ISOTOPES OF THE 'GEOCHRONOLOGICAL' ELEMENTS

Element	Z	Isotope	N	%	Notes
	원자번호	동위원소	중성자수	존재 함량	
Ar Argon	18	Ar-36	18	0.34	
		Ar-38	20	0.07	
		Ar-40	22	99.59	
K potassium	19	K-39	20	93.3	
		K-40	21	0.012	
		K-41	22	6.7	
Ca calcium	20	Ca-40	20	96.94	
		-42	22	0.65	
		-43	23	0.14	
		-44	24	2.08	
Rb rubidium	37	Rb-85	48	72.17	
		-87	50	27.83	
Sr strontium	38	Sr-84	46	0.56	
		-86	48	9.9	
		-87	49	7.0	
		-88	50	82.6	
Pb lead	82	Pb-204	122	1.4	
		-206	124	24.1	
		-207	125	22.1	
		-208	126	52.4	
Th Thorium	90	Th-232	142	100	
U Uranium	92	U-234	142	0.0055	
		-235	143	0.720	
		-238	146	99.28	

Element	Z	Isotope	N	%	Notes
Nd Neodymium	60	Nd-142	82	27.1	
		-143	83	12.2	
		-144	84	23.9	
		-145	85	8.3	
		-146	86	17.2	
		-148	88	5.7	
		-150	90	5.6	오래된 암석 연대 측정에 많이 사용
Sm Sm Sar um	62	Sm-144	82	3.1	
		-147	85	15.0	
		-148	86	11.2	
		-149	87	13.8	
		-150	88	7.4	
		-152	90	26.7	
		-154	92	22.8	오래된 암석연대 측정에 많이 사용
Lu Lutetium	71	Lu-175	104	97.4	
		-176	105	2.6	
Hf f Hafnium	72	Hf-174	102	0.18	
		-176	104	5.2	
		-177	105	18.5	
		-178	106	27.2	
		-179	107	13.8	
		-180	108	35.1	
Re Rhenium	75	Re-185	110	37.40	
		-187	112	62.60	
Os Osmium	76	Os-184	108	0.02	
		-186	110	1.6	
		-187	111	1.6	
		-188	112	13.3	
		-189	113	16.1	
		-190	114	26.4	
		-192	116	41.0	

xperimentally measured rates of decay of radioactive isotopes

$$\frac{dN}{dt} = -\lambda N$$ ...①

N : number of unchanged atoms at time t

λ : a constant characteristic of the decay of a given radioactive isotope (붕괴상수)
(Number of decayed atoms/atom/sec)

if N_o = number of atoms present when $t=0$

$$N = N_o \cdot e^{-\lambda t}$$ ...②

half-life $t_{\frac{1}{2}}$, $N = \frac{N_o}{2}$

$$\therefore \quad \frac{N_o}{2} = N_o \cdot e^{-\lambda \cdot t_{\frac{1}{2}}}$$

$$\frac{1}{2} = e^{-\lambda \cdot t_{\frac{1}{2}}} \quad or \quad t_{\frac{1}{2}} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$$ ...③

substitution

$N \rightarrow P$: Number of parent atoms currently present in a mineral
$N_o \rightarrow P_o$: Number of parent atoms originally present when the mineral formed

∴ Number of daughter atoms now present

$$D = P_o - P$$

$$\therefore \quad P_o = P + D$$

② → $P = (P+D) \cdot e^{-\lambda \cdot t}$ ...④

$D = P \cdot (e^{\lambda \cdot t} - 1)$ ☆☆☆ ...⑤ ☆ 꼭 기억!.

$$e^{\lambda \cdot t} = \frac{D}{P} + 1 = \frac{D+P}{P}$$

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

$\therefore \quad t = \frac{1}{\lambda} \ln\left(1 + \frac{D}{P}\right)$: time of formation(age) of the sample

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TABLE 2-4 Radioactive Systems Used in Geochronology

Parent/daughter	Type of decay	λ (yr^{-1})	Half-life (yr)	Effective range (yr) (T_0 = age of earth)	Isotopic abundance of parent and daughter	Typical materials dated
$^{238}U/^{206}Pb$	8 Alpha + 6 beta	1.55125×10^{-10}	4.468×10^9	10^7–T_0 (천만년 ~ 46억년)	0.9928 g/g U 0.252 g/g Pb	Zircon, uraninite, monazite, lead-bearing minerals
$^{235}U/^{207}Pb$	7 Alpha + 4 beta	9.8485×10^{-10}	0.7038×10^9	10^7–T_0	0.0072 g/g U 0.215 g/g Pb	Zircon, uraninite, monazite, lead-bearing minerals
$^{232}Th/^{208}Pb$	6 Alpha + 4 beta	4.9475×10^{-11}	14.010×10^9	10^7–T_0	1.00 g/g Th 0.520 g/g Pb	Zircon, uraninite, monazite, lead-bearing minerals
$^{87}Rb/^{87}Sr$	Beta	1.42×10^{-11}	48.8×10^9	10^7–T_0	0.278 g/g Rb 0.07 g/g Sr	Biotite, muscovite, microcline, whole rocks
$^{40}K/^{40}Ar$	Electron capture	0.581×10^{-10} 4.962×10^{-10}	1.250×10^9 (total)			
$^{40}K/^{40}Ca$	Beta			5,000–T_0	0.0001 g/g K 0.996 g/g Ar	Biotite, muscovite, hornblende, whole rocks
$^{147}Sm/^{143}Nd$	Alpha	0.654×10^{-11}	106×10^9	0–T_0	0.150 g/g Sm 0.122 g/g Nd	Feldspars, pyroxenes, amphiboles, whole rocks
$^{14}C/^{14}N$	Beta	1.209×10^{-4}	5,730	0–70,000	10^{-12} g/g C 0.996 g/g N	Charcoal, wood, peat

Note: Ages of rocks and other materials obtained by use of radioactive systems are expressed in three different forms: (1) descriptive (millions of years, etc.); (2) numerical notation (10^6 years, etc.); and (3) by use of Standard International (SI) units (Ma and Ga, which equal 10^6 and 10^9 years respectively).

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*문제에 atomic ratio인지,
weight ratio인지 확인할 것!

①

응용지구화학 : Isotope Geochemistry

XRF (X-ray Fluorescence)로 측정.

1. Following is Rb-Sr isotopic data for the Geita granites from the Tanzanian Shield of East Africa.

mass spectrometer로 측정

Samples	Rb(ppm)	Sr(ppm)	$^{87}Sr/^{86}Sr$ (atomic)
TAN 217	100	633	0.7197
218	303	163	0.9093
219	275	164	0.8919
221	90	620	0.7173
222	113	293	0.7441
224	75	197	0.7430

Calculate the initial $^{87}Sr/^{86}Sr$ ratio and the formation age of the granites from first regression.

2. 다음은 우리나라의 분천 화강편마암(경상북도 옥방-쌍전 부근)에 대한 $^{87}Rb/^{86}Sr$ 및 $^{87}Sr/^{86}Sr$ data이다. 이 화강편마암의 ($^{87}Sr/^{86}Sr$) 초생치와 그 연대를 계산하라.

Sample	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
BU-2	6.2010	0.88453
BU-4	3.9883	0.83378
BU-9	8.4053	0.94527
BU-12	6.8364	0.91097
BU-13	53.9891	2.22539
BU-14	24.0038	1.37149

3. Following is Rb-Sr isotopic data for whole rocks and mineral separates from a layered ultramafic-leucogabbro sequence in the Marcy anorthosite massif of the Adirondack highlands in northern New York State, U.S.A. Calculate the initial $^{87}Sr/^{86}Sr$ and the age of formation.

초염기성암.

Samples	Rb(ppm)	Sr(ppm)	$^{87}Sr/^{86}Sr$
SA-3D	0.505	22.96	0.70511
SA-3C	2.32	410.7	0.70448
SA-3A	5.79	610.2	0.70468
SA-5	5.50	532.7	0.70466
SA-5(plag.)	1.19	886.6	0.70434
SA-5(pyx.)	0.62	10.11	0.70661
SA-5(garnet)	12.69	128.8	0.70804

(end member)
plagioclase (사장석): albite $NaAlSi_3O_8$ … anorthite $CaAl_2Si_2O_6$) solid solution.

anorthite → anorthosite에 많이 들어있다.
↑ Ca-rich Ultramafic rock.

숙제: 1번/3번.

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②

☆

1. Follow the decay of parent ^{87}Rb and growth of daughter ^{87}Sr in a granite sample over the course of six half-lives. Assume that the granite initially contain 1.2×10^{20} atoms of ^{87}Rb and 0.3×10^{20} atoms of ^{87}Sr. The half-life of ^{87}Rb is 48.8 Ga, and the decay constant is 1.42×10^{-11}/yr. 6번!! 해석.

2. Using the following isotopic data for a whole-rock(WR) sample and for mineral separates of plagioclase(Pl), pyroxene(Px), and ilmenite(Il) from Apollo 12 lunar basalt, what is the age of this rock?

	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
WR	0.02960	0.70096
Pl	0.00537	0.69989
Px	0.04920	0.70200
Il	0.11270	0.70490

☆

3. Explain the growth of radiogenic ^{40}Ar* atoms in a K-bearing mineral as follows :

$$^{40}Ar^* = 0.104\ ^{40}K\ (e^{\lambda t} - 1)$$

solve the equation for t and determine the age of a biotite sample, for which the following data have been obtained :

$$K = 7.10\ \text{wt.\%},\ \text{and}\ ^{40}Ar = 1.5\times10^{12}\ \text{atoms/g.}$$

$$(\ \lambda = 5.543\times10^{-10}/\text{yr}\ \ \text{and}\ \ ^{40}K = 0.01167\%\ \text{of total K}\ )$$

숙제 ; 1번 /2번/3번.

○ Potassium-Argon System

Radioactive decay of $^{40}K \overset{decay}{\rightarrow}$ $^{40}Ca^*$(Ca : abundant) and $^{40}Ar^*$

└ (β decay) └ (electron capture)

Decay constant $\lambda_\beta = 4.962\times10^{-10}$ $\lambda_e = 0.581\times10^{-10}$

Total Decay Constant of ^{40}K, $\lambda = \lambda_\beta + \lambda_e$

$$\lambda_e = 0.581\times10^{-10}/yr$$

$$\lambda_\beta = 4.962\times10^{-10}/yr$$

$$\lambda = (0.581 + 4.962)\times10^{-10} = 5.543\times10^{-10}/yr$$

$$t_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{5.543\times10^{-10}} = 1.250\ Ga$$

^{40}K : mass spectrometer로 측정

^{40}K = 0.01167% of total K (XRF %)

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

$$^{40}Ar^* + {}^{40}Ca^* = {}^{40}K(e^{\lambda t} - 1)$$

branching ratio, $R = \frac{\lambda_e}{\lambda_\beta} = 0.117$

$^{40}K \rightarrow {}^{40}Ar^*$ $^{40}K \cdot \left(\frac{\lambda_e}{\lambda}\right)$

◎ Growth of radiogenic ^{40}Ar atoms in a K-bearing mineral

$$^{40}Ar^* = \frac{\lambda_e}{\lambda}\,{}^{40}K(e^{\lambda t} - 1)$$

Total ^{40}Ar atoms

$$(^{40}Ar)_m = {}^{40}_{i}Ar + {}^{40}Ar^*$$

(광물 形成時 $^{40}_{i}Ar = 0$)

$$\therefore {}^{40}Ar = {}^{40}Ar^*$$

$$t = \frac{1}{\lambda}\ln\left[\frac{^{40}Ar^*}{^{40}K}\left(\frac{\lambda}{\lambda_e}\right) + 1\right]$$

$$= \frac{1}{5.543\times10^{-10}}\ln\left[\frac{5.543}{0.581}\cdot\frac{^{40}Ar^*}{^{40}K} + 1\right]$$

$$t = 1.804\times10^9\ln\left(9.54\frac{^{40}Ar^*}{^{40}K} + 1\right)$$

K-feldspar
$KAlSi_3O_8$

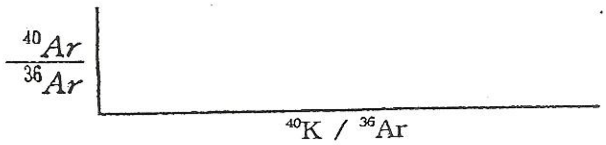
muscovite
$KAl_2(AlSi_3)O_{10}(OH)_2$

biotite
$K(Mg,Fe^{2+})_3(Al,Fe^{3+})Si_3O_{10}(OH)_2$

hornblende

K-Ar isochron

$$\frac{^{40}Ar}{^{36}Ar} = \left(\frac{^{40}Ar}{^{36}Ar}\right)_i + \left(\frac{\lambda_e}{\lambda}\right)\frac{^{40}K}{^{36}Ar}(e^{\lambda t} - 1)$$



③

K-Ar age dating

Problem 1) The analysis of a biotite yields the following results: K = 7.34 % (by weight) and $^{40}Ar = 24.5 \times 10^{-7}$ cm³/gr of sample (25°C and 1 atm). Assuming that all the ^{40}Ar is radiogenic, what is the age of the sample?

(Answer: 8.57 Ma)

Problem 2) Biotite from the Silver Point quartz monzonite of Idaho contains 8.45 % K_2O and 6.016×10^{-10} moles/g of radiogenic ^{40}Ar. Calculate a K-Ar age for this mineral.

(Answer: 48.78 Ma)

Problem 3) 강원도 영월군 상동읍 순경 Sn 광상에서 채취된 백운모의 K 함량이 7.94%, 그리고 $^{40}Ar^*$ 함량은 9.89×10^{-4} cm³/gr 이다. 이 백운모의 K-Ar 연대를 계산하라.

(Answer: 1,842 Ma)

Problem 4) A small pluton east of Chewelah in northeastern Washington contains biotite and hornblende.

	K_2O %	$^{40}Ar^*$ (moles/g)
Biotite	8.71	12.83×10^{-10}
Hornblende	1.44	4.348×10^{-10}

Calculate dates for both minerals and speculate regarding the age of this pluton assuming that it may have been reheated during a later phase of intrusive activity in the area.

숙제: 4번.

K–Ar dating

Problem 1) $K = 7.34\ \%$

$^{40}\text{Ar} = 24.5 \times 10^{-7}$ ㎤/gr

$24.5 \times 10^{-7}\ ^{40}\text{Ar}$ ㎤/gr

$$= 24.5 \times 10^{-7}\ ^{40}\text{Ar} \times \frac{39.9623/mole}{22.4\times 10^{3}/\text{mole}} \times \frac{1}{39.9623}$$

$= 1.0937 \times 10^{-10}$

$K = 7.34\ \%$

$$\frac{^{40}Ar}{^{40}K} = \frac{1.0937\times 10^{-10}}{\dfrac{7.34\times 10^{-2}\times 1.167\times 10^{-4}}{39.0983}}$$

$$= \frac{1.0937\times 10^{-10}\times 39.0983}{7.34\times 10^{-2}\times 1.167\times 10^{-4}}$$

$= 4.9921 \times 10^{-4}$

$$\therefore\ t = 1.804 \times 10^{9} \ln\left(9.54\frac{^{40}Ar^{*}}{^{40}K}+1\right)$$

$= 1.804 \times 10^{9} \ln(9.54 \times 4.9921 \times 10^{-4} +1)$

$= 1.804 \times 10^{9} \ln(1.004762)$

$= 1.804 \times 10^{9} \times 4.75069 \times 10^{-3}$

$= 8.57 \times 10^{6}$

$= 8.57$ Ma

Problem 2) $K_2O = 8.45\ \%$

$^{40}\text{Ar}^{*} = 6.016 \times 10^{-10}$ mole/gr

$$K = 8.45 \times \frac{39.0983\times 2}{39.0983\times 2 + 15.9994}$$

$$= 8.45 \times \frac{78.1966}{94.196}$$

$= 7.0147\ \%$

$$^{40}K = 7.0147 \times 10^{-2} \times \frac{0.1167\times 10^{-3}}{39.0983}$$

$= 2.0937 \times 10^{-7}$

$$^{40}Ar^{*} = 6.016 \times 10^{-10} \text{ mole/gr}$$

$$= \frac{\dfrac{6.016\times10^{-10} mole}{\dfrac{1}{39.9623/mole}}}{39.9623}$$

$$= 6.016 \times 10^{-10}$$

$$\therefore\ t = 1.804 \times 10^{9} \ln(9.54 \times \frac{6.016\times10^{-10}}{2.0937\times10^{-7}} + 1)$$

$$= 1.804 \times 10^{9} \ln(0.02741 + 1)$$

$$= 1.804 \times 10^{9} \times 0.02704$$

$$= 0.04878 \times 10^{9}$$

$$= 48.78 \text{ Ma}$$

Problem 3) $K = 7.94\ \%$

$$^{40}Ar = 9.89\times10^{-4}\ cm^{3}/gr$$

$$= 9.89 \times 10^{-4} \times \frac{\dfrac{1}{22.4\times10^{3}}}{\dfrac{1}{39.9623}} \times \frac{1}{39.9623}$$

$$= \frac{9.89\times39.9623\times10^{-4}}{22.4\times10^{3}\times39.9623}$$

$$= 4.4151\times10^{-8}$$

$$^{40}K = 7.94\times10^{-2}\times\left(\frac{0.1167\times10^{-3}}{39.0983}\right)$$

$$= (2.3699\times10^{-2})\times10^{-5}$$

$$= 2.3699\times10^{-7}$$

$$\therefore\ t = 1.804\times10^{9}\ln(9.54\times\frac{4.4151\times10^{-8}}{2.3699\times10^{-7}} + 1)$$

$$= 1.804\times10^{9}\ln(1.7772 + 1)$$

$$= 1.804\times10^{9}\times1.0214$$

$$= 1.842\times10^{9}\ yr$$

$$= 1842\ Ma$$

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○ Carbon-14 Method of Dating

연대가 오래되지 않을 경우에 powerful

$${}^{1}_{0}n + {}^{14}_{7}N \rightarrow {}^{14}_{6}C + {}^{1}_{1}H$$

└ Proton

└ stable ${}^{14}N$ 원자핵

└ cosmic-ray neutron

${}^{14}_{6}C \rightarrow CO_2$ molecule에 incorporated ${}^{14}CO_2$

* Decay of ${}^{14}C$

$${}^{14}_{6}C \rightarrow {}^{14}_{7}N + \beta^- + \bar{\nu} + Q$$

Q : 0.156 MeV

The radioactivity of a specimen of Carbon extracted from plant or animal tissue that died t years ago

$$A = A_0 \cdot e^{-\lambda t}$$

A : measured activity due to ${}^{14}C$ 단위 (disintegration / min / gr C) "dpm"

A_0 : activity of ${}^{14}C$ in the same specimen at the time the plant or animal were alive

$$\ln \frac{A}{A_0} = -\lambda t$$

$$\therefore t = \frac{1}{\lambda} \ln \frac{A_0}{A}$$

$$\therefore 5730 = \frac{1}{\lambda} \ln 2$$

$$\therefore \lambda = \frac{0.6931}{5730} = 1.209 \times 10^{-4}/yr$$

, $t = 8267 \ln \frac{A_0}{A}$

$$\therefore t = 19.035 \times 10^3 \log\left(\frac{A_0}{A}\right) \text{ yr}$$

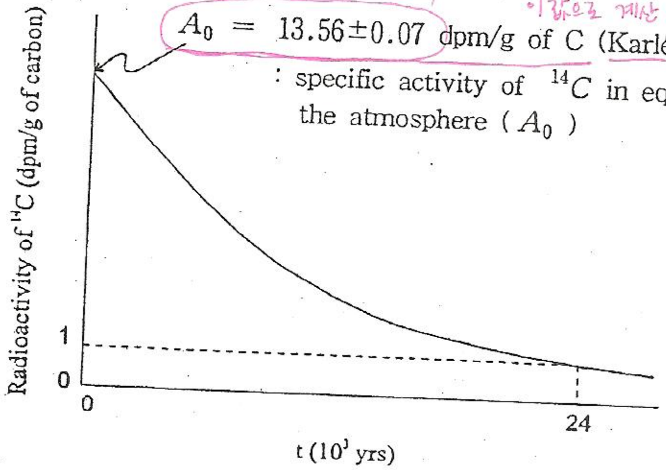
half life of ${}^{14}C$ = 5730 ± 40yr
(Godwin, 1962)

반감기가 매우 짧다.

$$A = A_0 \cdot e^{-\lambda t}$$

특별히 A_0 주어지지 않으면 이 값으로 계산!

A_0 = 13.56±0.07 dpm/g of C (Karlén et al., 1966)
: specific activity of ${}^{14}C$ in equilibrium with the atmosphere (A_0)



Decay of ${}^{14}C$ in plant or animal tissue that was initially in equilibrium with ${}^{14}CO_2$ molecules of the atmosphere or hydrosphere.

^{14}C dating 연습문제

1. The specific radiocarbon activity of a sample of wood is 6.25 dpm/g of carbon. The specific activity of the NBS oxalic acid standard is 14.27 dpm/g of carbon. What is the age of the wood sample, assuming that the half-life of ^{14}C is 5,730 years ?

   (Answer: 6,367 years)

2. The specific radiocarbon activity of a sample of wood from the seventeenth-century A.D. that was 310 years old in 1970 when it was analyzed, was found to be 15.09 dpm/g of carbon. What was the initial activity of ^{14}C in this sample and how does it differ from that of nineteenth-century wood ?

   (Answer: 15.67 dpm/g, higher by about 2 percent)

3. You have a piece of wood with a measured ^{14}C activity of 0.03 dpm/g. Assume that the concentration of ^{14}C in the atmosphere at the time that the wood grew was similar to the value found today of about 16 dpm/g. How old is the wood sample? Use ~~5,370~~ 5,730 years for the half-life of ^{14}C.

   (Answer: 52,000 years)

4) The measured activity of a sample of charcoal(C) found at an archaeological site is 5.30 dpm/gr. What is the age of the sample? Use 5730 years for the half-life of ^{14}C.

Growth of Radiogenic Daughters

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$$D^* = N_0 - N$$

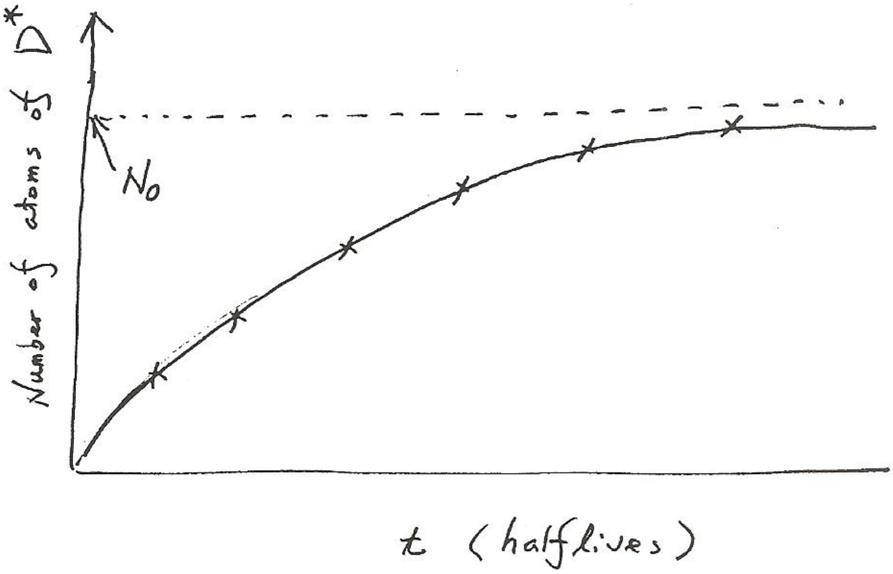
(Radiogenic daughter)

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

$$D^* = N_0 (1 - e^{-\lambda t})$$

$$\lim_{t \to \infty} (1 - e^{-\lambda t}) = 1$$

$$D^* \to N_0$$



$$D^* = N_0 - N$$

$$= \cancel{N_0 - N}$$

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

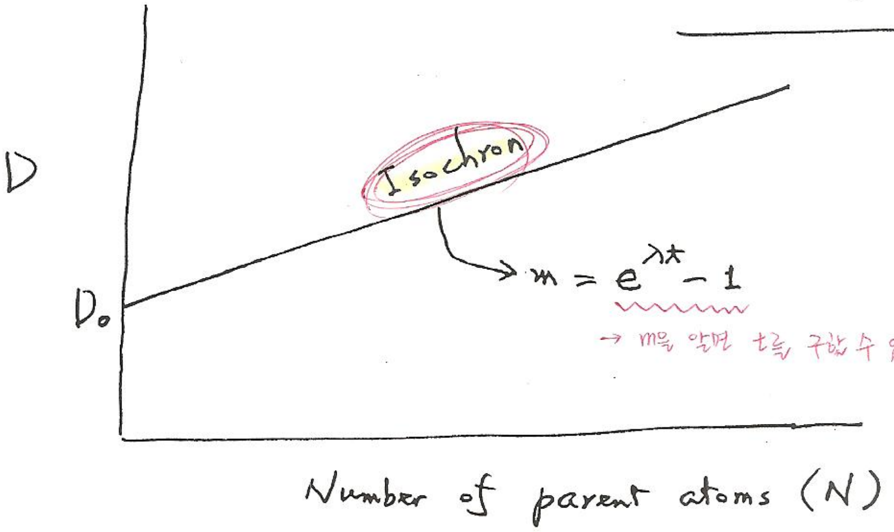
$$= N (e^{\lambda t} - 1)$$

mass spectrometer 이용.

$$\underset{\text{(measured)}}{D} = \underset{\text{(initial)}}{D_0} + \underset{\text{(radiogenic)}}{D^*}$$

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

$$\therefore t = \frac{1}{\lambda} \left(\frac{D_m - D_0}{N} + 1 \right)$$



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

→ m을 알면 t를 구할 수 있다.

*가정.

rock
mineral

오랜 시간 동안
전혀 변질이 없었다고 가정.

Rb - Sr System

Rb (rubidium) : Group IA (alkali metal) — (Li, Na, K, Rb, Cs,)

Rb^+ : 1.48 Å

K^+ : 1.33 Å (K-bearing minerals)

→ 2 isotopes $^{85}_{37}Rb$, $^{87}_{37}Rb$

(72,1654 %) (27,8346 %) — natural abundance

atomic wt. = 85.46776

$$\boxed{^{87}_{37}Rb \longrightarrow \, ^{87}_{38}Sr}$$ (emission of a negative β-particle)

Sr (strontium) : Group IIA : alkaline earth (Be, Mg, Ca, Sr, Ba, Ra)

Sr^{2+} (1.13 Å)

Ca^{2+} (0.99 Å) — (Ca-bearing minerals

pl, apatite, Ca-carbonates, aragonite)

사장석

$CaCO_3$

4 isotopes

가장 안정적

$^{88}_{38}Sr$	$^{87}_{38}Sr$	$^{86}_{38}Sr$	$^{84}_{38}Sr$
82.53 %	7.04 %	9.87 %	0.56 %

natural abundance

	Rb	K	Sr	Ca (ppm)
High-Ca granite	110	25,200	440	25,300
Low-Ca granite	170	42,000	100	5,100
Basaltic	30	8,300	465	76,000

$\begin{pmatrix} K^+ & Sr^{2+} \\ Si^{4+} & Al^{3+} \end{pmatrix}$

✓ $SrCO_3$ strontianite

✓ $SrSO_4$ celestite

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

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

$$\boxed{\begin{array}{l} ^{87}Sr^* = {}^{87}Rb\,(e^{\lambda t} - 1) \\ ^{87}Sr_m = {}^{87}Sr_0 + {}^{87}Sr^* \end{array}}$$

error를 줄이기위해.

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

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

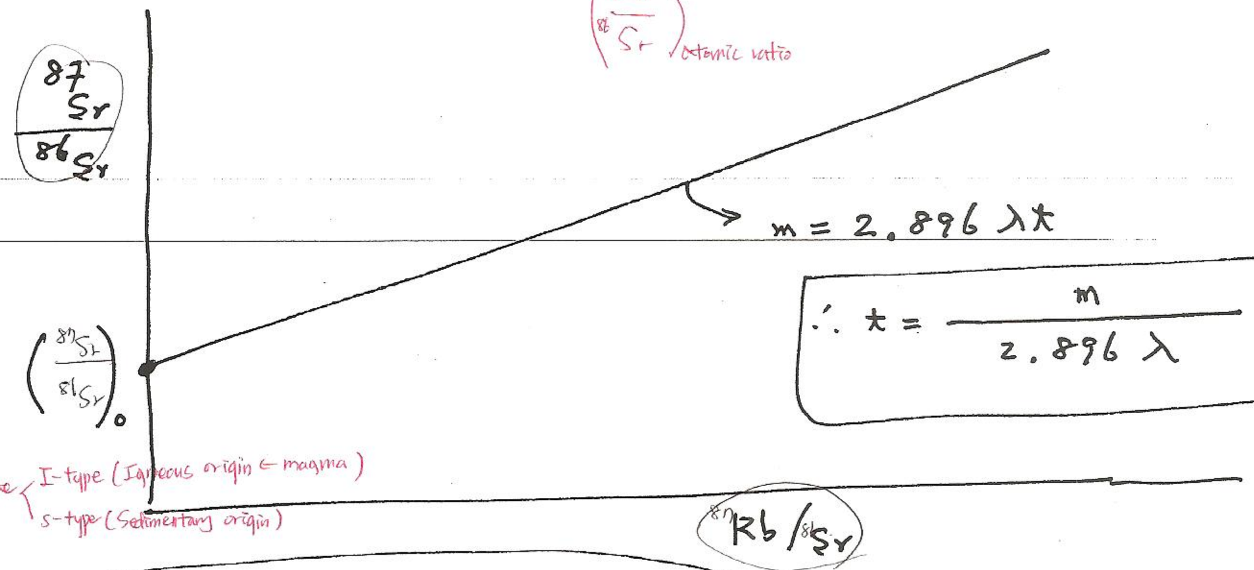
$\lambda = 1.42 \times 10^{-11}/yr$: very small

$$\left(e^{\lambda t} - 1 = (\lambda t + 1) - 1 = \lambda t \right)$$

$$\Rightarrow \frac{^{87}Sr}{^{86}Sr} = \left(\frac{^{87}Sr}{^{86}Sr}\right)_0 + \frac{^{87}Rb}{^{86}Sr} \cdot \lambda t$$

$$= (\quad)_0 + \underbrace{{}^*\boxed{2.896} \times \left(\overset{\text{weight ratio}}{\frac{Rb}{Sr}}\right)_c}_{\left(\frac{^{87}Rb}{^{86}Sr}\right)\text{ atomic ratio}} \lambda t$$

* 2.896



$m = 2.896\,\lambda t$

$$\boxed{\therefore\ t = \frac{m}{2.896\,\lambda}}$$

* Granite { I-type (Igneous origin ← magma)
s-type (Sedimentary origin)

↑ high (S-type)

$(\quad)_0 = 0.703 \pm 0.001$; magma of basaltic composition

↓ low (I-type)

암석의 성인을 다룰 때 중요한 값

; 화강암이 I-type / S-type인지 알려준다.

Ex) ① Liruel pluton, Nigeria :

$$\begin{cases} t = 167 \pm 2 \text{ Ma} \\ (\ \ )_0 = 0.729 \pm 0.009 \ ; \ \text{S-type} \end{cases}$$

② LL Chondrite :

(gkt,)

$$\begin{cases} t = 4.493 \pm 0.018 \text{ Ga} \\ (\ \ )_0 = 0.69893 \pm 0.00008 \ ; \ \text{I-type} \end{cases}$$

③ Olivine basalt Apollo 12, Ocean of Storms

$$\begin{cases} t = 3.36 \pm 0.10 \text{ Ga} \\ (\ \ )_0 = 0.69949 \pm 0.00005 \ ; \ \text{I-type} \end{cases}$$

$$\begin{cases} t = 4.34 \pm 0.15 \text{ Ga} \\ (\ \ )_0 = 0.699 \ ; \ \text{I-type} \end{cases}$$

$$\left(\frac{{}^{87}\text{Rb}}{{}^{86}\text{Sr}}\right)_{\text{atm}} = \left(\frac{\text{Rb}}{\text{Sr}}\right)_{\text{conc}} \times \frac{\text{Ab}\ {}^{87}\text{Rb} \times \overline{W}\text{Sr}}{\text{Ab}\ {}^{86}\text{Sr} \times \overline{W}\text{Rb}}$$

$$= (\ \ \ )_{\text{conc}} \times \frac{0.278346 \times 87.62}{0.0987 \times 85.46}$$

$$= (\ \ \ )_{\text{conc}} \times 2.89$$

Date . .

Table 8. The comparison of Sr isotope initial ratios between the Jurassic Granites and the Cretaceous Granites (Jin, 1981) in Korea

Surveyed area	Age by Rb-Sr	$(^{87}Sr/^{86}Sr)_o$
Jurassic Granites (142-206 Ma)	195 ~ 136 $\times 10^6$ yr	
1. Seoul Granites *(Park, 1972)*	160 ± 10 m.y.	0.712 (S-type)
2. Hwangdeung Granites Iri area *(Kim and Wendt, unpublished data)*	167 m.y.	0.7104
3. Jincheon Granites *(Choo, et al., 1979)*	194.1 ± 18.3 m.y.	0.7168 ± 0.0009
4. Cheongju Granites *(Choo, et al., 1979)*	146.3 ± 2.8 m.y.	0.7129 ± 0.0009
5. Andong Granites *(Choo, et al., 1979)*	172.3 ± 0.9 m.y.	0.7126 ± 0.0004
Cretaceous Granites (65~142 Ma)	136 ~ 65 $\times 10^6$ yr	
1. Masan Granites *(Kim and Wendt, unpublished data)*	70 ± 17 m.y.	0.704 ± 0.001
2. Gyeongsang Basin *(Hurley, et al., 1973)*	= 100 m.y.	= 0.705
3. Yucheon Granites *(Jin and Choo, 1980)*	75.5 ± 1.2 m.y.	0.7070 ± 0.0009
4. Changweon Granites	118.4 ± 7.3 m.y.	0.7058 ± 0.0004
5. Ilgwang Granites	125.0 ± 15.5 m.y.	0.7063 ± 0.0006

{ Sasaki, A. and Ishihara, S., 1979, Sulfur isotopic composition of the magnetite-series and ilmenite-series granitoids in Japan: Contrib. Mineral. Petrol., v. 68, p. 107-115

9/14

K - Ar System

K (Z = 19) — Group IA (alkali metal) ; 8th abundant element in earth's crust
(지각)

$^{39}_{19}K = 93.2581$ %

$^{40}_{19}K = 0.01167$

$^{41}_{19}K = 6.7302$

K atomic wt = 39.098304

$^{40}_{18}Ar = 99.60$ %

$^{38}_{18}Ar = 0.063$

$^{36}_{18}Ar = 0.337$

Ar = 39.9476

$$^{40}Ar / ^{36}Ar = 99.60 / 0.337 = 295.5$$

너무 큰 값. 빼버린다.

$$\boxed{^{40}Ar^* + {}^{40}Ca^* = {}^{40}K\,(e^{\lambda t} - 1)}$$

$$\lambda = \lambda_e + \lambda_\beta$$
$$= (0.581 + 4.962) \times 10^{-10} / yr$$
$$= 5.543 \times 10^{-10} / yr$$

$$\lambda_e / \lambda_\beta = 0.117 = R$$

$$t_{\frac{1}{2}} = \frac{\ln 2}{\lambda} = \frac{0.693}{5.543 \times 10^{-10}} = 1.250 \times 10^{9}\ yr$$

$$\boxed{^{40}Ar^* = {}^{40}K\,(e^{\lambda t} - 1)\,\frac{\lambda_e}{\lambda}}$$

$$\left(^{40}Ar = {}^{40}Ar_0 + {}^{40}Ar^* \right)$$

$$^{40}Ar = {}^{40}Ar_0 + {}^{40}Ar^*$$
$$^{40}Ar = 0 + {}^{40}Ar^*$$

"0"이다!

$$\boxed{t = \frac{1}{\lambda} \ln \left[\frac{^{40}Ar^*}{^{40}K} \left(\frac{\lambda}{\lambda_e} \right) + 1 \right]}$$

Ex) muscovite from a pegmatite in the Wisconsin Range, U.S.A.

$$\left(\begin{array}{l} K = 8.378\ \% \\ {}^{40}Ar^{*} = 0.3305\ \text{ppm} \end{array}\right.$$

K (atomic weight) = 39.098304

${}^{40}K$ = 0.0001167 of K

${}^{40}Ar$ (") = 39.9623

A (Avogadro's No.) = 6.022×10^{23} atoms/mol

$$\frac{{}^{40}Ar^{*}}{{}^{40}K} = \left(\frac{0.3305\times10^{-6}}{39.9623}\right)\times\left(\frac{39.098304}{8.378\times0.0001167\times10^{-2}}\right)\times\frac{A}{A}$$

number of atoms

$$= \frac{0.3305\times39.098304}{39.9623\times8.378\times0.0001167\times10^{4}}$$

$$= 0.03307$$

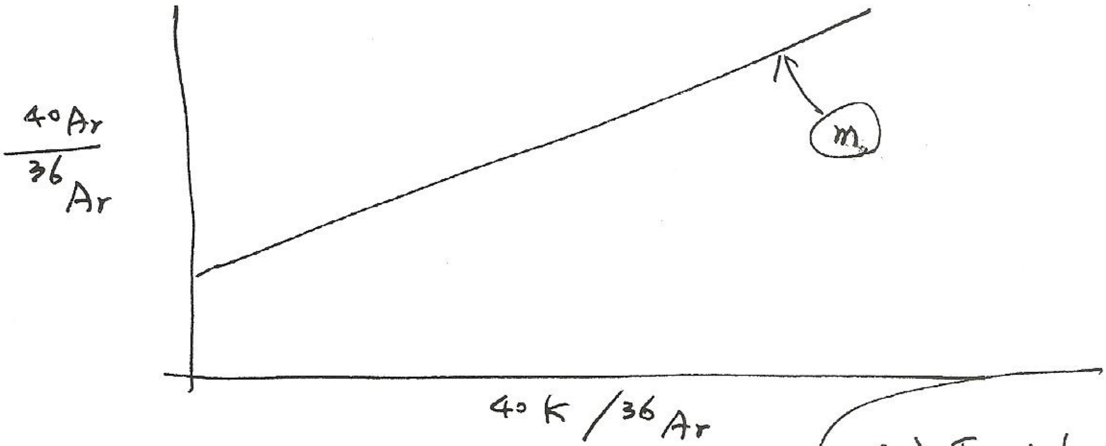
$$\therefore\ t = \frac{1}{5.543\times10^{-10}}\ln\left[\left(\frac{5.543\times10^{-10}}{0.581\times10^{-10}}\right)\times0.03307+1\right]$$

$$= 494.7\times10^{6}\ \text{yr}$$

$$= \underline{494.7\ \text{Ma}}$$

K-Ar isochrons

$$\frac{^{40}Ar}{^{36}Ar} = \left(\frac{^{40}Ar}{^{36}Ar}\right)_0 + \left(\frac{\lambda_e}{\lambda}\right)\frac{^{40}K}{^{36}Ar}\left(e^{\lambda t} - 1\right)$$



$$m = \left(\frac{\lambda_e}{\lambda}\right)\left(e^{\lambda t} - 1\right)$$

$$\therefore\ t = \frac{1}{\lambda}\ln\left[m\left(\frac{\lambda}{\lambda_e}\right) + 1\right]$$

ex) Ignimbrite,
~~Olda~~
Olduvai Gorge,
Tanzania

$t = 2.04 \pm 0.02$ Ma

$\alpha \rightarrow {}^{4}_{2}He$

Sm - Nd system

Samarium (Sm, $Z = 62$) }
Neodymium (Nd, $Z = 60$) } REEs (= rare earth elements)
희토류원소

$^{147}_{62}Sm$ (radioactive) $\xrightarrow{\alpha\text{-emission}}$ $^{143}_{60}Nd$ (stable) ← new inforation → ^{87}Sr

★ $t_{\frac{1}{2}} = 1.06 \times 10^{11}\,yr$ (very long)
$\lambda = 6.54 \times 10^{-12}/yr$

($Nd^{+3} = 1.08\,\text{Å}$
$Sm^{+3} = 1.04\,\text{Å}$)

REEs : generally +3
(La ($Z = 57$) 1.15 Å
~
Lu ($Z = 71$) 0.93 Å)
란타늄 (La), 루테튬 (Lu)

(Nd : 144.24
Sm : 150.36) atomic wt.

→ high in
- bastnaesite ($CeFCO_3$)
- monazite ($CePO_4$)
- cerite [$(Ca, Mg)_2 (Ce)_8 (SiO_4)_7 \cdot 3H_2O$]
- rock-forming silicates

(light REEs (Ce group) — Nd, Sm (LREE)
heavy REEs (Gd group) (HREE))

(Sm < Nd
(lower abundance))

	Sm	Nd	Sm/Nd	
Granite	8.22	43.5	0.188	
Gabbro	1.78	7.53	0.236	
Kimberlite	8.08	66.1	0.122	← ultramafic
Andesite	3.90	20.6	0.185	
Rhyolite	4.65	21.6	0.215	
Shale	10.4	49.8	0.209	
Sandstone	8.93	39.4	0.227	
Limestone	2.03	8.75	0.232	

$$\boxed{\frac{^{143}Nd}{^{144}Nd} = \left(\frac{^{143}Nd}{^{144}Nd}\right)_i + \frac{^{147}Sm}{^{144}Nd}\left(e^{\lambda t}-1\right)} \text{ ——— } ①$$

$$\underset{\text{(atomic ratio)}}{\frac{^{147}Sm}{^{144}Nd}} = \underset{\uparrow \text{ ppm 단위}}{\left(\frac{Sm}{Nd}\right)_c} \times \boxed{0.602}$$

$$\therefore \boxed{\frac{^{143}Nd}{^{144}Nd} = \left(\frac{^{143}Nd}{^{144}Nd}\right)_i + 0.602\left(\frac{Sm}{Nd}\right)_c \lambda t}$$

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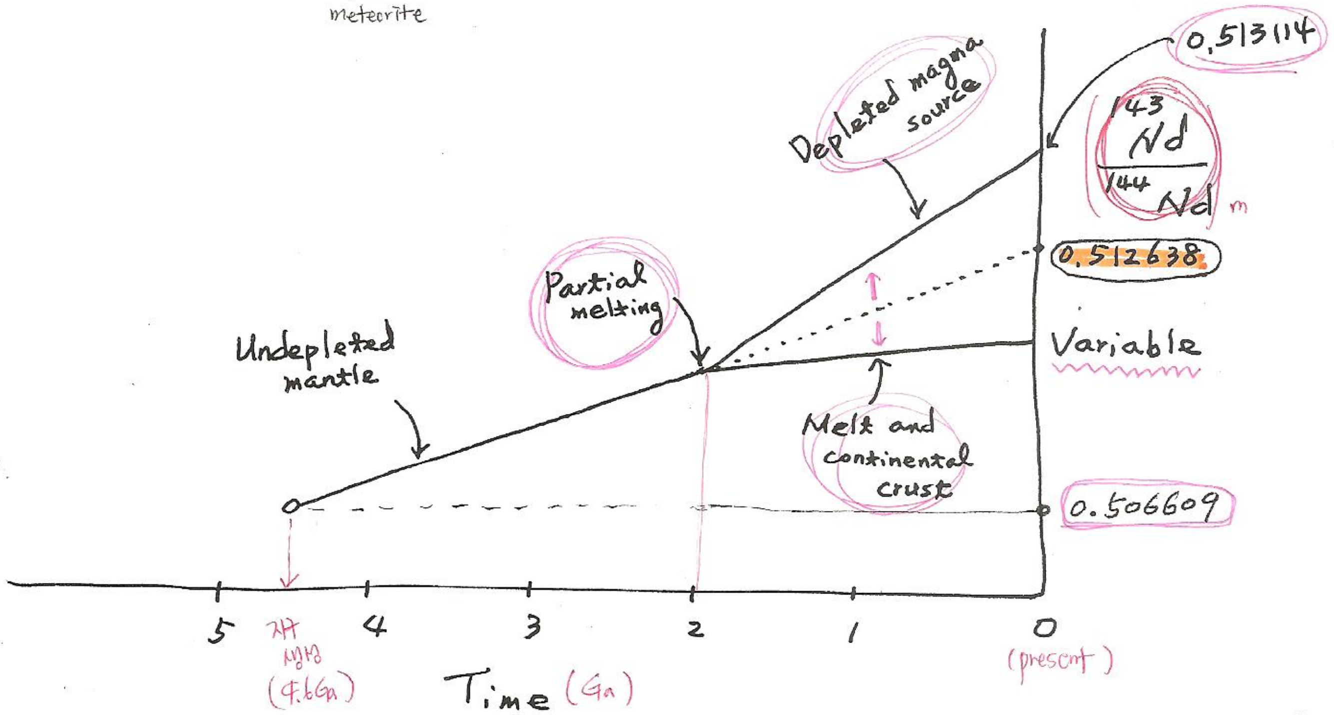
Global geochemistry of Sm and Nd

CHUR (chondritic uniform reservoir)

↑ meteorite



(Effect of partial melting in the mantle of the Earth on the isotropic evolution of Nd in the rocks of the resulting continental crust and in the residual (melt-depleted) mantle.

* 시간 t (지구 생성)에서 initial ratio 구하기.

① →

$$\underset{\text{present}}{\left(\frac{^{143}Nd}{^{144}Nd}\right)^{0}_{CHUR}} = \underline{\left(\frac{^{143}Nd}{^{144}Nd}\right)^{t}_{CHUR}} + \left(\frac{^{147}Sm}{^{144}Nd}\right)^{0}_{CHUR}\left(e^{\lambda t}-1\right)$$

(시간 t 에서의 initial ratio)

③

$$\left(\frac{{}^{143}Nd}{{}^{144}Nd}\right)^{t}_{CHUR} = \underbrace{\left(\frac{{}^{143}Nd}{{}^{144}Nd}\right)^{0}_{CHUR}}_{\text{현재 ratio.}} - \underbrace{\left(\frac{{}^{147}Sm}{{}^{144}Nd}\right)^{0}_{CHUR}}_{\text{이미 나와있는 값}} \left(e^{\overset{\text{정해져 있음}}{\lambda}\underset{\text{지구 나이}}{t}} - 1\right)$$

$$= 0.512638 - 0.1967\left(e^{0.02943} - 1\right)$$

$$= 0.506609 \quad \Longleftarrow \left(t = 4.\underset{6}{5} \times 10^{9}\ yrs\right)$$

* 실제 암석 t 구하기.

$$\underset{\text{시간 t에서 initial ratio.}}{\left(\frac{{}^{143}Nd}{{}^{144}Nd}\right)^{t}_{Rock}} = \left(\quad\right)^{0}_{Rock} - \left(\frac{{}^{147}Sm}{{}^{144}Nd}\right)^{0}_{Rock}\left(e^{\lambda t} - 1\right)$$

$$\left(since\ \boxed{\left(\quad\right)^{t}_{Rock} = \left(\quad\right)^{t}_{CHUR}}\right)$$ ☆☆

~~[illegible]~~

식 2개를 같다고 놓으면

↓

$$\left(\left(\quad\right)^{0}_{CHUR} - \left(\frac{{}^{147}Sm}{{}^{144}Nd}\right)^{0}_{CHUR}\left(e^{\lambda t} - 1\right) = \left(\quad\right)^{0}_{Rock} - \left(\frac{{}^{147}Sm}{{}^{144}Nd}\right)^{0}_{Rock}\left(e^{\lambda t} - 1\right)\right)$$

$$\rightarrow \left(e^{\lambda t} - 1\right)\left[\left(\frac{{}^{147}Sm}{{}^{144}Nd}\right)^{0}_{Rock} - \left(\frac{{}^{147}Sm}{{}^{144}Nd}\right)^{0}_{CHUR}\right] = \left(\frac{{}^{143}Nd}{{}^{144}Nd}\right)^{0}_{Rock} - \left(\frac{{}^{143}Nd}{{}^{144}Nd}\right)^{0}_{CHUR}$$

present

$$e^{\lambda t} - 1 = \frac{\left({}^{143}Nd/{}^{144}Nd\right)^{0}_{Rock} - \left({}^{143}Nd/{}^{144}Nd\right)^{0}_{CHUR}}{\left({}^{147}Sm/{}^{144}Nd\right)^{0}_{Rock} - \left({}^{147}Sm/{}^{144}Nd\right)^{0}_{CHUR}}$$

$$\boxed{t = \frac{1}{\lambda}\ln\left[\frac{\left({}^{143}Nd/{}^{144}Nd\right)^{0}_{Rock} - 0.512638}{\left({}^{147}Sm/{}^{144}Nd\right)^{0}_{Rock} - 0.1967} + 1\right]}$$

운석의 값.
(정해져있는 상수)

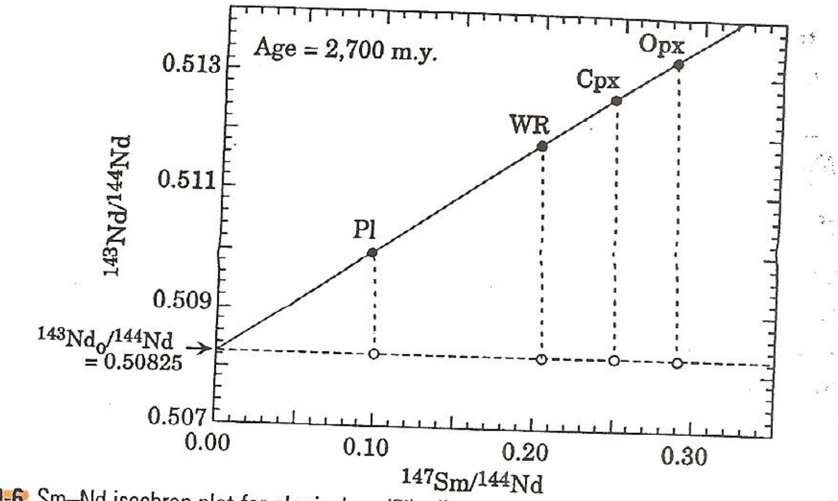


FIGURE 10-6 Sm–Nd isochron plot for plagioclase (Pl), clinopyroxene (Cpx), orthopyroxene (Opx), and the whole rock (WR) for the Stillwater complex gabbro. (From DePaolo and Wasserburg, 1979.)

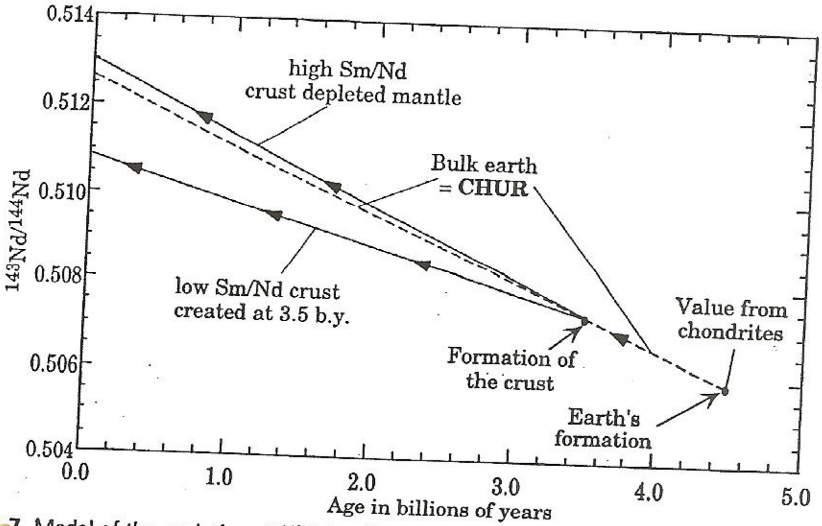


FIGURE 10-7 Model of the evolution of ^{143}Nd to ^{144}Nd in rocks formed from a chondritic uniform reservoir (CHUR) that partially melted at 3.5 b.y., producing reservoirs of ^{147}Sm depleted crust and ^{147}Sm enriched mantle.

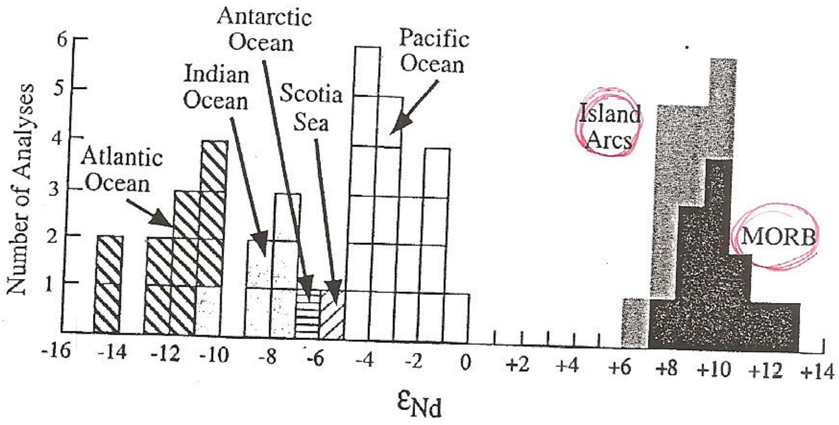


FIG. 14.15. The neodymium isotopic compositions of seawater and ferromagnesian nodules from different oceans, expressed as ε_{Nd}. Boxes represent individual analyses. These compositions are distinct from each other and from oceanic volcanic rocks. (After Piepgras et al. 1979.)

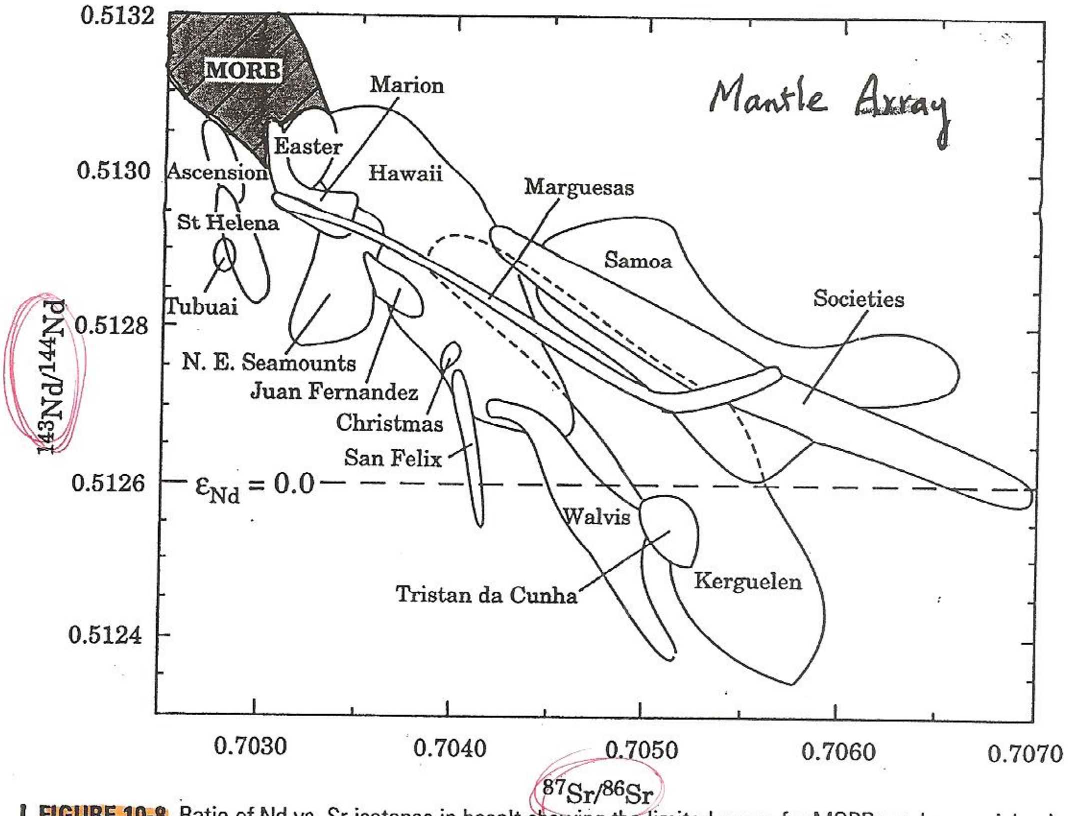


FIGURE 10-8 Ratio of Nd vs. Sr isotopes in basalt showing the limited range for MORBs and ocean island basalts. (From Hart et al., 1986.)

두가지 연대측정법을 사용해 data plot.
→ 전체적인 경향이 ↘ 을 나타냄.

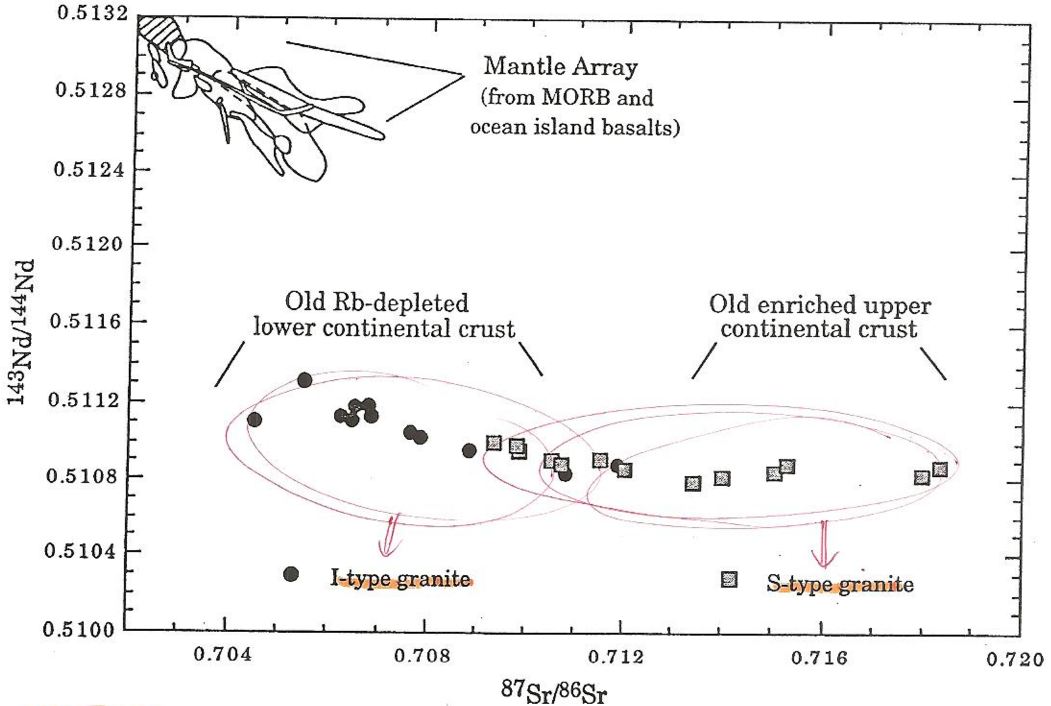


FIGURE 10-9 Expanded view of Nd and Sr isotopic ratios given in Figure 10-7 so that ratios from Paleozoic granitic batholiths from southeastern Australia are plotted. (From McCulloch and Chappell, 1982.)

Sm – Nd system

$$ {}^{143}Nd_m = {}^{143}Nd_i + {}^{147}Sm\,(e^{\lambda t} - 1) $$

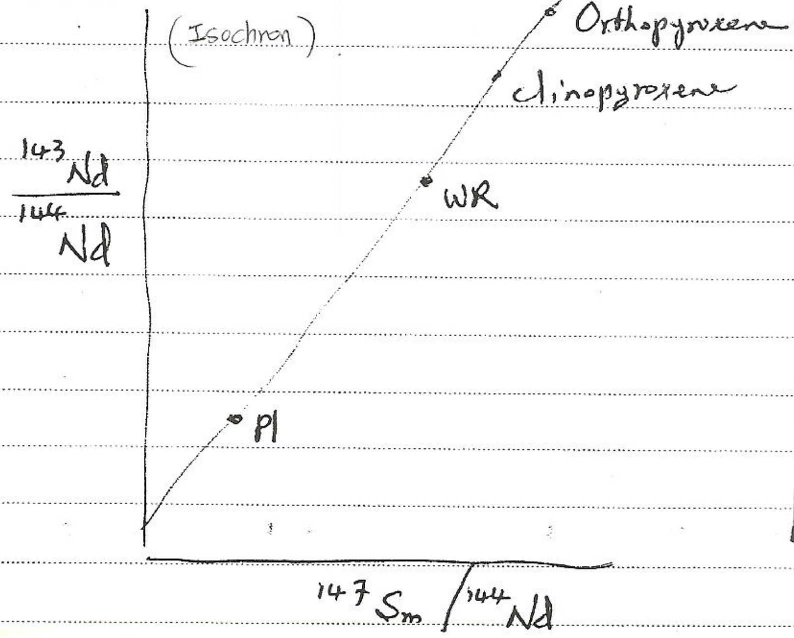
$$ \left(\begin{aligned} \lambda &= 0.654 \times 10^{-11}/yr \\ t_{\frac{1}{2}} &= 1.06 \times 10^{11}\ yr \end{aligned} \right. $$

$$ \left(\frac{{}^{143}Nd}{{}^{144}Nd}\right)_m = \left(\frac{{}^{143}Nd}{{}^{144}Nd}\right)_i + \left(\frac{{}^{147}Sm}{{}^{144}Nd}\right)(e^{\lambda t} - 1) $$

ppm ratio → atomic ratio.

$$ \frac{{}^{147}Sm}{{}^{144}Nd} = \left(\frac{Sm}{Nd}\right) \times \boxed{0.60} $$

concentration (in ppm)



CHUR

$({}^{143}Nd/{}^{144}Nd)_{\text{today chondrite}} \doteqdot \boxed{0.512638}$ ← evolution

$(\ \ "\ \ )_{\text{initial chondrite (46억)}} \doteqdot \boxed{0.506609} \pm 8$

primordial ratio
(초생)

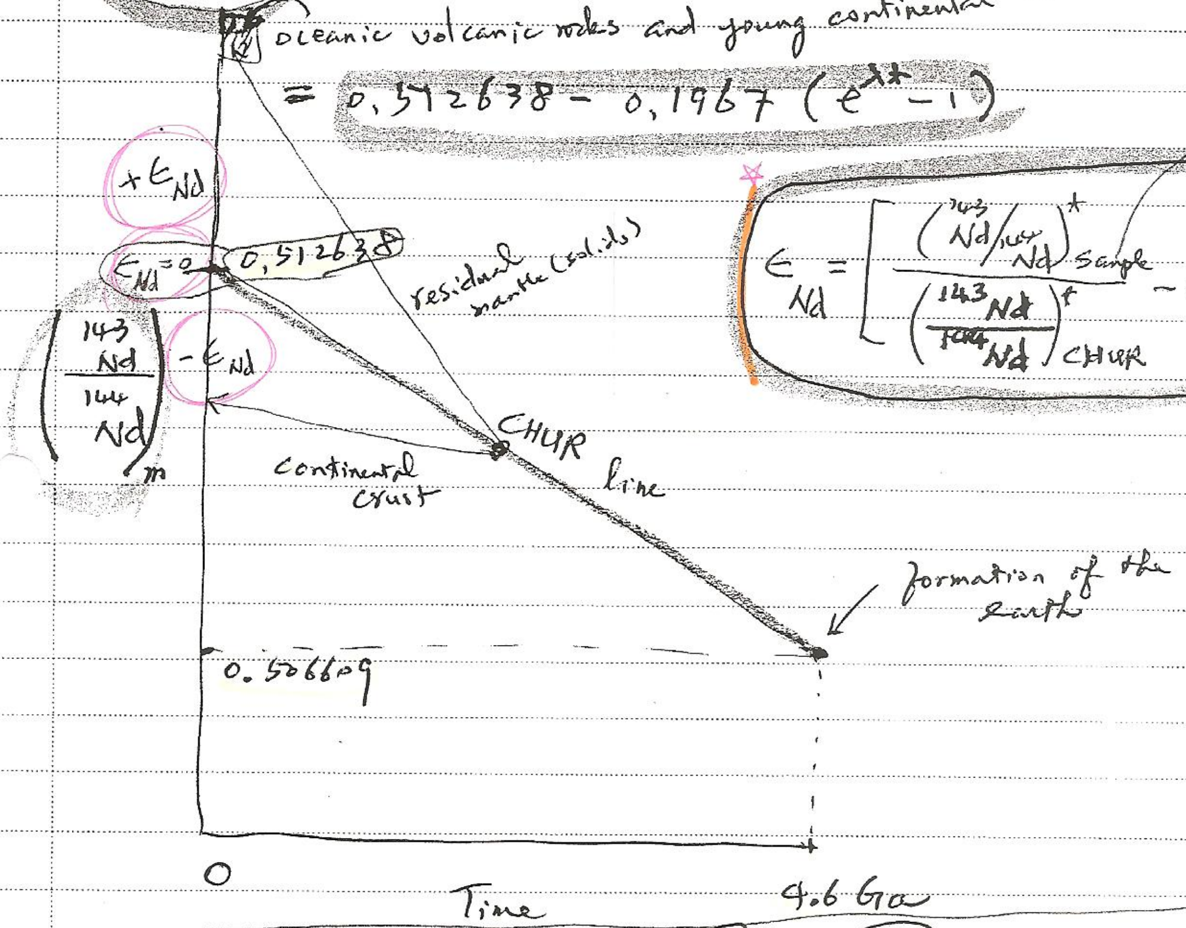
$({}^{147}Sm/{}^{144}Nd) = \boxed{0.1967}$

* ϵ_{Nd}

$$\left(\frac{^{143}Nd}{^{144}Nd}\right)_i = \left(\quad\right)_m - \left(\frac{^{147}Sm}{^{144}Nd}\right)\left(e^{\lambda t} - 1\right)$$

oceanic volcanic rocks and young continental crust rocks

$$= 0.512638 - 0.1967\left(e^{\lambda t} - 1\right)$$



$$\epsilon_{Nd} = \left[\frac{\left(^{143}Nd/^{144}Nd\right)^t_{sample}}{\left(\frac{^{143}Nd}{^{144}Nd}\right)^t_{CHUR}} - 1\right] \times 10^4$$

Rock

* Lunar basalt (Ga)

	Age (Ga) Sm/Nd	Rb/Sr	K/Ar
10062	3.88 ±0.06	3.93 ±0.11	3.82 ±0.06
10072	3.57 ±0.03	3.56 ±0.05	3.57 ±0.04

← 중간에 변질을 받지 않았다.

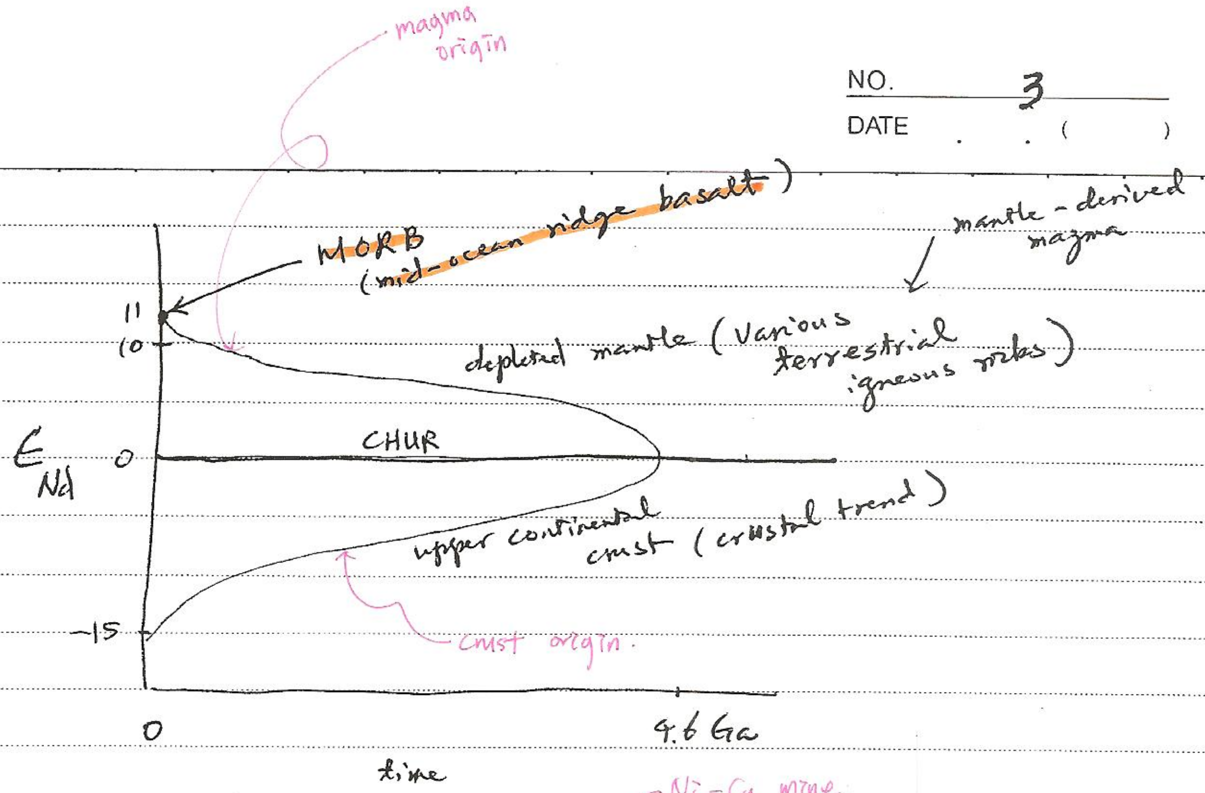
newly formed magma : lower Sm/Nd

이온반경 큼 magma에 농축

CHUR (= Chondritic Uniform Reservoir) : model

(De Paelo & Wasserburg, 1976)

(terrestrial Nd는 uniform reservoir (Sm/Nd ratio가 chondritic meteorite와 동일한)로부터 진화



Ni-Cu mine.

ex) rocks from the Sudbury Igneous Complex

$$\left(\begin{array}{l} \epsilon_{Nd} = \boxed{-7.54} \pm 1.1 \\ t = 1,840 \pm 21 \text{ Ma} \end{array} \right\} \rightarrow \text{crustal trend}$$

* ~~Epsilon parameter~~

$$\left({}^{143}Nd/{}^{144}Nd\right)_m = (\quad\quad)_i + \left(\frac{{}^{147}Sm}{{}^{144}Nd}\right)\left(e^{\lambda t} - 1\right)$$

$$0.512638 = 0.506609 + 0.1967\left(e^{\lambda t} - 1\right)$$

$$0.1967\left(e^{\lambda t} - 1\right) = 0.006029$$

$$e^{\lambda t} = 1 + 0.030650 = 1.030650$$

$$\lambda t \ln e = \ln 1.030650$$

$$t = \frac{0.030189}{0.654 \times 10^{-11}} = 0.046160 \times 10^{11}$$

$= $ [illegible] $\times 10^{9} = 4.616$ Ga

숙제 : 다음주 수업일 (9/23)

Sm-Nd system.

blem 1)

A pigeonite basalt (12039, 19) from the Moon collected by the astronauts of Apollo 12 yielded the following results (Nyquist et al. 1979);

Sample	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$
whole rock	0.2090	0.513142
plagioclase	0.1727	0.512365
pyroxene	0.2434	0.513861

a. Calculate a date by means of least-squares regression of these data (Equations 8.12 and 8.13, Chapter 8).

b. Calculate the initial $^{143}Nd/^{144}Nd$ ratio of this rock and express it as an epsilon value relative to CHUR.

not atomic ratio.

c. Estimate the Sm/Nd ratio of the source rocks in the interior of the Moon, assuming that its primordial $^{143}Nd/^{144}Nd$ ratio was 0.506609 and that its age is 4.6×10^9 y. (**Answer:** $t = 3.20 \times 10^9$ y, initial $^{143}Nd/^{144}Nd = 0.508707$, $\epsilon^t_{CHUR} = +4.50$, Sm/Nd $\simeq$ ~~0.380~~).

0.327

em 2)

Balsaltic rocks from the greenstone belts of Zimbabwe have yielded the following analytical results (Hamilton et al., 1977).

No	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$
1	0.2088	0.512868
2	0.2151	0.512872
3	0.2267	0.513101
4	0.1485	0.511785
5	0.1710	0.512104
6	0.1675	0.512183
7	0.2036	0.512796
8	0.1873	0.512426
9	0.1196	0.511221
10	0.1222	0.511352

a. Plot these data and fit an isochron by least-squares regression.

b. Calculate the age and initial $^{143}Nd/^{144}Nd$ ratio.

c. Recalculate the initial $^{143}Nd/^{144}Nd$ ratio as an ϵ value relative to CHUR at the indicated time. (**Answer:** $t = 2.62 \times 10^9$ y, initial $^{143}Nd/^{144}Nd = 0.50920$, $\epsilon^t_{CHUR} =$ ~~1.77~~).

− 0.78

lem 3) Given are the following analytical results for minerals separated from 3 samples of an igneous rock

Mineral	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$
plagioclase 1	0,0909	0.5109
〃 2	0,0868	0.5109
〃 3	0,0780	0.5108
pyroxene 1	0,1460	0.5116
〃 2	0,1524	0.5118
〃 3	0.1716	0.5120

1) Calculate the time of crystallization and initial $^{143}Nd/^{144}Nd$ ratio for the rock ($t = 1.986$ Ga).

2) Calculate an ϵ value relative to CHUR for the time of crystallization. Assume the CHUR value at the time of crystallization was 0.5110 for $^{143}Nd/^{144}Nd$

3) What does the ϵ value tell you about the source of the magma responsible for the rock? (crustal origin)

$$\boxed{\epsilon_{Nd} = -24.4}$$

Problems

(Use normalization to $^{146}Nd/^{144}Nd = 0.7219$, row 2, Table 12.4).

1 Calculate the $^{147}Sm/^{144}Nd$ ratio of a rock containing 1.83 ppm Sm and 5.51 ppm Nd. Use isotopic abundances from Figure 12.2. The atomic weight of Sm is 150.4 and that of Nd is 144.24. (**Answer:** $^{147}Sm/^{144}Nd = 0.200$).

2 What is the average time-integrated Sm/Nd ratio of a magma source whose present $^{143}Nd/^{144}Nd$ ratio is 0.51300? Assume that $t = 4.60 \times 10^9$ y and that the initial $^{143}Nd/^{144}Nd$ ratio of the source was 0.50684 (**Answer:** Sm/Nd = 0.389).

3 Calculate the $^{143}Nd/^{144}Nd$ ratio of CHUR at a time 2.5×10^9 y ago given that $I^0_{\mathrm{CHUR}} = 0.512638$ and that $(^{147}Sm/^{144}Nd)^0_{\mathrm{CHUR}} = 0.1967$ (**Answer:** $I^t_{\mathrm{CHUR}} = 0.509395$).

4 Calculate the value of the epsilon parameter for $^{143}Nd/^{144}Nd = 0.51150$ for $t = 1.8 \times 10^9$ y (**Answer:** $\epsilon^t_{\mathrm{CHUR}} = +23.35$).

5 Calculate a model date relative to CHUR for a rock given the following data: Sm = 0.580 ppm, Nd = 1.539 ppm, $^{143}Nd/^{144}Nd = 0.513101$ (**Answer:** $t = 2.33 \times 10^9$ y).

$^{40}Ar^*/^{39}Ar$ method

$$\left(\underset{\text{parent}}{^{39}Ar} \longrightarrow \underset{\text{daughter}}{^{40}Ar^*}\right)$$

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$$^{40}Ar^* = \frac{\lambda_e}{\lambda}\,{}^{40}K\,(e^{\lambda t}-1)$$

$$^{40}Ar^* = J\cdot{}^{39}Ar\,(e^{\lambda t}-1)$$

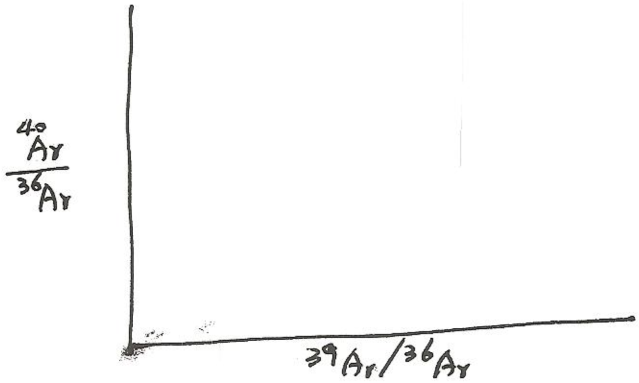
$$\left(J = \frac{e^{\lambda t_m}-1}{(^{40}Ar^*/^{39}Ar)_m}\right)$$

t_m: known age of the flux monitor

$(^{40}Ar^*/^{39}Ar)_m$: measured value of this ratio in the mornitor

$$t = \frac{1}{\lambda}\ln\left(\frac{^{40}Ar^*}{^{39}Ar}J+1\right)$$

$$\frac{^{40}Ar}{^{36}Ar} = J\cdot\frac{^{39}Ar}{^{36}Ar}\,(e^{\lambda t}-1)$$



K - Ca method

$$\left(\underset{\text{parent}}{^{40}K} \rightarrow \underset{\text{daughter}}{^{40}Ca^*}\right)$$

$$\lambda = \lambda_e + \lambda_\beta$$

$\lambda_e = 0.581\times10^{-10}/yr$ (decay to ^{40}Ar)

$\lambda_\beta = 4.962\times10^{-10}/yr$ (decay to ^{40}Ca)

$\therefore\ \lambda = 5.543\times10^{-10}/yr$

$$\left(\frac{^{40}Ca}{^{42}Ca}\right)_m = \left(\frac{^{40}Ca}{^{42}Ca}\right)_i + \left(\frac{\lambda_\beta}{\lambda}\right)\frac{^{40}K}{^{42}Ca}\,(e^{\lambda t}-1)$$

$$\therefore\ (\text{기울기}) = \frac{\lambda_\beta}{\lambda}(e^{\lambda t}-1)$$

Lu - Hf method

	ion charge
Lutetium ($Z=71$)	$+3$
Hafnium ($Z=72$)	$+4$

산성암 in granite Lu = 1.43 ppm, Hf = 5.08 ppm Lu/Hf = 0.28

염기성암 in peridotite Lu = 0.039 ppm, Hf = 1.14 ppm Lu/Hf = 0.034

$$\left(^{176}Lu \longrightarrow {}^{176}Hf^*\right)^*$$

$$\lambda = (1.94\pm0.07)\times10^{-11}/yr$$

$$\frac{^{176}Hf}{^{177}Hf} = \left(\frac{^{176}Hf}{^{177}Hf}\right)_i + \frac{^{176}Lu}{^{177}Hf}\left(e^{\lambda t} - 1\right)$$

안정동위원소.

$$\frac{^{176}Lu}{^{177}Hf} = \left(\frac{Lu}{Hf}\right)_c \times 0.142$$

$\boxed{\text{Re} - \text{Os method}}$

Re : Rhenium ($Z = 75$) ⟶ Similar to Mo ($Z = 42$)

Os : Osmium ($Z = 76$)

Platinum Group Elements (PGEs) :

- Ru (ruthenium)
- Rh (rhodium)
- Pd (palladium)
- Os (osmium)
- Ir (iridium)
- Pt (platinum)

siderophile elements (친철원소)

0.71 Å

Re^{4+} (0.71 Å) — Mo^{4+} (0.68 Å) in molybdenite (MoS_2)

Cu^{2+} (0.69 Å)

$$^{187}Re : \lambda = (1.64 \pm 0.05) \times 10^{-11}/yr \Rightarrow \boxed{1.666 \times 10^{-11}/yr}$$

$$t_{\frac{1}{2}} = (4.23 \pm 0.13) \times 10^{10}\ yr$$

$$^{187}_{75}Re \longrightarrow {}^{187}_{76}Os^*$$

$$\boxed{\frac{^{187}Os}{^{188}Os} = \left(\frac{^{187}Os}{^{188}Os}\right)_i + \frac{^{187}Re}{^{188}Os}\left(e^{\lambda t} - 1\right)}$$

$$\frac{^{187}Re}{^{188}Os} = \left(\frac{Re}{Os}\right)_c \times \frac{1}{0.2078}$$

μg/g/mole.

mole/g

in molybdenite (MoS_2)

$$^{187}Os^* = {}^{187}Re\left(e^{\lambda t} - 1\right)$$

$$t = \frac{1}{\lambda}\ln\left(\frac{^{187}Os^*}{^{187}Re} + 1\right)$$

$$\frac{\mu g/g \times g}{g/mole}$$

62.6% (natural abundance)

mass

Ex) Re = 55.2 ppm, ^{187}Os = 0.98 ppm (in molybdenite from Godthaab, Greenland)

Denmark 땅.

$$^{187}Re = \frac{55.2 \times 0.626 \times 186.955}{186.207} = 34.69\ \mu g/g$$

atomic wt.

$$\therefore t = \frac{1}{1.666 \times 10^{-11}}\ln\left(\frac{0.98}{34.69} + 1\right) = 1.67\ Ga$$

$^{187}Re - ^{187}Os$ Isochron

$$^{187}Os^{*} = ^{187}Re\,(e^{\lambda t} - 1)$$

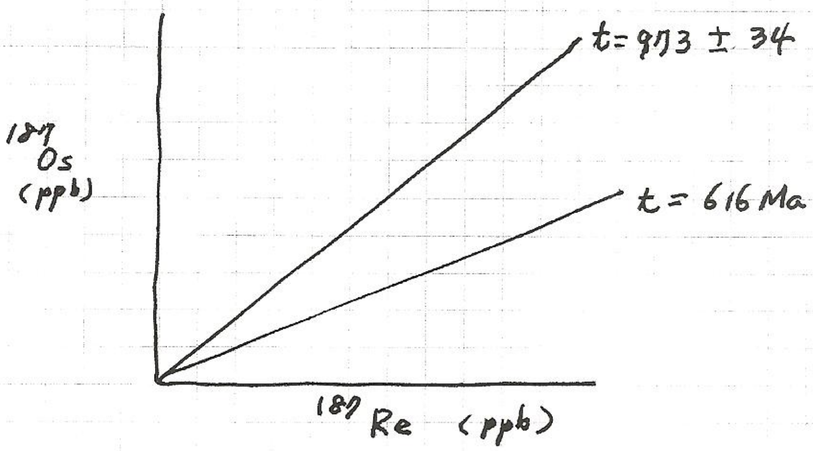
Ex) pyrite (FeS_2) & chalcopyrite ($CuFeS_2$) in Au-bearing quartz veins at Harnäs in SW Sweden

(2000) Stein et al., : Re (< 1-5 ppb) $^{187}Os^{*}$ (0.005 - 0.074 ppb)

Os (0.002 - 0.017 ppb)

Isochron age : 973 ± 34 Ma ($\lambda = 1.666 \times 10^{-11}$/yr)

one sample of pyrite in quartz vein ; t = 616 Ma (late)



(9/30)

La-Ce Method

$(^{138}La \rightarrow ^{138}Ce$ & $^{138}Ba)$ β-decay

La (lanthanum, Z = 57) 1.15 Å, +3

Ce (cerium, Z = 58) 1.11 Å, +3, +4

→ similar to Sm, Nd, Lu (lutetium)

$$\boxed{\frac{^{138}Ce}{^{142}Ce} = \left(\frac{^{138}Ce}{^{142}Ce}\right)_i + \frac{\lambda_\beta}{\lambda}\,\frac{^{138}La}{^{142}Ce}\,(e^{\lambda t} - 1)}$$

$\lambda = \lambda_\beta + \lambda_e$

$= 2.33 \times 10^{-12} + 4.42 \times 10^{-12}$/yr

$= 6.75 \times 10^{-12}$/yr

$t_{\frac{1}{2}} = (1.03 \pm 0.10) \times 10^{11}$ yr

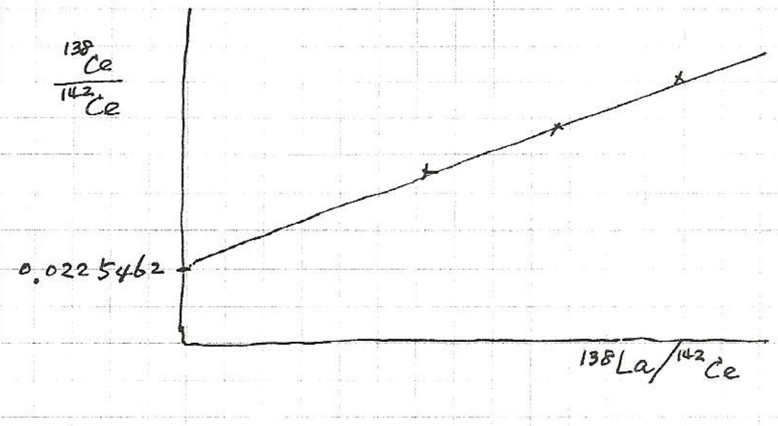
Ex) Bushveld Complex (화성 변성암 복합체), South Africa (gabbro (반려암.) sample)

$\left(\frac{La}{Ce}\right) \times 0.00819 = \left(\frac{^{138}La}{^{142}Ce}\right)$, $\frac{^{138}Ce}{^{142}Ce} = 0.0002874$

concentration ratio, atomic ratio

$\longrightarrow m = 0.0062779$, $(\quad)_i = 0.0225462$

$$\frac{\lambda_\beta}{\lambda}(e^{\lambda t} - 1) = 0.0062779 \implies t = 2.67 \pm 0.53 \text{ Ga}$$



Ex 2) Lewisian gneiss, Scotland

t = 3.04 ± 0.50 Ga

*우리나라 경기 massif.

; gneiss. ~~shist~~ schist

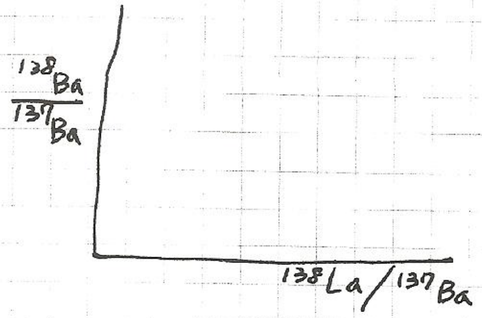
영남.

→ 25억년 정도 (2.5 Ga)

La – Ba method

$$^{138}_{57}La \rightarrow {}^{138}_{56}Ba \qquad \left(\begin{array}{lll} Ba & +2, & 1.35\,Å \\ La & +3, & 1.15\,Å \end{array} \right.$$

$$\frac{^{138}Ba}{^{137}Ba} = \left(\frac{^{138}Ba}{^{137}Ba}\right)_i + \frac{\lambda_e}{\lambda}\,\frac{^{138}La}{^{137}Ba}\left(e^{\lambda t}-1\right)$$



$$\lambda_e = 4.42\times10^{-12}/yr$$
$$\lambda = 6.75\times10^{-12}/yr$$

$$\left(\frac{^{138}La}{^{137}Ba}\right) = \boxed{0.007923}\times\left(\frac{La}{Ba}\right)_c$$

Ex) Amitsoq gneiss, Greenland : t = 2419 ± 24 Ma

↖ Denmark. 2.4 Ga.

U – Th – Pb system

① $^{238}U \xrightarrow[\lambda_1]{decay} {}^{206}Pb$ $\quad ^{206}Pb/\underset{\text{Stable.}}{^{204}Pb} = (\quad)_i + {}^{238}U/^{204}Pb\,(e^{\lambda_1 t}-1)$ ——— ①

② $^{235}U \xrightarrow[\lambda_2]{} {}^{207}Pb$ $\quad ^{207}Pb/^{204}Pb = (\quad)_i + {}^{235}U/^{204}Pb\,(e^{\lambda_2 t}-1)$ ——— ②

③ $^{232}Th \xrightarrow[\lambda_3]{} {}^{208}Pb$ $\quad ^{208}Pb/^{204}Pb = (\quad)_i + {}^{232}Th/^{204}Pb\,(e^{\lambda_3 t}-1)$ ——— ③

② ÷ ①

Pb-Pb dating

$$\frac{\overset{y}{\boxed{^{207}Pb/^{204}Pb}} - \left(\frac{^{207}Pb}{^{204}Pb}\right)_i}{\underset{x}{\boxed{^{206}Pb/^{204}Pb}} - \left(\frac{^{206}Pb}{^{204}Pb}\right)_i} = \frac{\overset{\cancel{238}}{^{235}U}\left(e^{\lambda_2 t}-1\right)}{^{238}U\left(e^{\lambda_1 t}-1\right)} \qquad ——— ④$$

$$y - \left(\frac{^{207}Pb}{^{204}Pb}\right)_i = \left[x - \left(\frac{^{206}Pb}{^{204}Pb}\right)_i\right]\cdot\frac{^{235}U\left(e^{\lambda_2 t}-1\right)}{^{238}U\left(e^{\lambda_1 t}-1\right)}$$

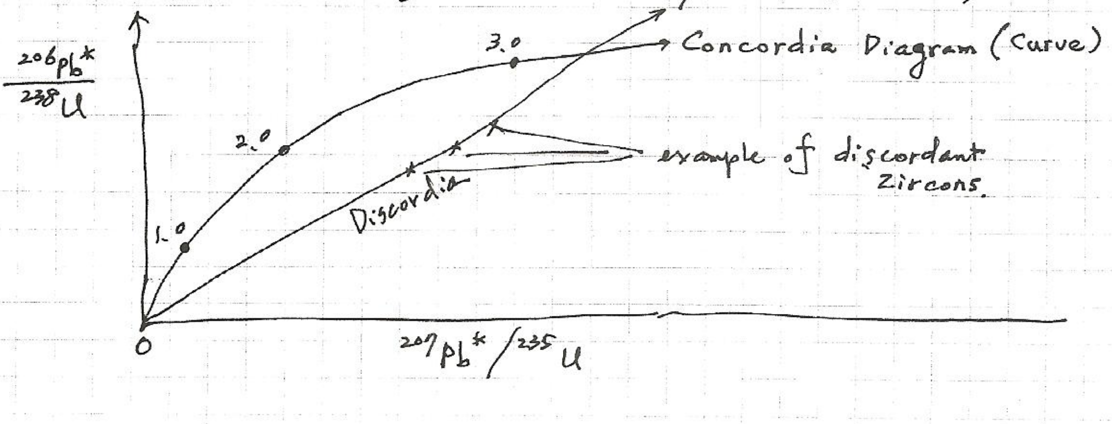
$$y = \boxed{\frac{^{235}U\left(e^{\lambda_2 t}-1\right)}{^{238}U\left(e^{\lambda_1 t}-1\right)}}\,x + \left(\frac{^{207}Pb}{^{204}Pb}\right)_i - \left(\frac{^{206}Pb}{^{204}Pb}\right)_i \underset{\underset{\text{기울기.}}{m}}{\boxed{\frac{^{235}U\left(e^{\lambda_2 t}-1\right)}{^{238}U\left(e^{\lambda_1 t}-1\right)}}}$$

$$m = \left(\frac{^{207}Pb}{^{206}Pb}\right)^* = \frac{\left(\frac{^{207}Pb}{^{204}Pb}\right) - (\quad)_i}{\left(\frac{^{206}Pb}{^{204}Pb}\right) - (\quad)_i} = \boxed{\left(\frac{^{207}Pb^*}{^{206}Pb^*}\right)}^{*}$$

$*\ D = P(e^{\lambda t}-1)$에 의해

$$^{207}Pb^* = {}^{235}U(e^{\lambda_2 t}-1)$$
$$^{206}Pb^* = {}^{238}U(e^{\lambda_1 t}-1)$$

$$\left\{ \begin{array}{lll} ^{206}Pb^* = {}^{238}U\left(e^{\lambda_1 t}-1\right) & \longrightarrow & ^{206}Pb^*/^{238}U = \left(e^{\lambda_1 t}-1\right) \\ ^{207}Pb^* = {}^{235}U\left(e^{\lambda_2 t}-1\right) & \longrightarrow & ^{207}Pb^*/^{235}U = \left(e^{\lambda_2 t}-1\right) \end{array} \right.$$



$$\begin{cases} e^{\lambda_1 t}-1 = \dfrac{^{206}Pb^*}{^{238}U} = \dfrac{\left(^{206}Pb/^{204}Pb\right)-\left(^{206}Pb/^{204}Pb\right)_i}{^{238}U/^{204}Pb} \\ e^{\lambda_2 t}-1 = \dfrac{^{207}Pb^*}{^{235}U} \end{cases}$$

Concordia Diagram : calculation of $^{206}Pb^*/^{238}U$ and $^{207}Pb^*/^{235}U$ ratios of U-Pb system

ex) Zircon
Monazite
apatite etc

Radiogenic Pb.

* common Pb ; Pb in a mineral in which no significant Pb^* has been produced since the mineral formed.

ex) galena (PbS), K-feldspar ($KAlSi_3O_8$), micas.

$$\left(\text{Common Pb}\right) = \underbrace{\left(\text{Primeval Pb}\right)}_{\uparrow\ \text{지구형성시 존재}} + \underbrace{\left(\text{Radiogenic Pb}\right)}_{\uparrow\ \text{U, Th decay}}$$

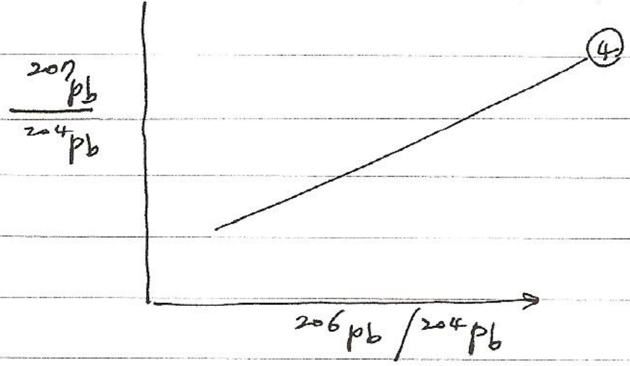
$$\begin{cases} \left(^{206}Pb/^{204}Pb\right)_t = \left(^{206}Pb/^{204}Pb\right)_T + \left(^{238}U/^{204}Pb\right)_{present}\left(e^{\lambda_{238}T}-e^{\lambda_{238}t}\right) & \text{— ①} \\ \left(^{207}Pb/^{204}Pb\right)_t = \left(^{207}Pb/^{204}Pb\right)_T + \left(^{235}U/^{204}Pb\right)_{present}\left(e^{\lambda_{235}T}-e^{\lambda_{235}t}\right) & \text{— ②} \\ \left(^{208}Pb/^{204}Pb\right)_t = \left(^{208}Pb/^{204}Pb\right)_T + \left(^{232}Th/^{204}Pb\right)_{present}\left(e^{\lambda_{232}T}-e^{\lambda_{232}t}\right) & \text{— ③} \end{cases}$$

(T : the time the Earth formed (= age of the Earth)
t : a later time

② / ① ⟹

$$\frac{\overbrace{\left(^{207}Pb/^{204}Pb\right)_t}^{y} - \overbrace{\left(^{207}Pb/^{204}Pb\right)_T}^{b_0}}{\underbrace{\left(^{206}Pb/^{204}Pb\right)_t}_{x} - \underbrace{\left(^{206}Pb/^{204}Pb\right)_T}_{a_0}} = \underbrace{\overbrace{\left(\frac{^{235}U}{^{238}U}\right)_{present}}^{\frac{1}{137.88}\ \text{(정해져있음)}} \left(\frac{e^{\lambda_{235}T}-e^{\lambda_{235}t}}{e^{\lambda_{238}T}-e^{\lambda_{238}t}}\right)}_{A} \quad \text{— ④}$$

$$\therefore \boxed{y = b_0 + \underbrace{\textcircled{A}}_{\text{slope of the isochron}}(x-a_0)} \Longrightarrow \text{직선}$$



$$\frac{(^{207}Pb/^{204}Pb)_{present} - (^{207}Pb/^{204}Pb)_T}{(^{206}Pb/^{204}Pb)_{present} - (^{206}Pb/^{204}Pb)_T} = \left(\frac{^{235}U}{^{238}U}\right)_{present} \cdot \left(\frac{e^{\lambda_{235}T}-1}{e^{\lambda_{238}T}-1}\right) \quad — ⑤$$

The initial (primeval) composition ; troilite (FeS) in Fe meteorite (U, Th ; negligib

$$\begin{cases} (^{207}Pb/^{204}Pb)_T = 10.29 \\ (^{206}Pb/^{204}Pb)_T = 9.31 \end{cases}$$

$$\therefore \frac{\underbrace{(^{207}Pb/^{204}Pb)_{present}}_{\Rightarrow y} - 10.29}{\underbrace{(^{206}Pb/^{204}Pb)_{present}}_{\Downarrow x} - 9.31} = \underbrace{\frac{1}{137.88}\left(\frac{e^{\lambda_{235}T}-1}{e^{\lambda_{238}T}-1}\right)}_{\Downarrow}$$

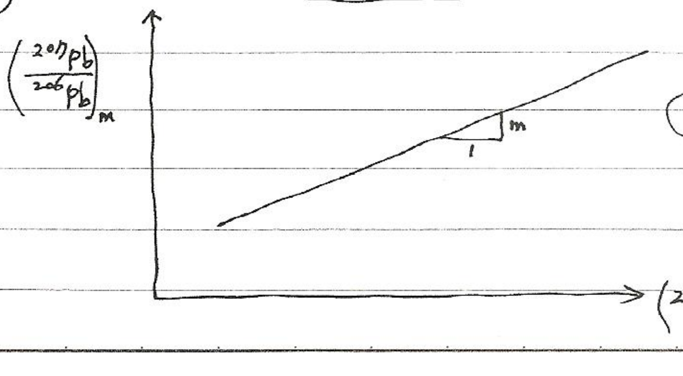
slope (즉 지구의 나이 T = ?)

$$\begin{cases} \lambda_{235} = 9.8485 \times 10^{-10}/yr \quad (\lambda_2) \\ \lambda_{238} = 1.55125 \times 10^{-10}/yr \quad (\lambda_1) \end{cases}$$

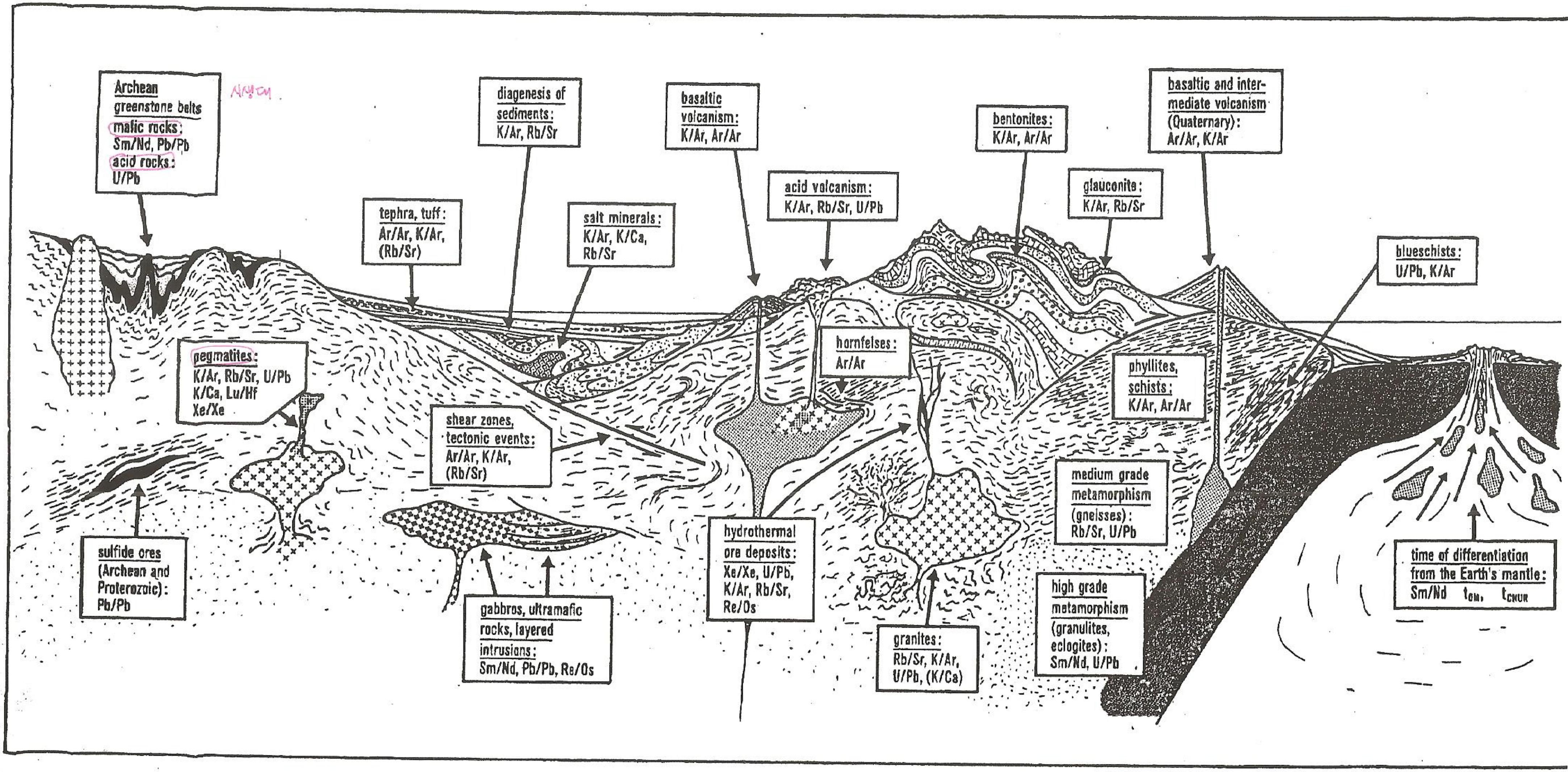
$$\text{slope}, m = \left(\frac{^{207}Pb^*}{^{206}Pb^*}\right) = \frac{1}{137.88}\left(\frac{e^{\lambda_{235}T}-1}{e^{\lambda_{238}T}-1}\right)$$

$\boxed{^{207}Pb - ^{206}Pb \text{ Method}}$

$$\frac{\overbrace{(^{207}Pb/^{204}Pb)_m}^{\Rightarrow y} - 10.29}{\underbrace{(^{206}Pb/^{204}Pb)_m}_{\Downarrow x} - 9.31} = \overbrace{\frac{1}{137.88} \times \left(\frac{e^{\lambda_{235}t}-1}{e^{\lambda_{238}t}-1}\right)}^{\Rightarrow m}$$



m ⇒ t = ?



시생대.

Fig. 6.1. Scheme illustrating the applicability of the different methods for dating hard rocks in terms of rock type and kind of geological event

암석 종류,
지질학적 사건에 따라
사용하는 방법.

${}^{1}_{1}H$ ← H_2O (water)

${}^{2}_{1}H$ = 중수소(D) deuterium. → stable

${}^{3}_{1}H$ = 삼중수소 tritium → radiogenic.

meteoric water (rain water)
magmatic water ; magma의 5% 정도
oceanic water.
Connate water ; 암석에 (퇴적암..) 포획되어 있는 물.

물의 나이 측정 "

$$1\ Ci = 3.7 \times 10^{10}\ \text{disintegration}/s = 3.7 \times 10^{10}\ Bq = 10^{+12}\ pCi$$

Radioisotopes

${}^{3}H$ (tritium) $t_{\frac{1}{2}} = 12.43\ yr$ (반감기가 매우 짧다)

hydrogen bomb → ${}^{3}H$ huge influx (in 1952

1962 (peak) → one year before the test-ban treaty between US and Soviet Union

n

$1 + {}^{12}_{6}C$

unit: tritium units (TUs) = one ${}^{3}H$ atom / 10^{18} hydrogen atoms

= 0.018 Bq/L " = 1 TU.

natural production of ${}^{3}H$ = 5 ~ 10 TUs

1960s 초 → 1,000 TUs (북반구 middle latitudes)

1 pCi/L = 37 Bq/m³

대기中 ${}^{3}H + O_2 \rightarrow {}^{3}HO_2 \rightarrow {}^{1}H{}^{3}HO$

$${}^{3}H \xrightarrow{decay} {}^{3}He + \beta^-$$

(Fig. 8-19) seasonal variation → spring peak

① application (279 p.)
→ direct dating of the water age
→ use of ${}^{3}H$ distribution in an aquifer
→ understanding of flow processes

$${}^{3}H_t = {}^{3}H_0 e^{-kt} \quad (\text{at time } t) \quad (N = N_0 \cdot e^{-\lambda t})$$

$${}^{3}He_t = {}^{3}H_0 - {}^{3}H_0 e^{-kt} = {}^{3}H_0 (1 - e^{-kt}) \quad (D = P_0 - P)$$

$$* \boxed{{}^{3}He_t = {}^{3}H_t (e^{kt} - 1)} \quad (D = P(e^{\lambda t} - 1))$$

k : 5.57 × 10⁻²/yr.

$$* \boxed{t = \frac{12.43}{\ln 2} \ln\left(1 + \frac{{}^{3}He_t}{{}^{3}H_t}\right)}$$

$$t_{\frac{1}{2}} = \frac{\ln 2}{\lambda} \Rightarrow = 12.43$$

$$\lambda = \frac{0.693}{t_{\frac{1}{2}}} = \frac{0.693}{12.43} = 5.57 \times 10^{-2}/yr$$

$$\boxed{{}^{14}_{7}N + {}^{1}_{0}n \longrightarrow {}^{3}_{1}H + {}^{12}_{6}C}$$

삼중수소의 생성.

$$\boxed{{}^{3}_{1}H \rightarrow \underset{\text{(stable)}}{{}^{3}_{2}He} \quad (\beta \text{ emission})}$$

$$T_{\frac{1}{2}} = 12.26 \text{ yrs}$$

$$\lambda = 5.6537 \times 10^{-2}/\text{yr}$$

unit of ${}^{3}_{1}H$ = TU (tritium unit)

1 TU = 1 atom of ${}^{3}_{1}H$ / 10^{18} atoms of hydrogen

1 TU/1 l of water ⇒ decay rate of 0.119 Bq = 3.21×10^{-12} Ci

(1 Ci = 3.70×10^{10} Bq)

Dating water (cosmogenic $^{3}_{1}H$)

$$^{3}H_{A} = {}^{3}H_{A}^{\circ}\,(e^{-\lambda t})$$

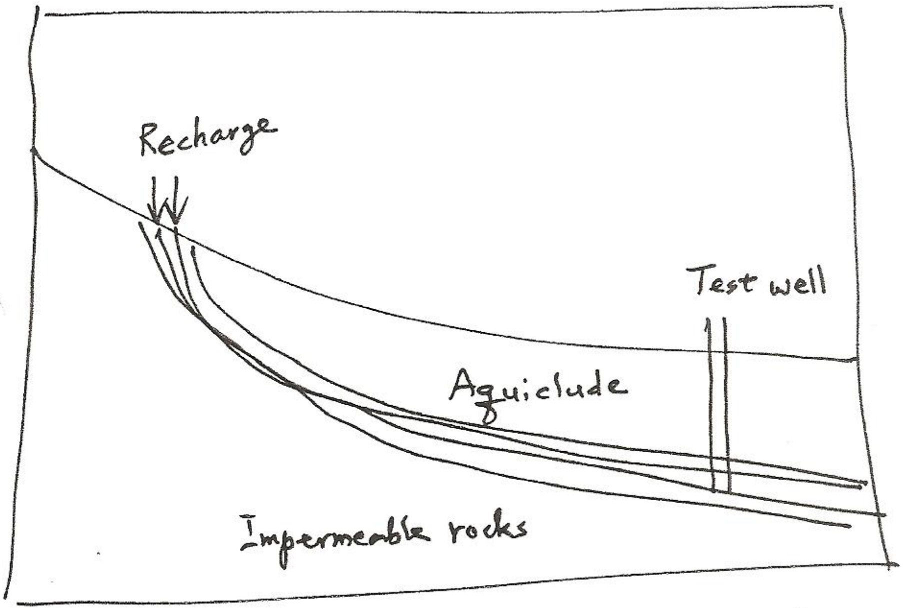
↓

activity in water (TU)

mean life $\tau = \frac{1}{\lambda} = 1/(5.6537\times10^{-2}/yr) = 17.69$ yrs

$$^{3}H_{A} = {}^{3}H_{A}^{\circ}\cdot e^{-t/\tau} = \underline{{}^{3}H_{A}^{\circ}\cdot e^{-t/17.69}}$$

(Distribution of $^{3}_{1}H$ in mixed and dispersive groundwater system)



Piston Flow Model in a Confined Aquifer.

$$\underline{^{3}He} = {}^{3}He_{0} + \underline{{}^{3}H\,(e^{\lambda t}-1)}$$

(radiogenic, tritiogenic)

$$t = \frac{1}{\lambda}\ln\left(\frac{^{3}He - {}^{3}He_{0}}{^{3}H} + 1\right)$$

$$\boxed{\frac{^{3}He}{^{4}He} = \left(\frac{^{3}He}{^{4}He}\right)_{0} + \frac{^{3}H}{^{4}He}\,(e^{\lambda t}-1)}$$

Isochron 그릴 때 사용.

$$\underline{(^{3}He/^{4}He)_{0} = 1.40\times10^{-6}}$$ (atmospheric origin) 이미 주어져있다.