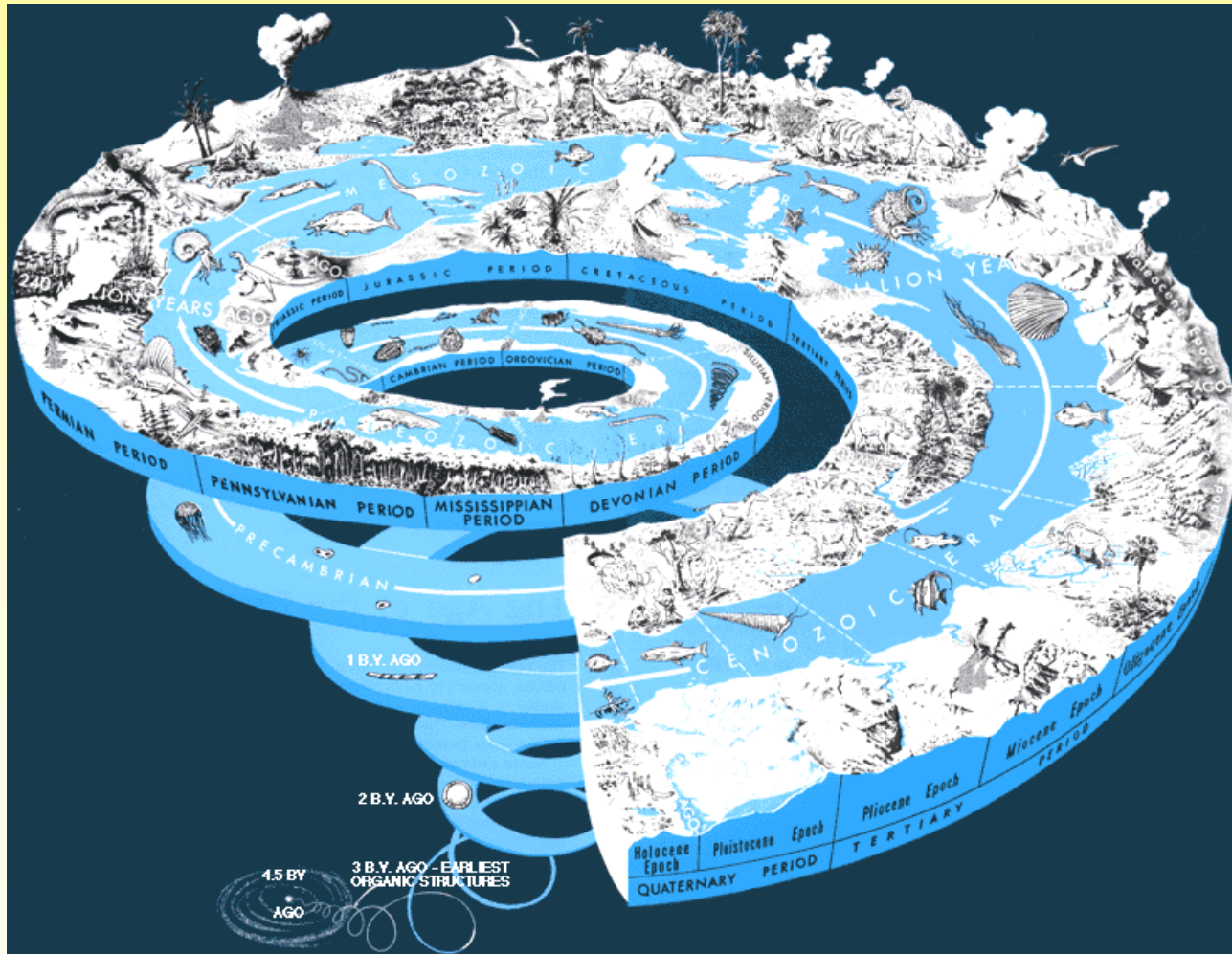


Isotopengeochemie Geochronologie



Radiogene Isotopensysteme

Goldschmidt-Klassifikation im Periodensystem der Elemente

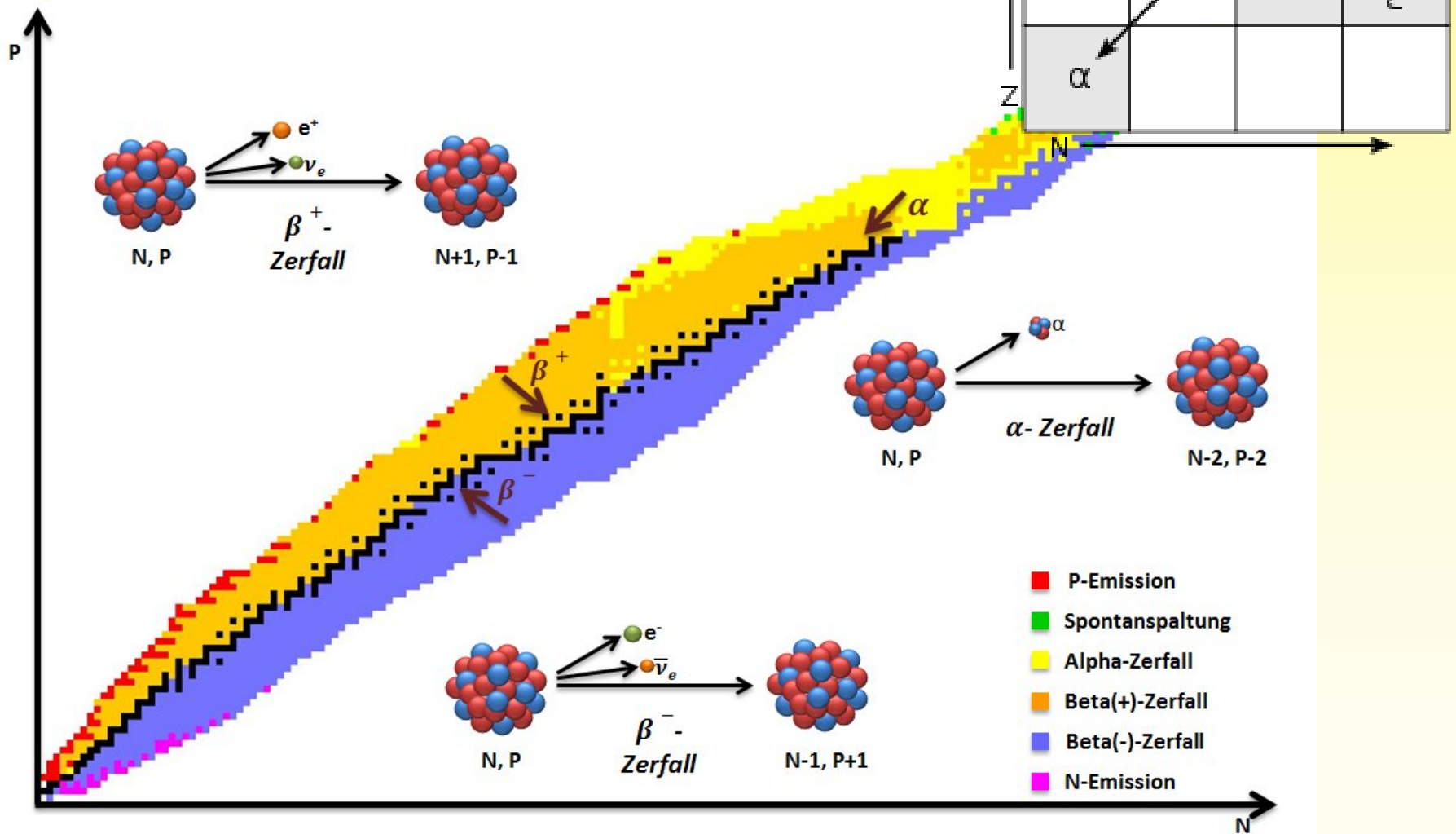
	1																	18	
1	1 H	2												5 B	6 C	7 N	8 O	9 F	10 Ne
2	3 Li	4 Be												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
3	11 Na	12 Mg	3	4	5	6	7	8	9	10	11	12	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 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:

Atmosphäphil	Chalcophil	Lithophil	Siderophil	sehr selten
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Radioaktiver Zerfall

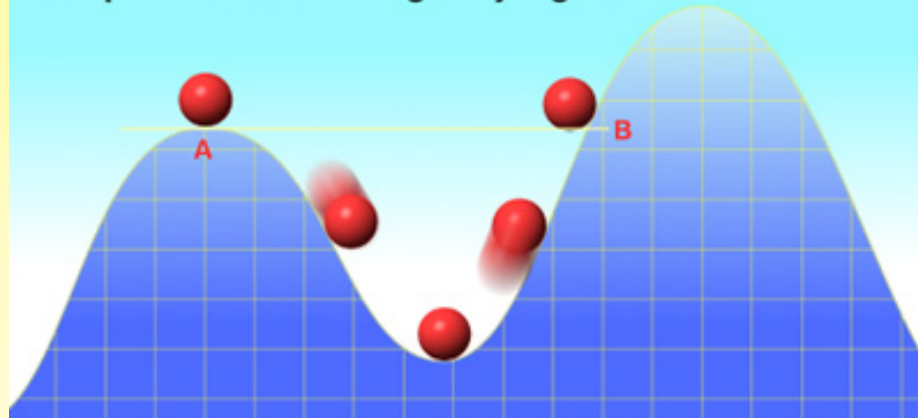
Die (wichtigsten) Zerfallsarten



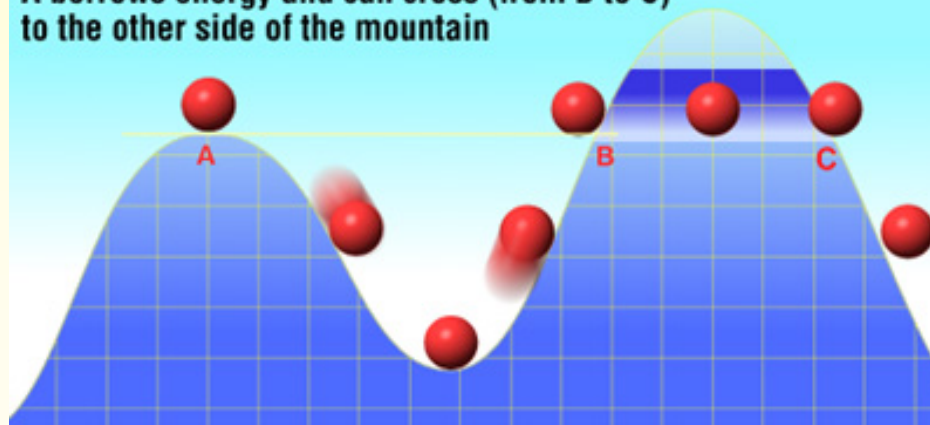
Alpha (α) Zerfall

Tunnel Effekt

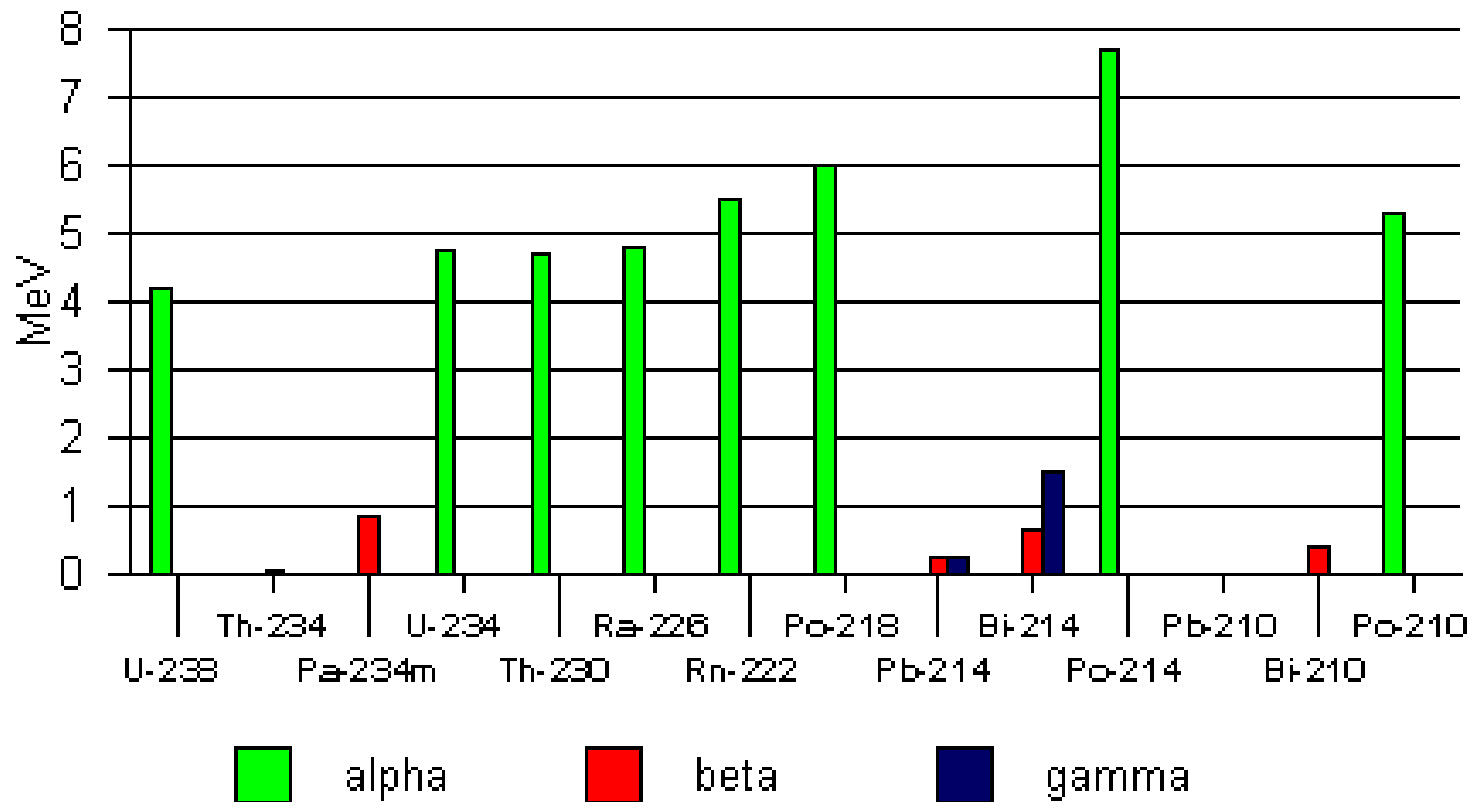
In classical dynamics,
A stops at B and cannot go any higher



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

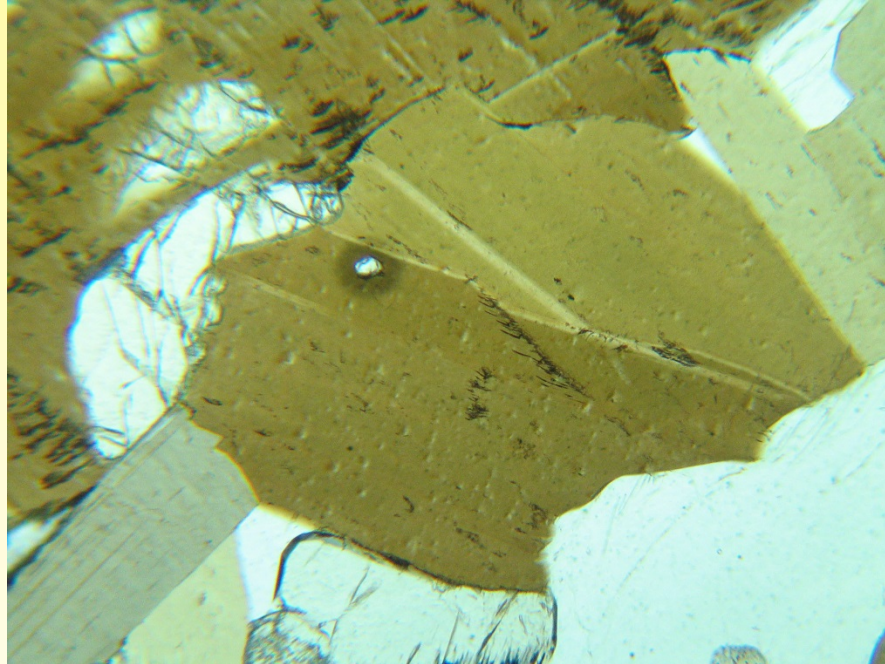


Zerfallsenergien: U-238 Serie



Alpha (α) Zerfall - Kristallgitterschäden

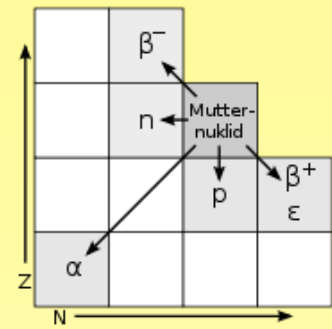
Biotite with a halo around a zircon inclusion



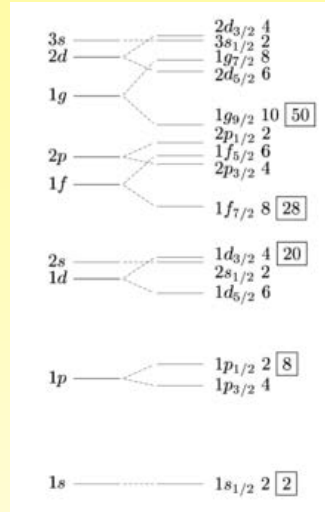
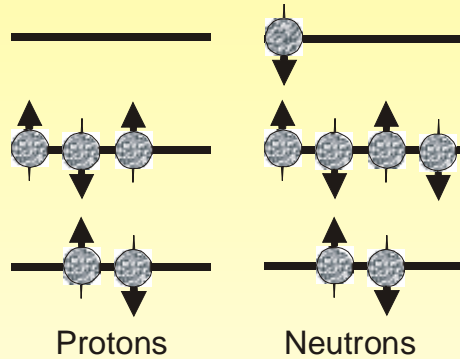
The field of view is about 2 mm

β -Zerfall

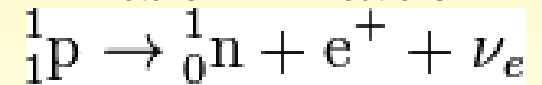
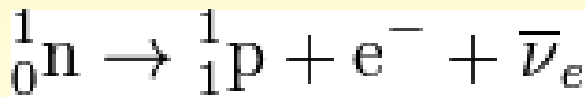
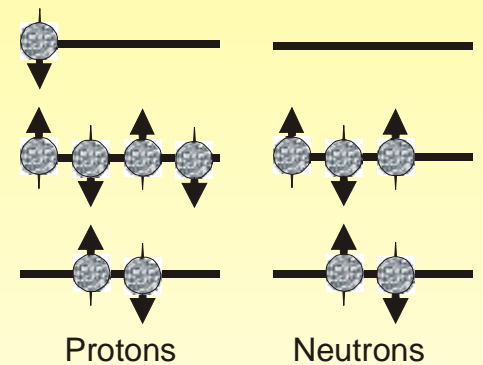
Kernschalenmodell



$^{12}_5\text{B}$



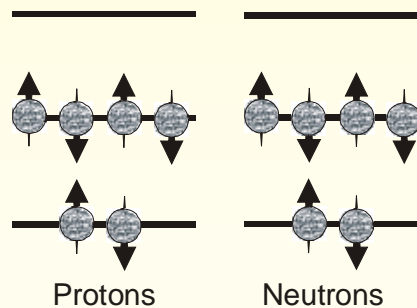
$^{12}_7\text{N}$



Beta Minus
Decay

Beta Plus
Decay

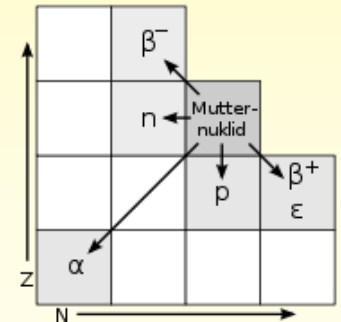
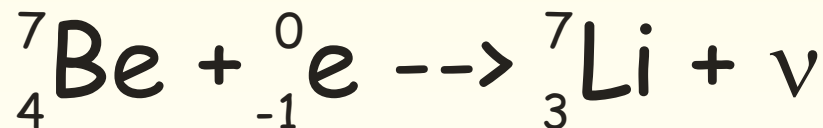
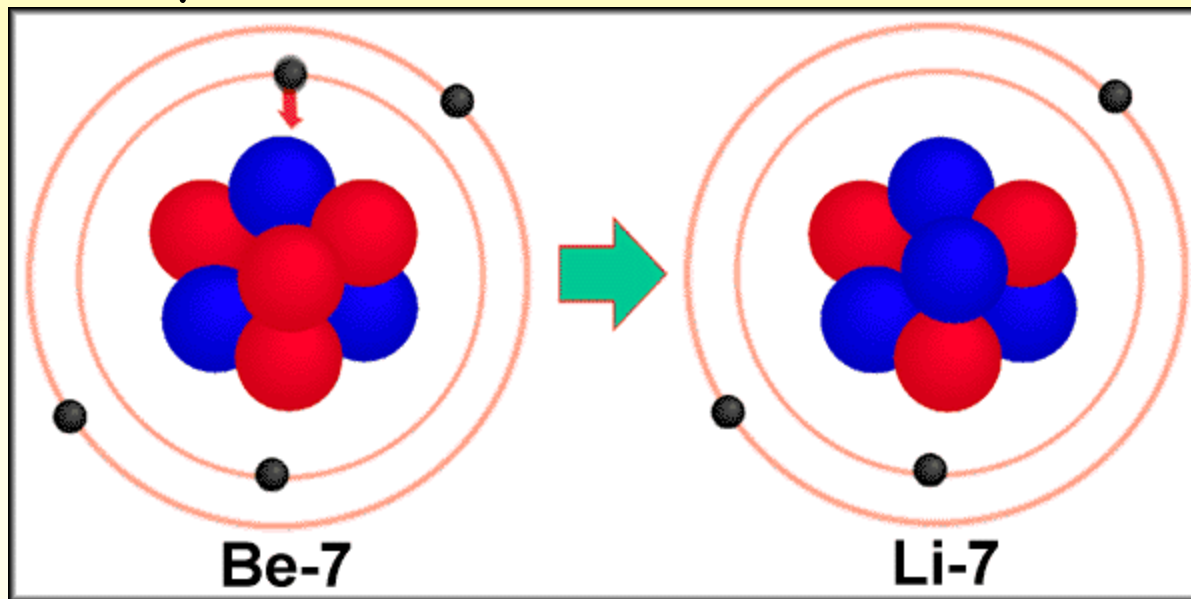
$^{12}_6\text{C}$



Elektroneneinfang

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

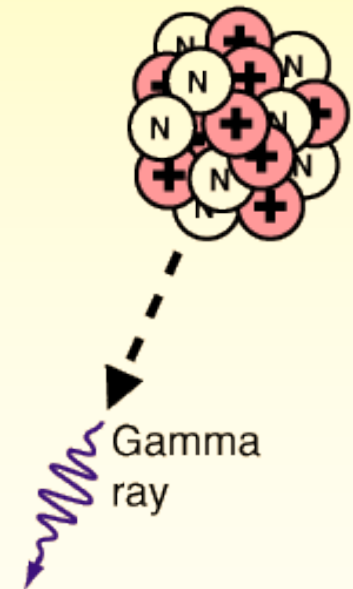
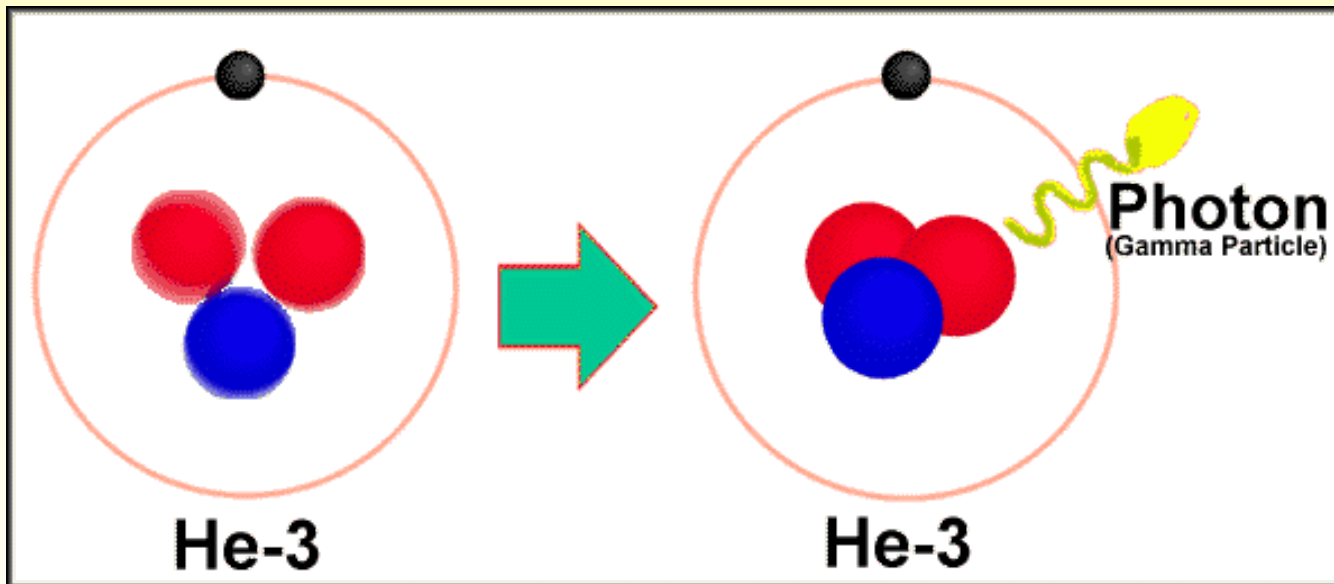
Most commonly, it is a K-shell electron which is captured, and this is referred to as K-capture



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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One Hundred Years of Geochronology

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

...and Counting

Precision and Accuracy in Geochronology

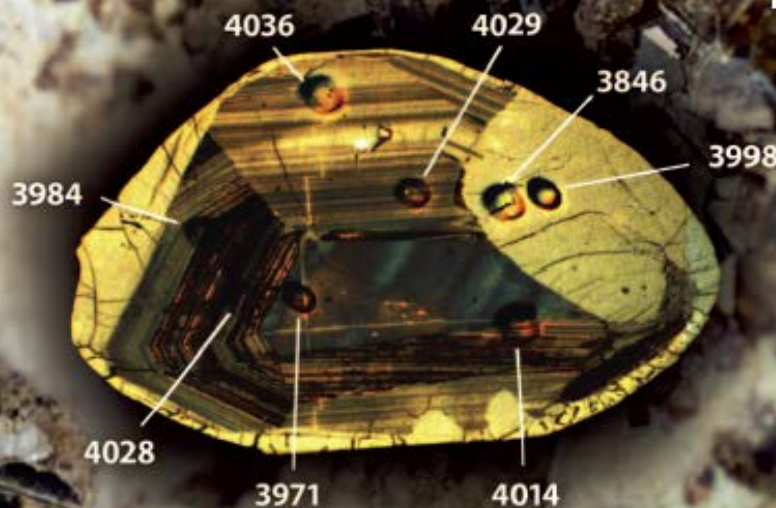
High-Precision Geochronology

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

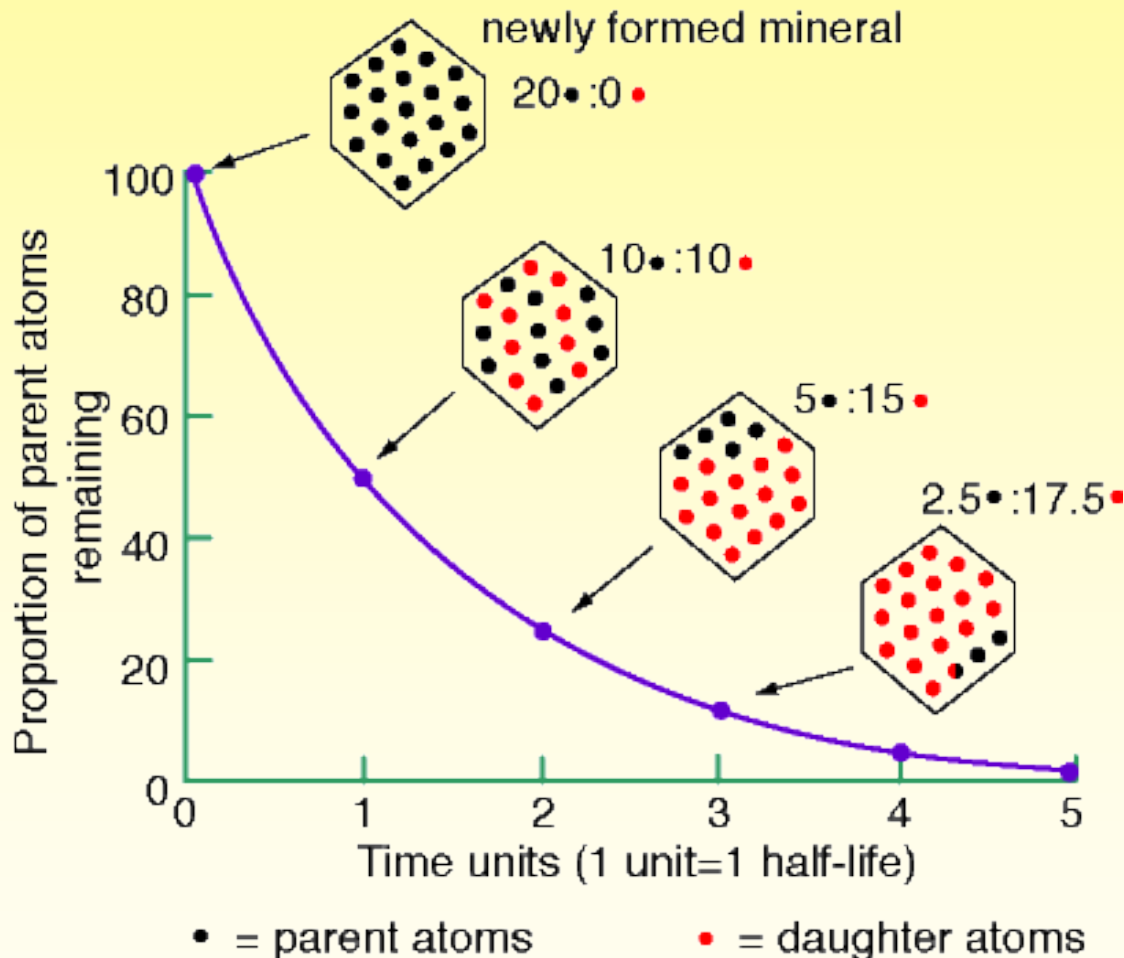
Relative Ereignisabfolge?



Jutulhogget, Antarctica

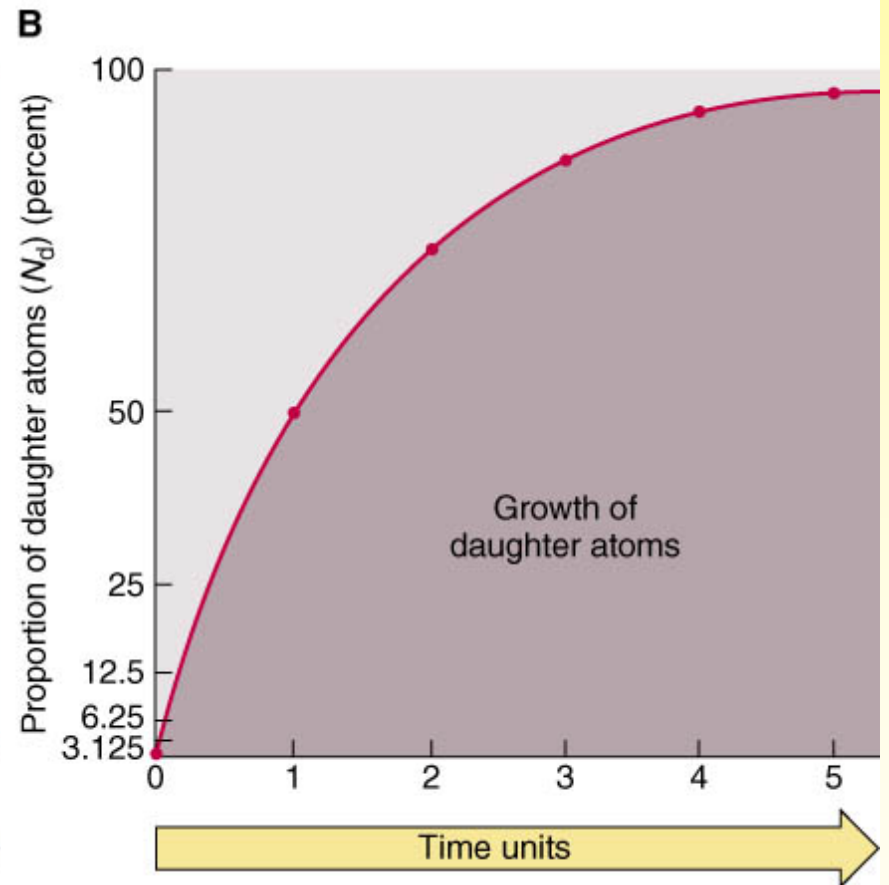
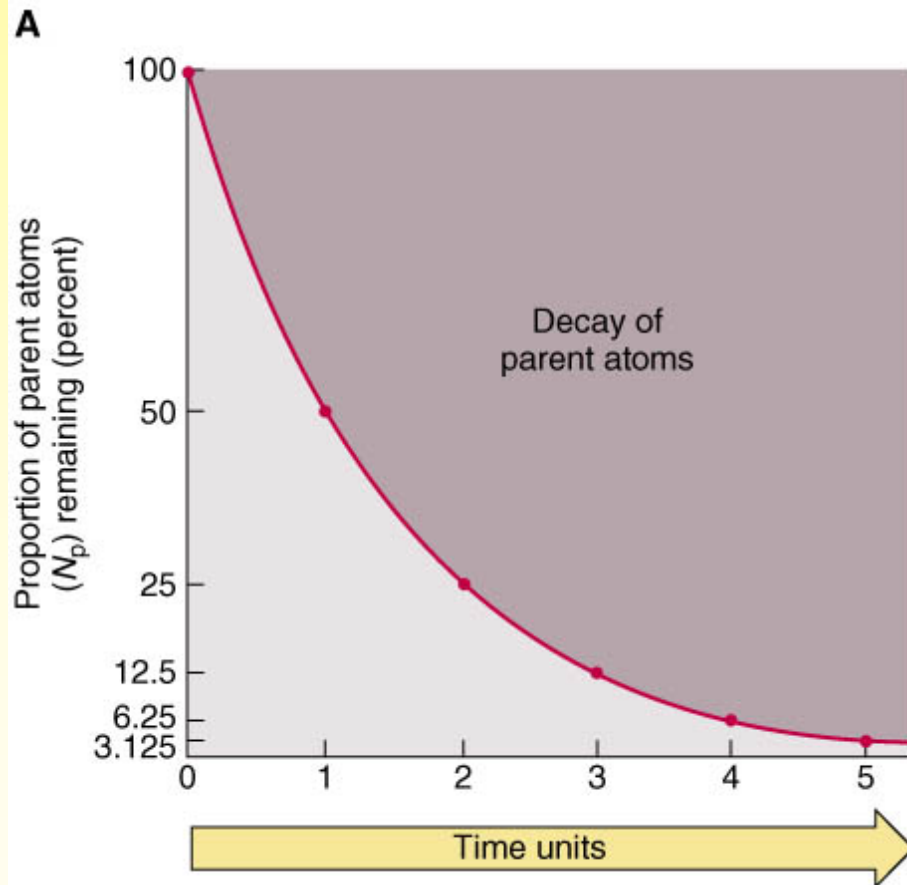
Radioaktiver Zerfall

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:

$$\int_{N_0}^{N(t)} \frac{1}{N} dN = - \int_0^t \lambda dt$$

- Resultat $N(t)$:

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

Mutter-Tochter
System:

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

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

$$N = N_0 \cdot e^{-\lambda \cdot t} \quad \text{or} \quad N_0 = N \frac{1}{e^{-\lambda t}} = N e^{\lambda t}$$

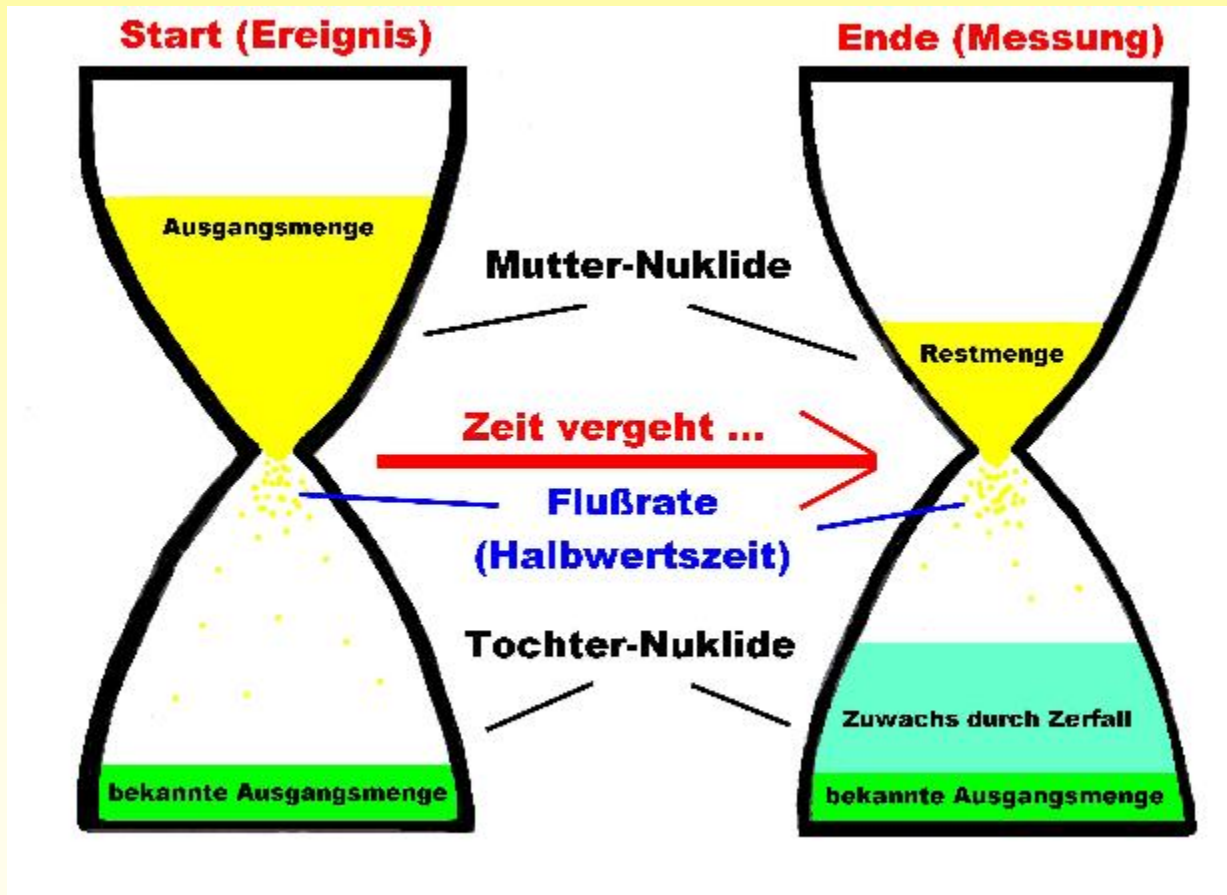
$$N_0 = D + N, \text{ hence: } D + N = N e^{\lambda t}, \text{ or } D = N e^{\lambda t} - N, \text{ or } D = N(e^{\lambda t} - 1)$$

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

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

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

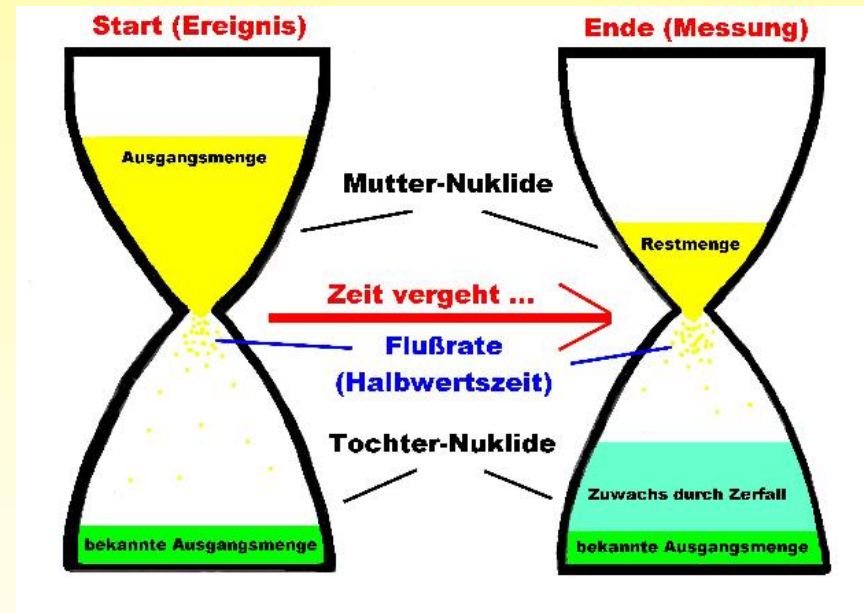
Radiometrische Datierung



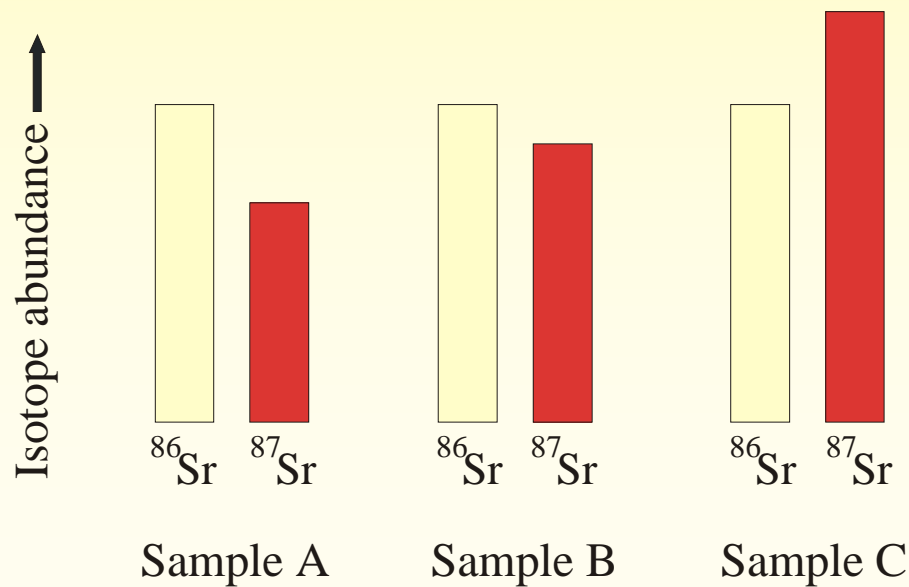
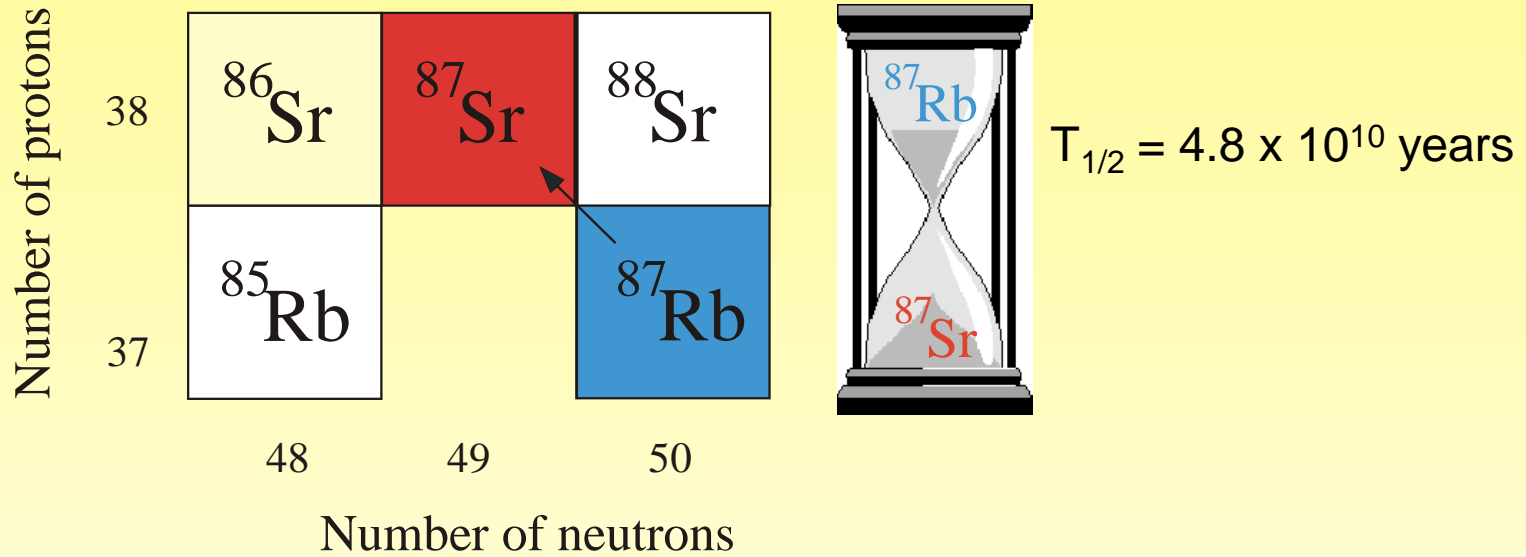
Radiometrische Datierung

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)

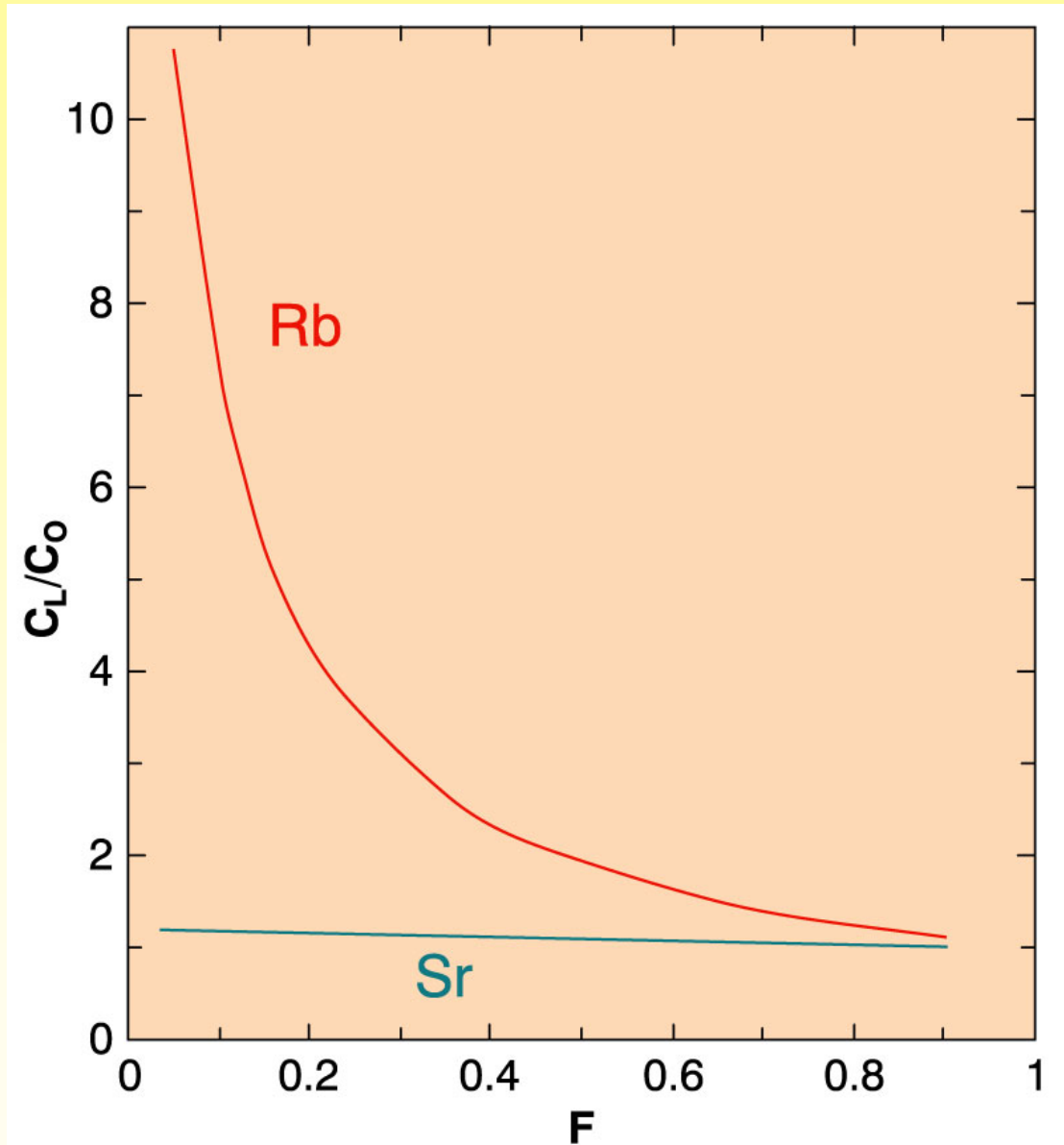


Rb–Sr System

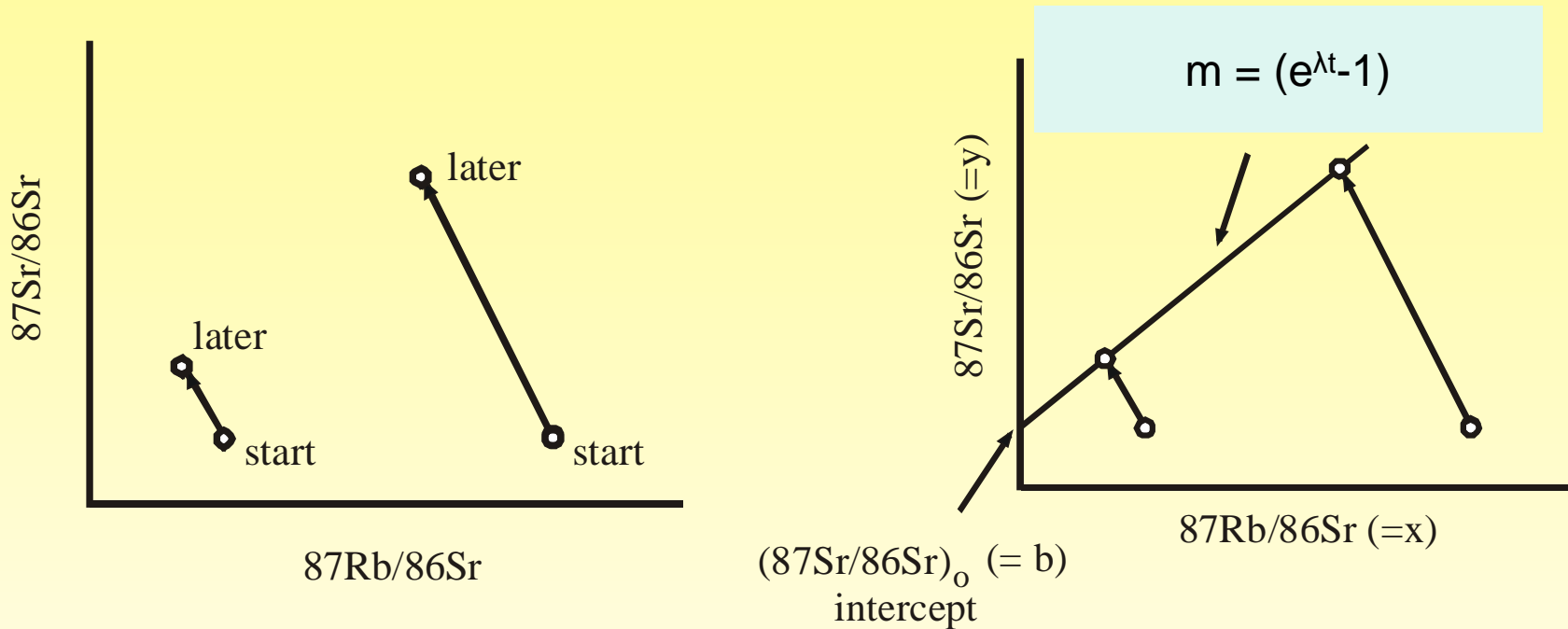


Geochemische Diagramme

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



Rb–Sr System – Nicolaysen Diagramm



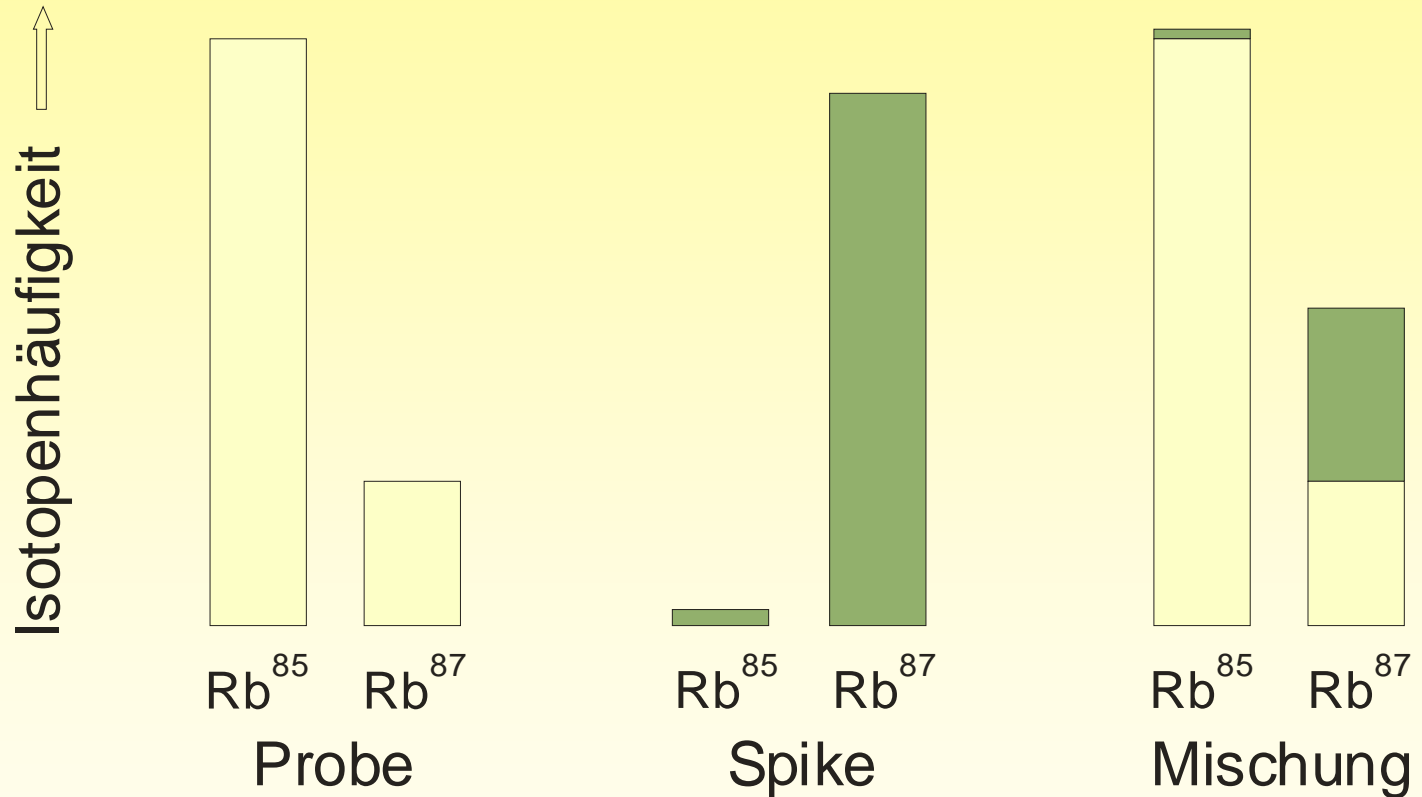
$$^{87}\text{Sr}/^{86}\text{Sr} = (^{87}\text{Sr}/^{86}\text{Sr})_0 + ^{87}\text{Rb}/^{86}\text{Sr} (e^{\lambda t} - 1)$$

$$y = b + x m$$

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

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

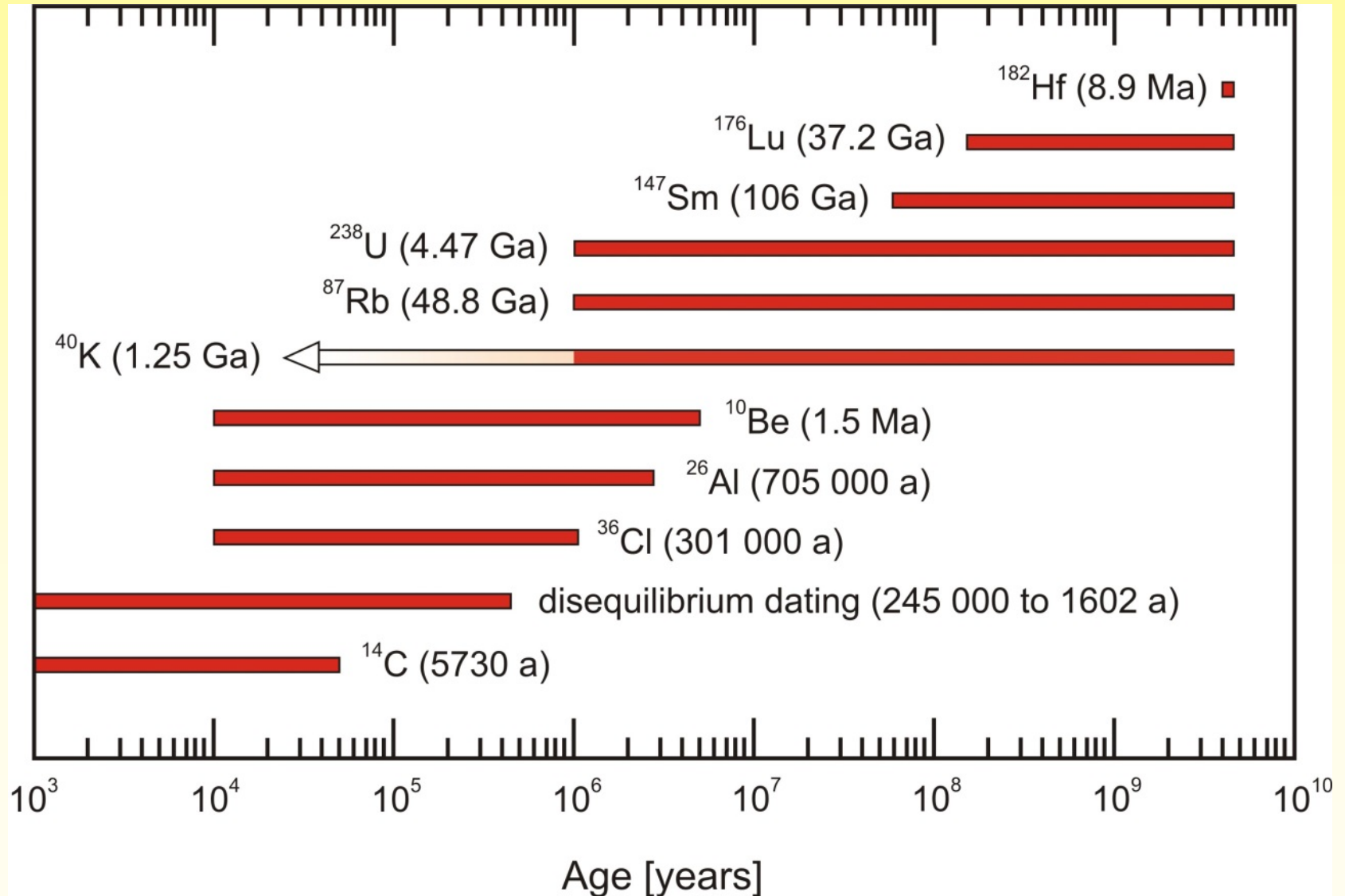
Isotopenverdünnungsanalyse



Isotopenverdünnungsanalyse

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

Datierungssysteme

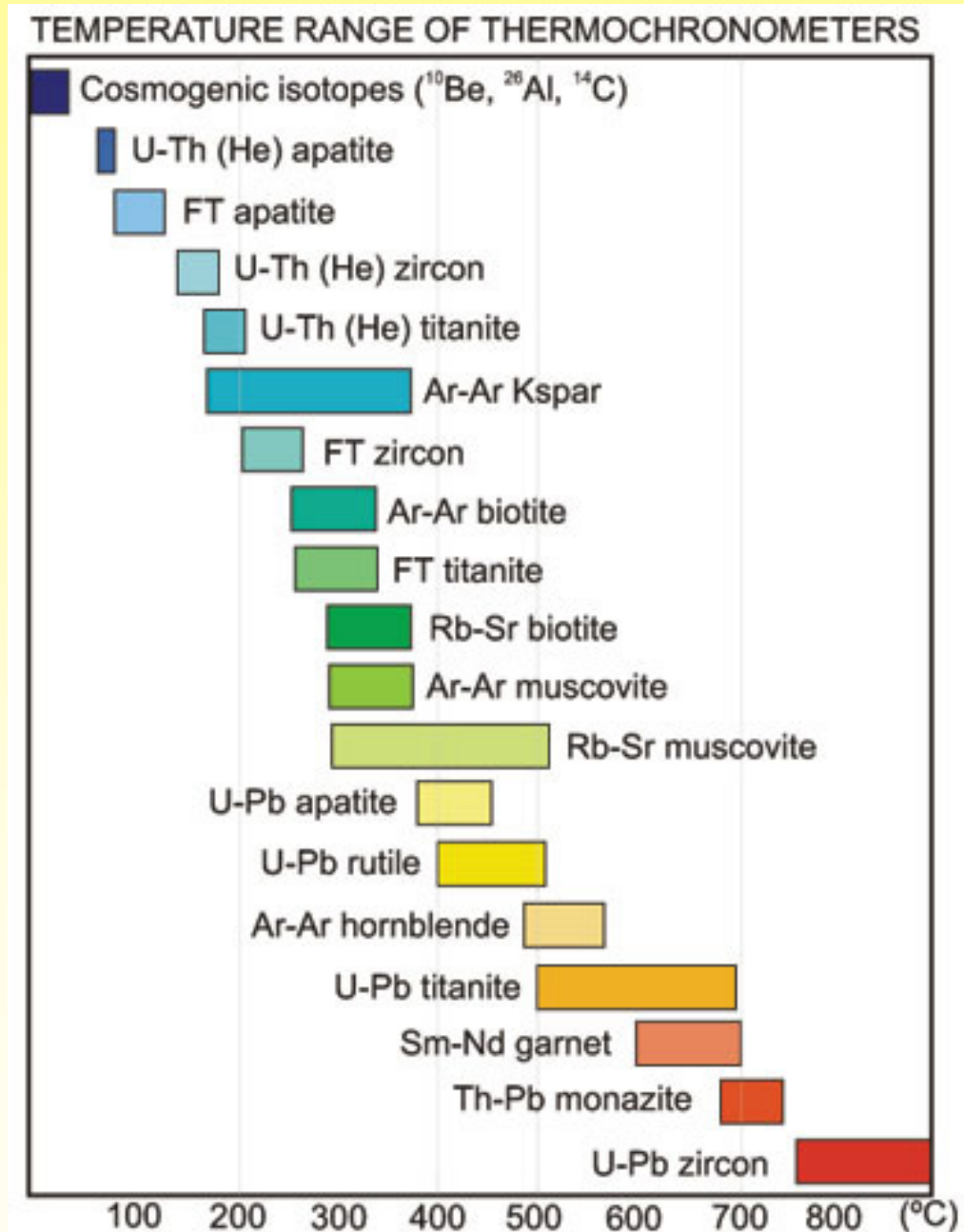


Datierungsmethoden und Schließungstemperatur

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 (inherited) Alter?

Abkühlungsalter (Abkühlalter) oder

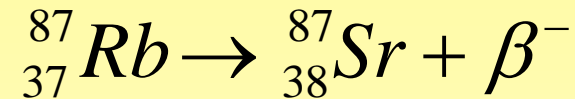
Metamorphosealter (Aufheizungsalter)?

Hebungsalter (bei Spaltspuren)

Welches Mineral oder Gestein wurde mit welcher Methode datiert?

Isochronenmethode

Beispiel Rb-Sr:



Halbwertszeit $T_{1/2} = 48.8 \text{ Ga}$,

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

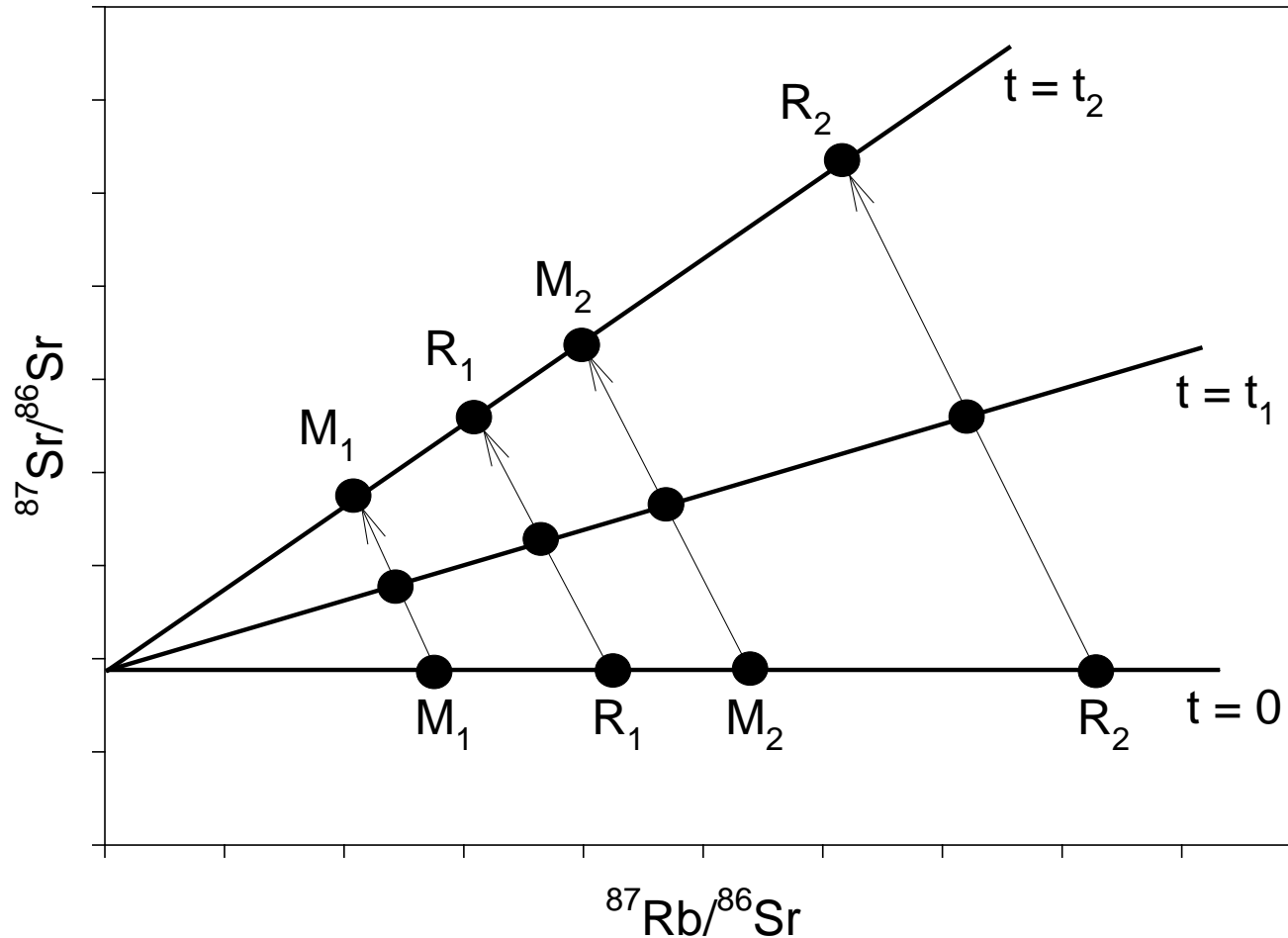
Altersgleichung:

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

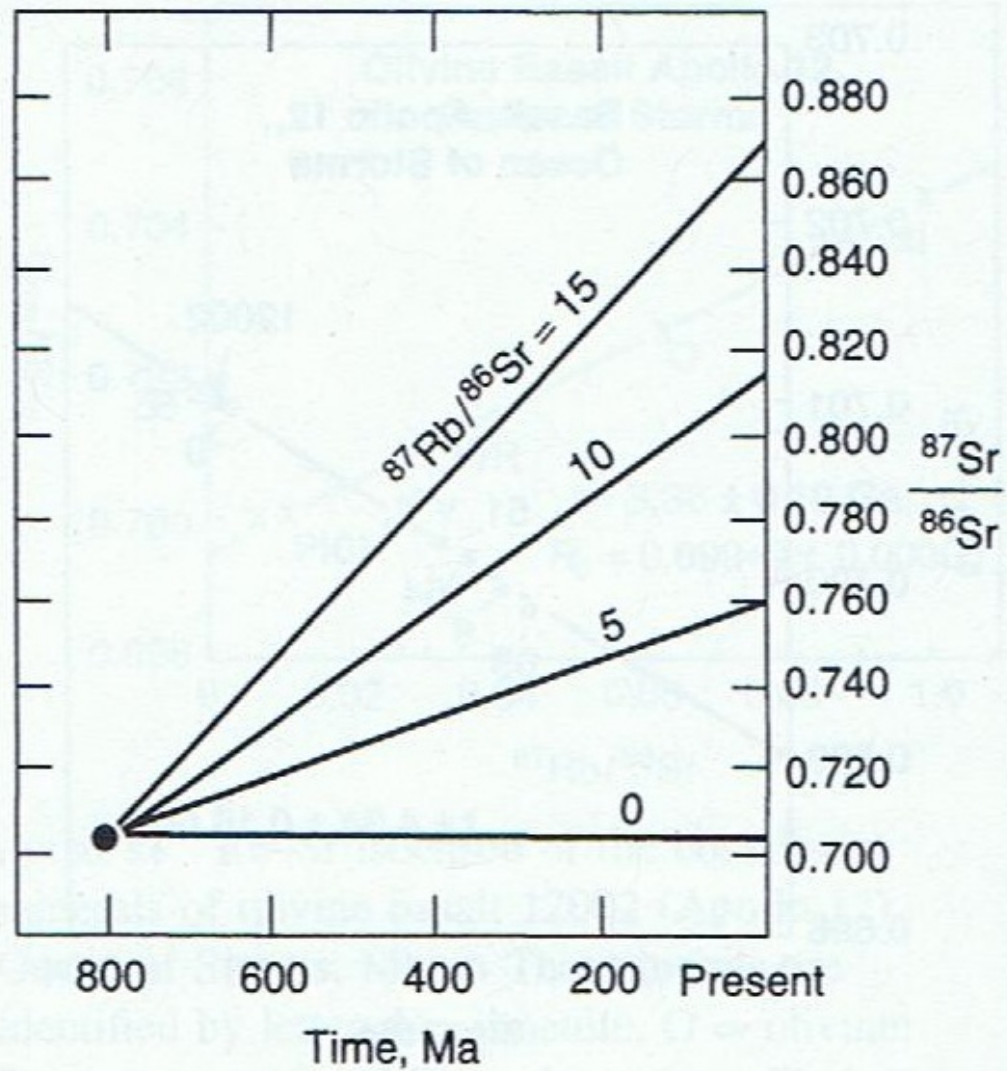
Rb-Sr Isochronendiagramm

M_1, M_2 = cogenetische Minerale

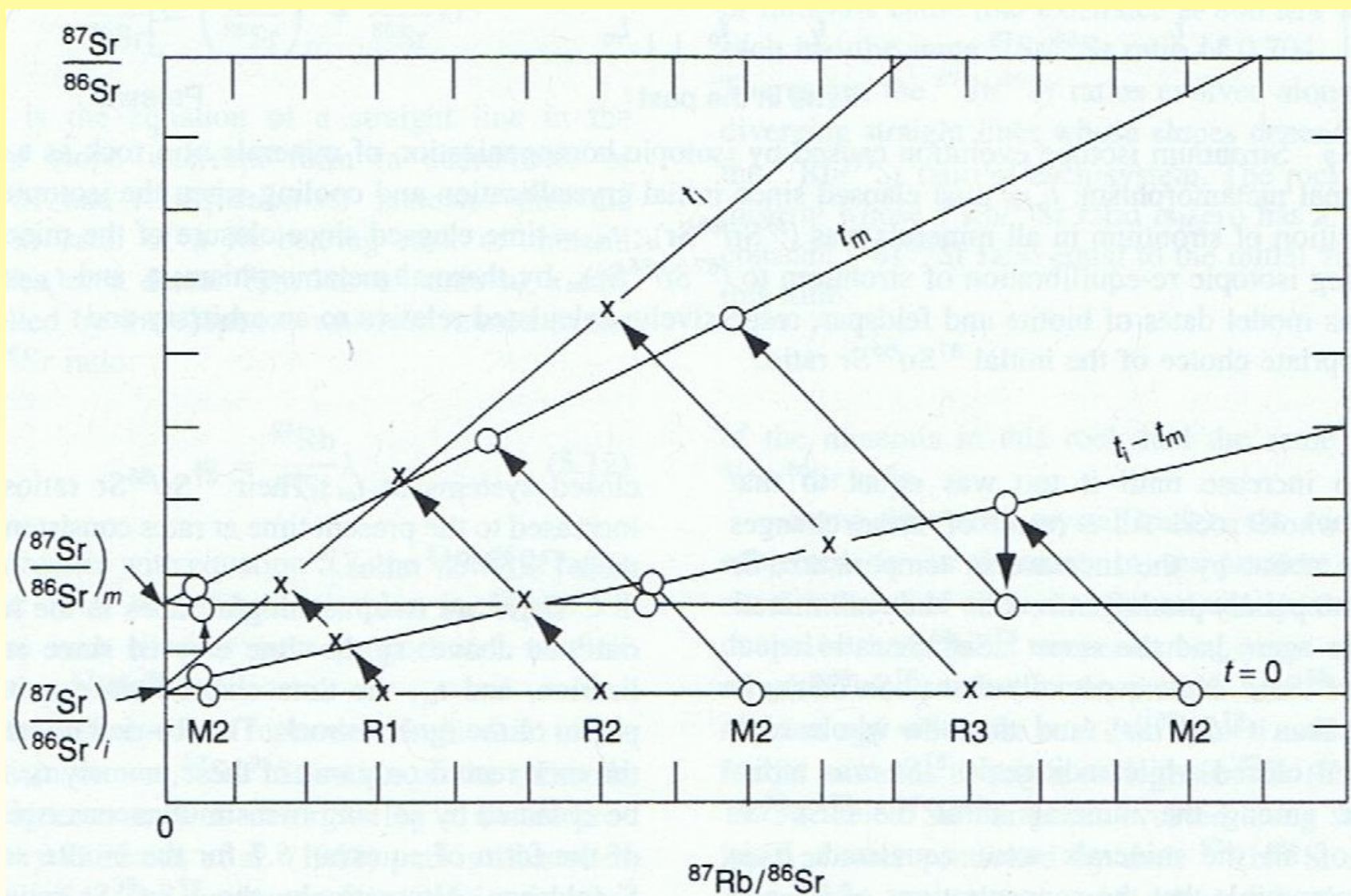
R_1, R_2 cogenetische Gesamtgesteine mit unterschiedlichen Rb/Sr Verhältnissen



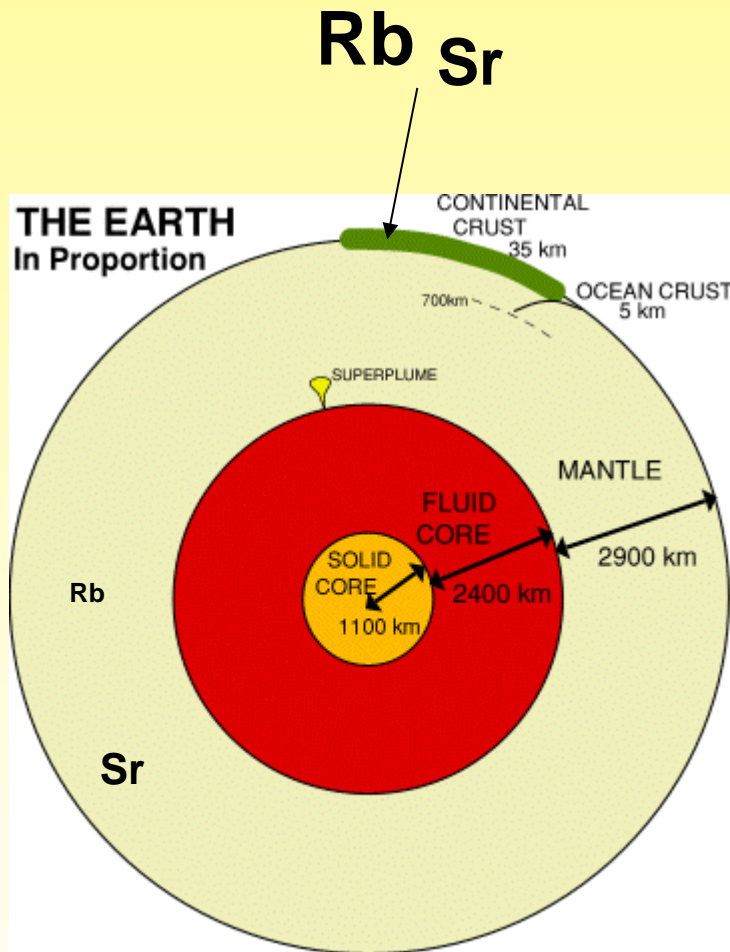
Compston-Jeffery Diagramm



Rb/Sr-System während einer Metamorphose

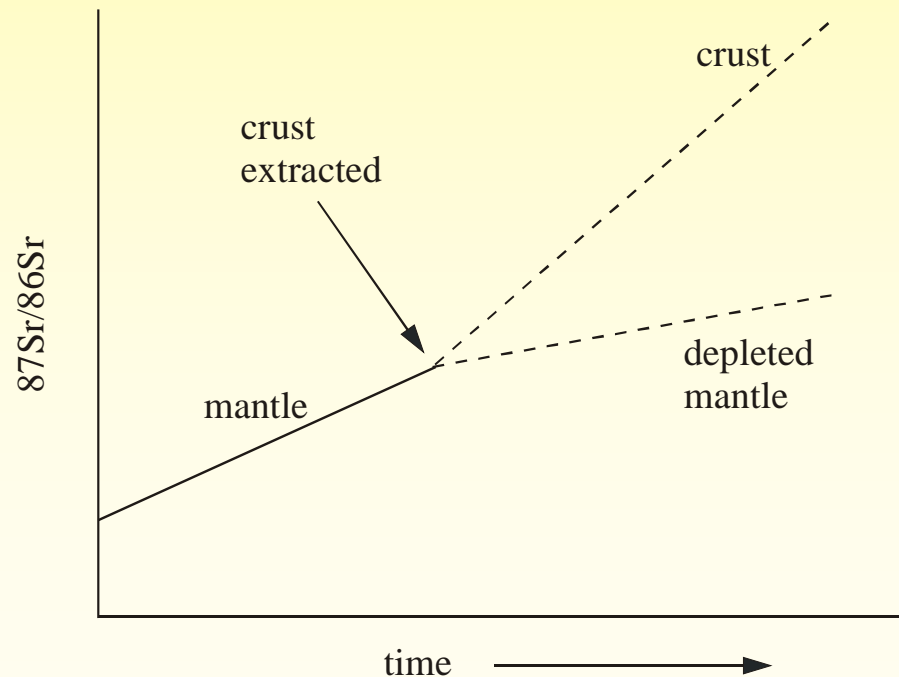


Die Sr-Isotopenentwicklung der Erde



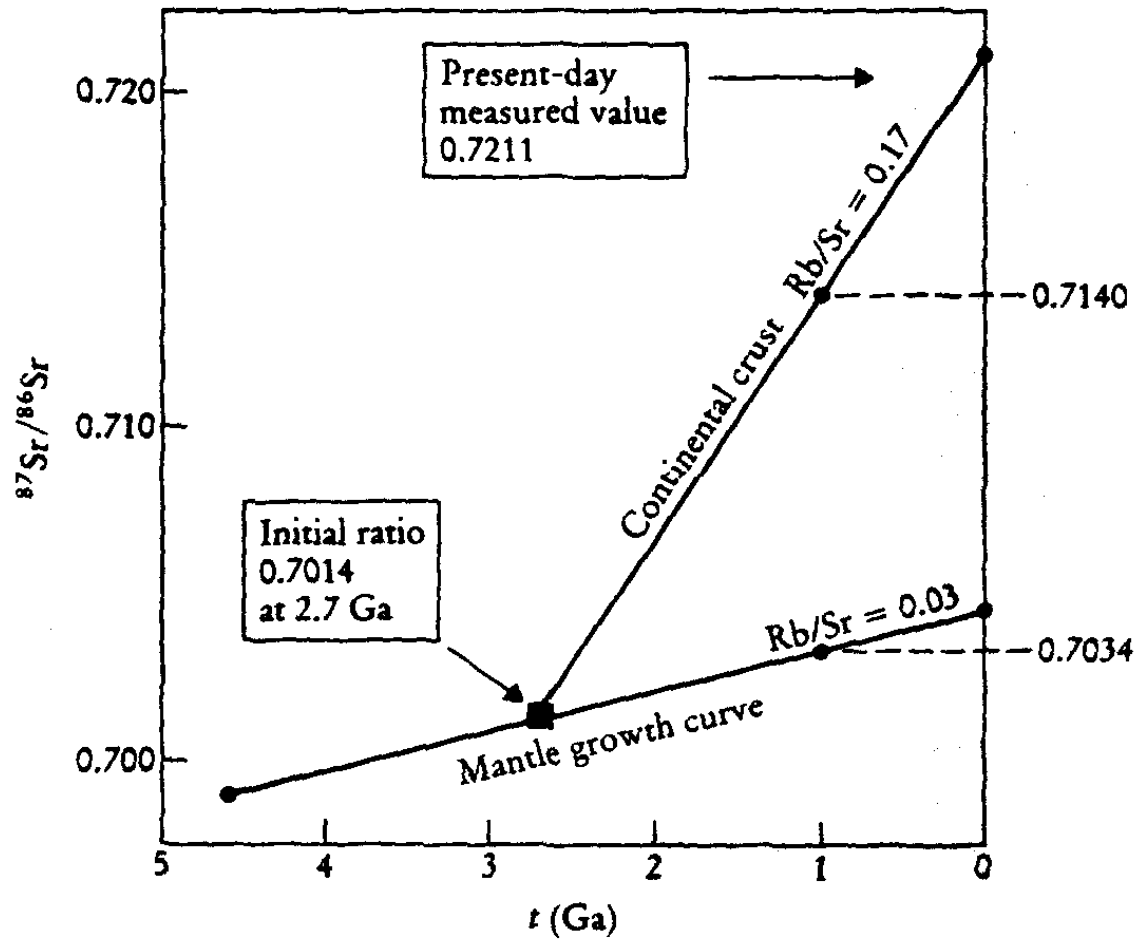
Mehr Rb in der Kruste als im Mantel

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



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

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

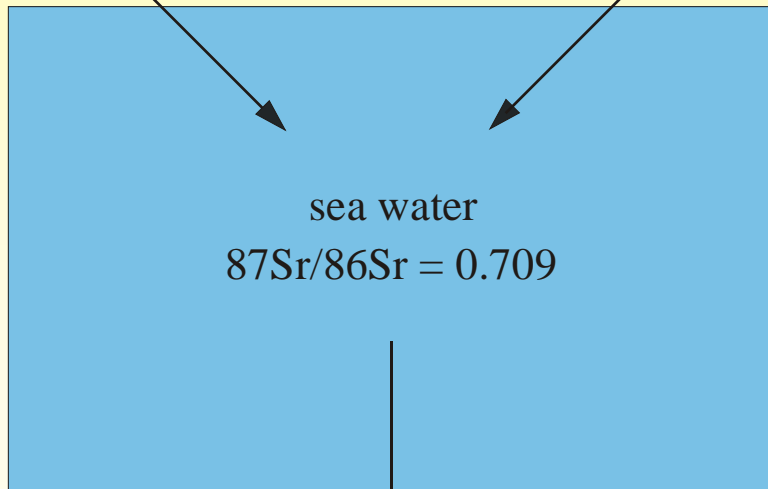


Sr-Isotopie der Ozeane

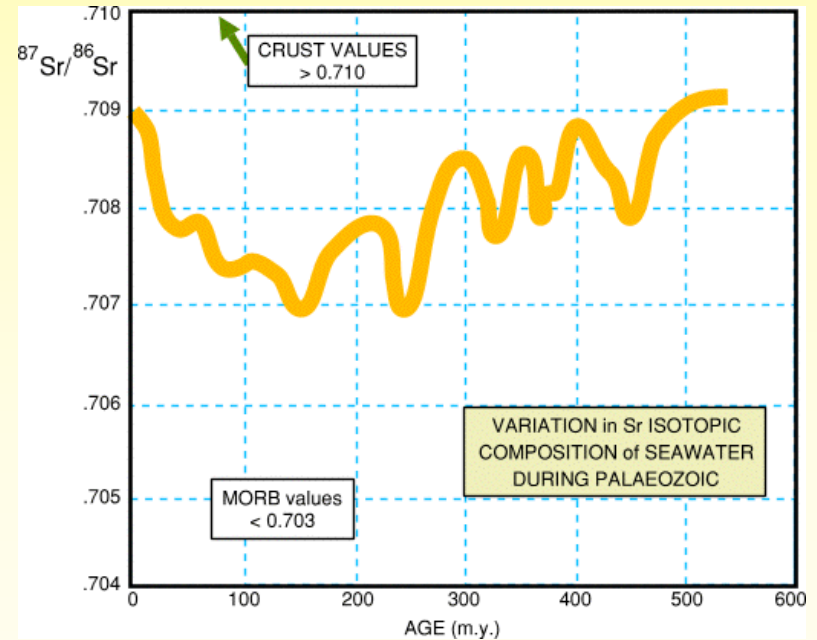
Sr isotope composition of the oceans is determined by the relative contributions of Sr from river waters and hydrothermal sources

river water
 $87\text{Sr}/86\text{Sr} = 0.711$

hydrothermal fluids
 $87\text{Sr}/86\text{Sr} = 0.703$

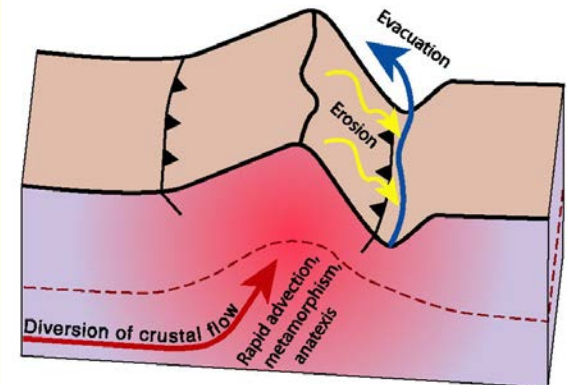
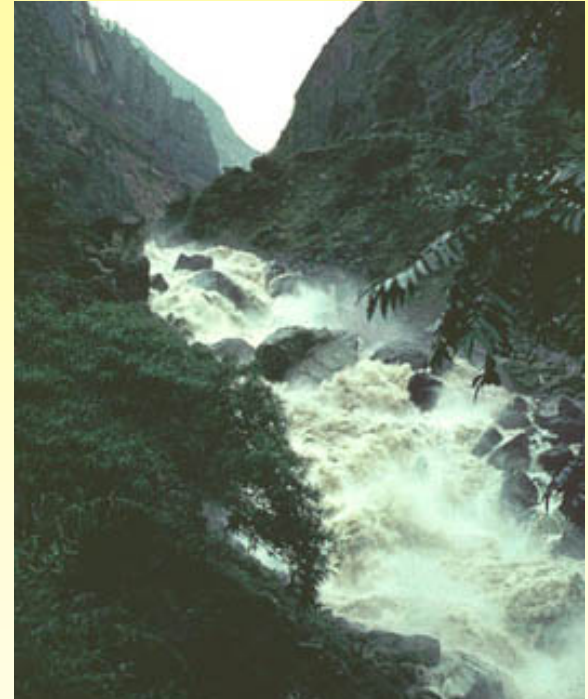
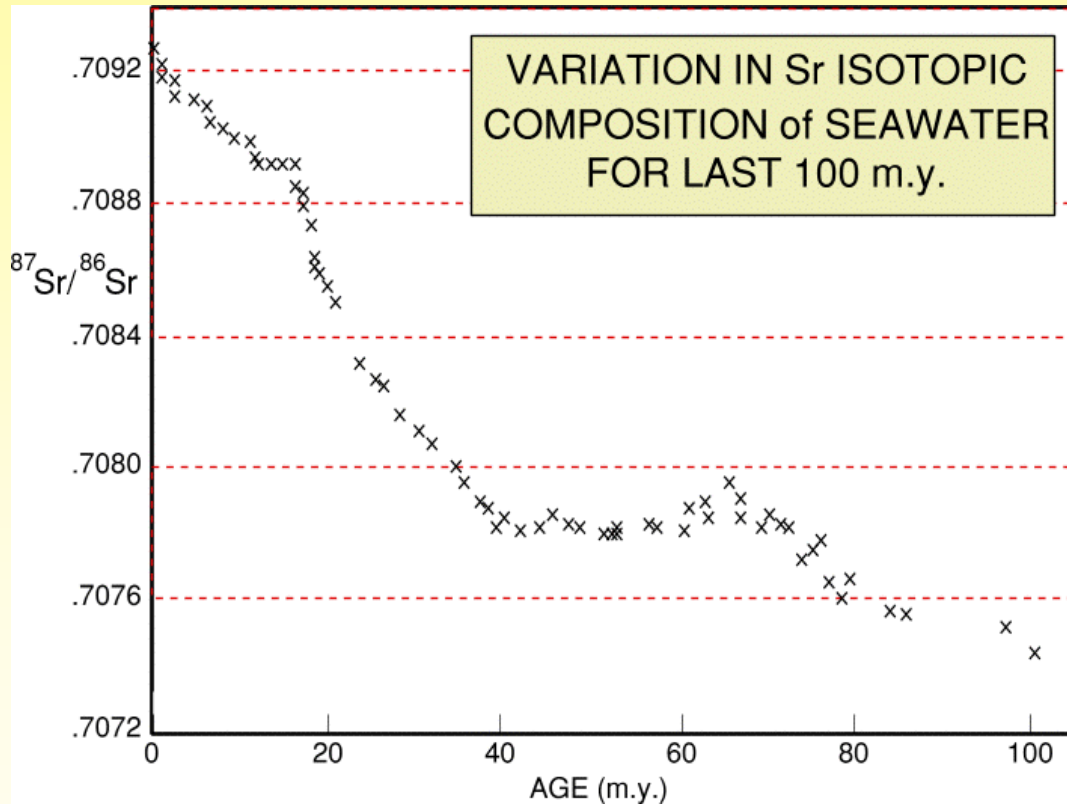


carbonate shells
 $87\text{Sr}/86\text{Sr} = 0.709$



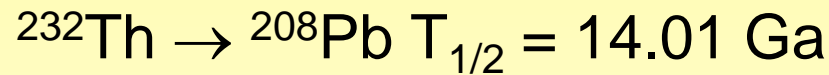
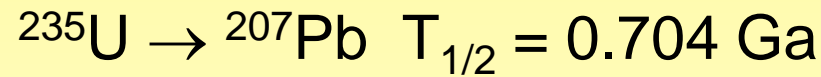
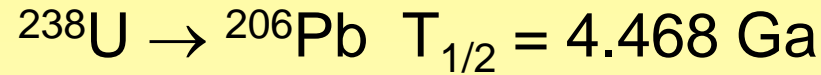
Sr-Isotopie der Ozeane

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



Die U-Th-Pb Methoden

Basiert auf drei verschiedenen Zerfallsreaktionen:



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

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

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

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

Die U-Th-Pb Methoden

With this geochronometer, we can get three independent age determinations of minerals or rocks containing both U and Th.

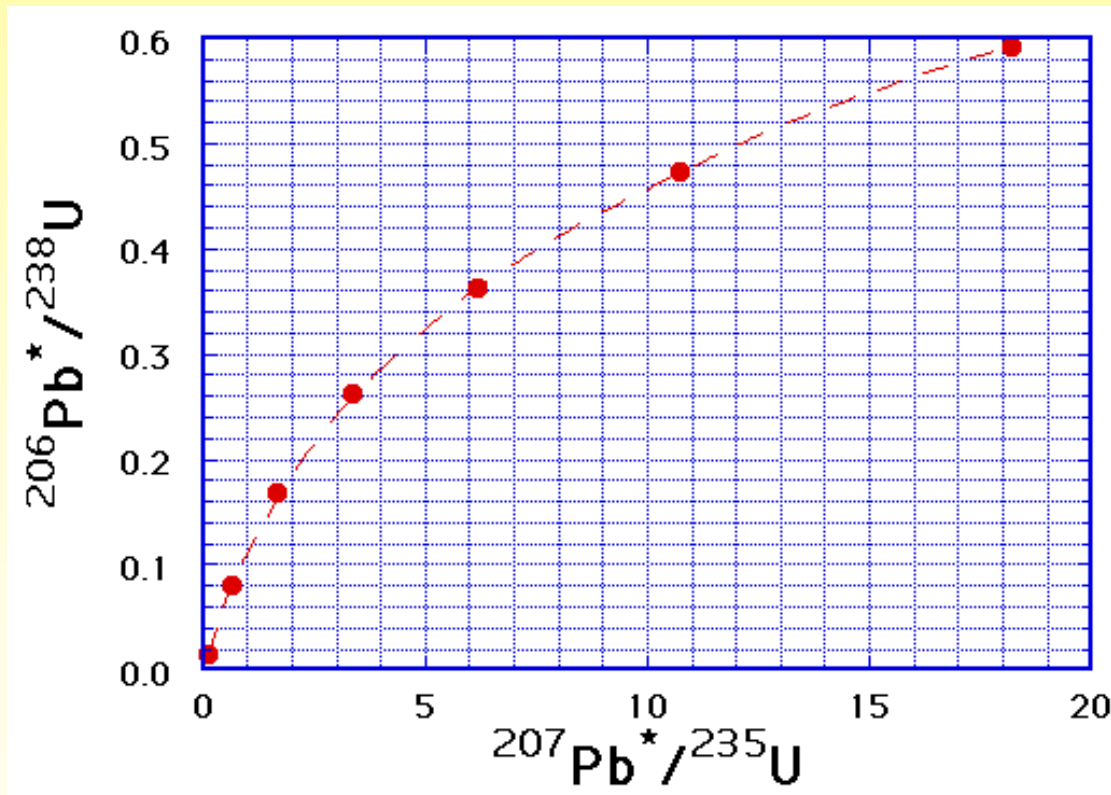
All three equations will give the same ages, provided no gain or loss of U, Th or Pb occurred during the lifetime of the system being dated. The ages are then said to be concordant.

Often, the three dates do not agree, i.e., they are discordant.

Generally, discordancy results from **loss of Pb**.

U-Pb Concordia Diagram

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



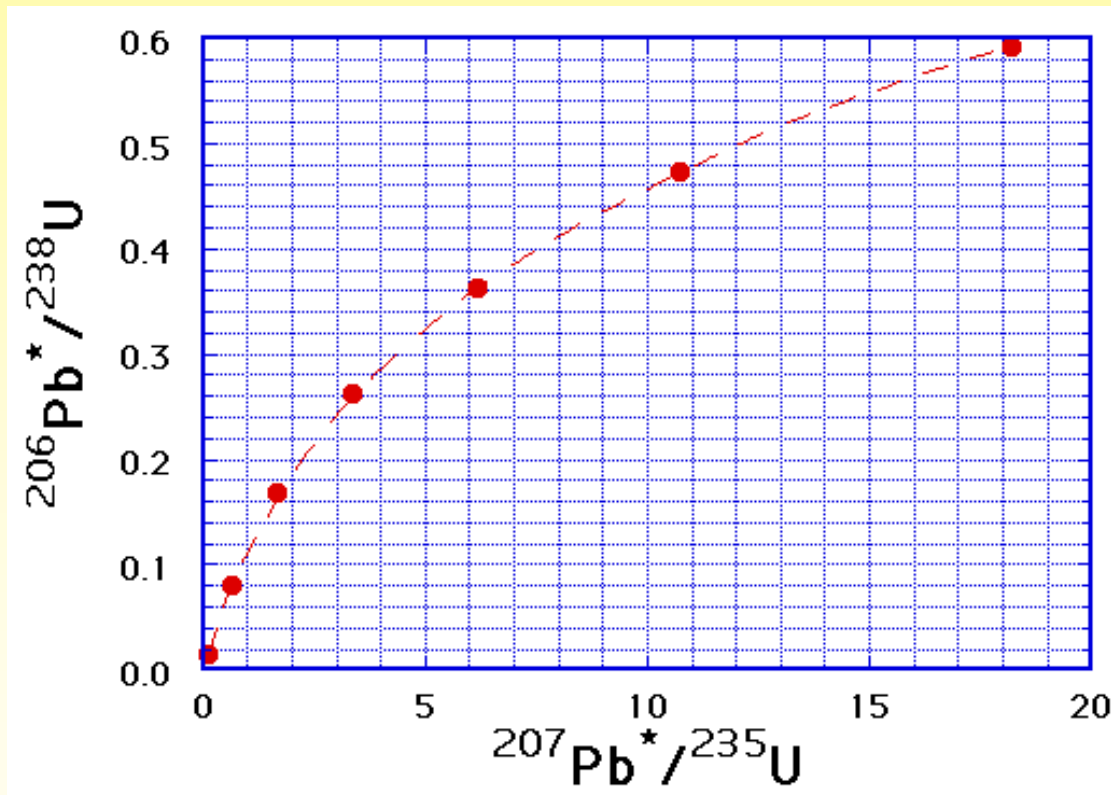
U-Pb Concordia Diagramm

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

Ga	$e^{\lambda_1 t} - 1$	$e^{\lambda_2 t} - 1$	$\left(\frac{^{207}\text{Pb}}{^{206}\text{Pb}}\right)^*$	Ga	$e^{\lambda_1 t} - 1$	$e^{\lambda_2 t} - 1$	$\left(\frac{^{207}\text{Pb}}{^{206}\text{Pb}}\right)^*$
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

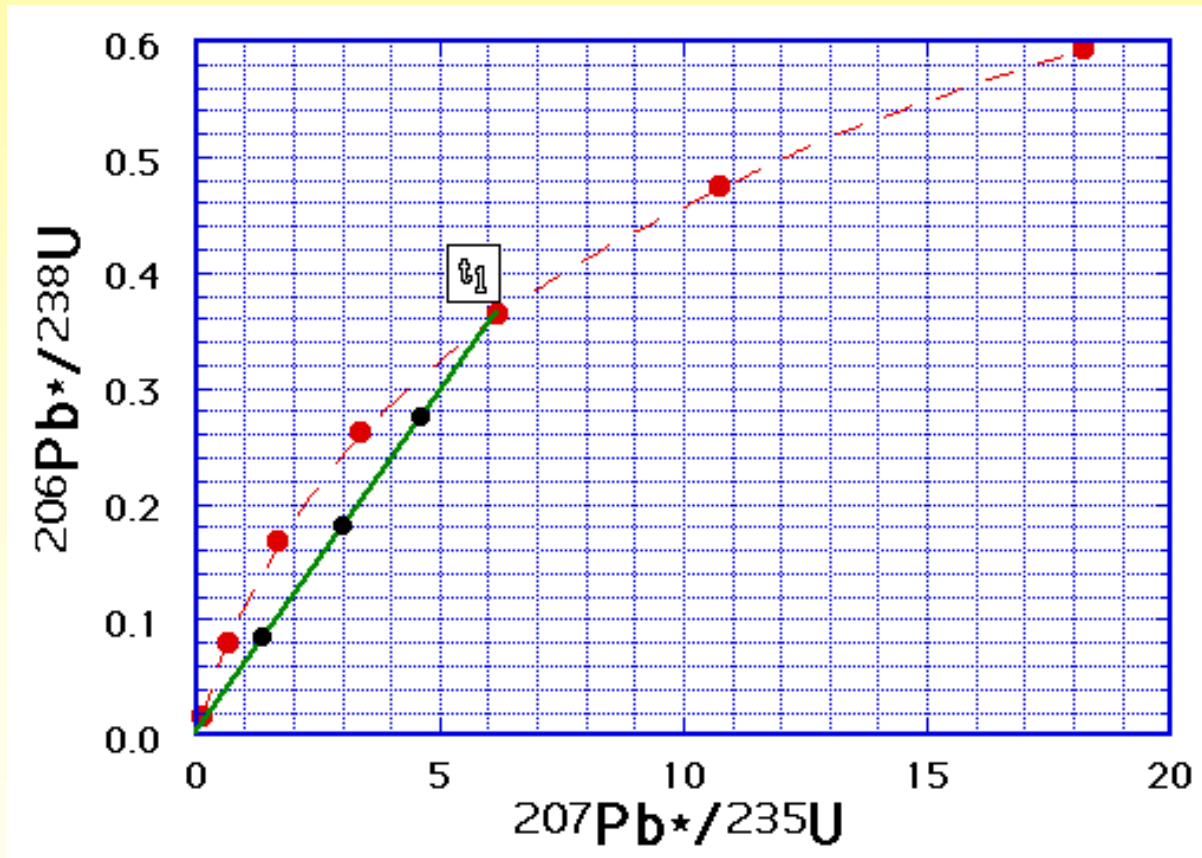
U-Pb Concordia Diagramm

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

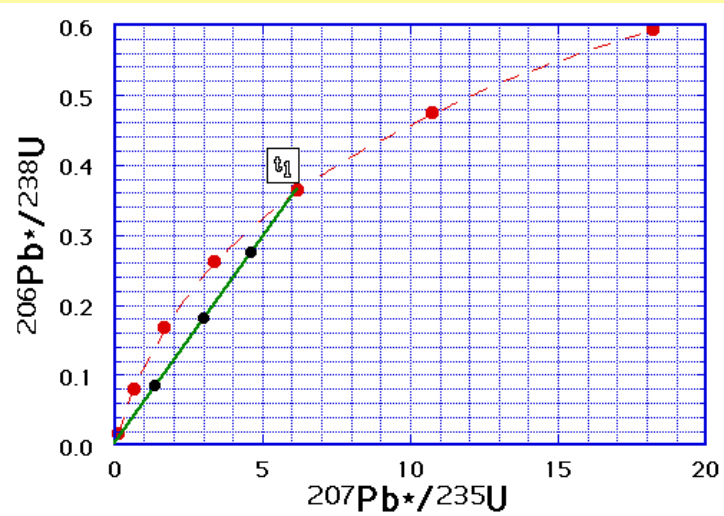


U-Pb Datierung

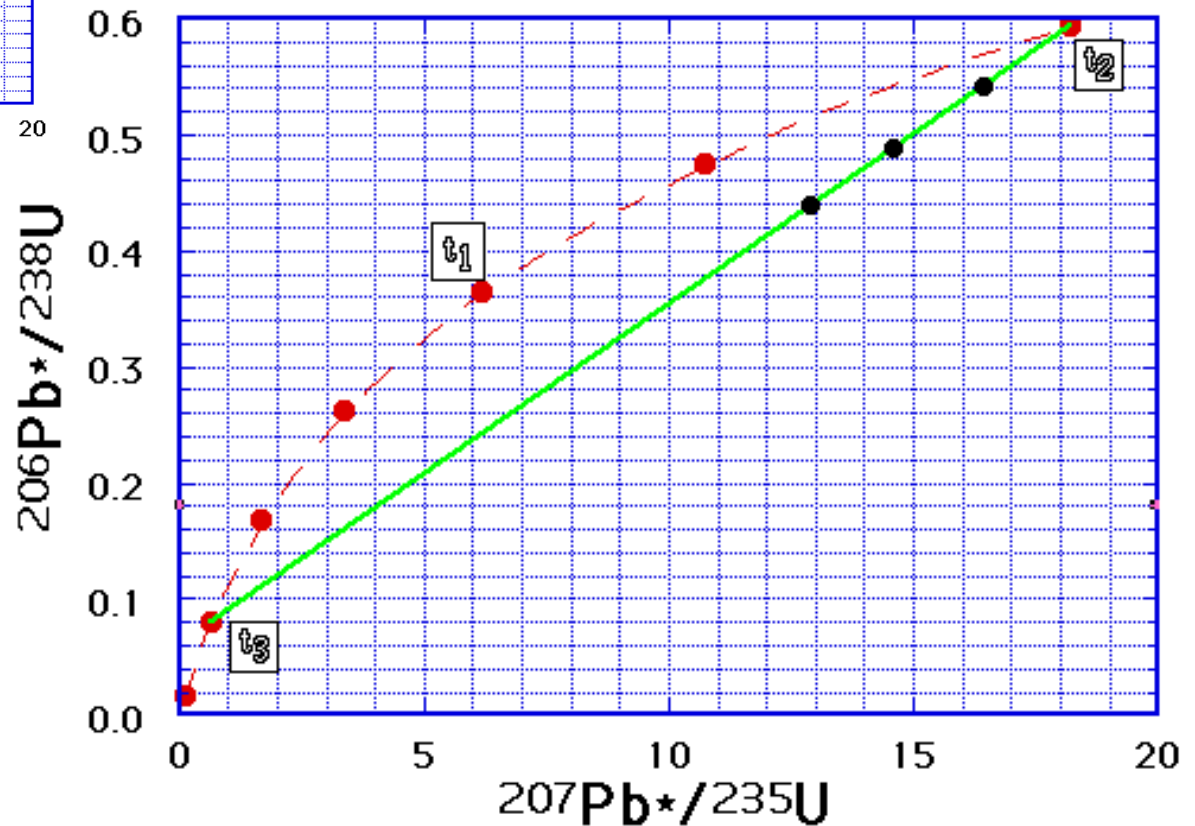
$$^{206}\text{Pb}^*/^{238}\text{U} = (e^{\lambda t} - 1), \quad ^{207}\text{Pb}^*/^{235}\text{U} = (e^{\lambda t} - 1)$$



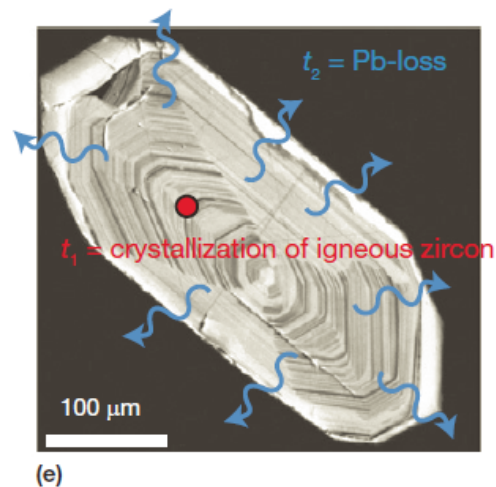
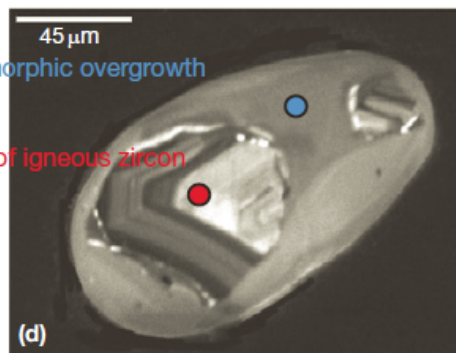
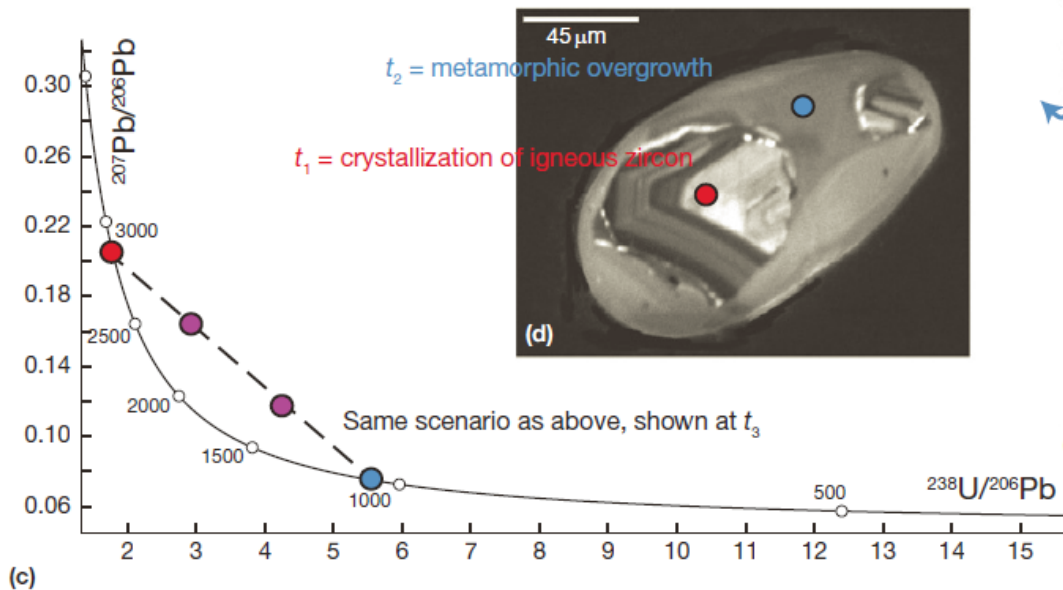
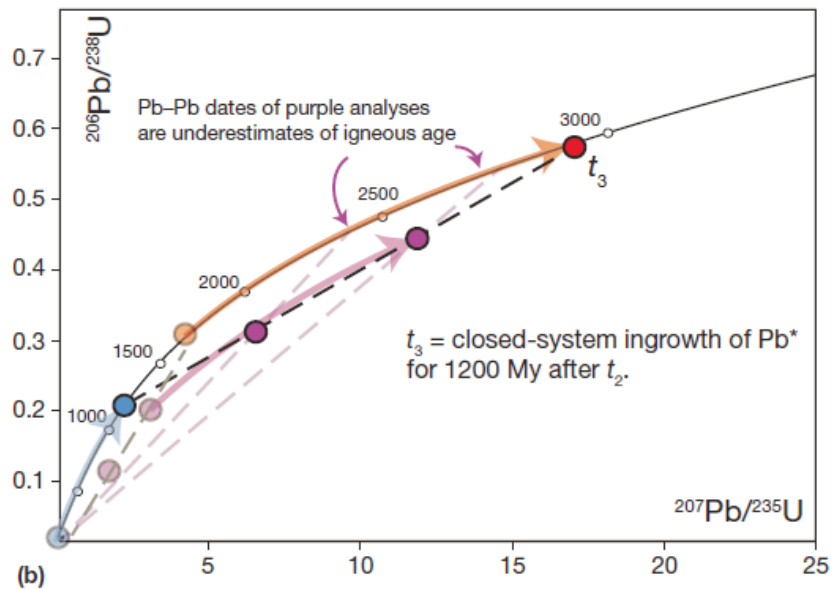
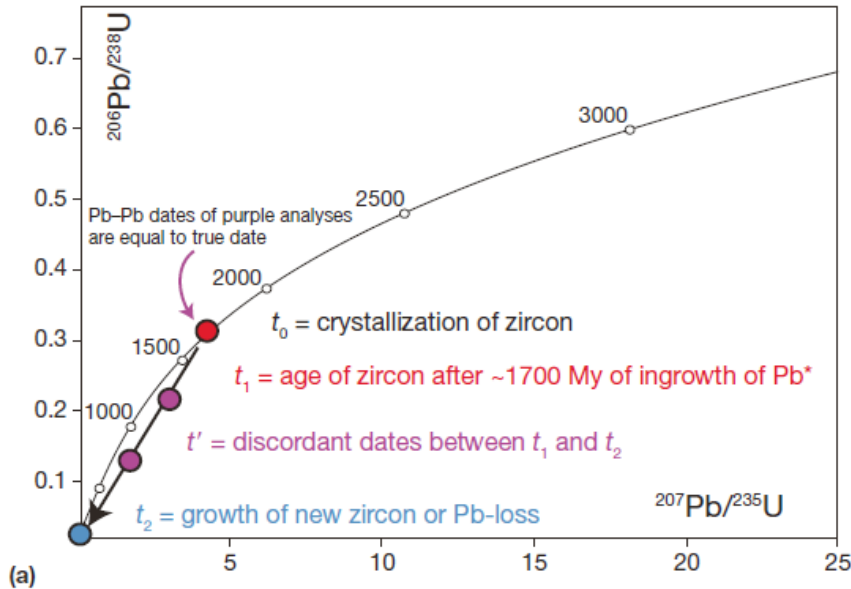
U-Pb Datierung



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



Wetherill & Tera-Wasserburg concordia

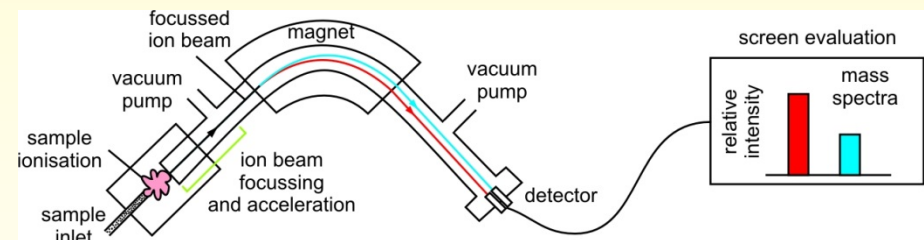


U-Pb Datierung

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”:

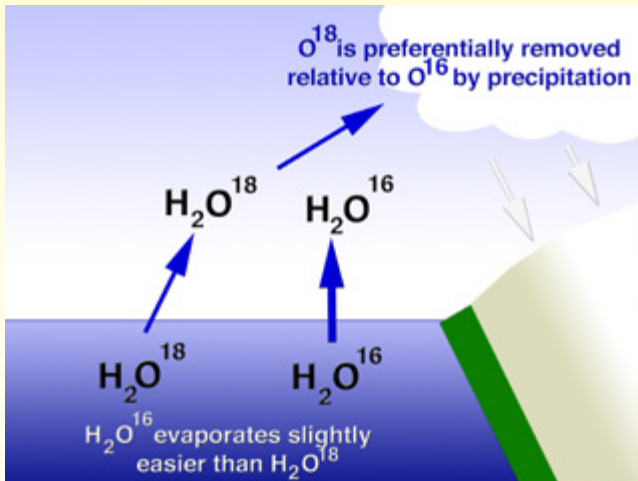
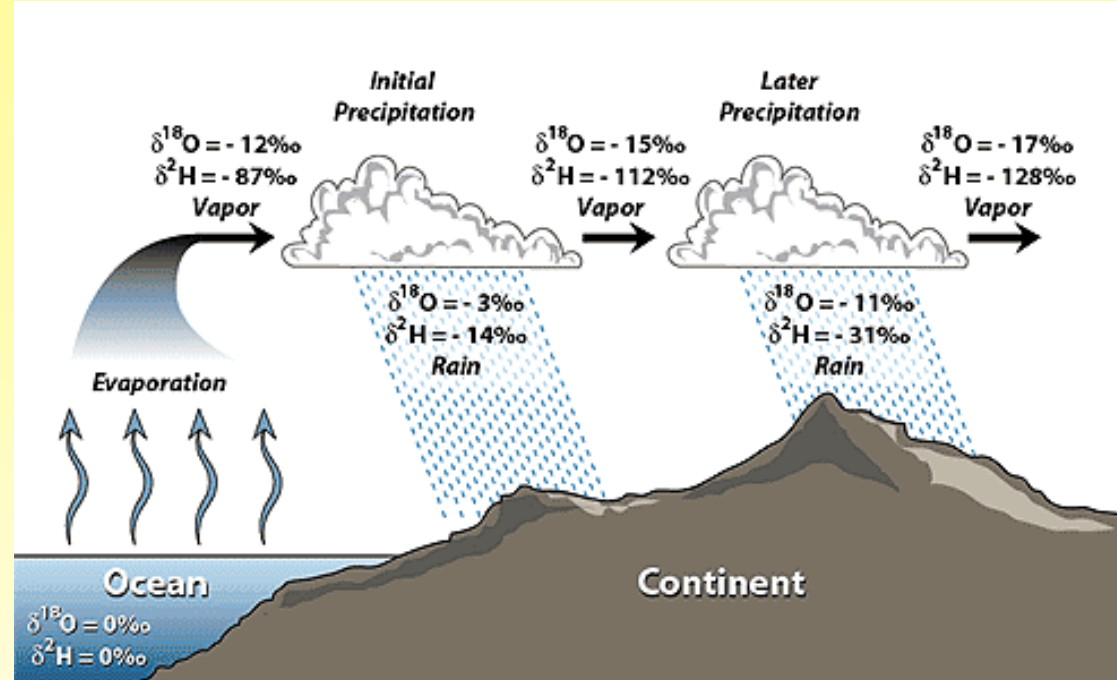
Differences in chemical and physical properties arising from variations in atomic mass of an element or molecule

Stabile Isotope

Evaporation/precipitation

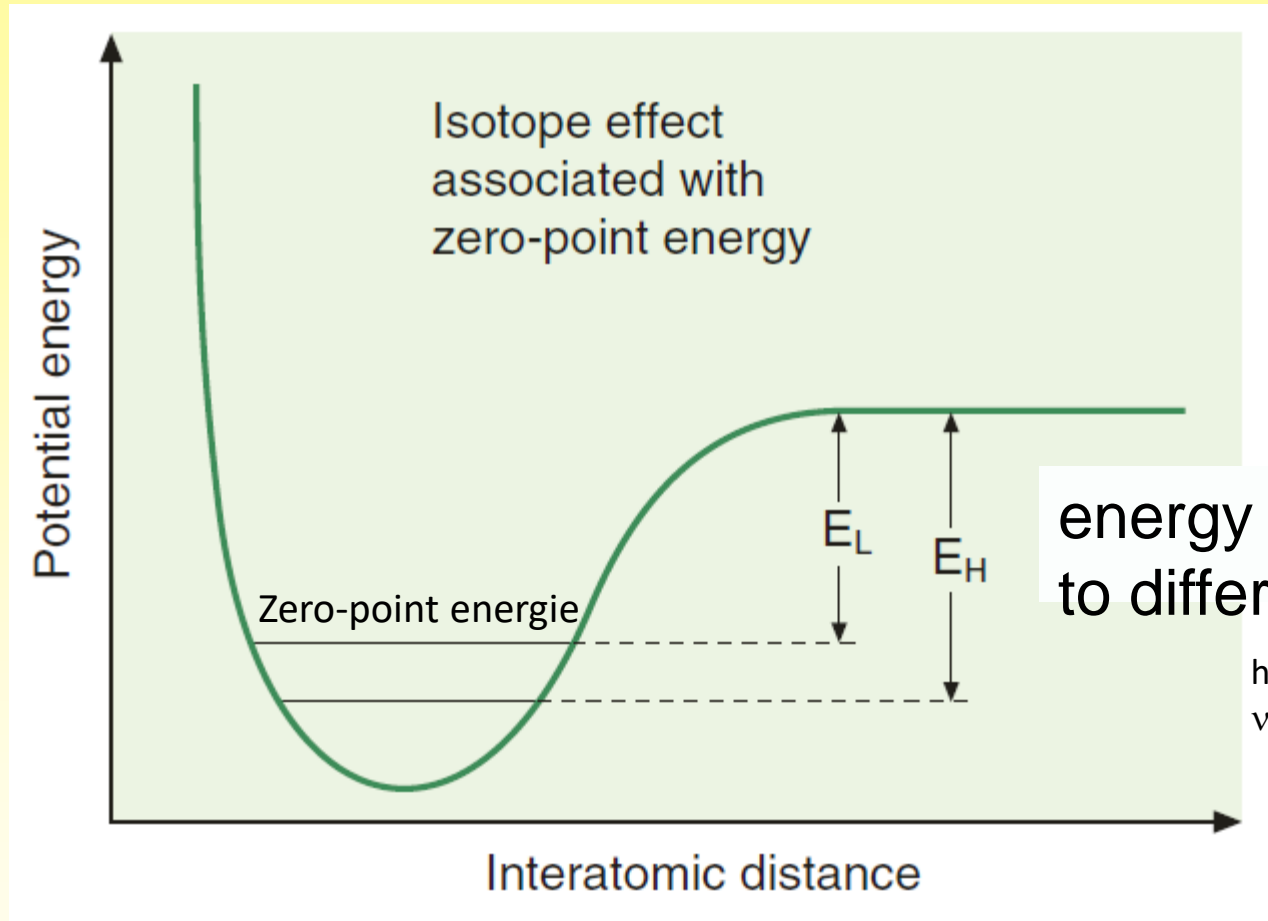
The lighter isotopes evaporate more easily

Heavier 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

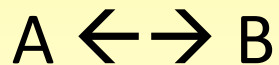
Stabile Isotope



Massenabhängige Isotopenfraktionierung

Isotope fractionation during chemical, physical and biological processes:

reversible chemical reaction at equilibrium state



physical changes – phase transitions

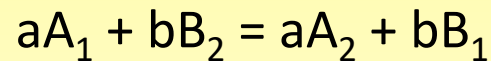
water – vapor

biological and biochemical reactions

CO₂ into C_{org}

Massenabhängige Isotopenfraktionierung

1. isotope exchange reactions (equilibrium isotope distribution)



$$K = \frac{\left(\frac{A_2}{A_1}\right)^a}{\left(\frac{B_2}{B_1}\right)^b}$$

$$\alpha_{A-B} = \frac{R_A}{R_B}$$

Massenabhängige Isotopenfraktionierung

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

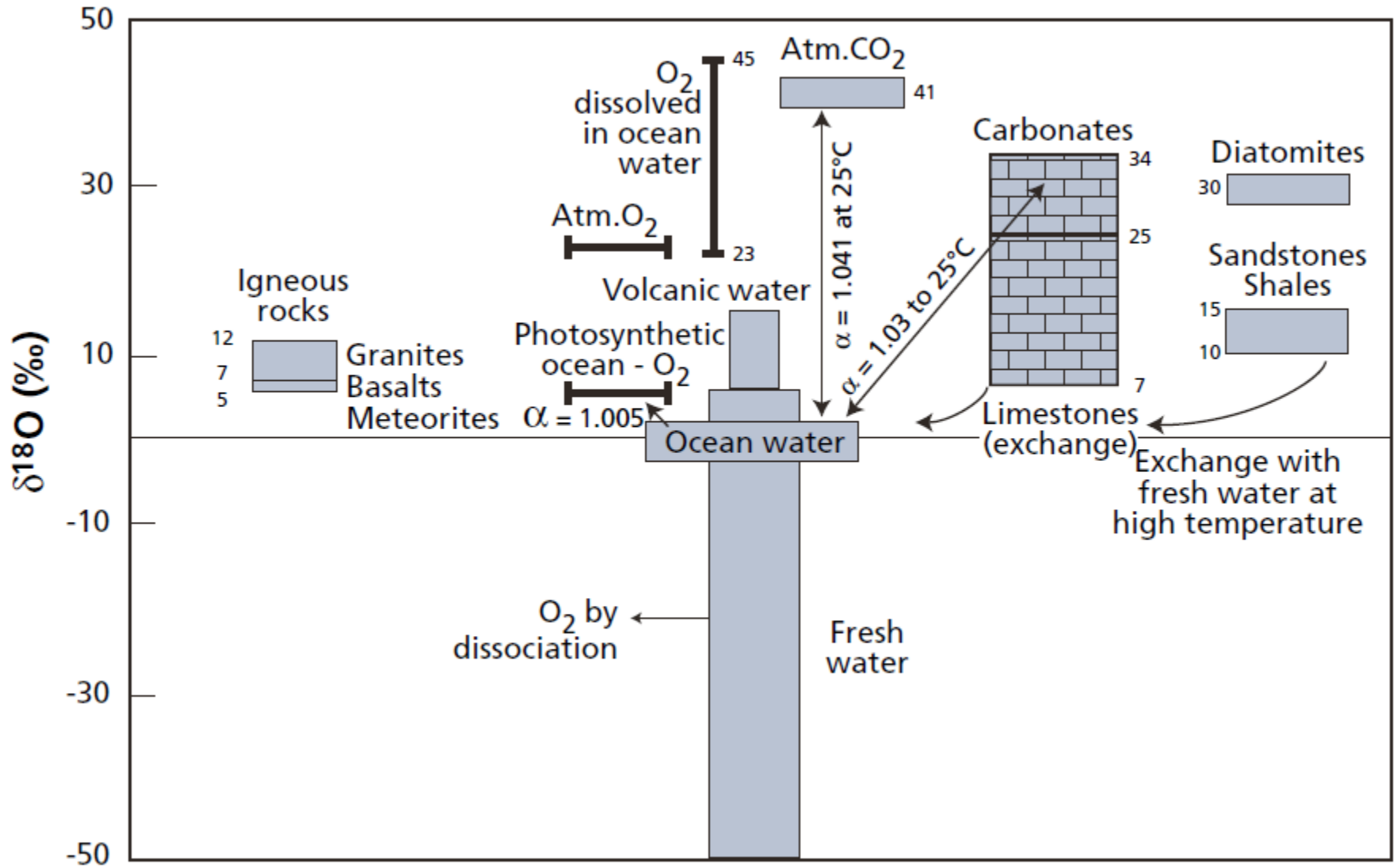
$$\delta = \left(\frac{\text{sample isotope ratio} - \text{standard isotope ratio}}{\text{standard isotope ratio}} \right) \times 10^3$$

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.:

$^{18}\text{O}/^{16}\text{O}$, D/H, $^{13}\text{C}/^{12}\text{C}$

Sauerstoff-Isotopenvariationen



Sauerstoff-Isotopenvariationen

