

Lecture 15 - Radioactive Isotopes

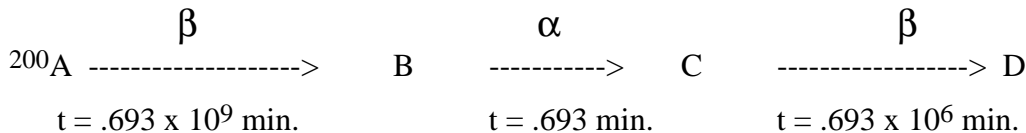
(1) List the following according to their $^{14}\text{C}/^{12}\text{C}$ ratio (large to small)

- | | |
|--|-----|
| (a) Recent benthic forams | II |
| (b) Recent planktonic forams | VI |
| (c) An 1866 French wine | IV |
| (d) The shroud of Turin | III |
| (e) The food at the Tresider cafeteria | V |
| (f) Your dad's polyester leisure suites (circa 1975) | I |

(2) Pb is a scavenged element that is rapidly removed from the water column by particulate organic matter. ^{210}Pb has a half-life of 22 years. Can you explain how this isotope might be used to estimate particulate export production? What experiment would you design to test this? What might be the limitations with this method?

We can correlate excess ^{210}Pb in shallow (< 500m) sediment traps to the organic matter flux out of the euphotic zone and find a relation that could be used to estimate the flux using ^{210}Pb . The fact that ^{210}Pb decays may give a measure of the time it takes for the particulate matter to reach different depths. We need to know atmospheric input too and to determine if Pb is particle specific (adsorbs preferentially on specific type of particles).

(3) A hypothetical naturally occurring decay chain is illustrated by the following sequence:



where A, B, C, D are radioactive isotopes, t is the half life, and the mode of decay is indicated by α and β . The atomic weight and atomic number of A are 200 and 100 respectively. The concentration of A in sea water is 1×10^{-14} mol/kg.

a) Predict the atomic weight and number of B, C, and D.

A, 200, 100; B = 200, 101; C = 196, 99; D = 196, 100

b) What is the activity of A in seawater?

$$A = \lambda N, \quad t = 0.693/\lambda, \quad \lambda = 0.693/t = 1 \times 10^{-9} \text{ min}^{-1}$$

$$A = 1 \times 10^{-9} \text{ min}^{-1} \times 1 \times 10^{-14} \text{ mol/kg} \times 6.1 \times 10^{23} \text{ atoms/mole} = 6.1 \text{ dpm/kg}$$

c) If seawater is a closed system, what are the activities of B, C, and D.

Will be at secular equilibrium e.g. same as the isotope with longest half-life thus 6.1 dpm/kg

d) What are two possible processes in the ocean that could alter this secular equilibrium?

Different chemistry of parent and daughter that would result in separation of the two (adsorption) or input from external anthropogenic sources

e) Which isotopes are the same element and would have the same chemistries?

A and D are isotopes of the same element and so should have the same chemistry

(4) ^{238}U ($t_{1/2} = 4.5 \times 10^9$ y) decays to ^{234}Th ($t_{1/2} = 24.1$ d). Define and give the conditions for secular equilibrium. Assuming the decay of $^{238}\text{U} = 2.3$ dpm kg^{-1} what is the molar concentration of ^{234}Th at secular equilibrium. Assume that here has been an extreme bloom period with intensive scavenging that removes most of the ^{234}Th from the water column in the euphotic zone. Suddenly the bloom stops. How long will it take for ^{234}Th to reach secular equilibrium with ^{238}U ?

An isotope is in secular equilibrium when its decay rate equals that of the parent. This occurs when the half-life of the parent is much greater than that of the daughter.

$$A_{238\text{U}} = A_{234\text{Th}} = 2.3 \text{ dpm kg}^{-1} = \lambda_{\text{Th}} \times N_{\text{Th}} \quad \lambda = 0.693/t_{1/2} = 0.693/24.1 = 0.028 \text{ d}^{-1}$$

$$N_{\text{Th}} = 2.3 \text{ dpm kg}^{-1} / 0.028 \text{ d}^{-1} = 2.3 \text{ dpm kg}^{-1} / 1.94 \times 10^{-5} \text{ min}^{-1} = 1.2 \times 10^5 \text{ atoms kg}^{-1}$$

It would take about 5 half lives of ^{234}Th or 120 days.

(5) Due to the input of radionuclides during bomb testing in the 1960s which information has been gained?

- Water mass ventilation using CFC tracers
- North-South mixing across the equator using ^3H as a tracer
- Export production using $\text{C}/^{234}\text{Th}$ ratios
- Stagnant film boundary layer thickness using the ^{14}C steady state model
- The rate of turbulent mixing in the bottom boundary layer

(6) A soil sample contains about 3×10^{-6} g U g^{-1} soil. The soil is 20 cm thick, has a porosity of 50% and a mean density of the grains of 2.5 g cm^{-3} . Assume that the activity of ^{226}Ra in the soil is as that of ^{238}U and that one-third of the Ra produced in the soil is released to the pore space and that half of this diffuses to the atmosphere. Calculate the flux of Rn atoms to the atmosphere and compare this to the ^{210}Pb fallout rate of 28 atoms $\text{cm}^{-2} \text{ min}^{-1}$. The half-life of ^{238}U is 4.55×10^9 years

First calculate the Rn production:

Find how many U atoms are in a cm^3 of soil and multiplying by the decay constant.

$$= 2.5 \text{ g cm}^{-3} \times 3 \times 10^{-6} \text{ g U g}^{-1} \times \frac{6 \times 10^{23} \text{ atoms}}{238 \text{ g}} \times \frac{0.693}{4.55 \times 10^9 \text{ yr}} \times 19 \times 10^7 \text{ y min}^{-1}$$

$$= 5.5 \text{ Rn atoms cm}^{-3} \text{ min}^{-1}$$

Now one third of the Rn is released to the pore space so $5.5/3 = 1.8 \text{ Rn atoms cm}^{-3} \text{ min}^{-1}$

This is produced over 20 cm depth and half is released so:

$1.8 \text{ Rn atoms cm}^{-3} \text{ min}^{-1} \times 20 \text{ cm} \times 0.5 = 18 \text{ Rn atoms cm}^{-2} \text{ min}^{-1}$ are released to the atmosphere.

This Rn forms ^{210}Pb with falls out at a rate on 28 atoms $\text{cm}^{-2} \text{ min}^{-1}$ so this cannot account for all the ^{210}Pb clearly deeper dry sediments or more efficient release of Rn from the soil are needed.

(7) Sediment traps are deployed for one month at a depth of 75 meters in a lake. Assume all the Th produced is caught onto particles and collected in the trap. Material caught in these traps yields the following activity ratios for the U isotope series. Assuming that these concentrations are at steady state calculate the apparent residence time for Th in the lake.

$$U = 108 \times 10^{-6} \text{ g l}^{-1}. \quad \lambda_{230} = 0.693/75000 = 9.24 \times 10^{-6} \text{ y}^{-1} \quad \lambda_{234} = 0.693/0.066 = 10.5 \text{ y}^{-1}$$

Activity ratios of U in the water column: $^{234}\text{U}/^{238}\text{U} = 1$
 Activity ratios of Th in the particles: $^{234}\text{Th}/^{230}\text{Th} = 25$

Calculate the ^{230}Th and ^{234}Th production rate. Both are from the same decay chain and thus at secular equilibrium their production in the water column is the same:

$$108 \times 10^{-6} \text{ g l}^{-1} \times \frac{6 \times 10^{23} \text{ atoms}}{238 \text{ g}} \times \frac{0.693}{4.55 \times 10^9 \text{ yr}} \times 19 \times 10^{-7} \text{ y min}^{-1} \times 7.5 \text{ l cm}^{-2} = 607 \text{ atoms cm}^{-2} \text{ min}^{-1}$$

*7.5 l cm⁻² is a conversion of a 75 m water depth to the liters in a water column of that depth and an area of 1 cm². This is done in order to cancel the liters.

Next calculate the decay rate of ^{230}Th and ^{234}Th in the particles assuming all of the produced Th is caught in the trap.

$$607 \text{ atoms cm}^{-2} \text{ min}^{-1} \times 4.32 \times 10^4 \text{ min} \times 9.24 \times 10^{-6} \text{ y}^{-1} \times 19 \times 10^{-7} \text{ yr min}^{-1} = 4.6 \times 10^{-4} \text{ atoms cm}^{-2} \text{ min}^{-1}$$

*4.32 x 10⁴ min is one month (the time the trap collected the flux).

For ^{234}Th the decay rate is:

$$607 \text{ atoms cm}^{-2} \text{ min}^{-1} \times 4.32 \times 10^4 \text{ min} \times 10.5 \text{ y}^{-1} \times 19 \times 10^{-7} \text{ yr min}^{-1} = 523 \text{ atoms cm}^{-2} \text{ min}^{-1}$$

If the residence time of Th was very small much smaller than 1 month then we would expect the activity ratio if 234/230 to be identical to the ratio of decay rates:

$523/4.6 \times 10^{-4} = 1.14 \times 10^6$. The observed ratio is 25 much lower than expected ratio produced indicating that the residence time of Th is longer than 1 month. We can calculate the residence time using:

$$(234/230 \text{ activity ratio in trap}) / (234/230 \text{ activity ratio produced}) = e^{-\lambda_{234} \tau_{\text{Th}}}$$

$$\tau_{\text{Th}} = 1/\lambda_{234} \ln(1.14 \times 10^6/25) = 0.0952 \times 10.727 = 1 \text{ year}$$

(8) The activity of ^{226}Ra in seawater is 50 dpm/100 liters, what would the mean flux of ^{226}Ra from the sea floor be to maintain this value (steady state), the depth of the ocean (volume to area ratio) is 3800m.

$$50 \times 10^{-2} \text{ atoms l}^{-1} \text{ min}^{-1} \times 3800 \text{ l cm}^{-2} = 190 \text{ atoms cm}^{-2} \text{ min}^{-1}$$

Decay rate = escape rate from sediments

- (9) Using a two-layer box model of the ocean similar to Broecker's (shown below) determine the residence time of water in the deep ocean with respect to its mixing rate through the thermocline ($\tau = V_o/V_{\text{mix}}$). Please include in your model the observations that the ($^{14}\text{C}/^{12}\text{C}$) ratio of DIC in the deep ocean is 12% (percent not permil) less than that in the surface ocean, that is:

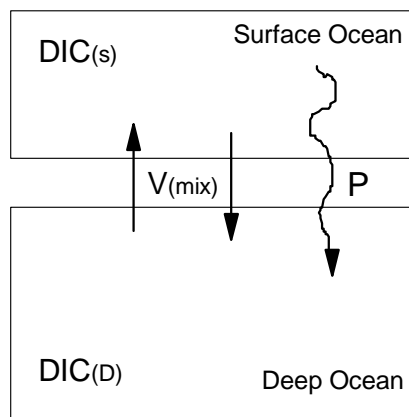
$$\frac{(^{14}\text{C}/^{12}\text{C})_D}{(^{14}\text{C}/^{12}\text{C})_S} = 0.88$$

An appropriate approach for solving this problem is to construct steady-state equations for DI^{12}C and DI^{14}C in the deep ocean, given $\lambda^{14}\text{C} = (0.693/5700 \text{ yr})$ and the following assumptions:

- river inflow and sedimentation of ^{14}C are not quantitatively important for the deep ocean
- insignificant ^{14}C decay occurs in the surface ocean.
- no isotope fractionation occurs on production or destruction of carbon-containing particles
- all the particulate material formed in the surface ocean degrades to DIC in the deep ocean

The following hints may help you out:

- write individual equations for DI^{12}C and DI^{14}C in the deep ocean using the formalism that $\text{DI}^{12}\text{C}(\text{}^{14}\text{C}/^{12}\text{C}) = \text{DI}^{14}\text{C}$, to put the ^{14}C equation in terms of the $^{14}\text{C}/^{12}\text{C}$ ratio
- write an atom balance equation (sources = sinks) first for DI^{12}C and then write an analogous DI^{14}C equation, where the latter includes a sink for radiochemical decay
- use the symbols and units given to the right of the below figure
- concentrations are not necessary to solve the equation



P = particle flux (mol yr^{-1})

V_{mix} = water flux ($\text{m}^3 \text{ yr}^{-1}$)

$[\text{DIC}]$ = DIC concentration (mol m^{-3})

You should be able to do this mass balance if you are not sure read chapter 5 in Tracers in the sea (Broecker and Peng 1982).

(10) Sediments taken at a depth of 50cm in a deep sea core contains foram shells with a $^{14}\text{C}/\text{C}$ ratio 12% that for sediments from the depth of 10cm. What is the apparent sedimentation rate?

$$^{14}\text{C}/\text{C}_{50} = ^{14}\text{C}/\text{C}_{10} \times e^{-\lambda t} \quad \Delta t = 1/\lambda \ln 1/ (^{14}\text{C}/\text{C}_{50} / ^{14}\text{C}/\text{C}_{10}) = 8200 \ln 1/0.12 = 17,400 \text{ years}$$

$$\text{Sed rate} = (50-10)/ 17,400 = 2.3 \text{ cm} / 10^3 \text{ y}$$

(11) The following results were obtained using U series measurements at various depths in a deep-sea core. The units are dpm g-1 (disintegrations per minute per gram sediment).

Depth (cm)	^{238}U	^{234}U	^{230}Th	Excess ^{230}Th
2	1.3	1.4	65.5	64.1
22	1.5	1.6	33.6	32.0
42	1.4	1.3	17.4	16.1
62	1.2	1.3	9.6	8.3
81	1.5	1.5	5.7	4.2
102	1.2	1.3	3.5	2.2
122	1.4	1.5	2.4	0.9

What is the apparent sedimentation rate? What assumptions are made?

Excess ^{230}Th drops $\frac{1}{2}$ for each 20 cm.

$$\text{Sed Rate} = 20\text{cm}/75,200 \text{ yr} = 0.27\text{cm} / 10^3 \text{ yr}$$

(12) $\Delta^{14}\text{C}$ surface is -50‰ , $\Delta^{14}\text{C}$ deep water is -230‰ (a) what would the ratio of $^{14}\text{C}/\text{C}$ in planktonic forams to benthic forams be in material formed recently? (b) Assuming that the rate of deep-sea ventilation remained constant with time what would be the above ratio for 6,000 and 18,000 years ago? If the $^{14}\text{C}/\text{C}$ activity of the standard is 13.5 dpm/ g-C can you determine the activity of the 18,000 year old samples?

$$\frac{\Delta^{14}\text{C surface}}{\Delta^{14}\text{C deep}} = \frac{0.950}{0.770} = 1.23$$

6,000 and 18,000 years ago with constant ventilation the ratio of $^{14}\text{C}/\text{C}$ in planktonic forams to benthic forams will be the same as for today e.g. 1.23. But the actual $^{14}\text{C}/\text{C}$ in the samples will be lower due to decay.

$$\text{Activity in present day planktonic foram} = 13.5 \times 0.95 = 12.8 \text{ dpm/g-C}$$

$$\text{Activity for benthic foram} = 13.5 \times 0.77 = 10.4 \text{ dpm/g-C}$$

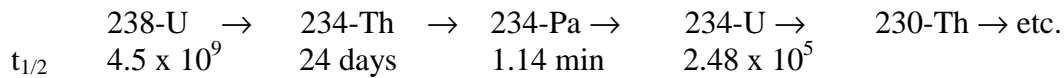
$$18,000 \text{ year old planktonic foram} = 12.8 \times e^{-\lambda t} = 12.8 \times e^{-18,000/8200} = 1.43 \text{ dpm/ g-C}$$

$$18,000 \text{ year old benthic foram} = 10.4 \times e^{-\lambda t} = 10.4 \times e^{-18,000/8200} = 1.16 \text{ dpm/ g-C}$$

13. This question correspond to the work of Coale and Bruland (1987) figure below:

Recently very good use has been made of the ^{238}U decay series in the investigation of ^{230}Th distribution in the upper water column. Below you will find some relevant data from Coale and Bruland offshore from Monterey.

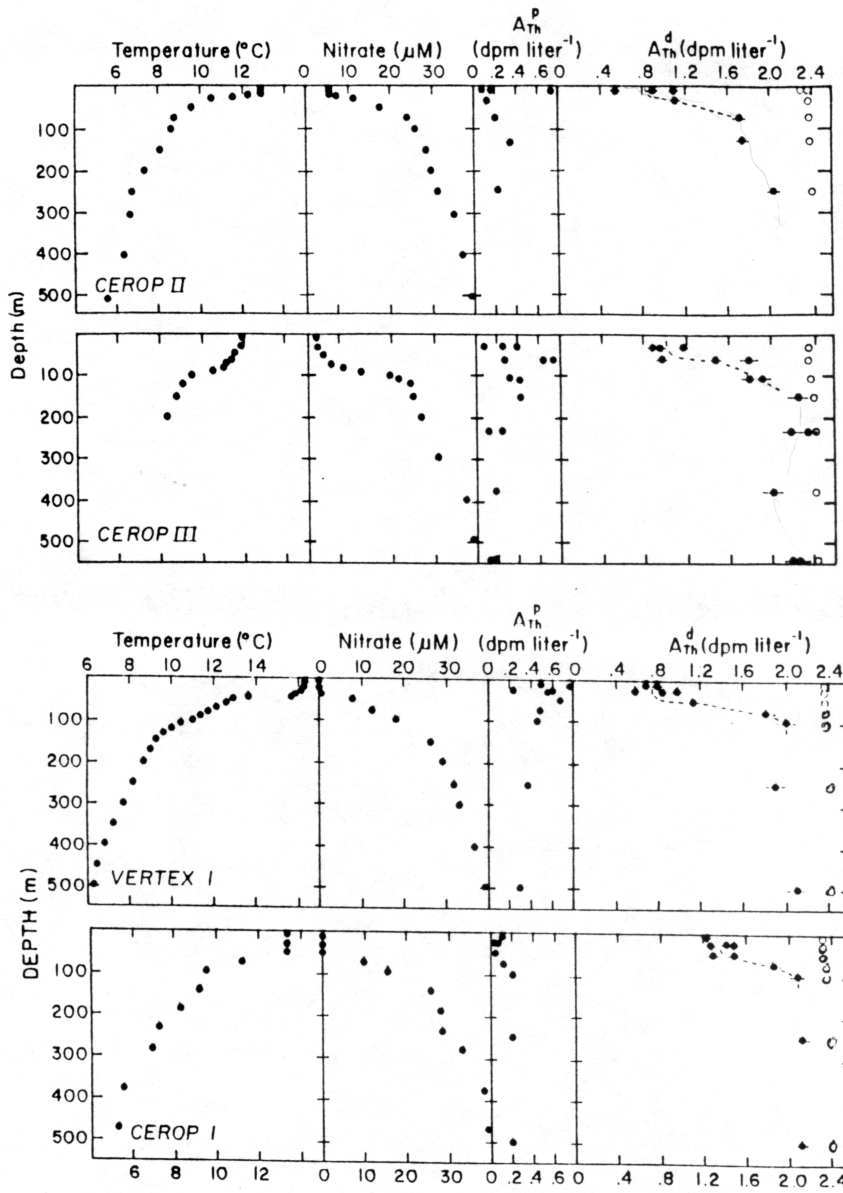
We know that:



- What do you think causes the distribution of dissolved ^{234}Th
- Suppose biogeochemically produced particles can be separated from inorganic suspended particles, and the latter contain U with an activity ratio of $^{234}\text{U}/^{238}\text{U}$ of 1.00. What might this imply?

We see that in surface water ^{234}Th is deficient relative to expected from secular equilibrium with ^{238}U . This disequilibrium decreases with depth approaching steady state. The parent ^{238}U activity is constant with depth. This can be explained as resulting from the particle reactive nature of ^{230}Th relative to ^{238}U . While U is soluble and has a long residence time Th is particle reactive and has a short residence time and it is scavenged and removed by particles. The large number of particles in the upper water column scavenge Th and moving it with the particles to the deep water where some disaggregation may occur (but mostly the lack of particles results in less scavenging). This explains the surface depletion and the disequilibrium.

This implies that ^{234}U - ^{238}U have approached equilibrium this takes a long time and thus indicates that the particle is of old terrigenous origin.



Vertical profiles of temperature, nitrate, particulate and dissolved ²³⁴Th activity (A_{Th}^P and A_{Th}^D) for VERTEX I and CEROP I, II, and III. ²³⁸U activity—○.

dissolved ²³⁸U activity

D = dissolved
P = particulate