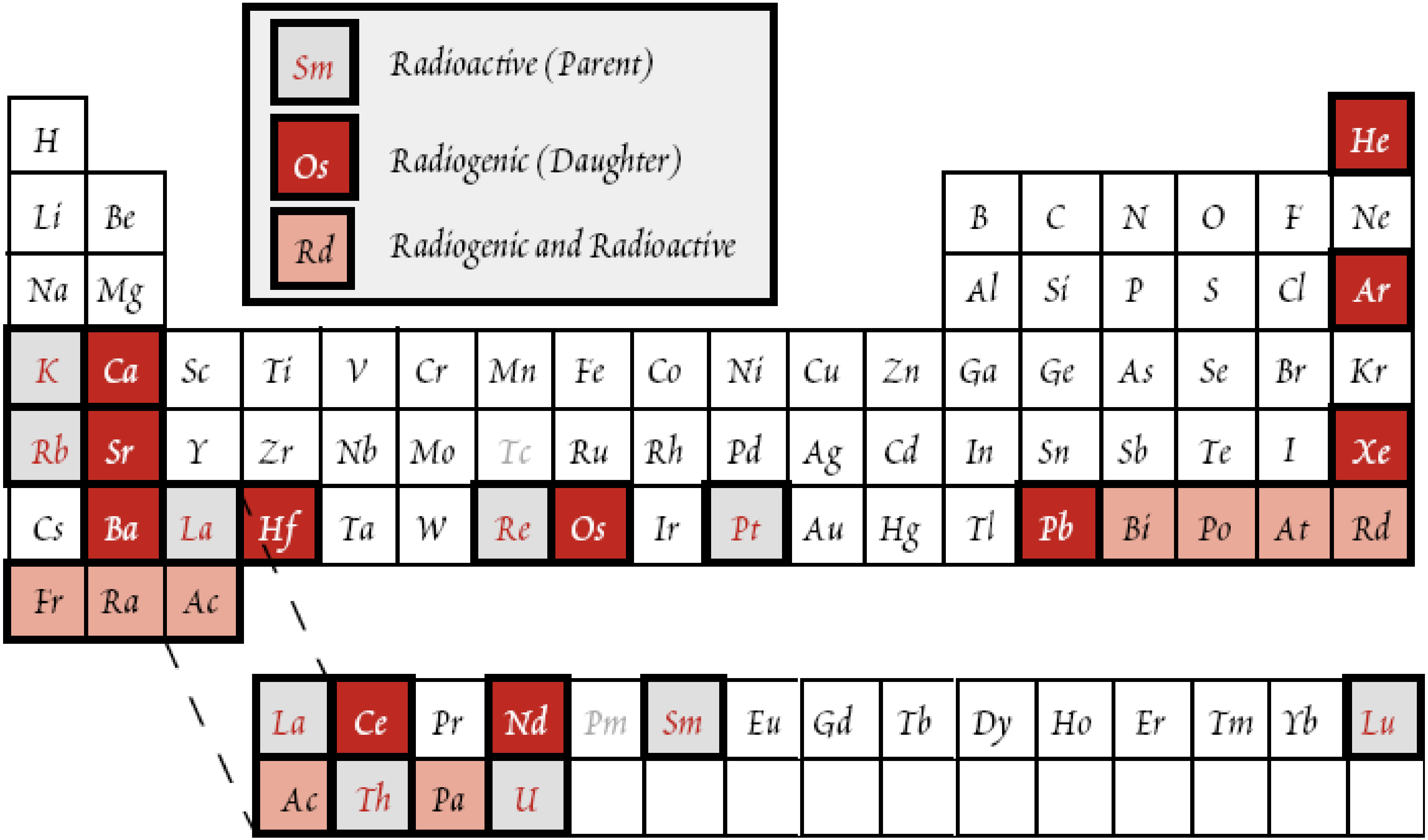
RADIOACTIVE DECAY

Radioactive Isotopes



- **two extremely interesting and important aspects of radioactive decay makes it so useful as a chronometer.**
  - Unstable nuclei decay to stable ones at **rates independent of all environmental influences**.
  - Each nucleus has a **fixed probability of decaying** per unit time. Nothing affects this probability (e.g., temperature, pressure, bonding environment, etc.)

Radiogenic Isotopic variations is a function of:

1. **Time (of decay since the system is closed)**
2. **Different parent/Daughters ratio**

Radioactive Decay

- **Basic equation of radioactive decay: first-order rate law: Curie-Rutherford-Soddy Law:**

$$-\frac{dN}{dt} \propto N \quad \text{or} \quad -\frac{dN}{dt} = \lambda N$$ = **Activity of radionuclide**

The minus sign simply indicates N (present-day parent concentration) decreases.

λ is the decay constant- probability of decay per unit time . Unit: time^{-1}.

- Integrating the decay equation, we get:

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

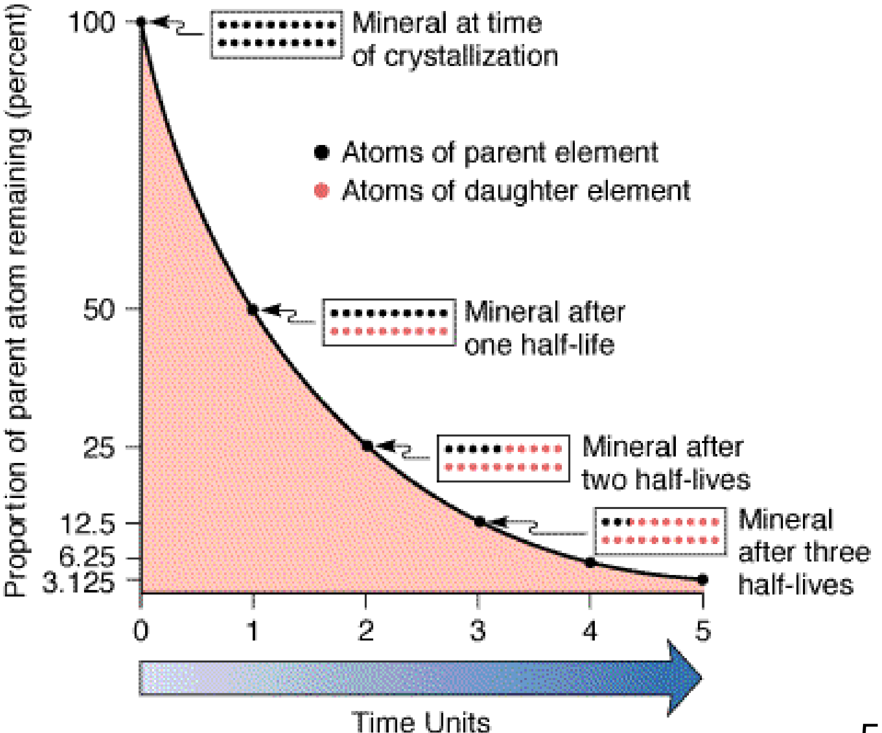
Half-life: $$t_{1/2} = \frac{Ln2}{\lambda} = \frac{0.693}{\lambda}$$

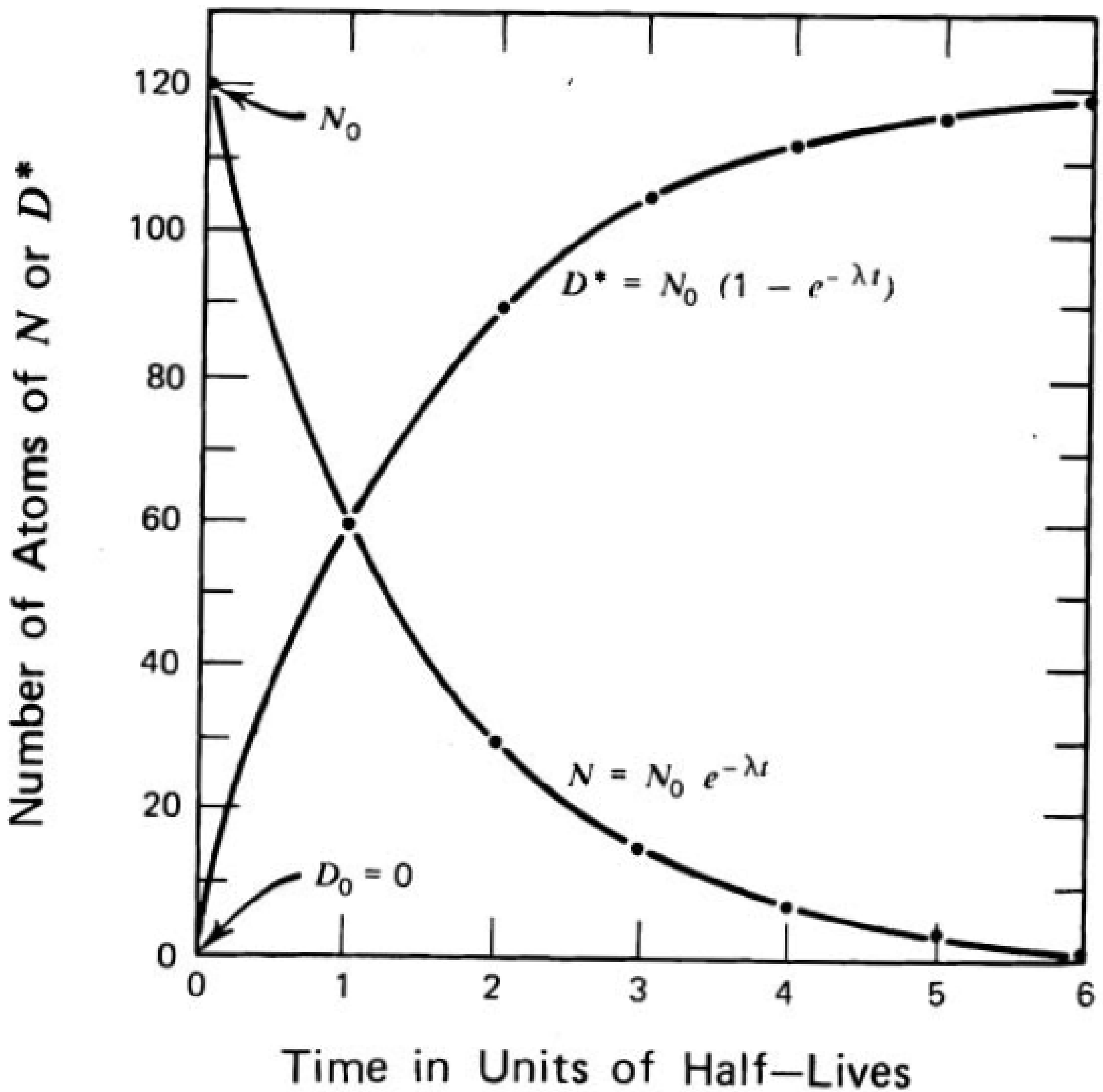
The **mean life** τ of a parent nuclide:

(average life expectancy of a radioactive atom)

$$t\tau = -\frac{1}{N_0}\int_{t=0}^{t=\infty} t\,.\,dN$$

$$\boxed{\tau = \frac{N}{\lambda N} = \frac{1}{\lambda}}$$





Number of Atoms of N or D*
120
100
80
60
40
20
0
0
1
2
3
4
5
6
Time in Units of Half-Lives
N0
D* = N0 (1 − e^−λt)
N = N0 e^−λt
D0 = 0

The decay of the parent produces a daughter (D^*), or radiogenic nuclide.

$$D^* = N_o - N$$

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

- **However, there might be some daughter isotope present in the system (initial value) to begin with.**

Therefore: $D = D_o + D^*$

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

D = number of daughter atoms

N = number of existing parent atoms

D_o = number of initial daughter atoms

λ = decay constant

t = time elapsed

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

Note that this equation is independent of N_0.

solve the above equation for age of the system (t):

$$t = \frac{1}{\lambda} \mathrm{Ln}\left[\frac{D - D_0}{N} + 1\right]$$

Practical limitations on age range:

Very young rocks: cannot measure tiny amount of daughter accurately

Very old rocks: cannot measure tiny amounts of parent left accurately

Applicability of an Isotopic system depends on λ.

Geologically Useful Long-Lived Radioactive Decay Schemes

TABLE 2.1: Geologically Useful Long-Lived Radioactive Decay Schemes

Parent	Decay Mode	λ	Half-life	Daughter	Ratio
^{40}K	β^-, e.c, β^+	$5.5492 \times 10^{-10} y^{-1*}$	1.28×10^{9} yr	^{40}Ar, ^{40}Ca	$^{40}Ar/^{36}Ar$
^{87}Rb	β^-	$1.42 \times 10^{-11} y^{-1£}$	48.8×10^{9} yr	^{87}Sr	$^{87}Sr/^{86}Sr$
^{138}La	β^-	$2.67 \times 10^{-12} y^{-1}$	2.59×10^{11} yr	^{138}Ce, ^{138}Ba	$^{138}Ce/^{142}Ce$, $^{138}Ce/^{136}Ce$
^{147}Sm	α	$6.54 \times 10^{-12} y^{-1}$	1.06×10^{11} yr	^{143}Nd	$^{143}Nd/^{144}Nd$
^{176}Lu	β^-	$1.867^{\dagger} \times 10^{-11} y^{-1}$	3.6×10^{10} yr	^{176}Hf	$^{176}Hf/^{177}Hf$
^{187}Re	β^-	$1.64 \times 10^{-11} y^{-1}$	4.23×10^{10} yr	^{187}Os	$^{187}Os/^{188}Os$, ($^{187}Os/^{186}Os$)
^{190}Pt	α	$1.54 \times 10^{-12} y^{-1}$	4.50×10^{11} yr	^{186}Os	$^{186}Os/^{188}Os$
^{232}Th	α	$4.948 \times 10^{-11} y^{-1}$	1.4×10^{10} yr	^{208}Pb, ^{4}He	$^{208}Pb/^{204}Pb$, $^{3}He/^{4}He$
^{235}U	α	$9.8571 \times 10^{-10} y^{-1\ddagger}$	7.07×10^{8} yr	^{207}Pb, ^{4}He	$^{207}Pb/^{204}Pb$, $^{3}He/^{4}He$
^{238}U	α	$1.55125 \times 10^{-10} y^{-1}$	4.47×10^{9} yr	^{206}Pb, ^{4}He	$^{206}Pb/^{204}Pb$, $^{3}He/^{4}He$

Note: the branching ratio, i.e. ratios of decays to ^{40}Ar to total decays of ^{40}K is 0.117. ^{147}Sm and ^{190}Pt also produce ^{4}He, but a trivial amount compared to U and Th.

*This is the value recently suggested by Renne et al. (2010). The conventional value is $5.543 \times 10^{-10} y^{-1}$

£The officially accepted decay constant for ^{87}Rb is that shown here. However, recent determinations of this constant range from $1.421 \times 10^{-11} y^{-1}$ by Rotenberg (2005) to $1.399 \times 10^{-11} y^{-1}$ by Nebel et al. (2006).

†This is the value recommended by Söderlund et al. (2004).

‡Value suggested by Mattinson (2010). The conventional value is $9.8485 \times 10^{-10} y^{-1}$.

Isochron Dating

$$^{87}Rb_{37} \rightarrow {}^{87}Sr_{38} + \beta^{-} + \nu + 0.275 \text{ Mev}$$

($\lambda = 1.42 \times 10^{-11}$ yr^{-1} ; $T_{1/2} = 48.8$ Ga)

$$\boxed{{}^{87}Sr = {}^{87}Sr_0 + {}^{87}Rb\left(e^{\lambda t} - 1\right)}$$

As it turns out, it is generally much easier, and usually more meaningful, to measure ratio of two isotopes precisely than the absolute abundance of one. We, therefore, measure the ratio of ^{87}Sr to a non-radiogenic isotope, which by convention is ^{86}Sr. We can recast the above equation as:

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

Measured for today

Estimated from isochrons

Measured for today

Assumptions in age determination

1) System was closed between $t = 0$ and time t (usually the present time)

   -no transfer of the parent or the daughter element into or out of the system

2) At $t = 0$, Concentration of parent must be different in different phases in the system, but concentration of initial daughter must be the same.

3) we must also know λ accurately

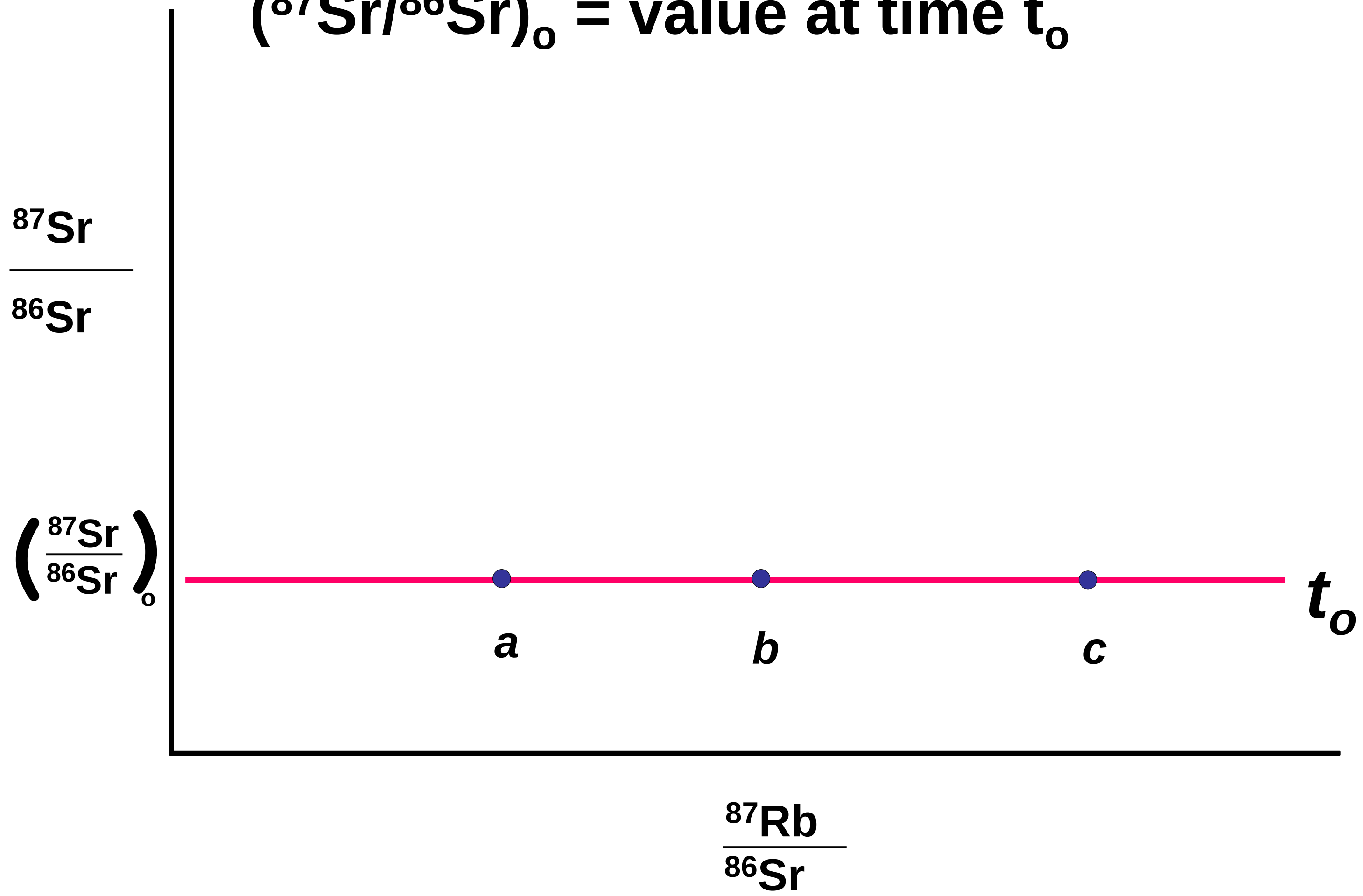
Violation of these conditions is the principal source of error in geochronology. Other errors arise from errors or uncertainties associated with the analysis.

Must satisfy: System is closed

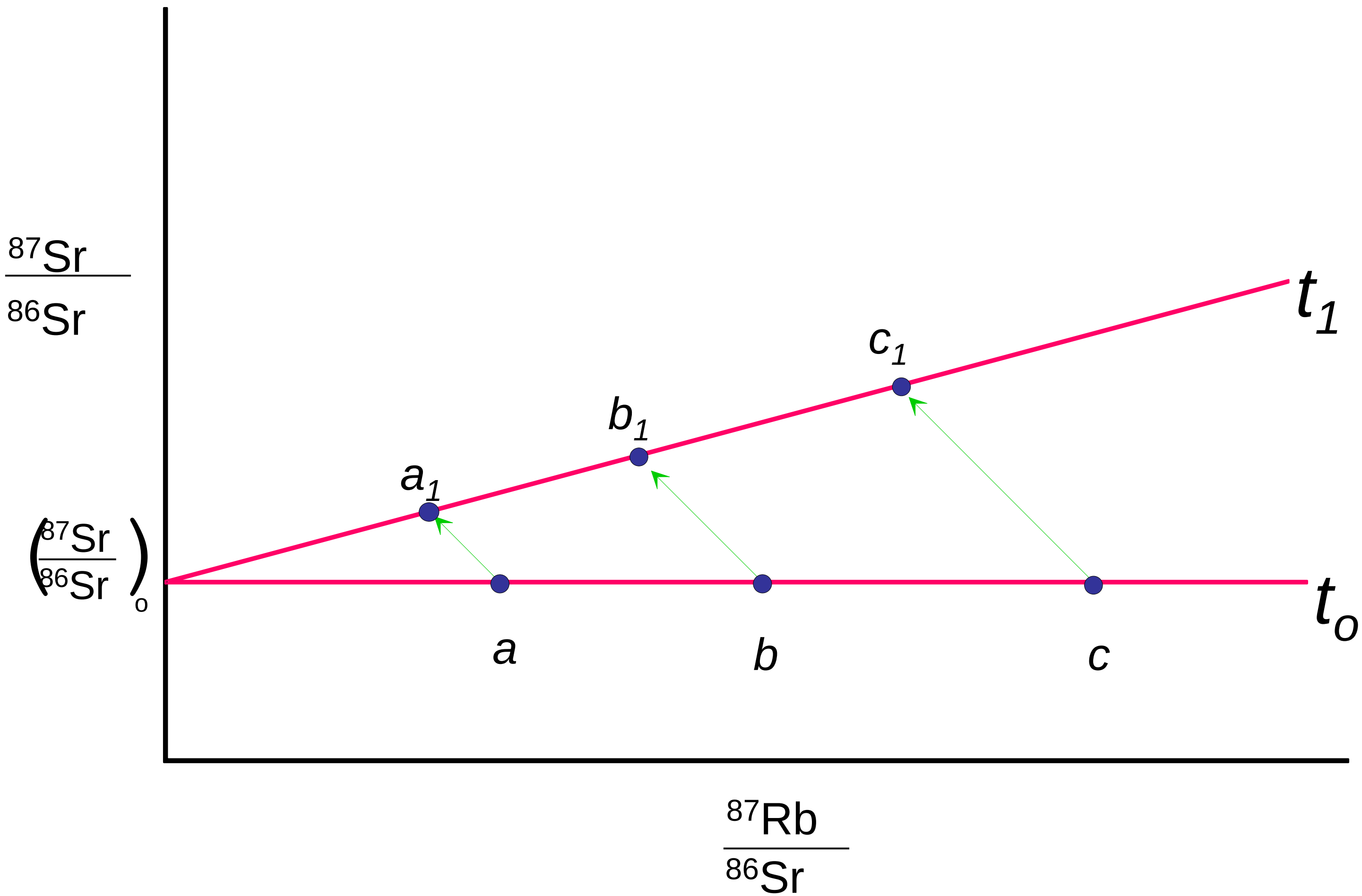
Begin with 3 rocks plotting at a, b, c at time t_o

They must have same value of initial $^{87}Sr/^{86}Sr$

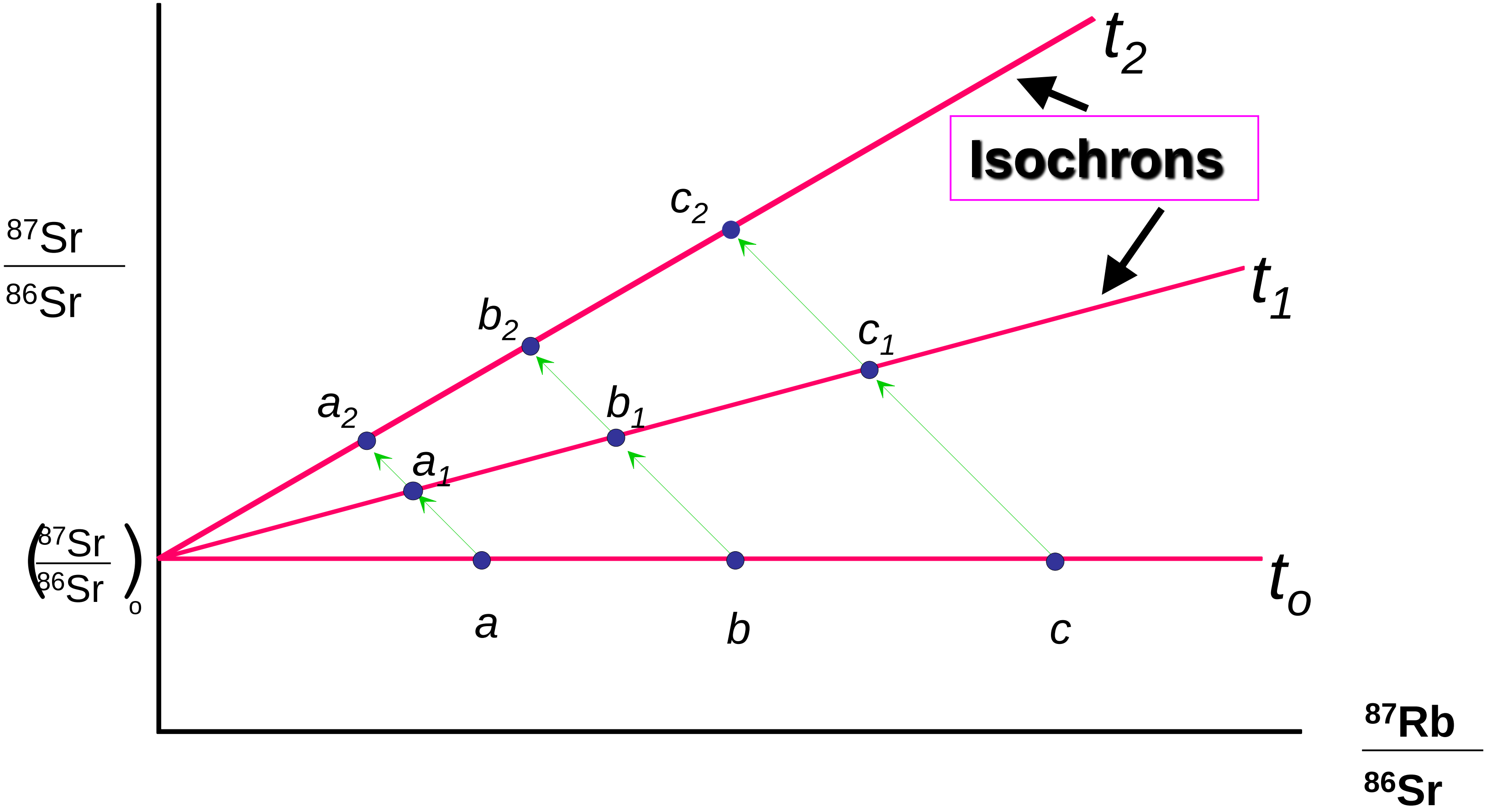
$(^{87}Sr/^{86}Sr)_o$ = value at time t_o



After some time increment ($t_0 \rightarrow t_1$) each sample loses some ^{87}Rb and gains an equivalent amount of ^{87}Sr (proportional to the amount of Rb present in the system)



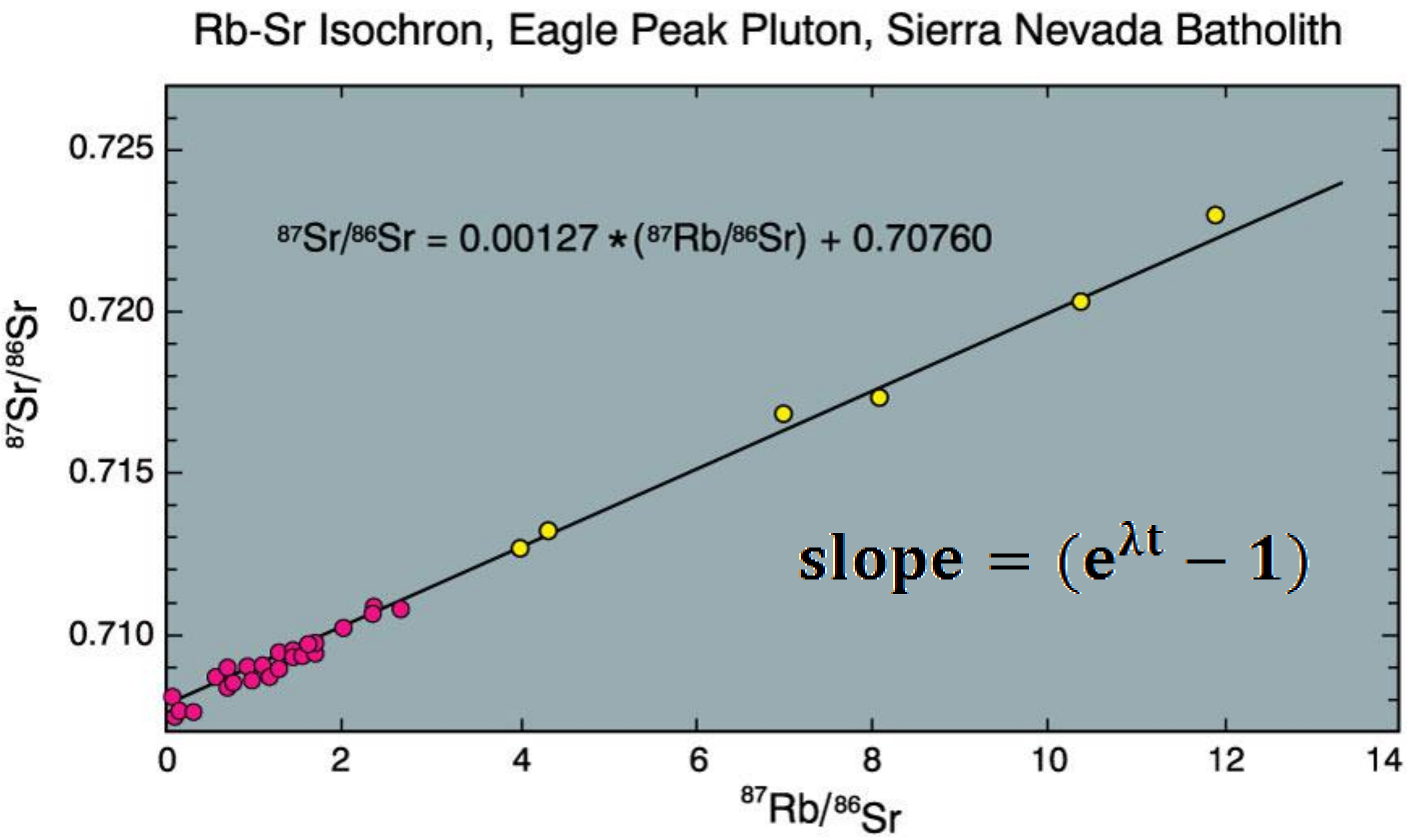
At time t_2 each rock system has evolved → new line. Again still linear and steeper line



All points on a single <u>isochron</u> line have same age.

Isochron technique produces 2 valuable things:

1. The **age** of the rocks (from the slope)
2. $(^{87}Sr/^{86}Sr)_o$ = the initial value of $^{87}Sr/^{86}Sr$, which we did not know beforehand



Rb-Sr isochron for the Eagle Peak Pluton, central Sierra Nevada Batholith, California, USA. Filled circles are whole-rock analyses, open circles are hornblende separates. The regression equation for the data is also given. After Hill et al. (1988). Amer. J. Sci., 288-A, 213-241.