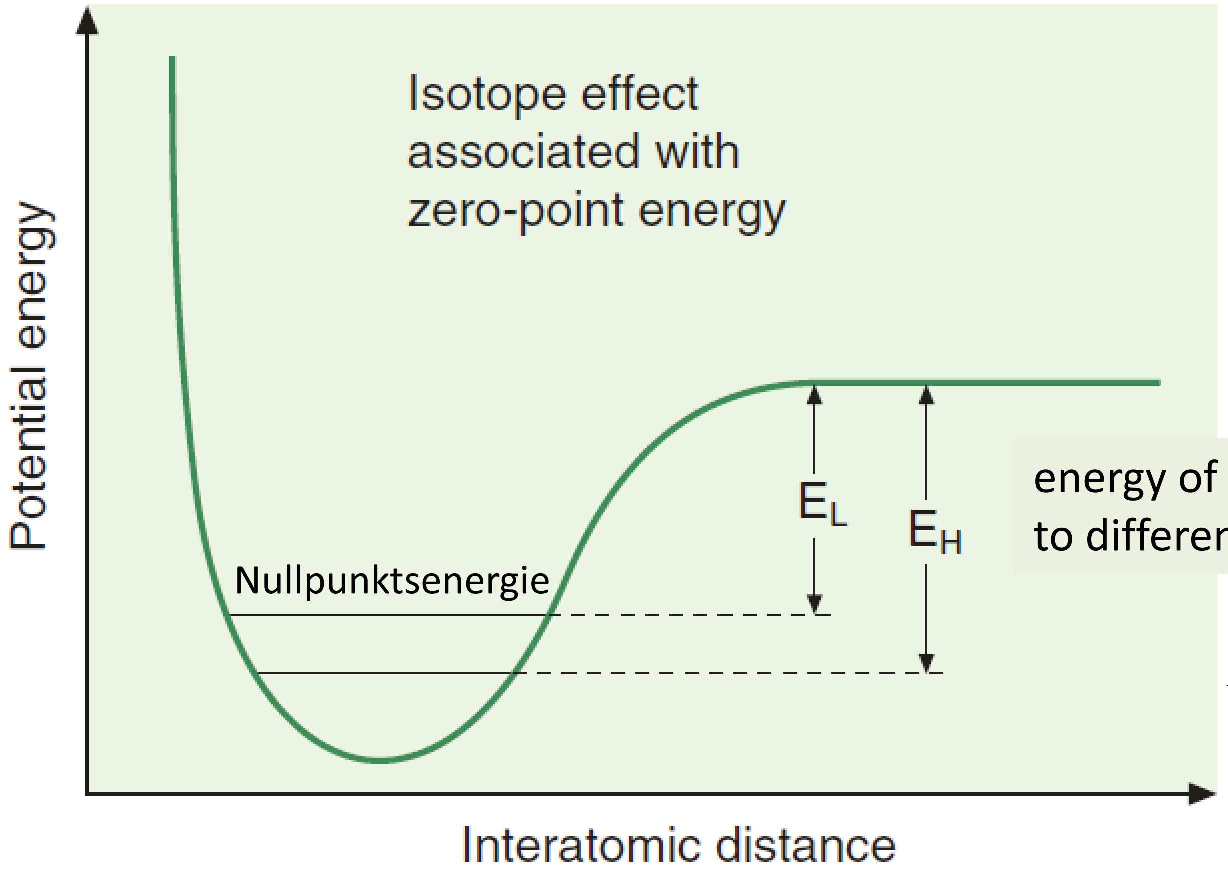






Property	H_2O	D_2O	$H_2{}^{18}O$
Density at 20°C [g cm^{-3}]	0.9982	1.1051	1.1106
Melting point [°C]	0	3.81	0.28
Boiling point [°C]	100	101.42	100.14

Stabile Isotope



energy of molecule restricted to different levels, i.e. ½ hν

h = Planck‘s constant
ν = energy of vibration

Jochen Hoefs (Stable Isotopes)

Massenabhängige Isotopenfraktionierung

Isotope fractionation during chemical, physical and biological processes:

reversible chemical reaction at equilibrium state

A ←→ B

physical changes, phase transitions (e.g. water – vapor), diffusion

biological and biochemical reactions

CO_2 into C_{org}

Massenabhängige Isotopenfraktionierung

1. isotope exchange reactions – example

$$aA_1 + bB_2 = aA_2 + bB_1$$

$$H_2^{18}O + \frac{1}{3}CaC^{16}O_3 \Leftrightarrow H_2^{16}O + \frac{1}{3}CaC^{18}O_3$$

$$\alpha_{\mathrm{CaCo_3-H_2O}} = \frac{\left(\frac{^{18}O}{^{16}O}\right)_{\mathrm{CaCo_3}}}{\left(\frac{^{18}O}{^{16}O}\right)_{\mathrm{H_2o}}} = 1.031 \text{ at } 25^\circ\mathrm{C}$$

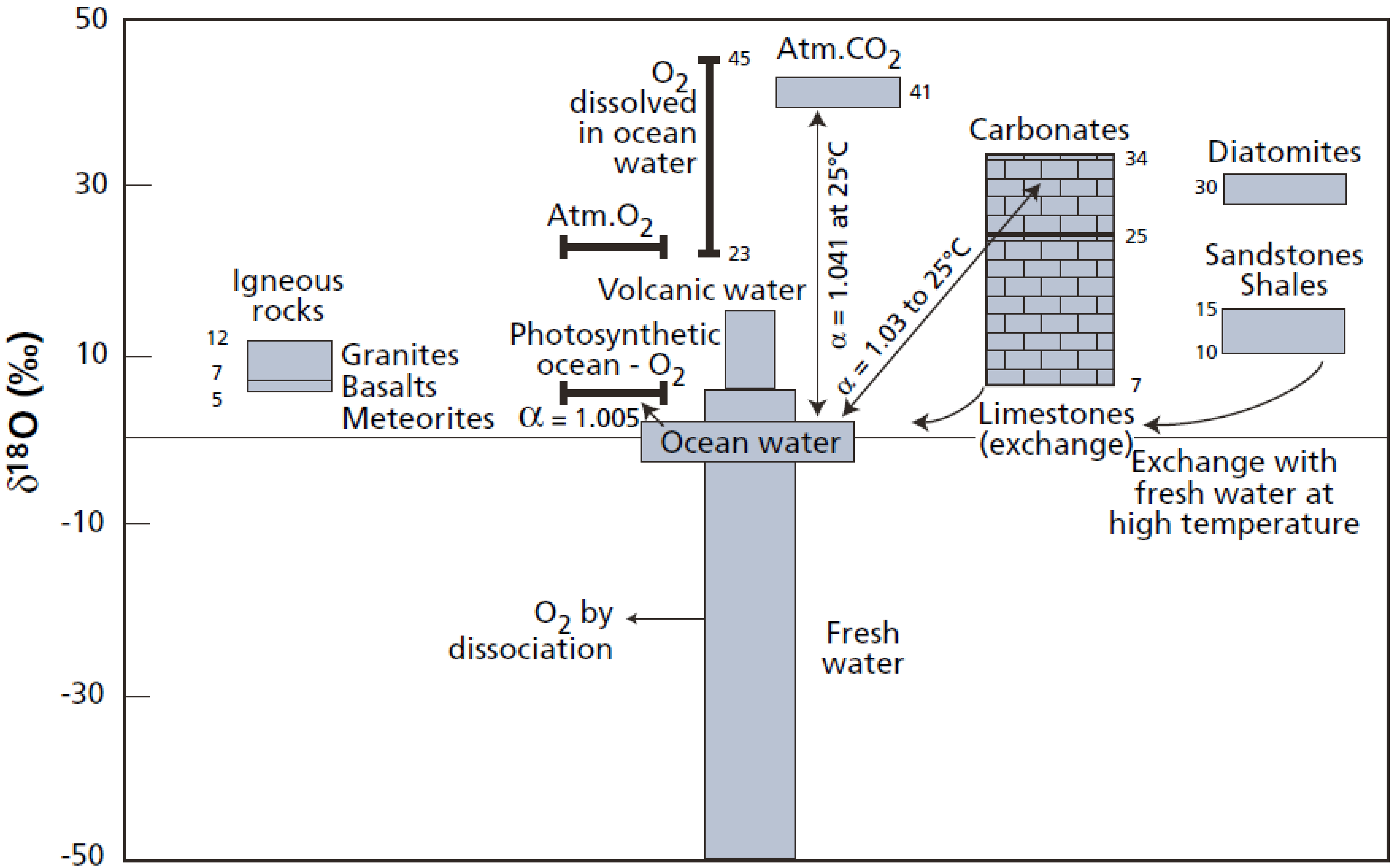
Massenabhängige Isotopenfraktionierung

1. isotope exchange reactions - Delta-value (δ)

$$\delta = \left(\frac{\text{sample isotope ratio} - \text{standard isotope ratio}}{\text{standard isotope ratio}} \right) \times 10^3$$

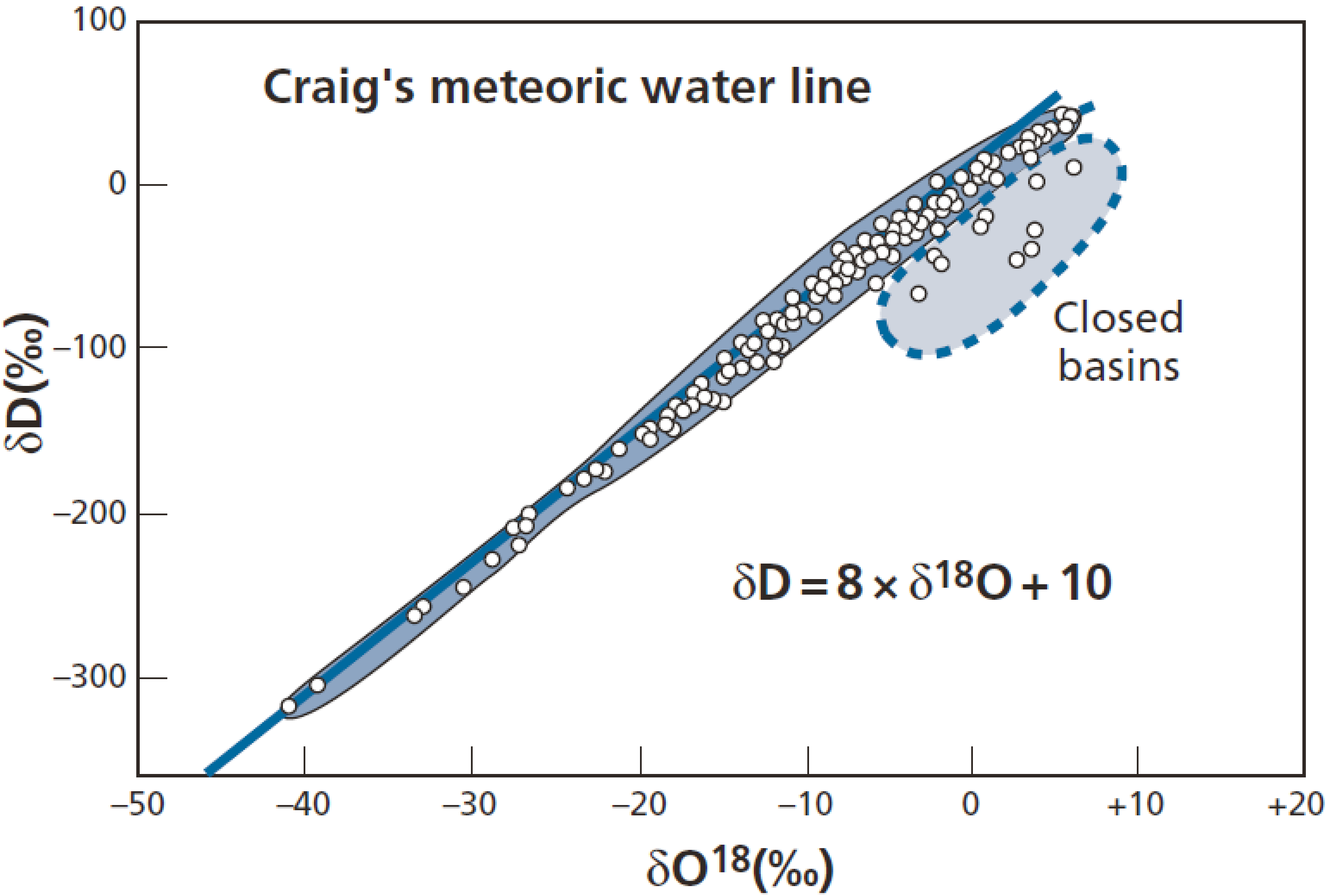
δ is a relative deviation from a standard, expressed as the number of parts per mil. Isotope ratios are expressed with the heavier isotope in the numerator, e.g.:
$^{18}O/^{16}O$, D/H, $^{13}C/^{12}C$

Sauerstoff-Isotopenvariationen



Claude Allègre (Isotope Geology)

Sauerstoff-Isotopenvariationen



Claude Allègre (Isotope Geology)