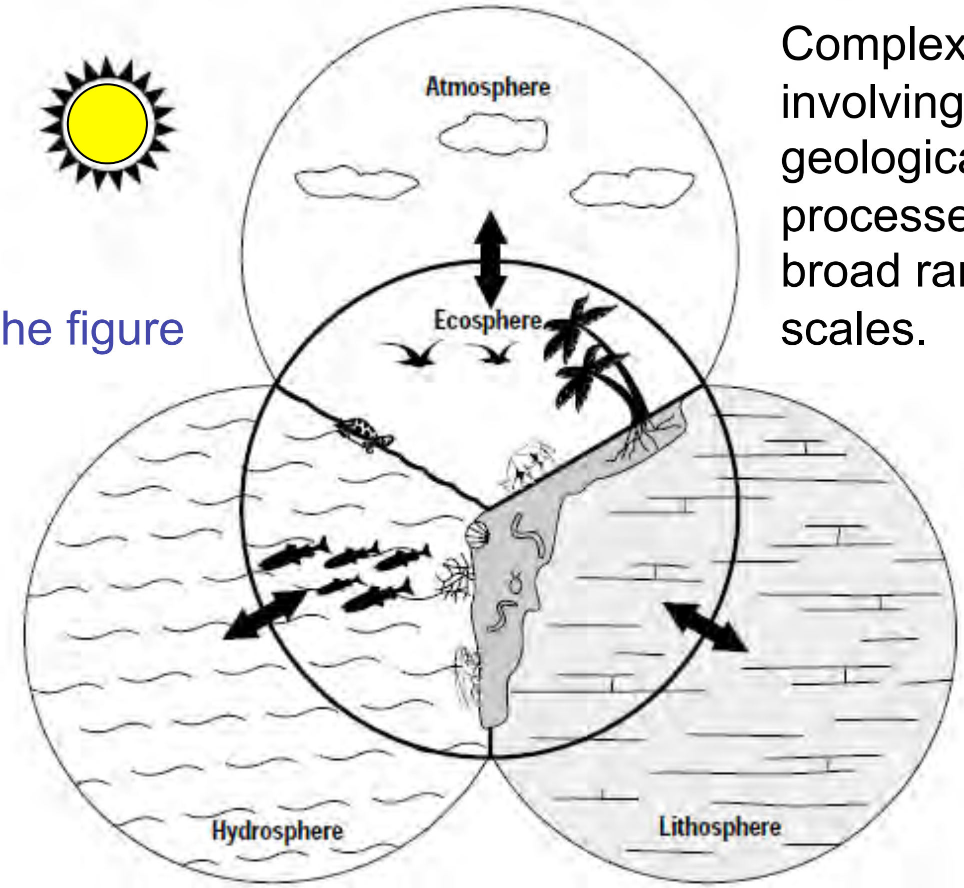
Global Biogeochemical Cycles

The interactions between the various spheres of the earth system

(after Christensen, 1991).



Place yourself on the figure

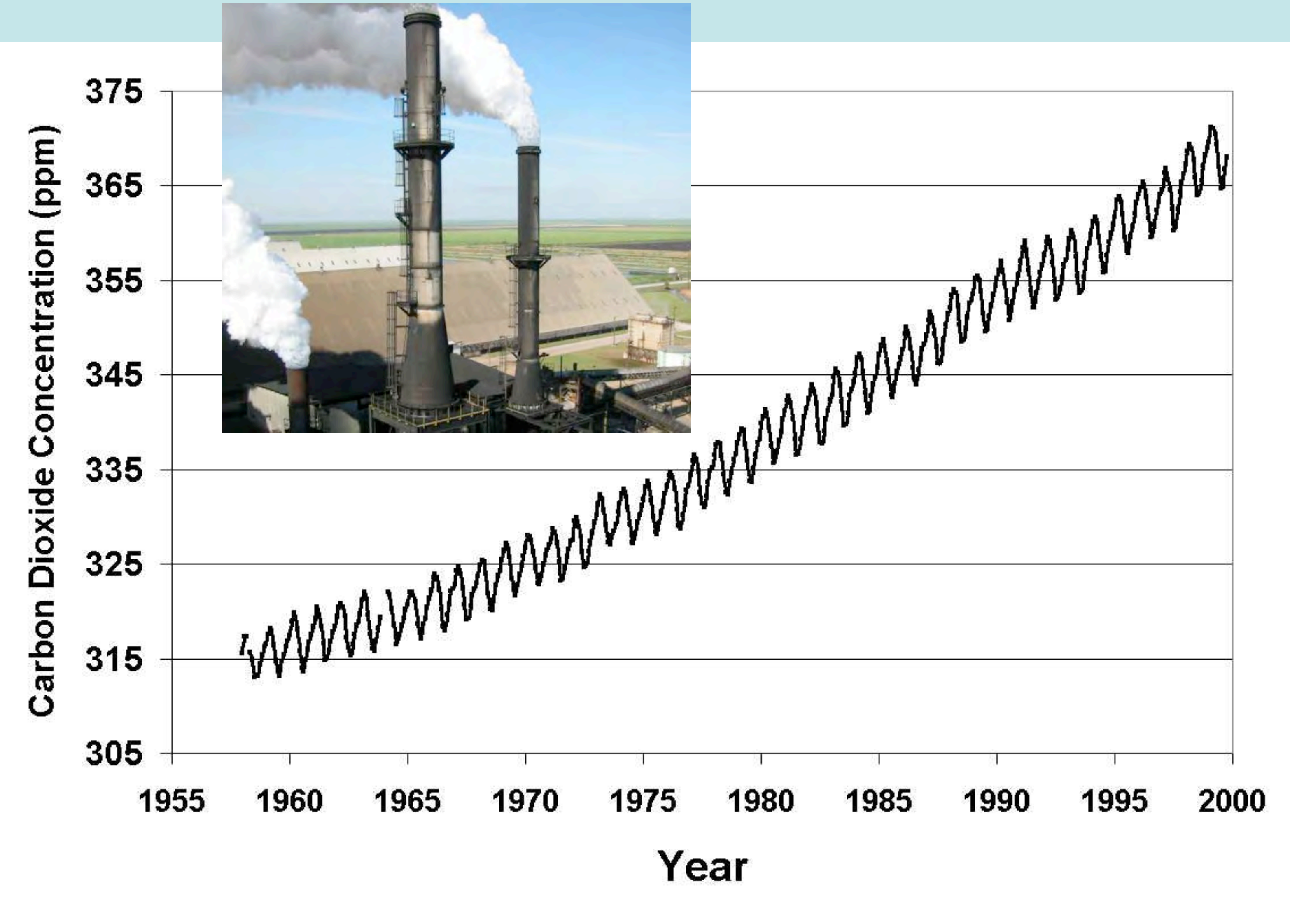
Complex interactions involving biological, geological, and chemical processes operating on a broad range of time scales.

Why Study Global Biogeochemical Cycles?

Understanding how the world works and how we are changing natural processes.

- Biogeochemical cycles provide the basic framework for investigating global change and its implications for life on earth.
- An understanding of biogeochemical cycles and anthropogenic impacts on them is fundamental for predicting impacts of global climate change.

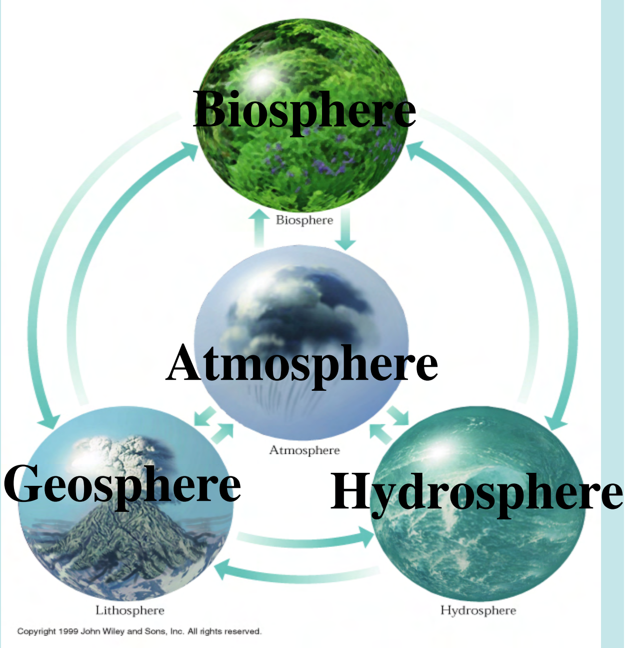
Atmospheric CO_2 concentrations at Mauna Loa, Hawaii



The global biogeochemical cycles of many elements have been altered by human (anthropogenic) activity

Fossil fuel burning alone accounts for perhaps 80% of sulfur dioxide (SO_2) emissions from the land surface to the atmosphere, 50% of carbon monoxide, 50% of NOx, 20% of methane, 5% of ammonia, and 4% of nitrous oxide. It is also responsible for 70–90% of anthropogenic CO_2 emissions to the atmosphere. CO_2 in the atmosphere increased by 30% since the industrial revolution.

What do we try to understand in these studies?



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The present state of the Earth's surface environment.

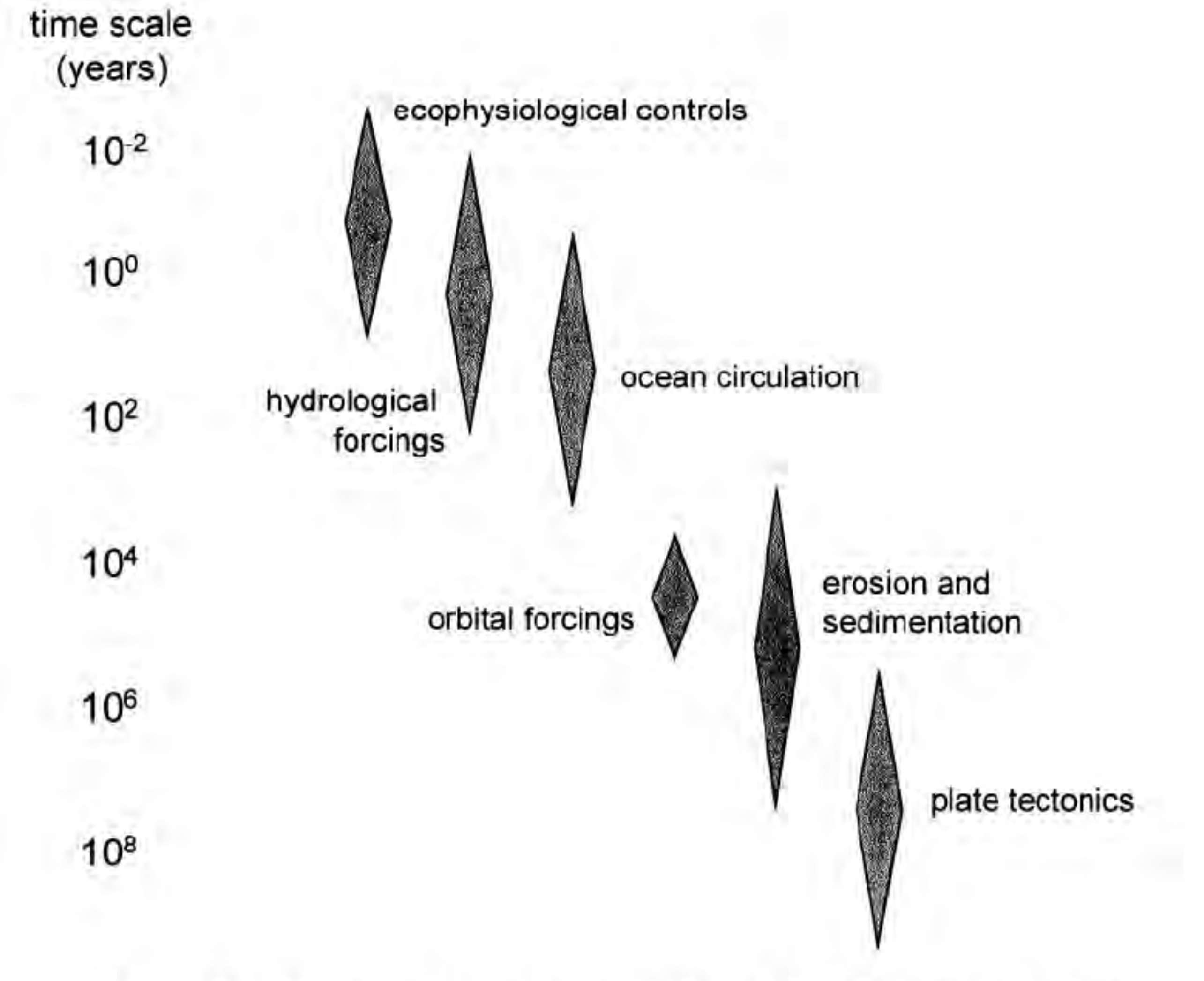
What controls it.

How it got to its present state.

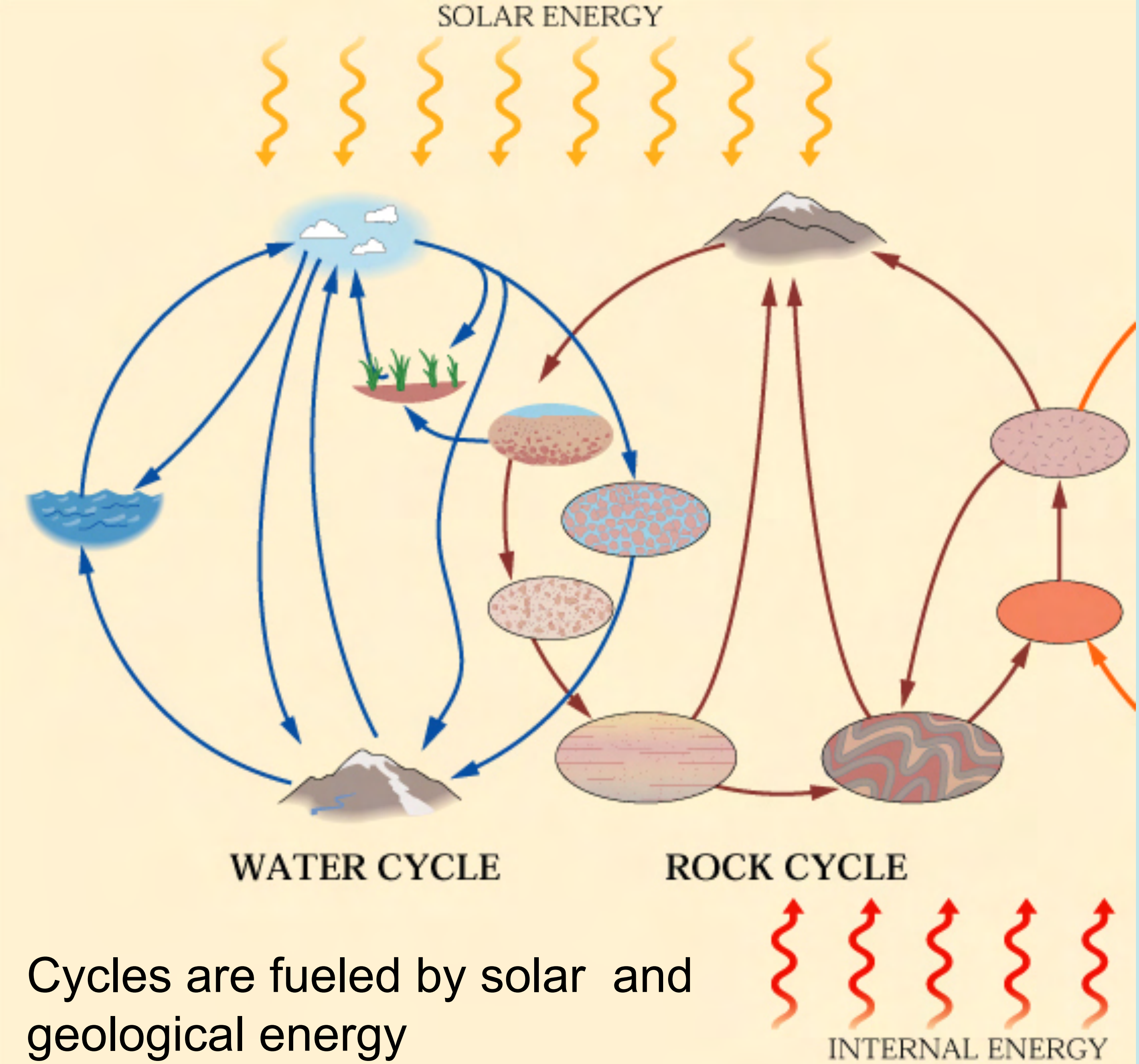
How did it change over Earth's history.

What are the processes/feedbacks that sustain a habitable planet.

Biogeochemical cycles operate on many different spatial and temporal scales

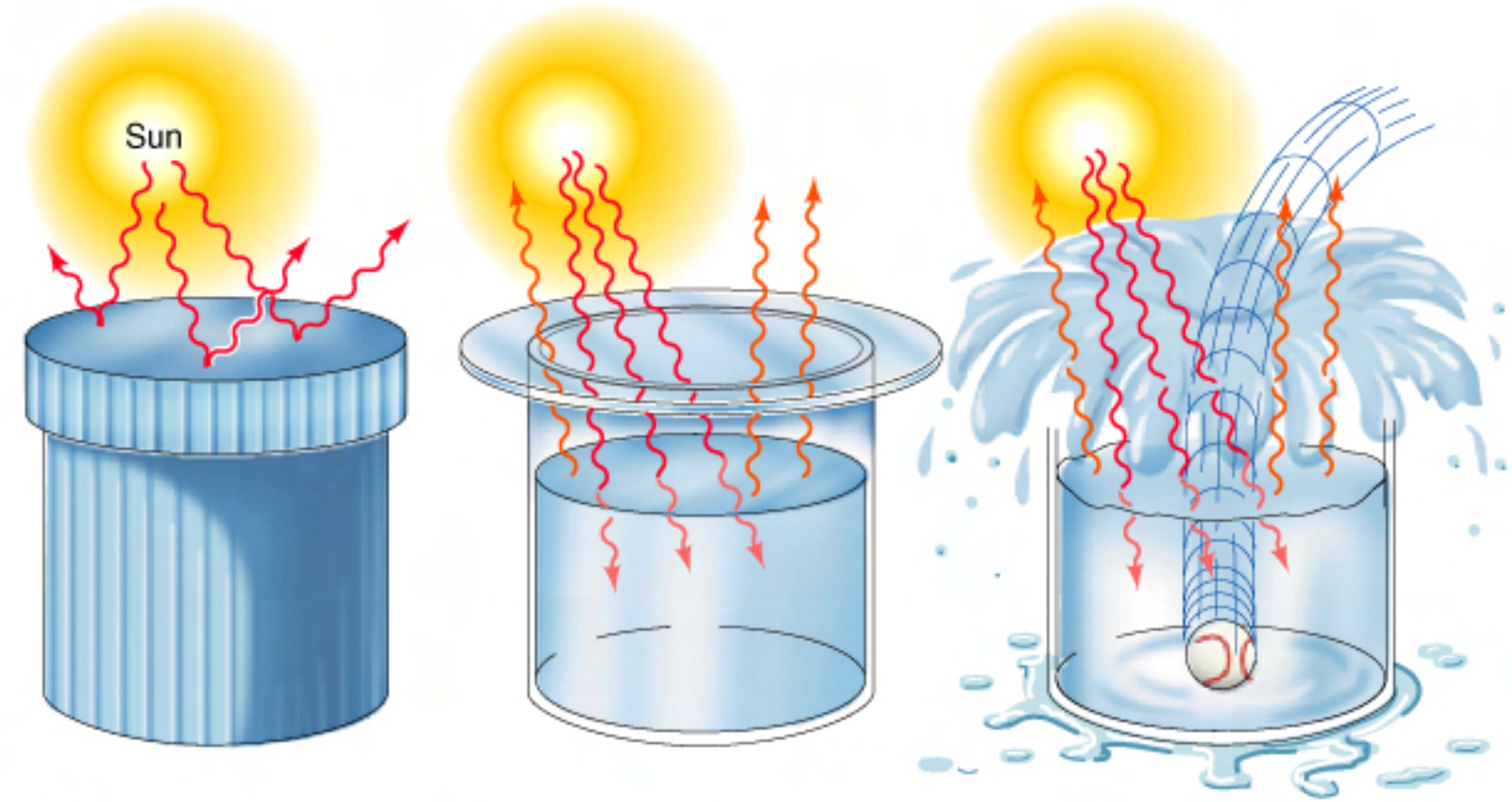


. Examples of forcings of biogeochemical cycles and their characteristic time scales.



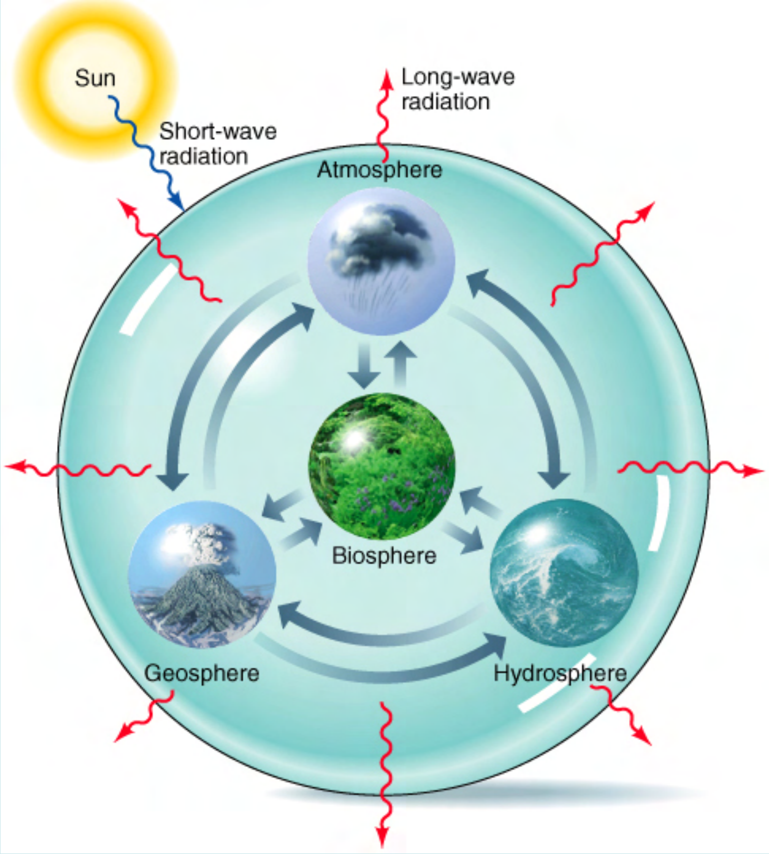
Cycles are fueled by solar and geological energy

Three basic types of system

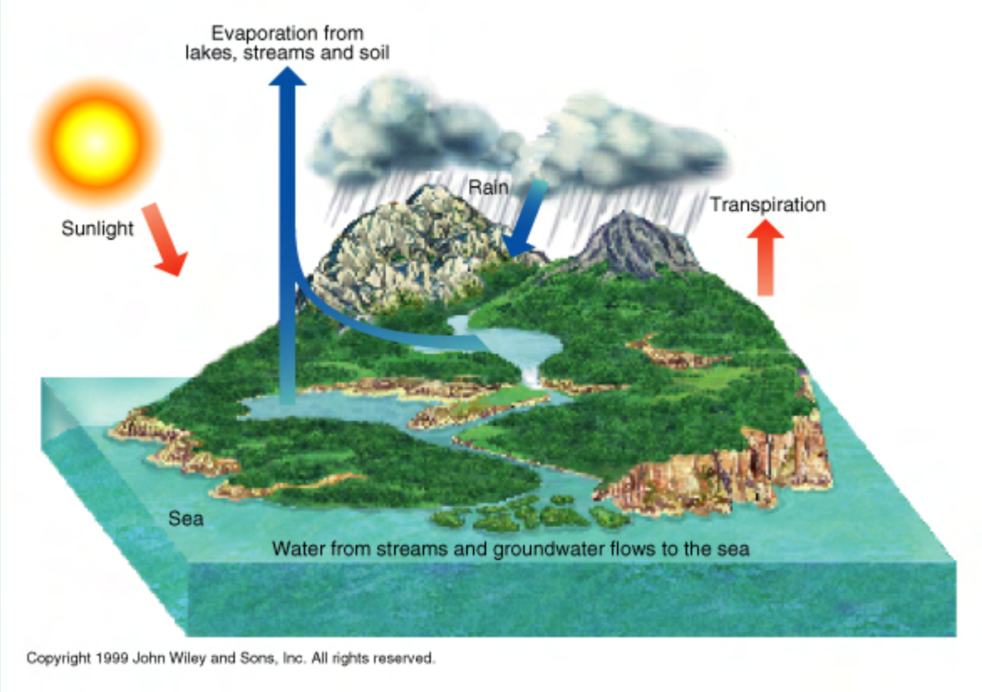


A. Isolated system B. Closed system C. Open system

A closed system



An open system



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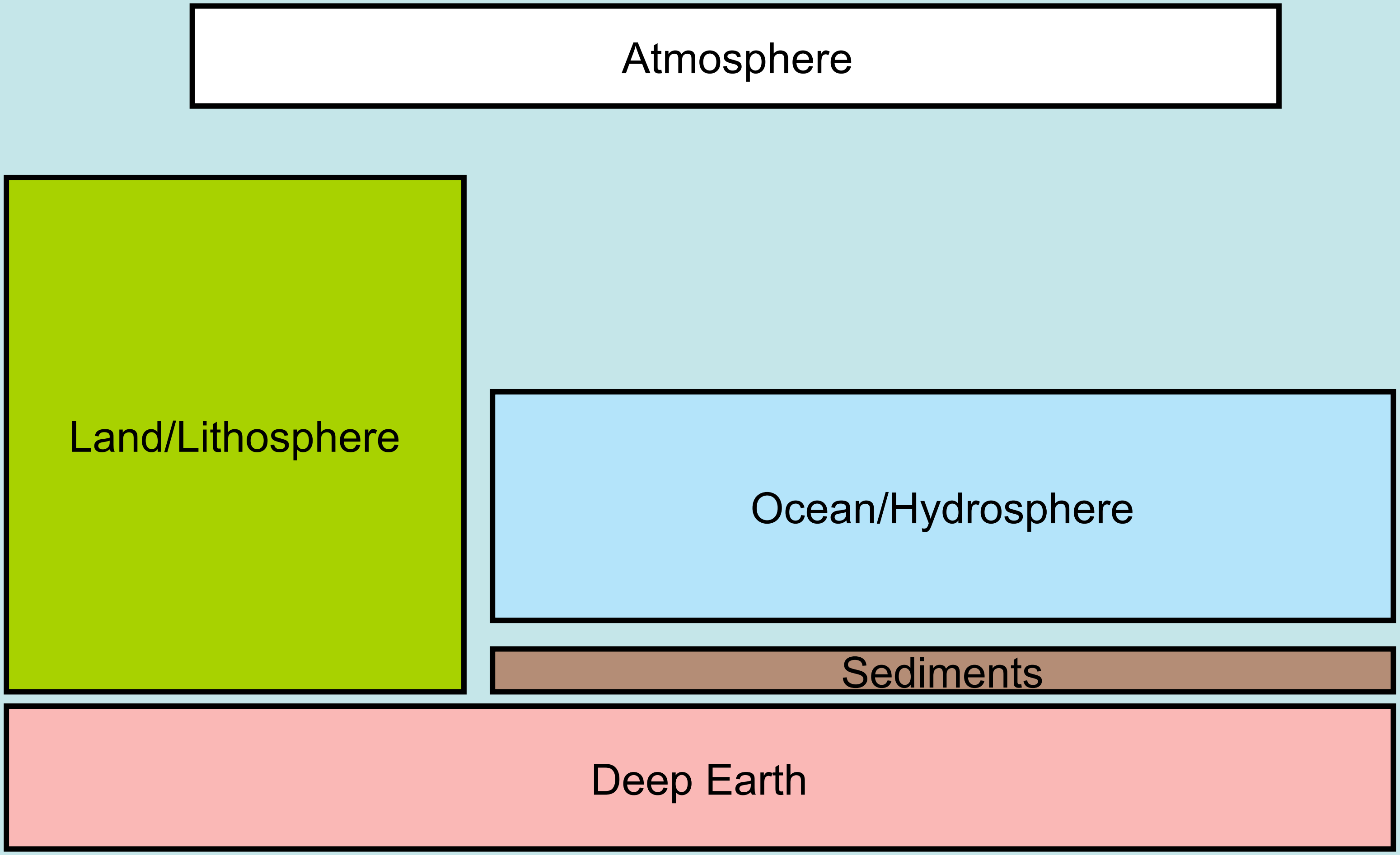
Reservoirs

A reservoir is a physically well-defined system. A given setting with defined physical and/or biological boundaries. In each reservoir, the relevant chemical, physical and biological properties are assumed to be (reasonably) uniform.
A reservoir will contain a collection of matter.

EXAMPLES?

Major Reservoirs



Atmosphere

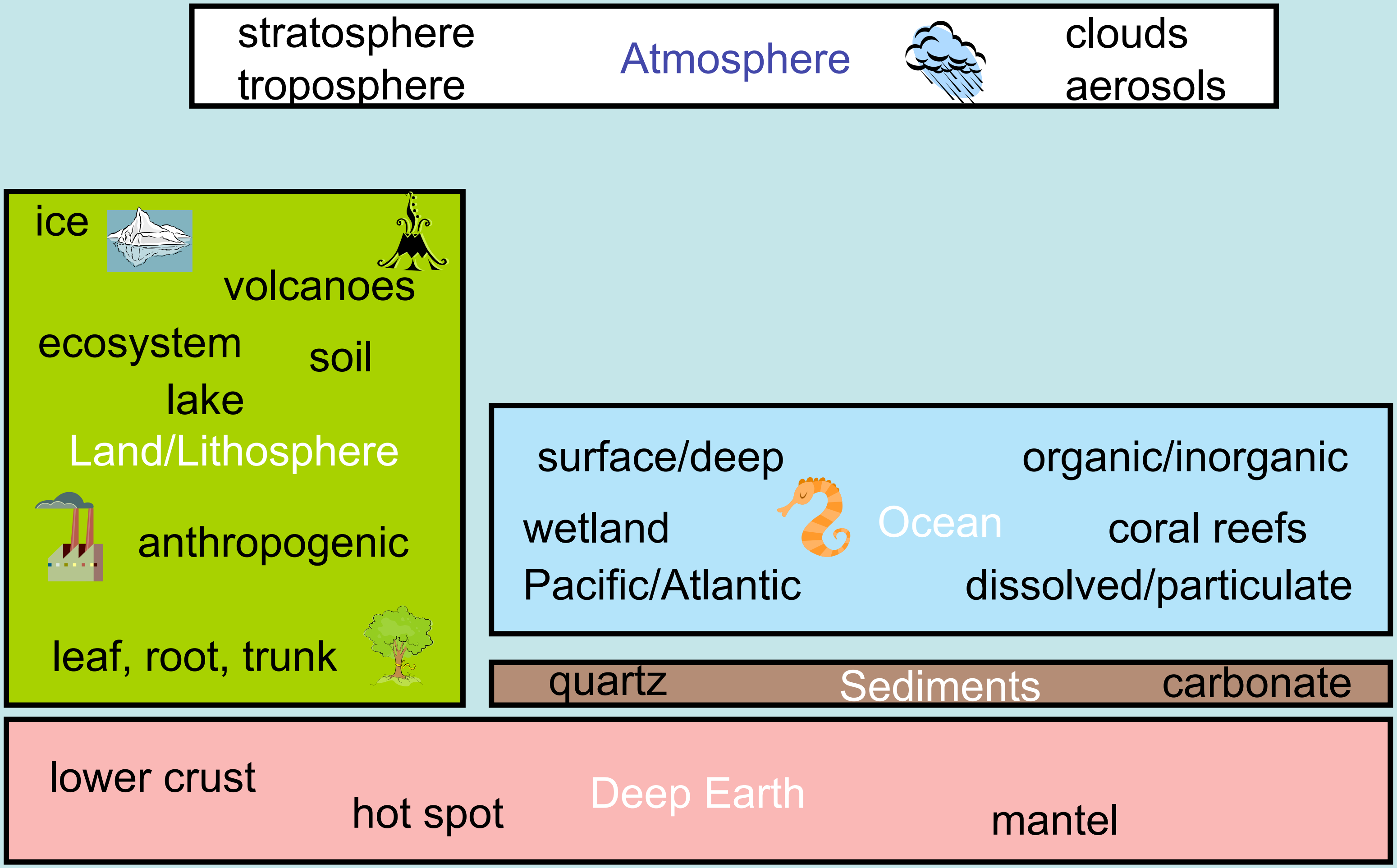
Land/Lithosphere

Ocean/Hydrosphere

Sediments

Deep Earth

Additional Reservoirs



stratosphere
troposphere

Atmosphere

clouds
aerosols

ice

volcanoes

ecosystem

soil

lake

Land/Lithosphere

anthropogenic

leaf, root, trunk

surface/deep

organic/inorganic

wetland

Ocean

coral reefs

Pacific/Atlantic

dissolved/particulate

quartz

Sediments

carbonate

lower crust

hot spot

Deep Earth

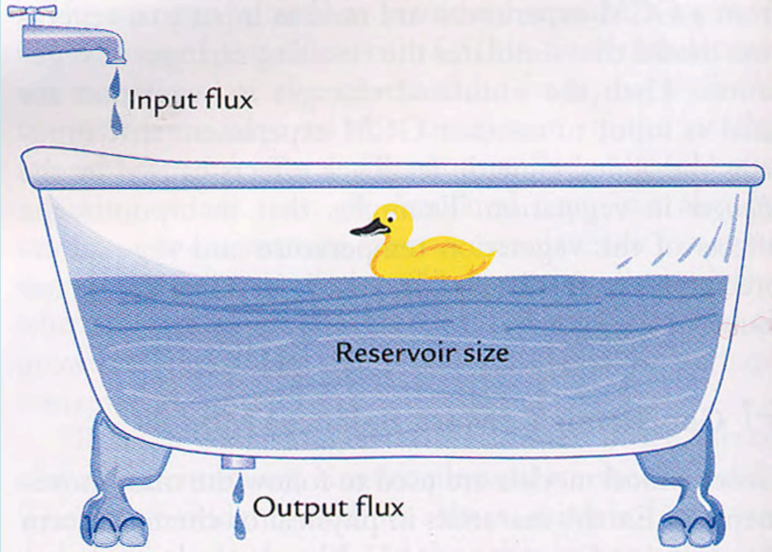
mantel

Fluxes - Material Transport

Fluxes transfer of matter from one reservoir to another. A flux into a reservoir is sometimes referred to as a *source*, a flux out of the reservoir as a *sink*.

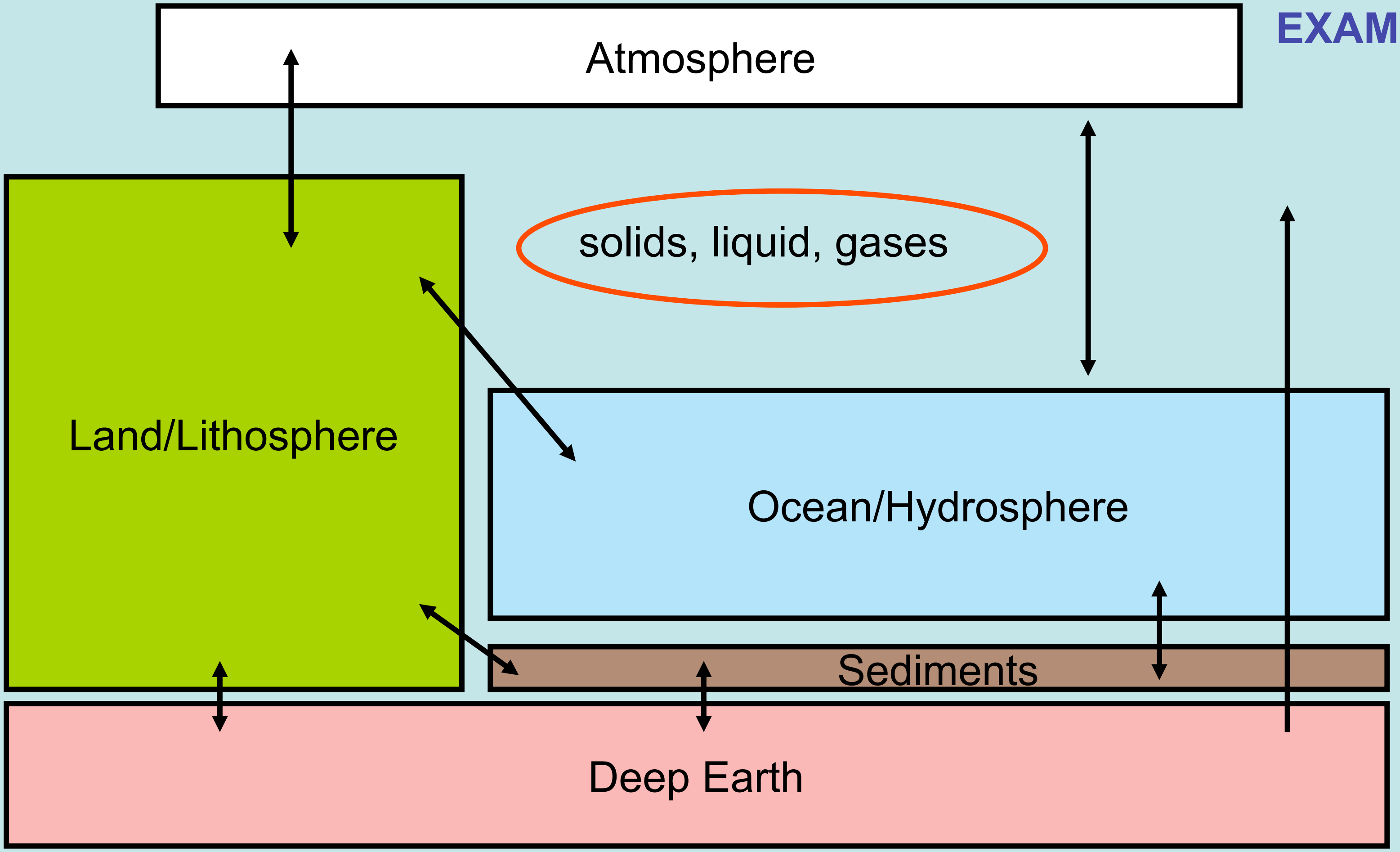
For a perfectly mixed reservoir, the concentration of a component in the outflow is equal to the uniform concentration inside the reservoir.

Biogeochemical Cycles – Matter and energy move all the time at different rates from one earth reservoir to another.



Material Transfer

Matter and energy flow between and within these reservoirs



Atmosphere

EXAMPLES?

solids, liquid, gases

Land/Lithosphere

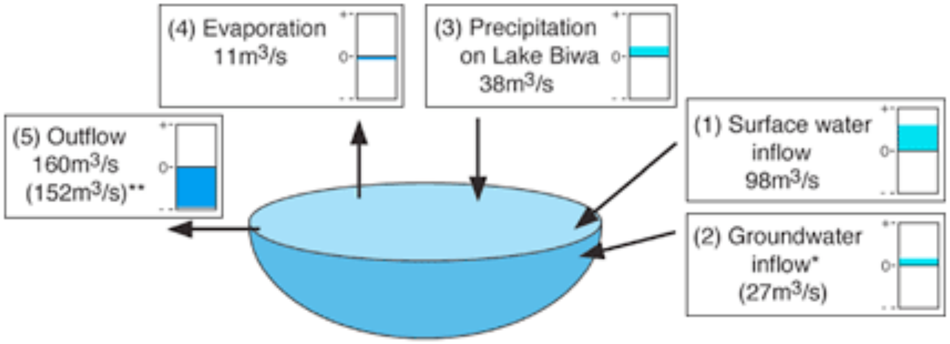
Ocean/Hydrosphere

Sediments

Deep Earth

Representing Biogeochemical Cycles

The two main tasks in depicting a biogeochemical cycle is the definition of the reservoirs and the parameterization of the fluxes. There are no magic guidelines, other than to clearly define the goals of the work and system of investigation and to start as simple as possible. Obviously, it is only possible to provide direct information on reservoirs, fluxes and parameters that are explicitly represented.



* Ground water inflow is still unknown because of few measurement data.

** Outflow of 152 m^3/s is calculated from the balance of surface water inflow, groundwater inflow, precipitation, and evaporation on the lake.

(C)LBERI

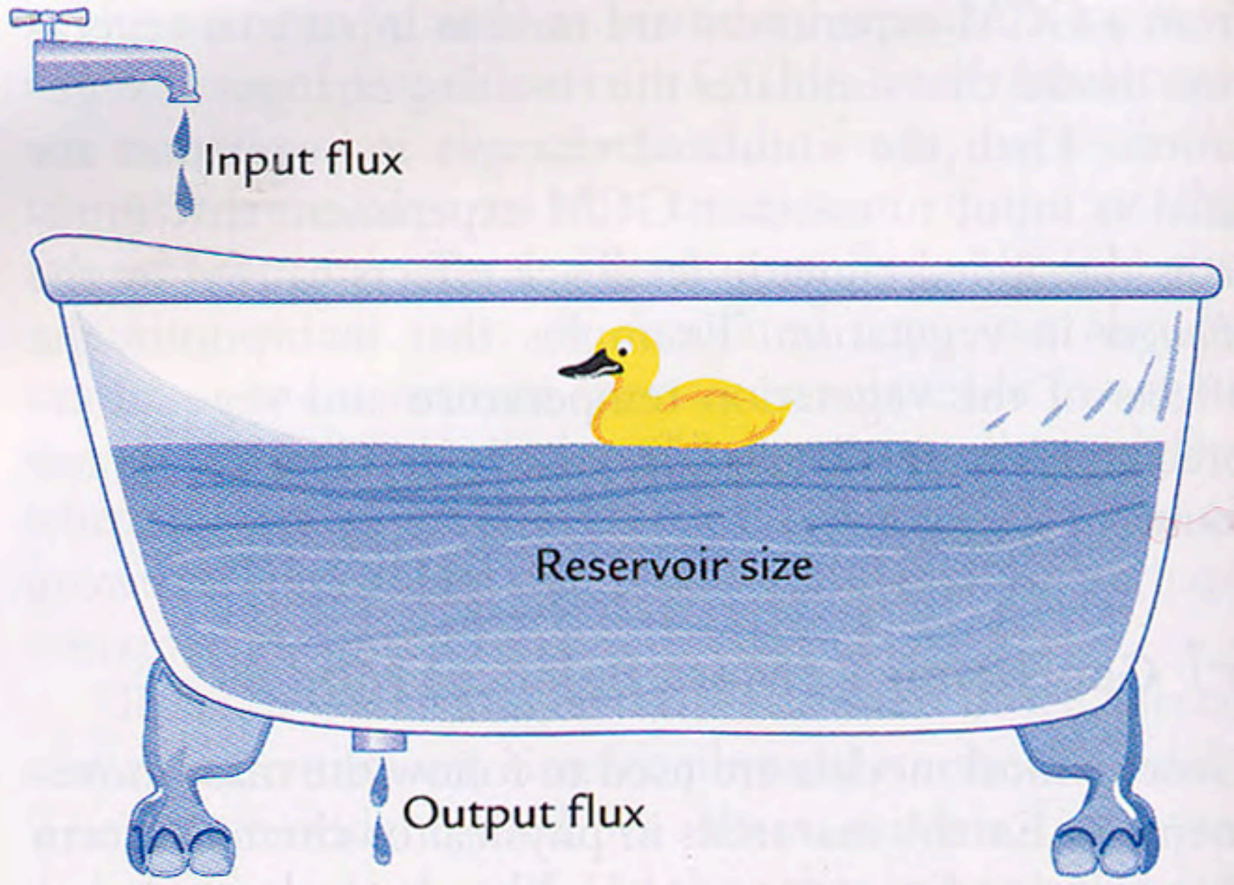
Steady State

Steady-state is a common assumption made about the changes in the components of a system (lack of)

For steady-state:

$\text{Flux}_{in} = \text{Flux}_{out}$

An
equilibrium
state



Residence Time

- **Residence Time** – how quickly a substance cycles through a reservoir (exchange rate)
- **Content** – the total amount of any constituent in a reservoir (standing stock)
- **Capacity** – maximum concentration of a substance a reservoir can reach before saturation occurs
- **Rate of In/outflux** – how much of a substance get into/out a reservoir at a given time.

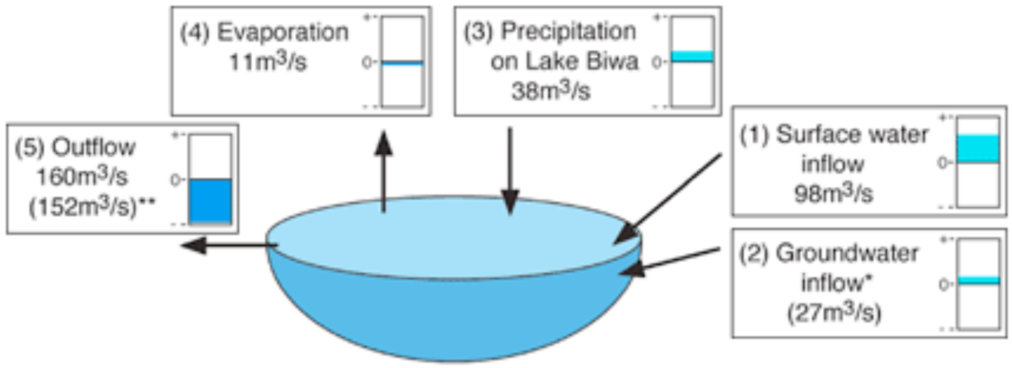
- Residence times for different elements vary widely
- Humans can alter the rate of influx/outflux by our activity (pumping, diversion, adding pollution)

Mass Balance

The turnover time is defined as

$$t_R = \frac{M}{F_{out}}$$

where *M* is the mass of the reservoir (say, the total number of moles of organic carbon in marine biota) and F_{out} is the total flux out of the reservoir (i.e., the sink or source).



* Ground water inflow is still unknown because of few measurement data.
** Outflow of 152 m^3/s is calculated from the balance of surface water inflow, groundwater inflow, precipitation, and evaporation on the lake.

(C)LBERI

Content = 1,000,000 m^3
Input = 163 m^3/s

Residence Time
1,000,000/163 =
6000 seconds = 1.66 hours

Non Steady State Conditions

- In many instances the source (Q) and sink (S) rates are not constant with time or they may have been constant and suddenly change (transient events or perturbation).
- To describe how the mass in a reservoir changes with time after an increase in source (or sink) for a reservoir

Starting with: $dM/dt = Q_0 – S = Q_0 – kM$

We let the input change to a new value Q_1 and we assume that the initial amount at $t = 0$ is M_0.

The new equation is: $dM/dt = Q_1 – kM$

and the solution is: $M(t) = M_1 – (M_1 – M_0) \exp(-kt)$

This describes how M changes from M_0 to the new equilibrium value M_1 ($= Q_1 / k$) with a response time equal to k^{-1}.

For constant exponential change $Q = Q_0 \exp[m (t – t_0)]$

The solution for dM/dt for these conditions is:

$M = M_0 \{(m/m+k) \exp[-k (t-t0)] + k / m+k \exp[m (t-t_0)]\}$ for $t_0 < t < t_1$

Reactive Transport Models

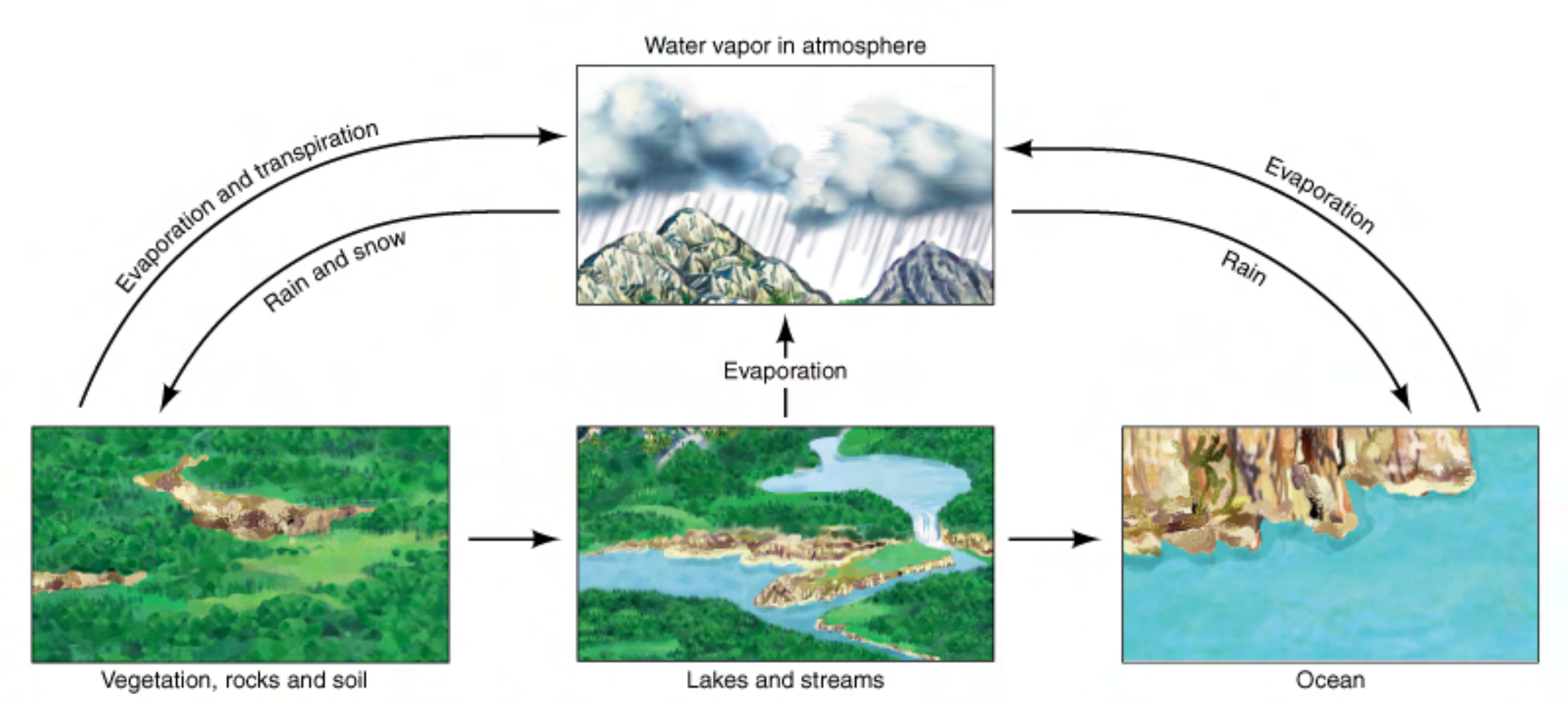
Reactive transport models

$$\frac{dC_{res}}{dt} = \frac{1}{\bar{t}_f}(C_{in} - C_{res}) + R$$

For a system with a single inlet and a single outlet

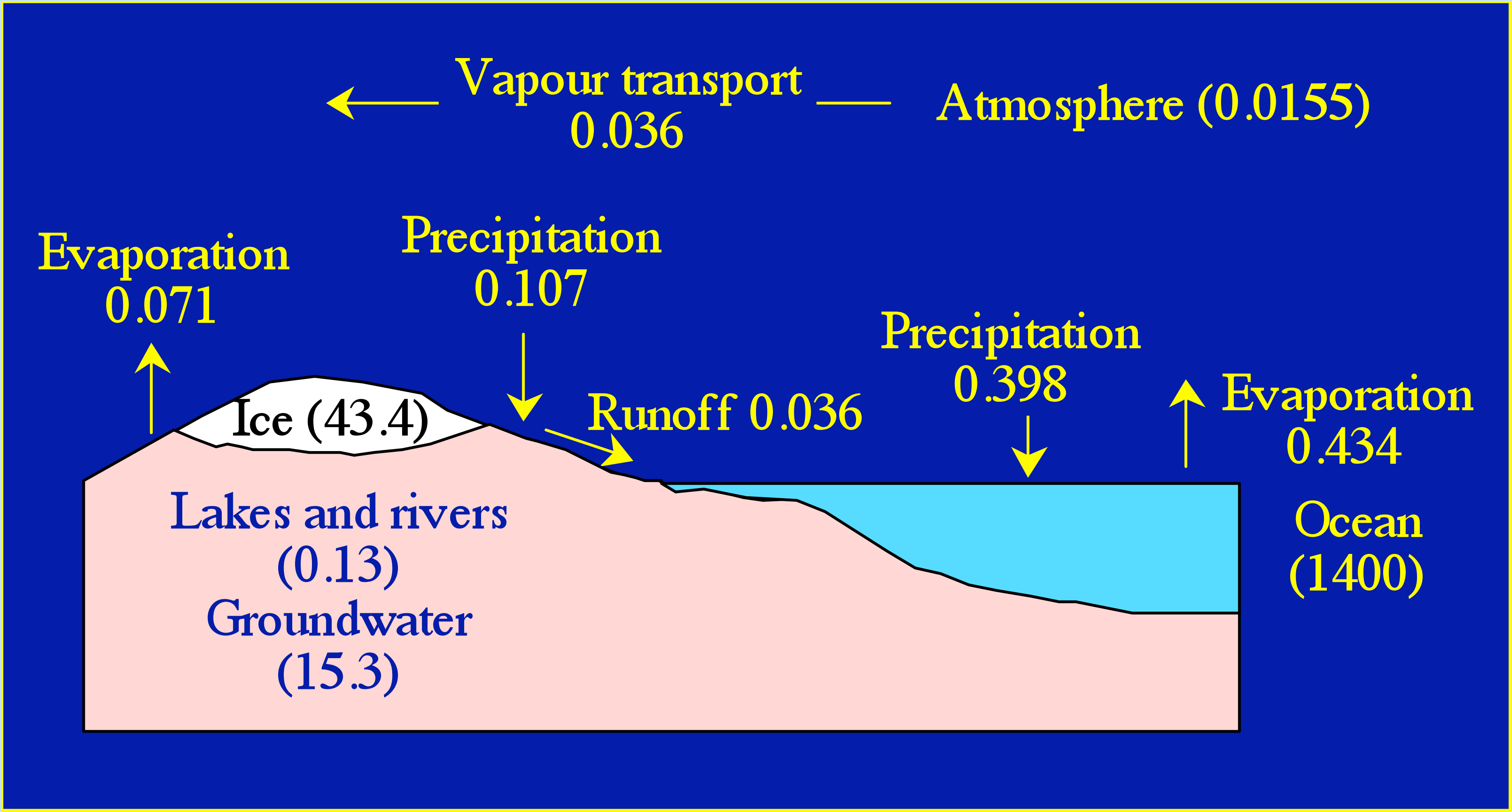
where C_{in} is the concentration of the species in the inflow, R is the rate, per unit volume, at which the species is produced in the system (note: when the species is being consumed R is negative), and t_f is the mean residence time (or transit time) of the carrier fluid in the system.

Box models - Reservoirs and Fluxes



Changes in the Water Cycle

Box models - Reservoirs and Fluxes



Vapour transport
0.036

Atmosphere (0.0155)

Evaporation
0.071

Precipitation
0.107

Ice (43.4)

Runoff 0.036

Precipitation
0.398

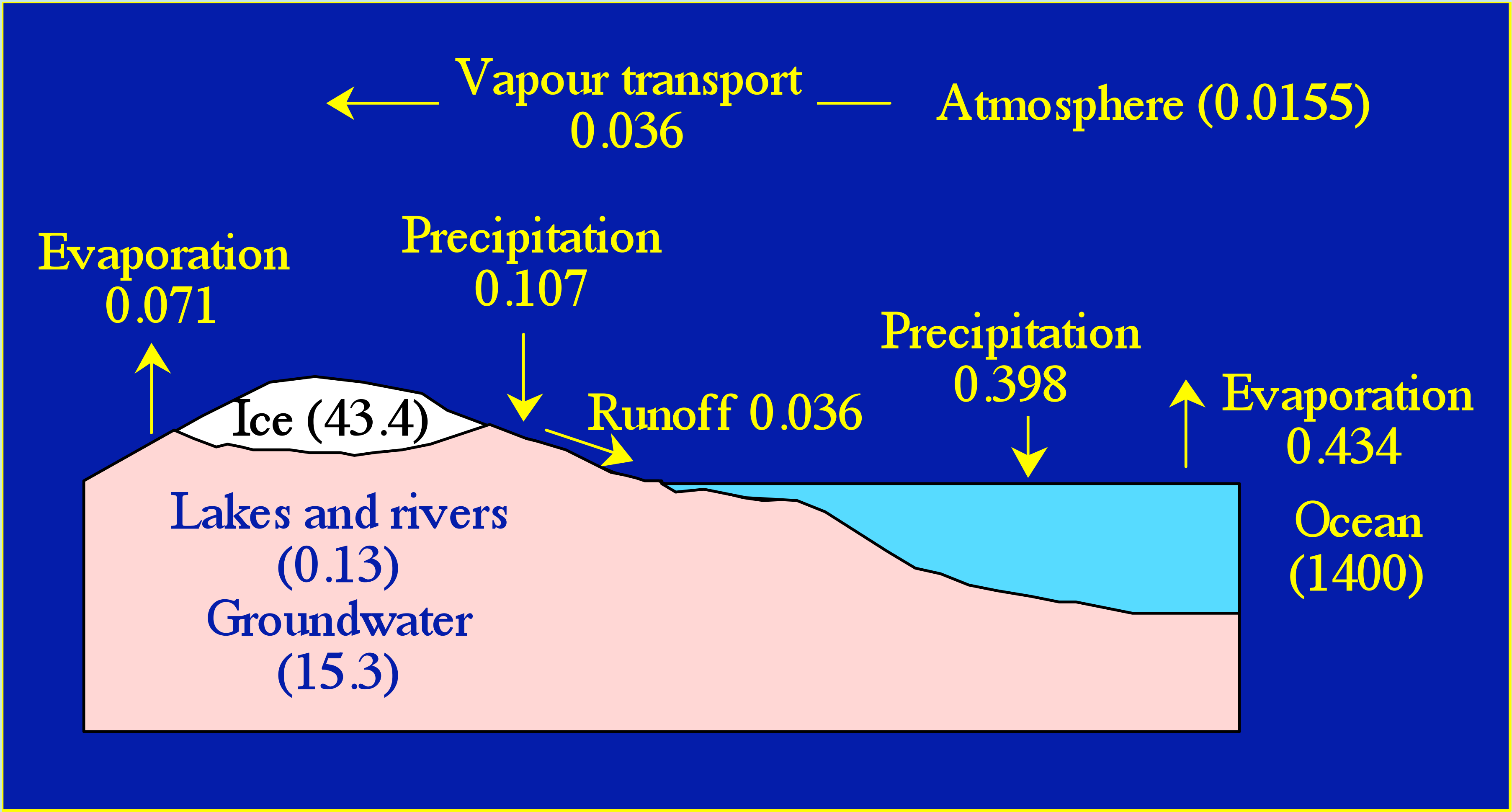
Evaporation
0.434

Lakes and rivers
(0.13)
Groundwater
(15.3)

Ocean
(1400)

Reservoir total inventories (in brackets) in units of 10^6 km^3.
Fluxes in units of 10^6 km^{3}yr^{-1} .

Box models - Reservoirs and Fluxes

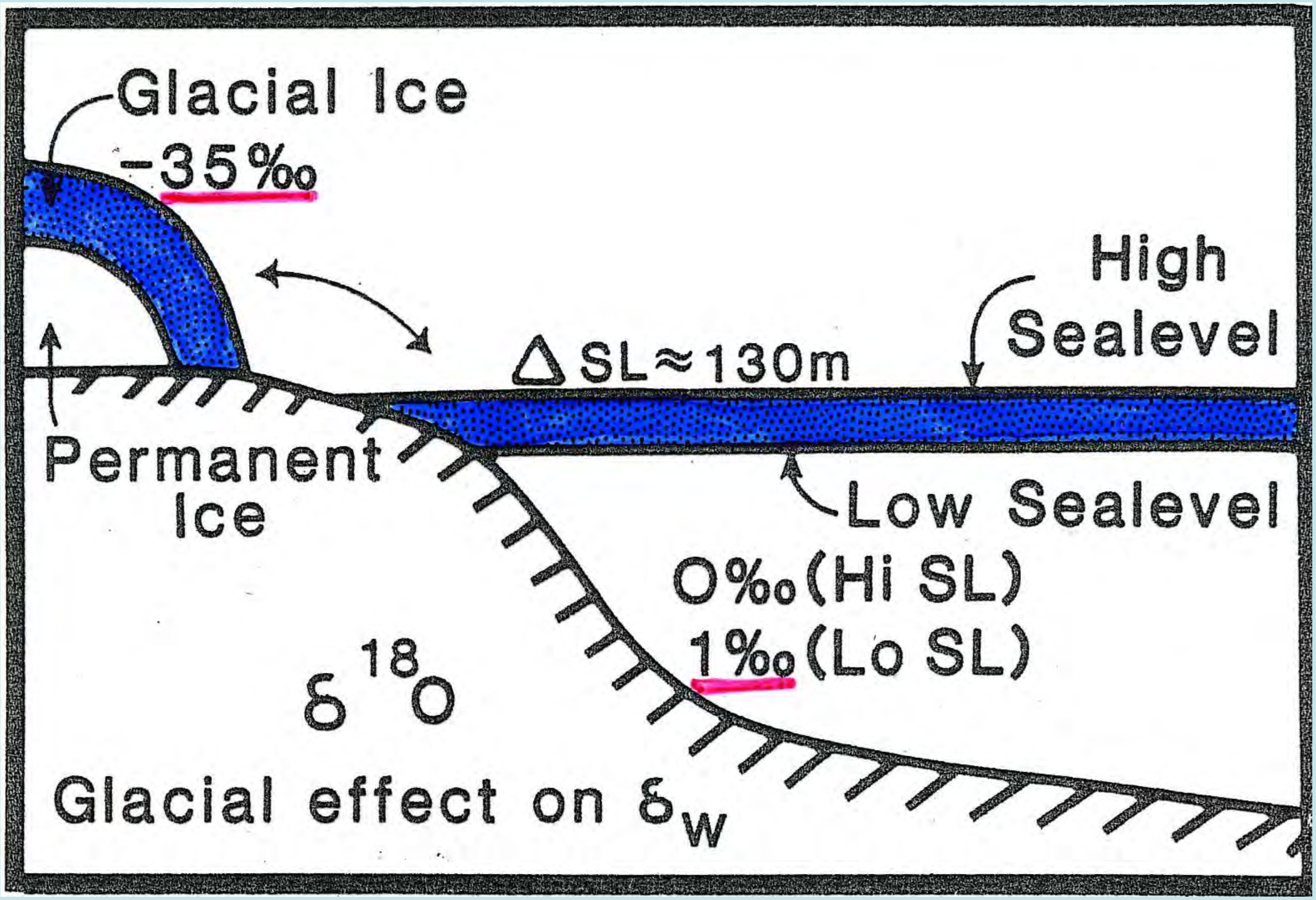


Ocean

Flux in = 0.398 (precipitation) + 0.036 (runoff) = 0.434

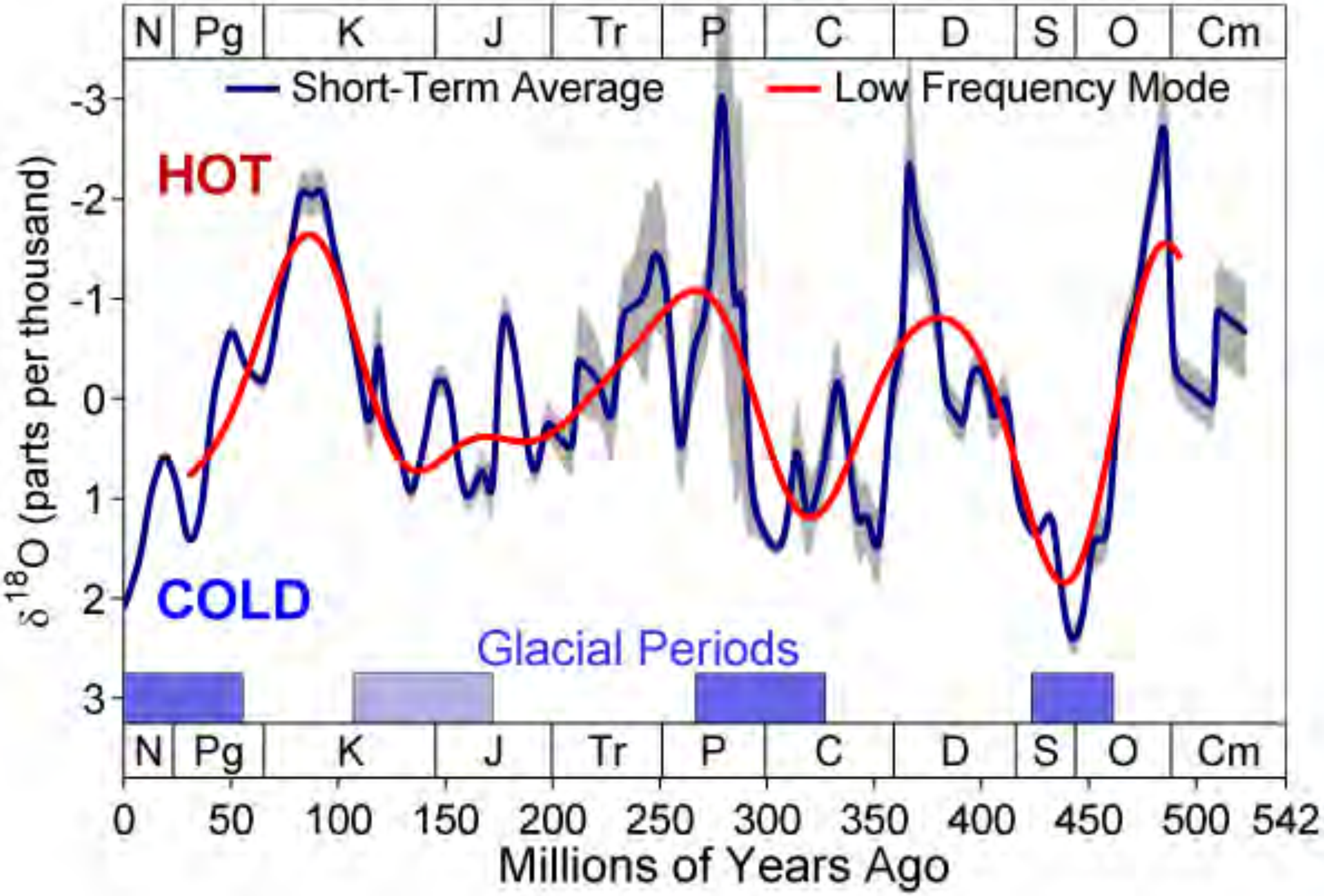
Flux out = 0.434 (evaporation)

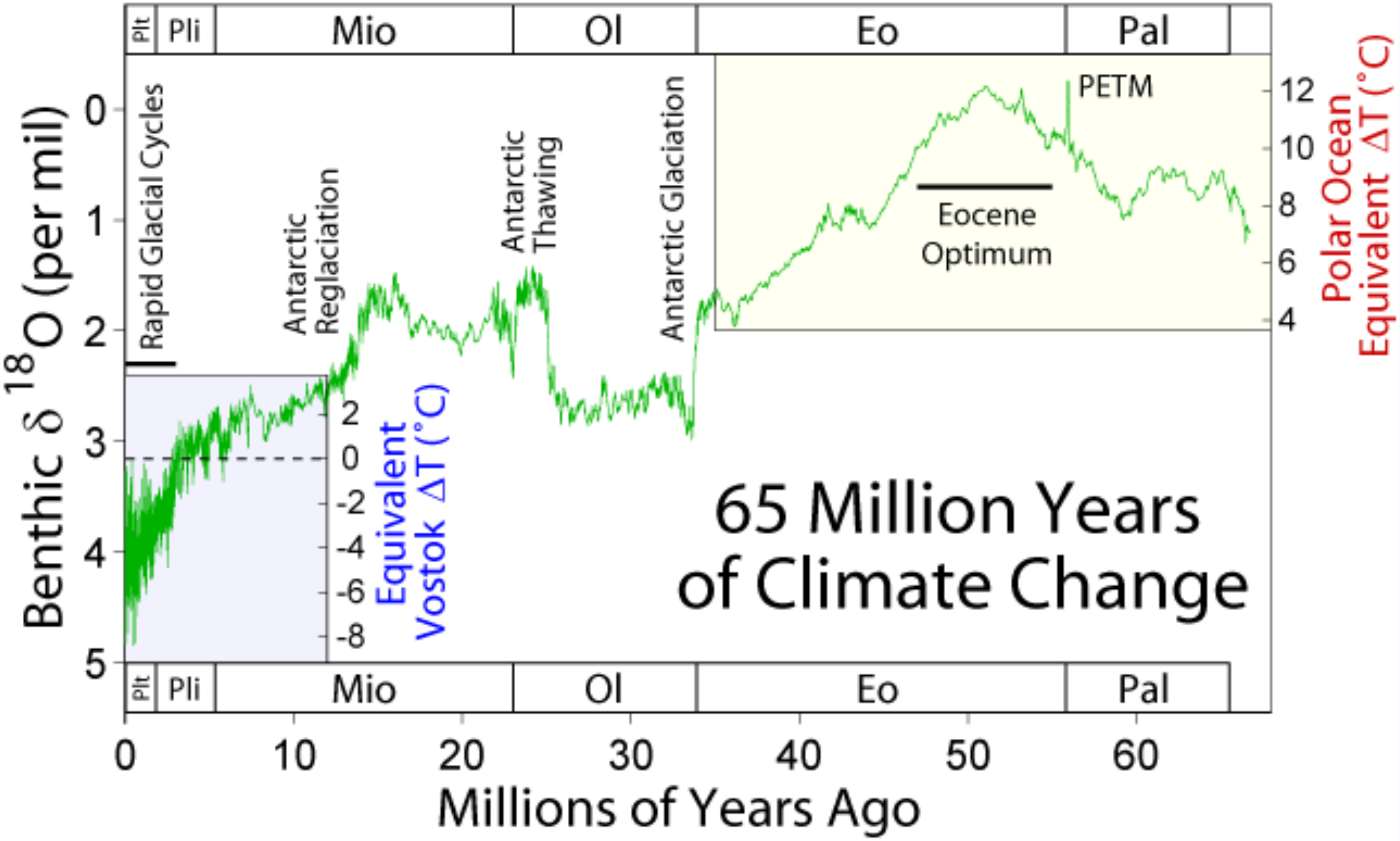
Residence Time 1400/0.434 = 3200 years

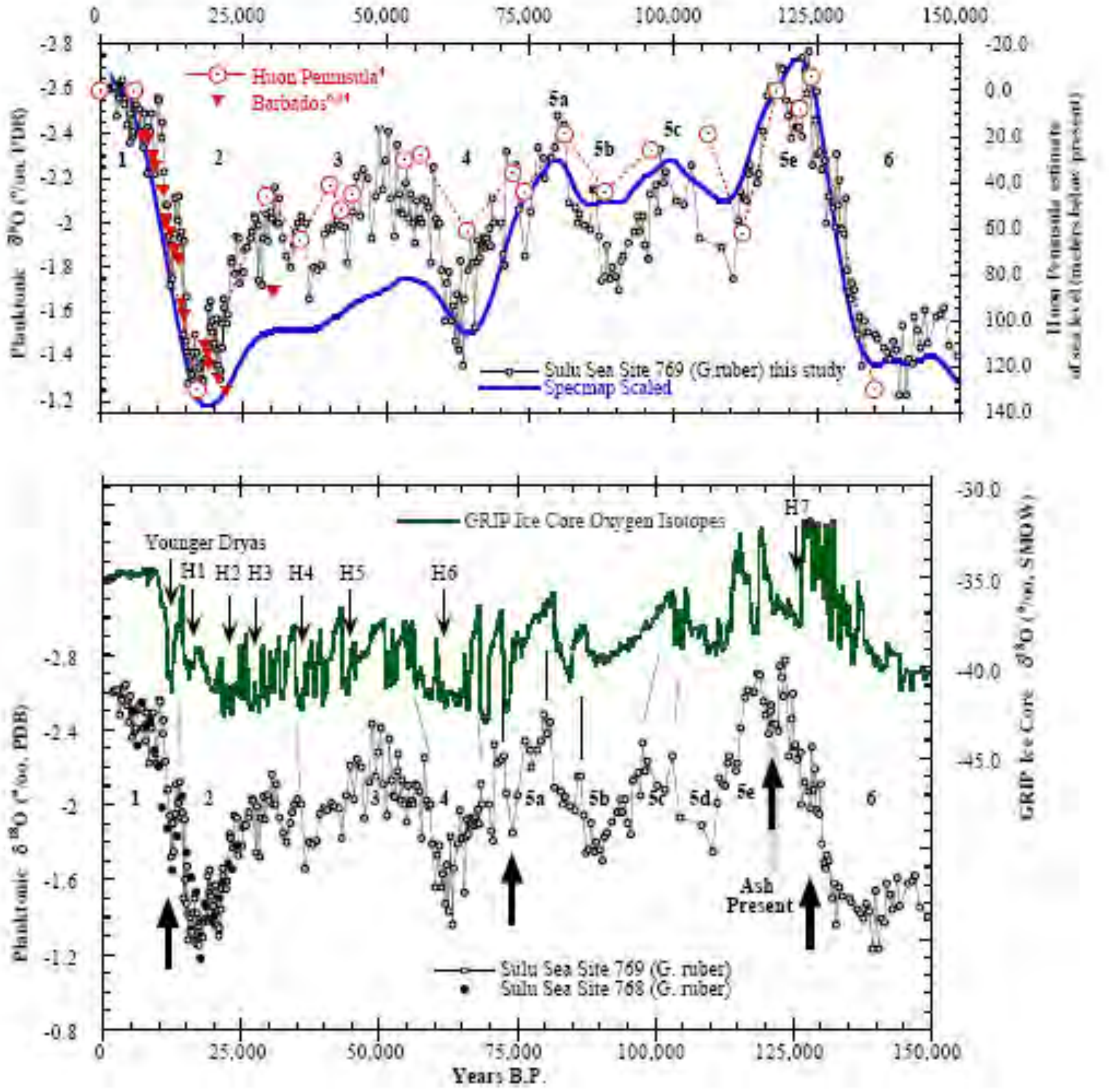


Oxygen isotope fluctuations in seawater as recorded in marine sediments can be indicative of ice volume and thus sea level changes. Temperature effects will be included as well. Indicative of exchange among water reservoirs.

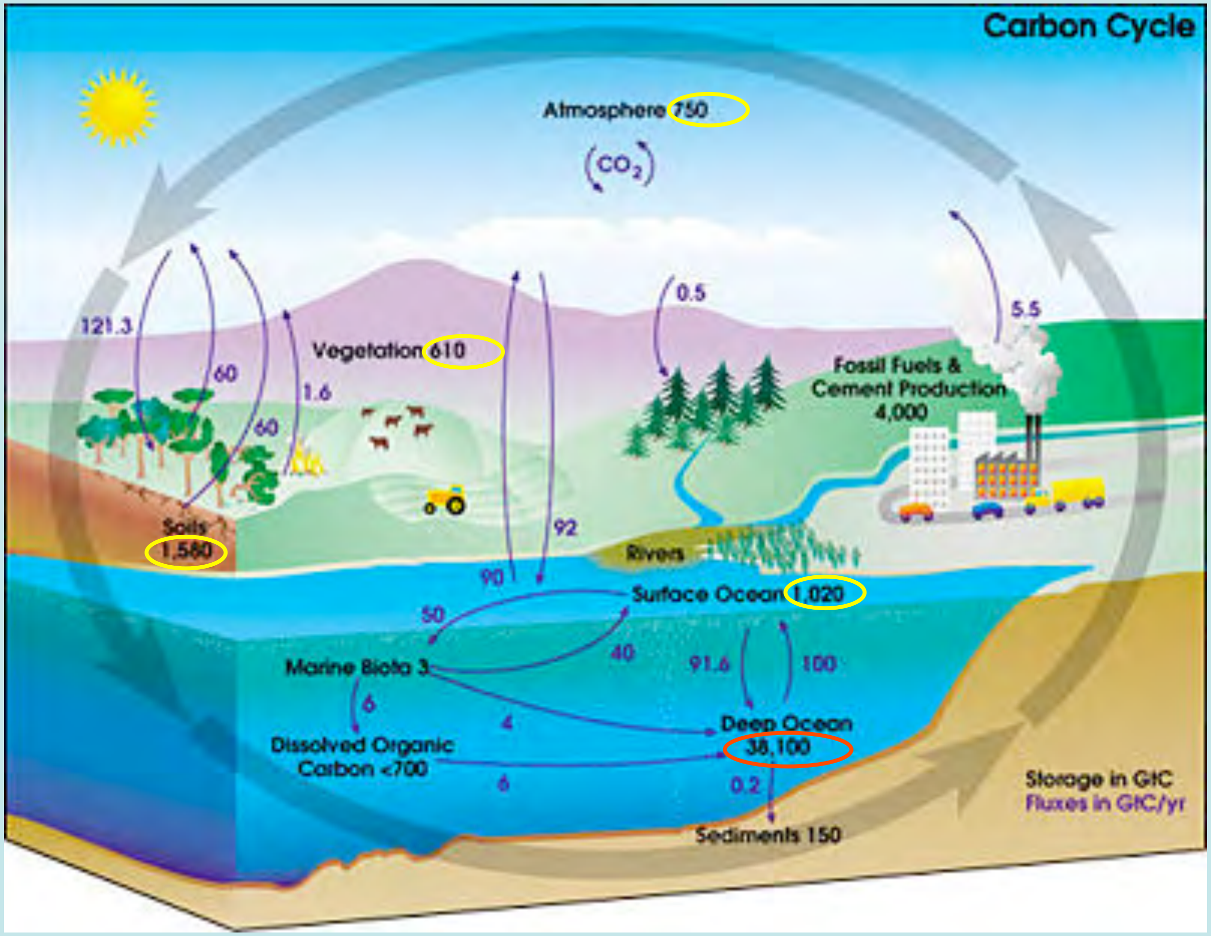
Phanerozoic Climate Change




65 Million Years of Climate Change
Plt
Pli
Mio
Ol
Eo
Pal
Benthic $\delta^{18}O$ (per mil)
0
1
2
3
4
5
Rapid Glacial Cycles
Antarctic Reglaciation
Antarctic Thawing
Antarctic Glaciation
PETM
Eocene Optimum
Equivalent Vostok ΔT (°C)
2
0
-2
-4
-6
-8
Polar Ocean Equivalent ΔT (°C)
12
10
8
6
4
0
10
20
30
40
50
60
Millions of Years Ago


Huon Peninsula¹
Barbados
Sulu Sea Site 769 (G.ruber) this study
Specmap Scaled
Planktonic δ¹⁸O (°/oo, PDB)
Huon Peninsula estimate of sea level (meters below present)
1
2
3
4
5a
5b
5c
5e
6
0
25,000
50,000
75,000
100,000
125,000
150,000
-2.8
-2.6
-2.4
-2.2
-2
-1.8
-1.6
-1.4
-1.2
-20.0
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
GRIP Ice Core Oxygen Isotopes
Younger Dryas
H1
H2
H3
H4
H5
H6
H7
5d
Ash Present
Sulu Sea Site 769 (G. ruber)
Sulu Sea Site 768 (G. ruber)
Planktonic δ¹⁸O (°/oo, PDB)
GRIP Ice Core δ¹⁸O (°/oo, SMOW)
-0.8
-30.0
-35.0
-40.0
-45.0
Years B.P.

The Carbon Cycle



The black numbers indicate how much carbon is stored in various reservoirs, in billions of tons (GigaTons, circa 2004). The purple numbers indicate how much carbon moves between reservoirs each year. The sediments, as defined in this diagram, do not include the ~70 million GtC of carbonate rock and kerogen.

The Carbon Cycle

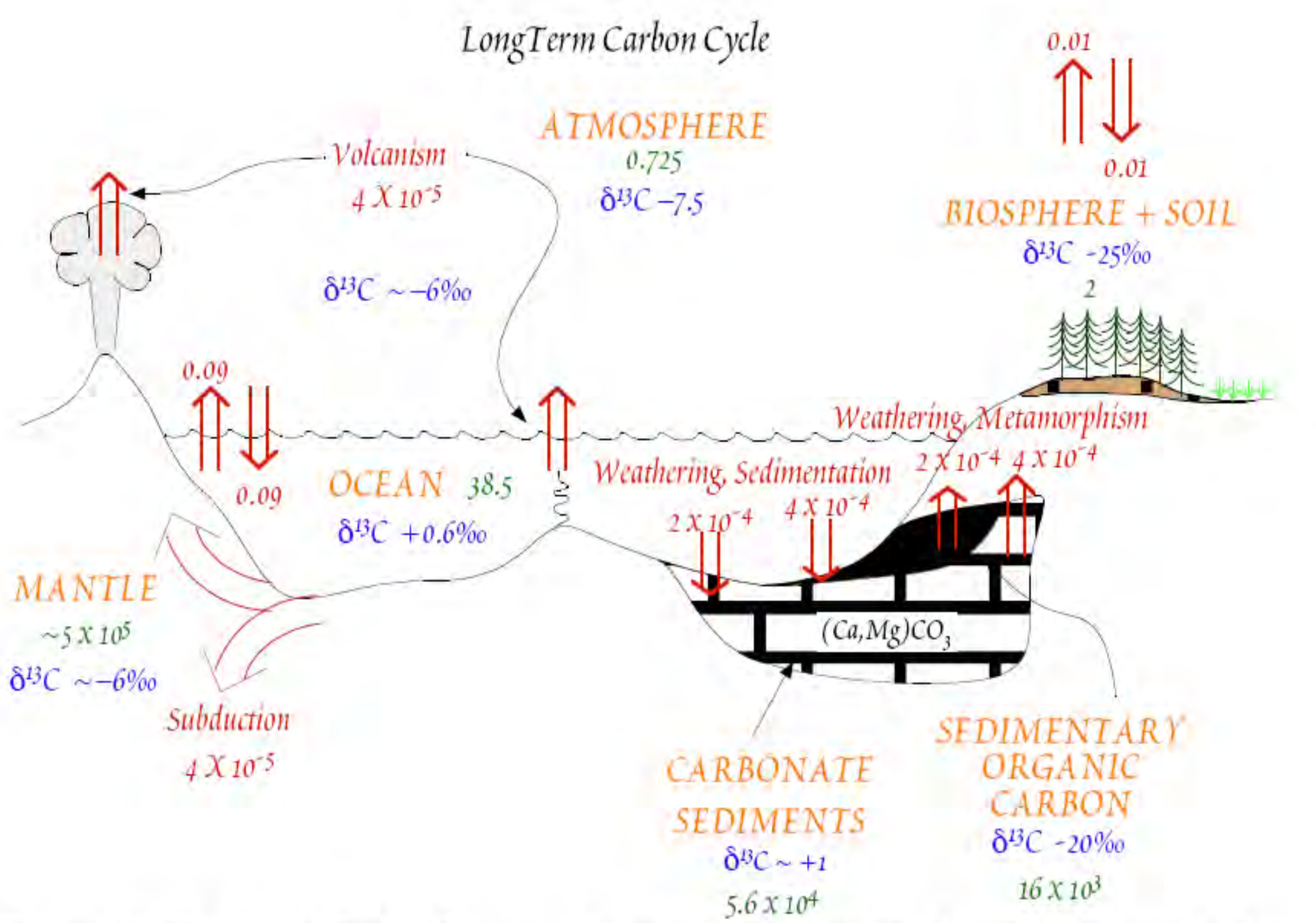
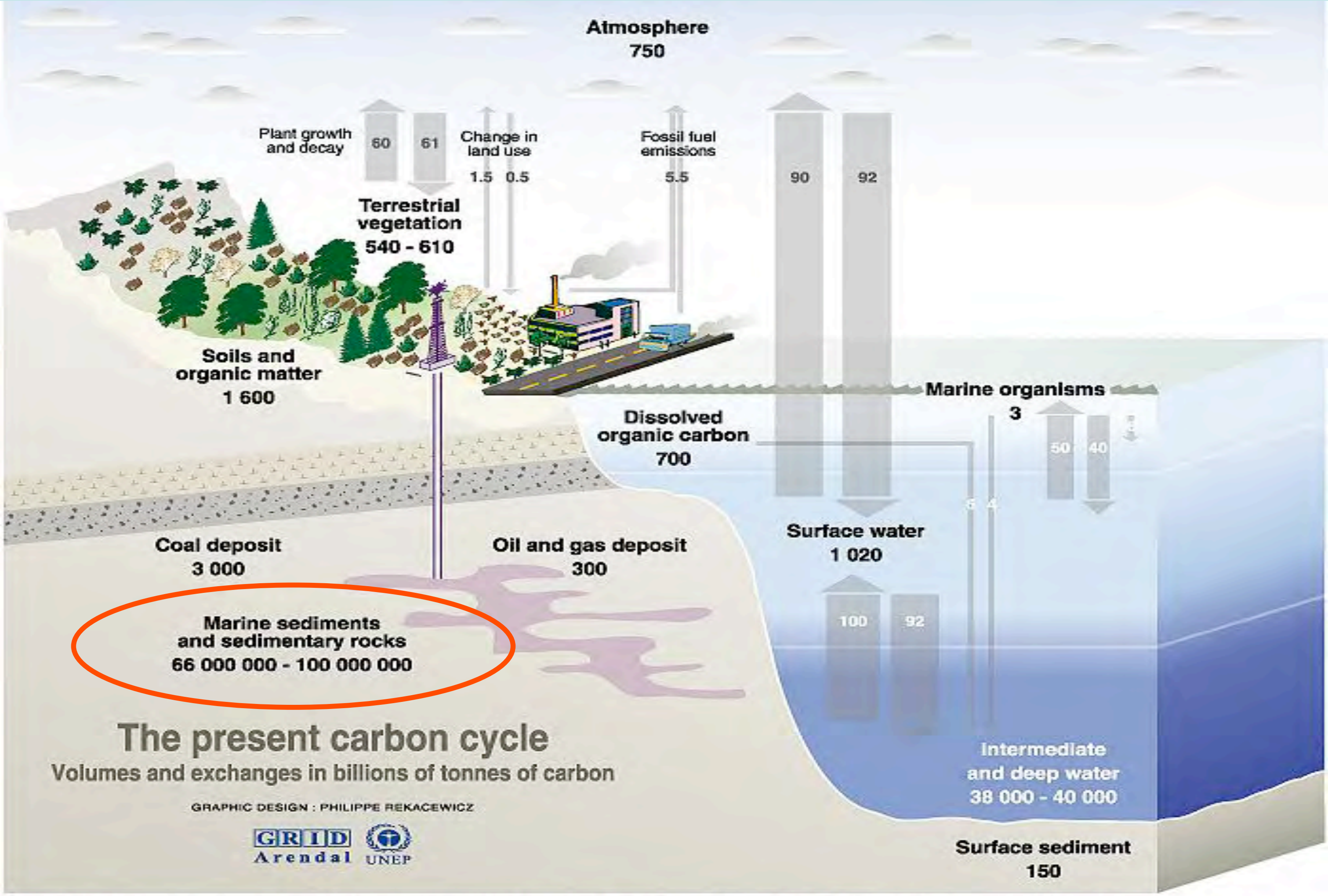


Figure 38.1. The Carbon Cycle. Green numbers show the amount of carbon (in 10^{18} grams) in the reservoirs. Fluxes between these reservoirs (arrows) are shown in italics in units of 10^{18} g/yr (in red). Masses and fluxes refer to the pre-Industrial Revolution state of the system. Uncertainties on many of the masses and fluxes are large. Also shown are estimates of the carbon isotopic composition.

On geologic times scales, the carbon cycle model can be augmented by 3 reservoirs, sedimentary carbonate, sedimentary organic carbon, and the mantle, as well as fluxes between these reservoirs and the oceans and atmosphere.

The Carbon Cycle



The present carbon cycle

Volumes and exchanges in billions of tonnes of carbon

Sources: Center for climatic research, Institute for environmental studies, university of Wisconsin at Madison; Okanagan university college in Canada, Department of geography; World Watch, November-December 1998; Climate change 1995, The science of climate change, contribution of working group 1 to the second assessment report of the intergovernmental panel on climate change, UNEP and WMO, Cambridge press university, 1996.

The Carbon Cycle

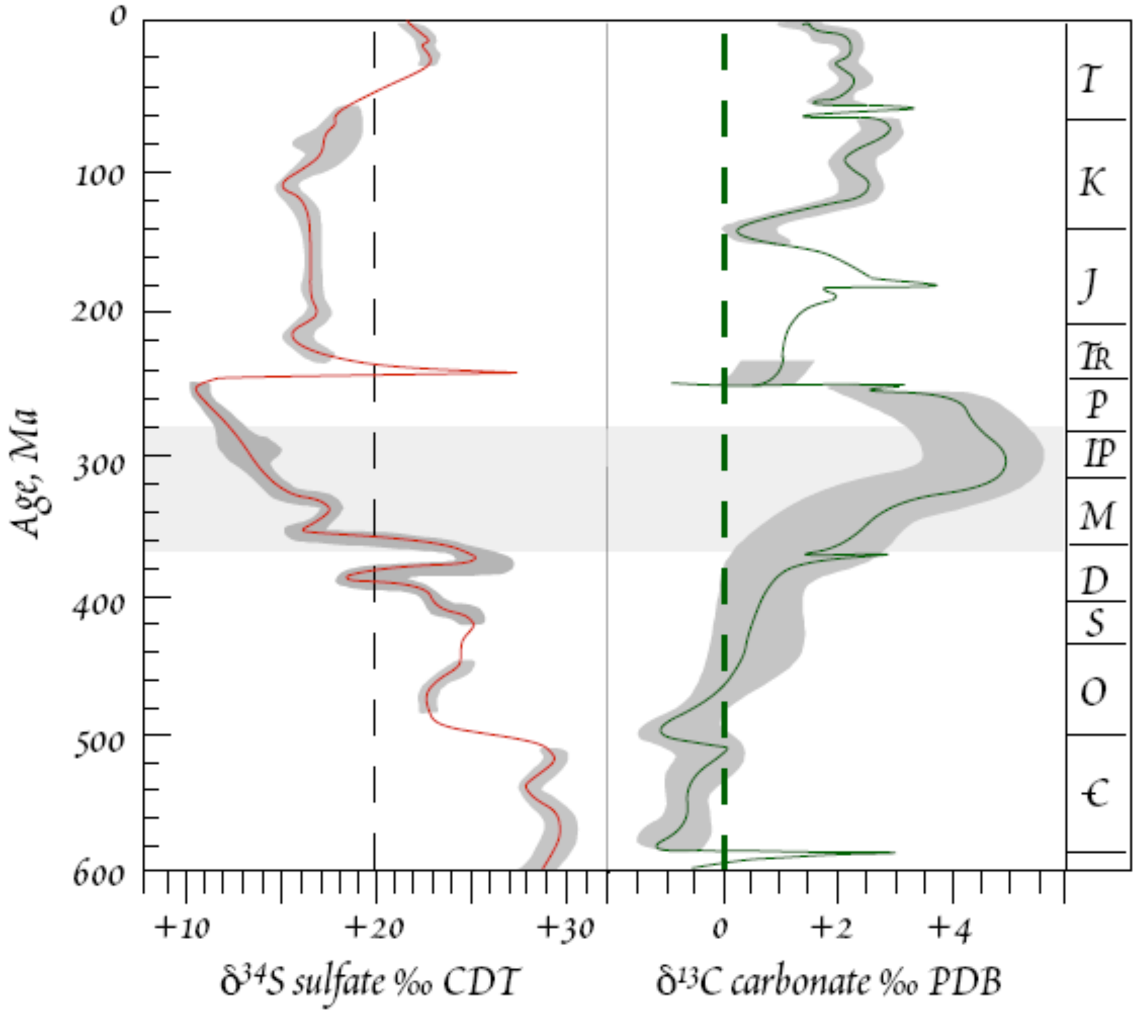
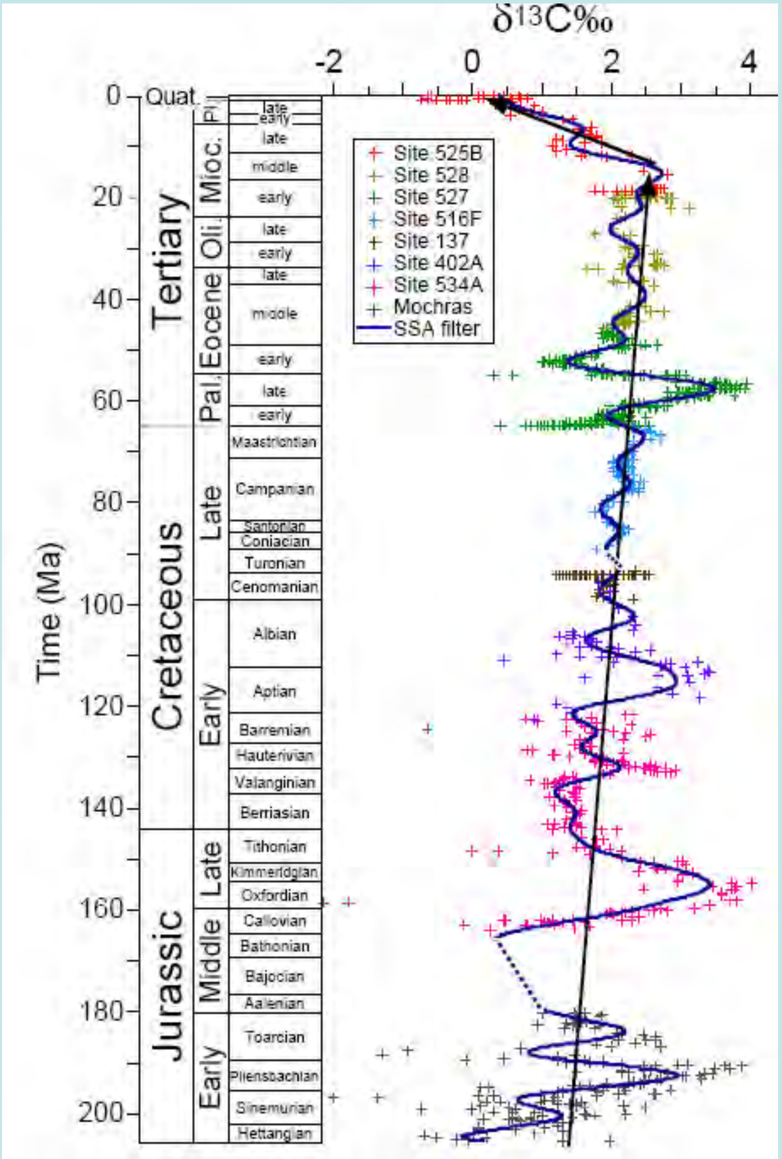


Figure 38.3. Isotopic compositions of carbon and sulfur in the oceans through Phanerozoic time. After Holser (1984).

When more C is removed into the reduced organic C reservoir residual C in the ocean and carbonates becomes enriched in ^{13}C (heavy) and atmospheric CO_2 is lower and O_2 is higher (less consumed for oxidation).

The Carbon Cycle



The long-term increases in δ^{13}Ccarb (e.g. more organic C burial) that began in the Mesozoic were accompanied by major evolutionary changes among the primary producers in the marine biosphere. Three groups of eucaryotic marine phytoplankton (calcareous nannoplankton, dinoflagellates, and diatoms) began their evolutionary trajectories to ecological prominence at ~ 200 Ma. As Pangea fragmented and the Atlantic Ocean basin widened, the total length of coastline increased and sea level rose, flooding continental shelves and low-lying continental interiors. Nutrients that were previously locked up in the large continental interior were transported to newly formed shallow seas and distributed over wider shelf areas and longer continental margins.

Katz et al., 2005

The Carbon Cycle

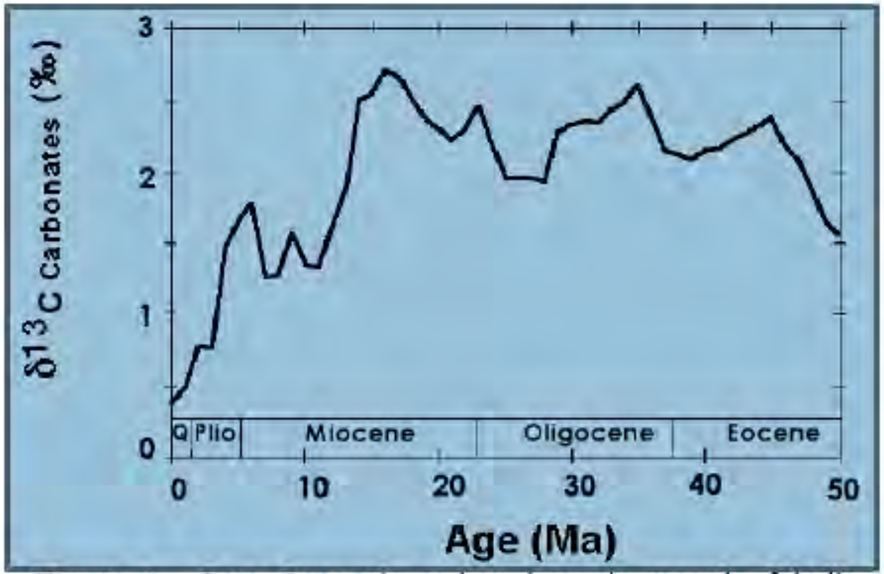


Figure 1. Late Cenozoic carbon isotopic record of bulk marine carbonate averaged in million year increments. Data from *Shackleton and Hall* [1984]

The decline since the late Miocene in addition to changes in ocean circulation could be related to the evolution of C4 plants (less fractionation in organic C burial).

Large perturbations in the global C cycle.
Gas hydrate ?

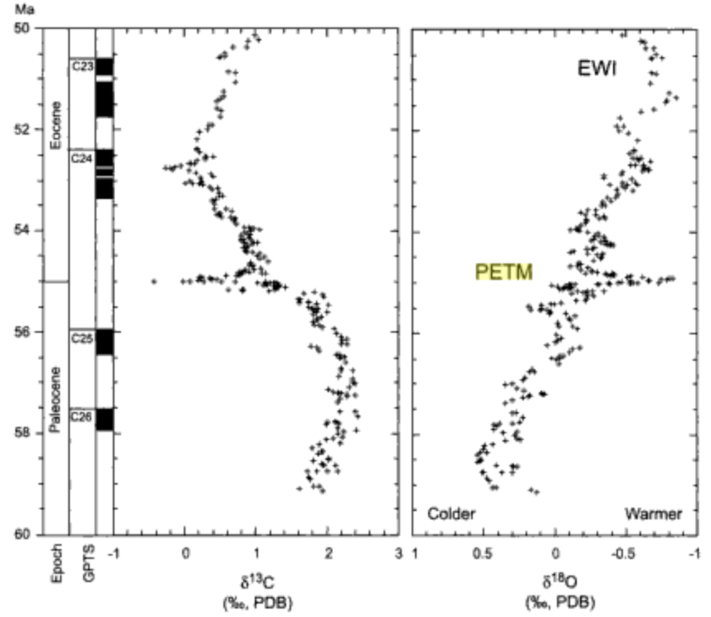
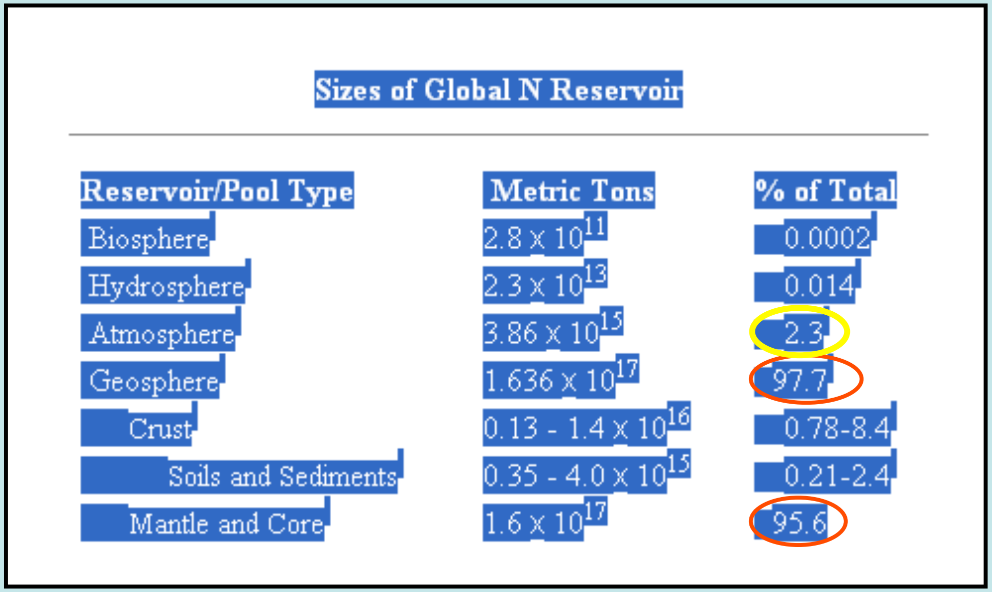


Figure 1. Carbon and oxygen isotope data for benthic foraminifera spanning the Paleocene-Eocene boundary. The figure is based on data compiled in Zachos et al. (2001). EWI—Eocene Warm Interval; GPTS—geomagnetic polarity time scale; PDB—Peedee belemnite; PETM—Paleocene-Eocene Thermal Maximum.

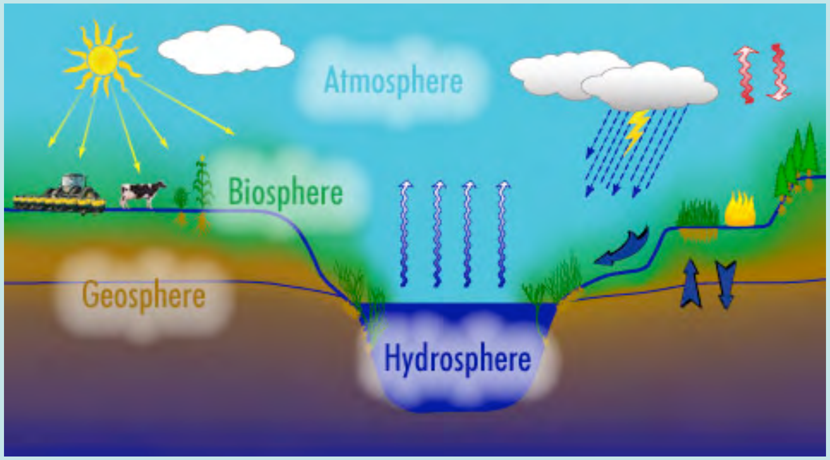
The Nitrogen Cycle

N is present in many chemical forms, both organic and inorganic, in the atmosphere, biosphere, hydrosphere, and geosphere. It occurs in the gas, liquid (dissolved in water), and solid phases. N can be associated with organic species and with inorganic species. Important inorganic species include N_2, nitric acid (HNO_3), nitrate (NO^{3-}), nitrite (NO^{2-}), nitrous oxide (N_2O), nitric oxide (NO), N dioxide (NO_2), ammonium (NH^{4+}), and ammonia (NH_3). Most organic N species are bio-molecules, such as proteins, peptides, enzymes, and genetic material (RNA and DNA). NO^{3-} and organic-N species exist in solution and as particulates.



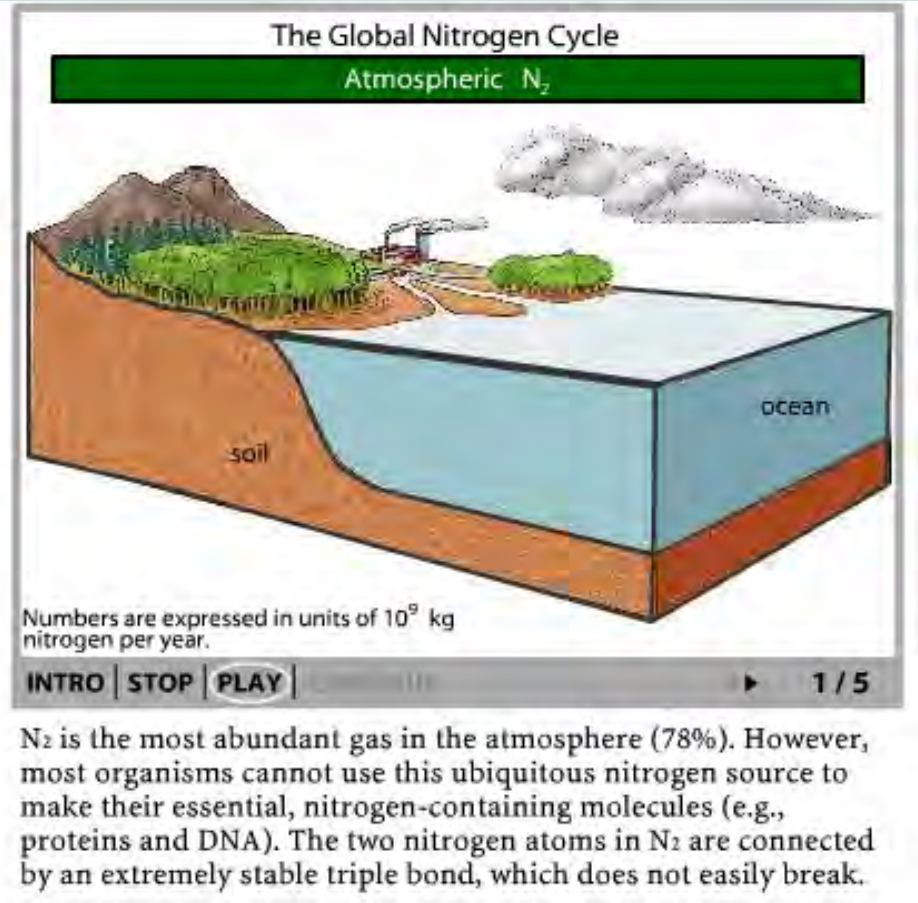
Sizes of Global N Reservoir

Reservoir/Pool Type	Metric Tons	% of Total
Biosphere	2.8×10^{11}	0.0002
Hydrosphere	2.3×10^{13}	0.014
Atmosphere	3.86×10^{15}	2.3
Geosphere	1.636×10^{17}	97.7
Crust	$0.13 - 1.4 \times 10^{16}$	0.78-8.4
Soils and Sediments	$0.35 - 4.0 \times 10^{15}$	0.21-2.4
Mantle and Core	1.6×10^{17}	95.6

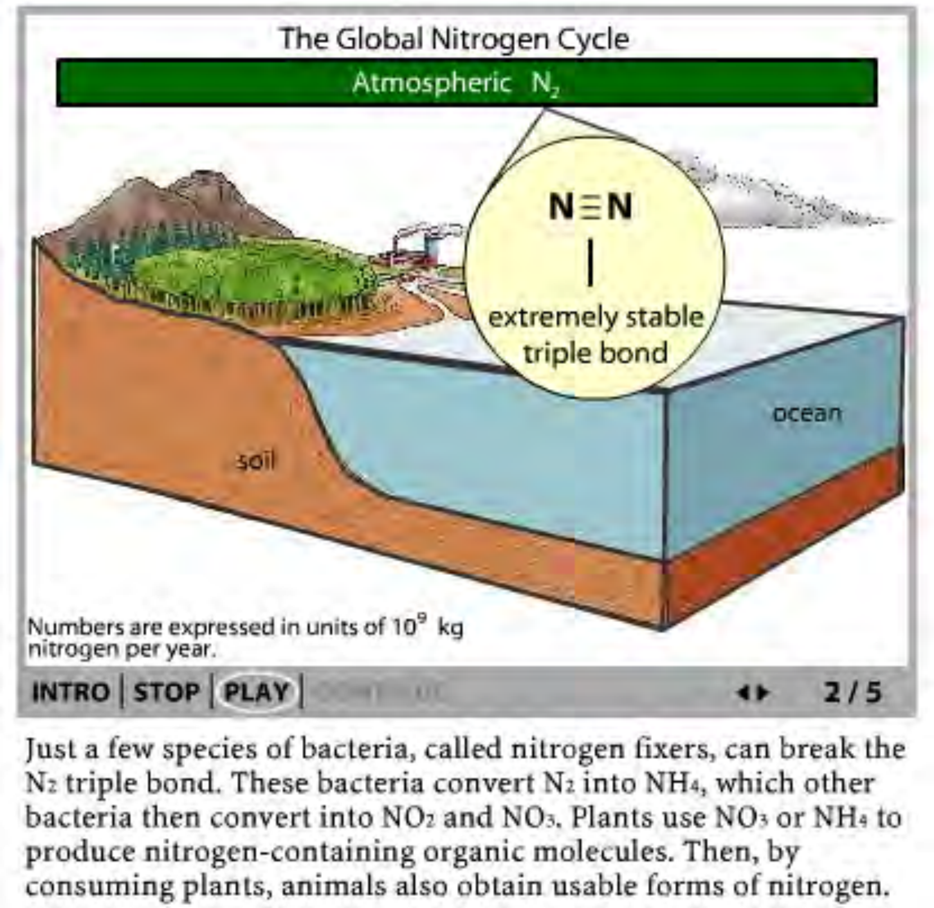


No evidence for change in atmospheric N_2

The Nitrogen Cycle

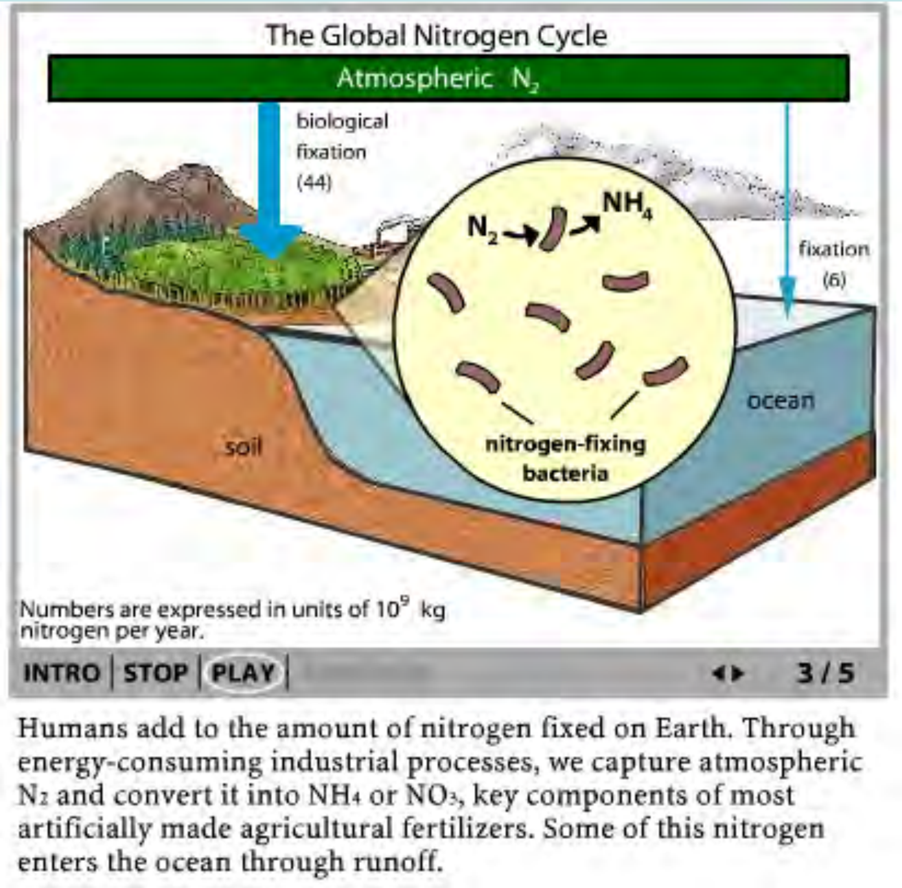


N_2 is the most abundant gas in the atmosphere (78%). However, most organisms cannot use this ubiquitous nitrogen source to make their essential, nitrogen-containing molecules (e.g., proteins and DNA). The two nitrogen atoms in N_2 are connected by an extremely stable triple bond, which does not easily break.



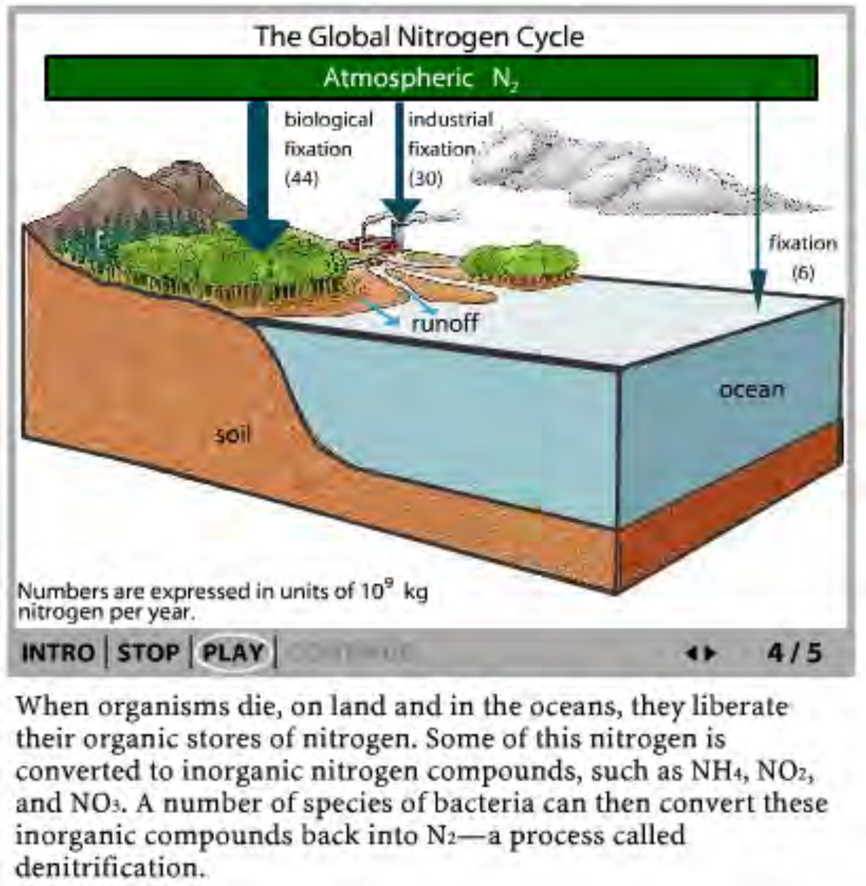
Just a few species of bacteria, called nitrogen fixers, can break the N_2 triple bond. These bacteria convert N_2 into NH_4, which other bacteria then convert into NO_2 and NO_3. Plants use NO_3 or NH_4 to produce nitrogen-containing organic molecules. Then, by consuming plants, animals also obtain usable forms of nitrogen.

The Nitrogen Cycle



Numbers are expressed in units of 10^9 kg nitrogen per year.

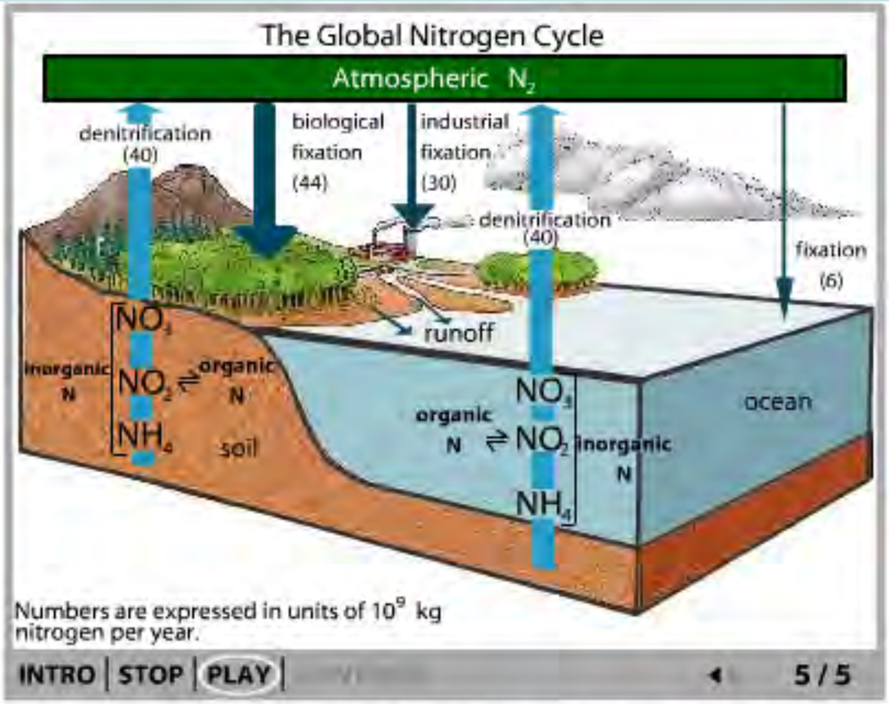
Humans add to the amount of nitrogen fixed on Earth. Through energy-consuming industrial processes, we capture atmospheric N_2 and convert it into NH_4 or NO_3, key components of most artificially made agricultural fertilizers. Some of this nitrogen enters the ocean through runoff.



Numbers are expressed in units of 10^9 kg nitrogen per year.

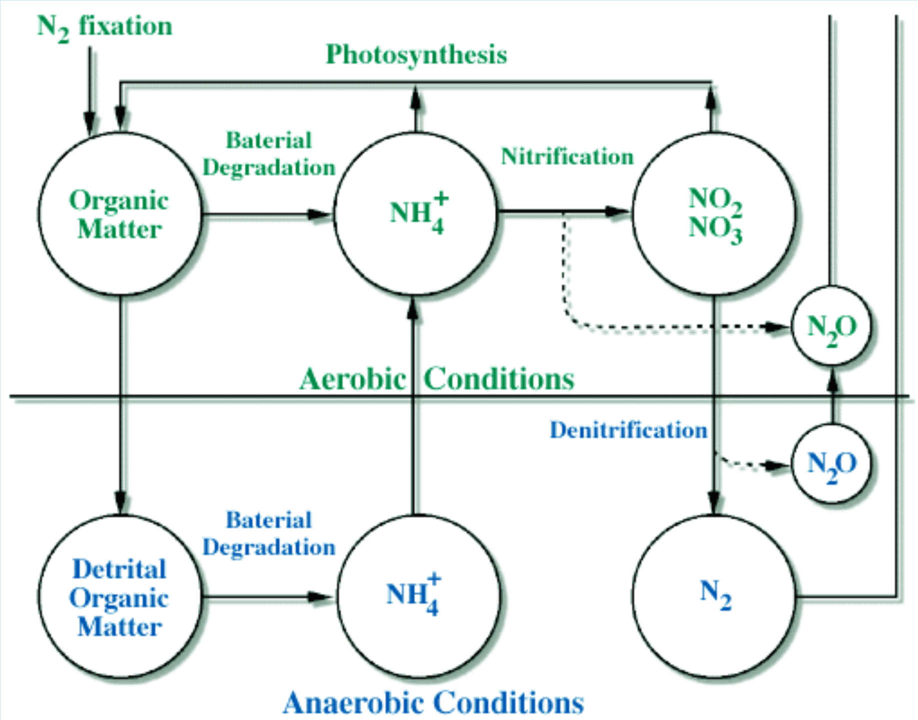
When organisms die, on land and in the oceans, they liberate their organic stores of nitrogen. Some of this nitrogen is converted to inorganic nitrogen compounds, such as NH_4, NO_2, and NO_3. A number of species of bacteria can then convert these inorganic compounds back into N_2—a process called denitrification.

The Nitrogen Cycle

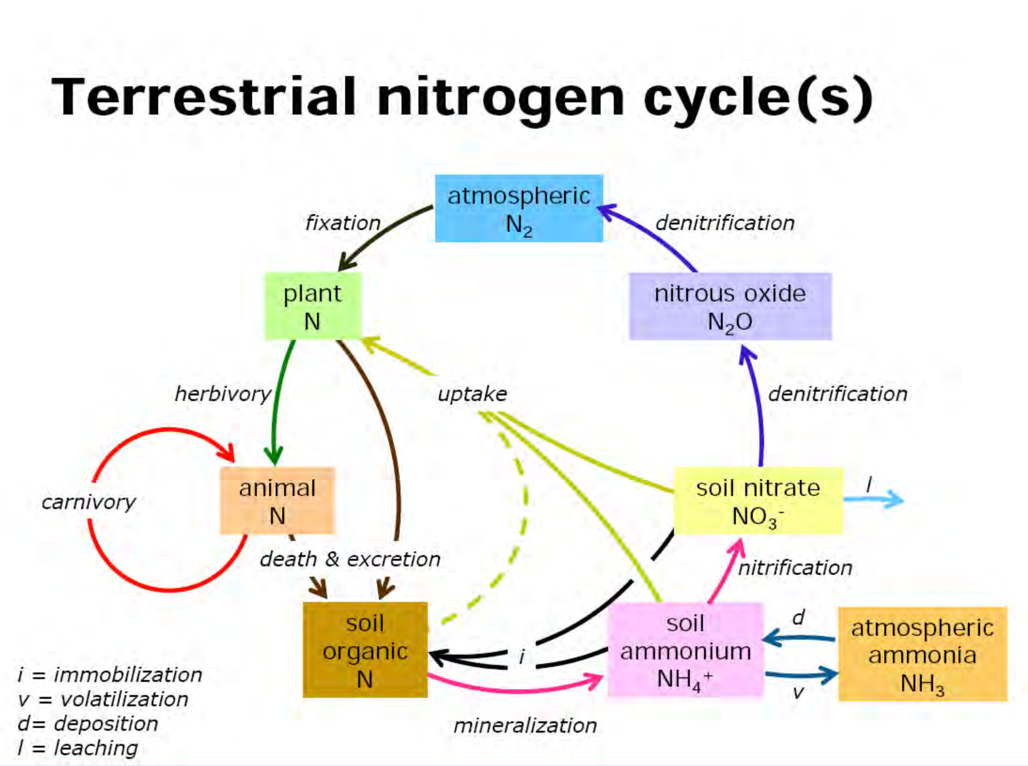


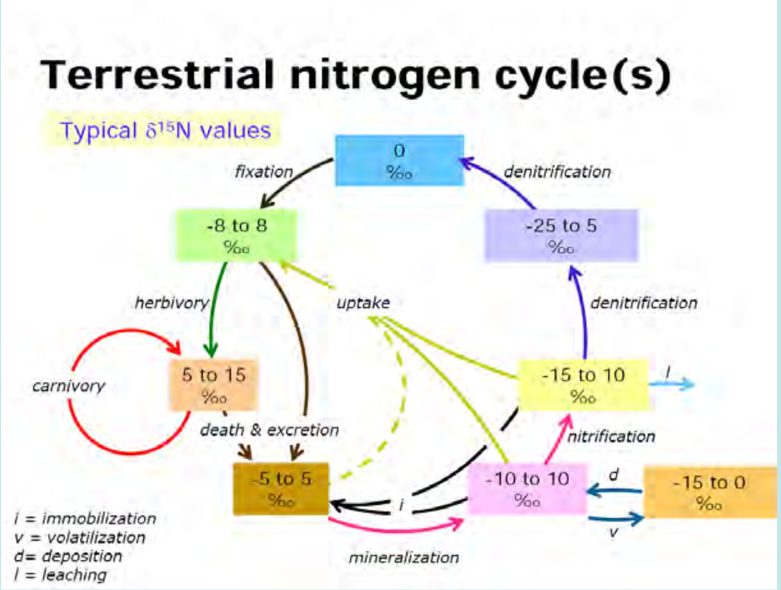
Numbers are expressed in units of 10^9 kg nitrogen per year.

A large quantity of "fixed" nitrogen does not return to the atmosphere. Before becoming converted to N_2 gas, the small, inorganic molecules (NH_4, NO_2, and NO_3) are taken up again by organisms and used to create organic compounds. This movement accounts for 95% of the flux in the global nitrogen cycle.

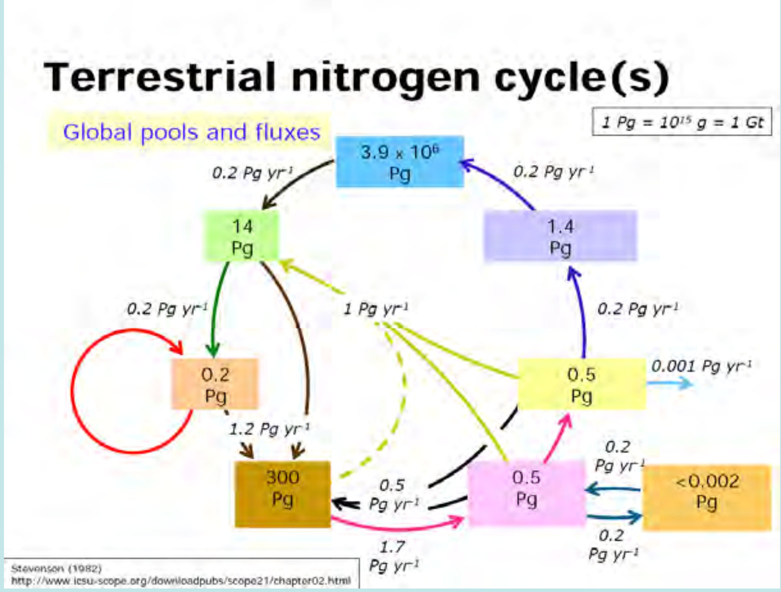


The Nitrogen Cycle


Terrestrial nitrogen cycle(s)


Terrestrial nitrogen cycle(s)

Typical δ¹⁵N values


Terrestrial nitrogen cycle(s)

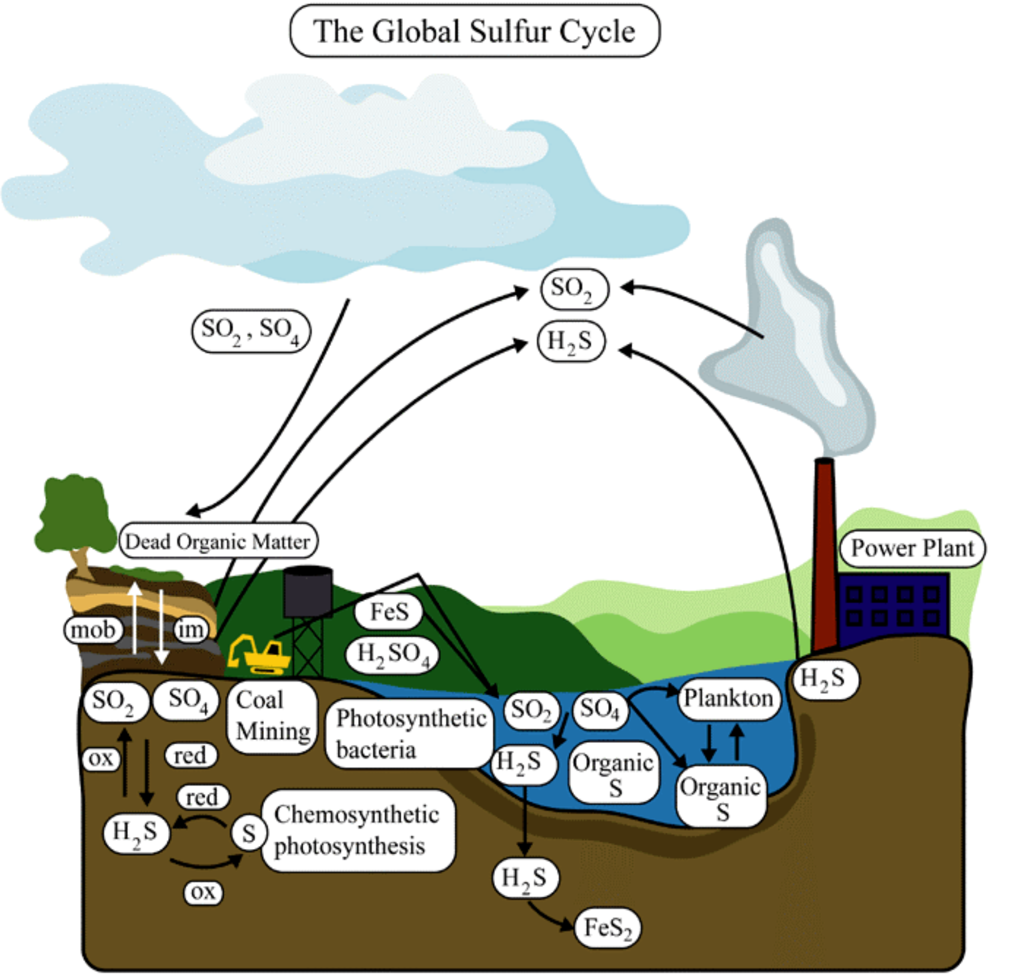
Global pools and fluxes

1 Pg = 10^{15} g = 1 Gt

Stevenson (1982)
http://www.icsu-scope.org/downloadpubs/scope21/chapter02.html

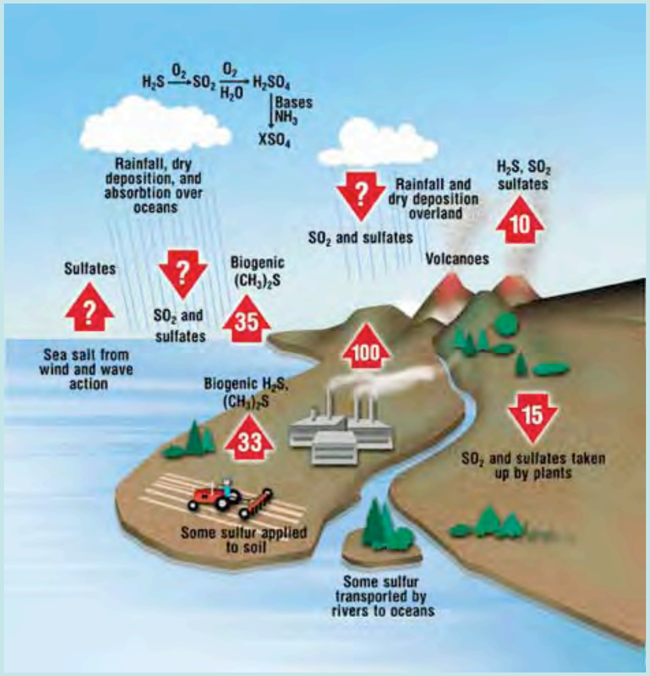
Transformations and isotopes in the N cycle

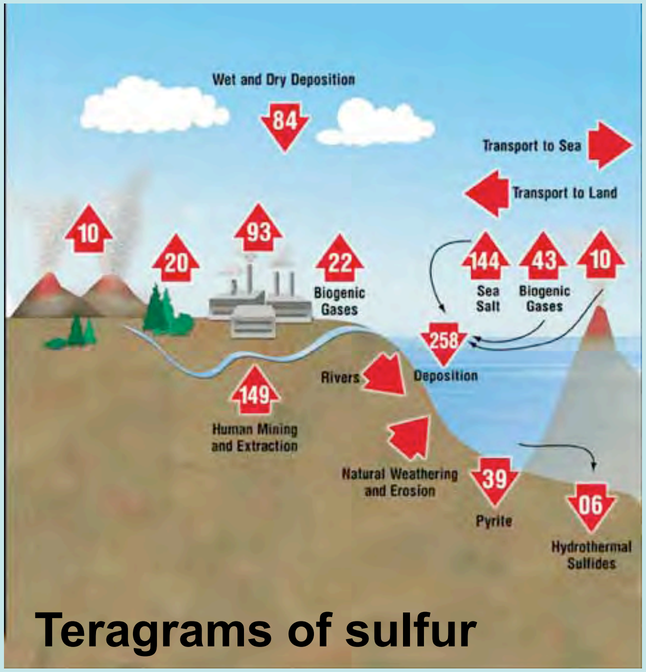
The Sulfur Cycle


The Global Sulfur Cycle

red: reduction
ox: oxidation
im: immobilization
mob: mobilization

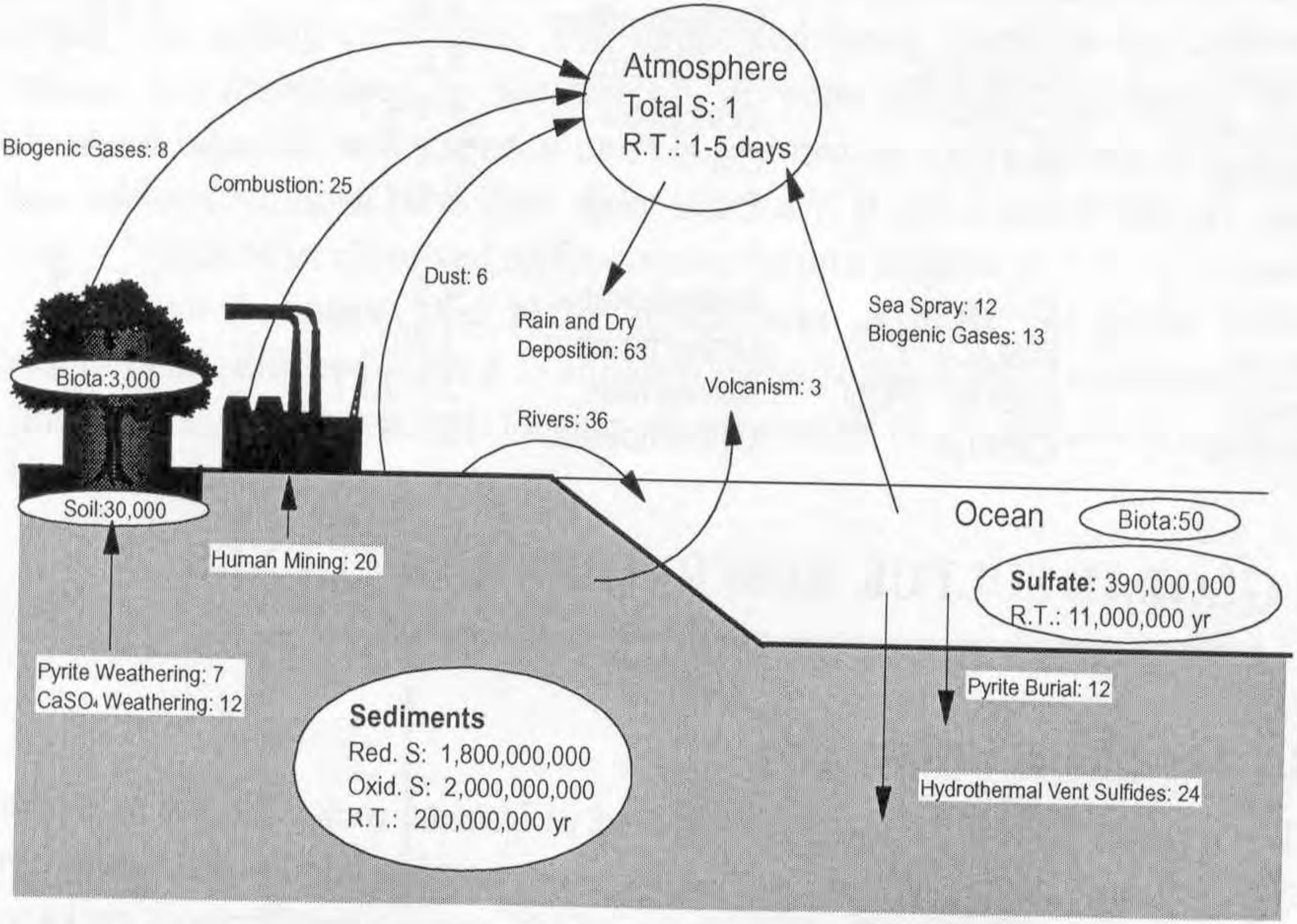
The global sulfur cycle, with two components: gaseous and sedimentary. Human activities which contribute to the cycle include: acid drainage from coal mining and fossil fuel burning.



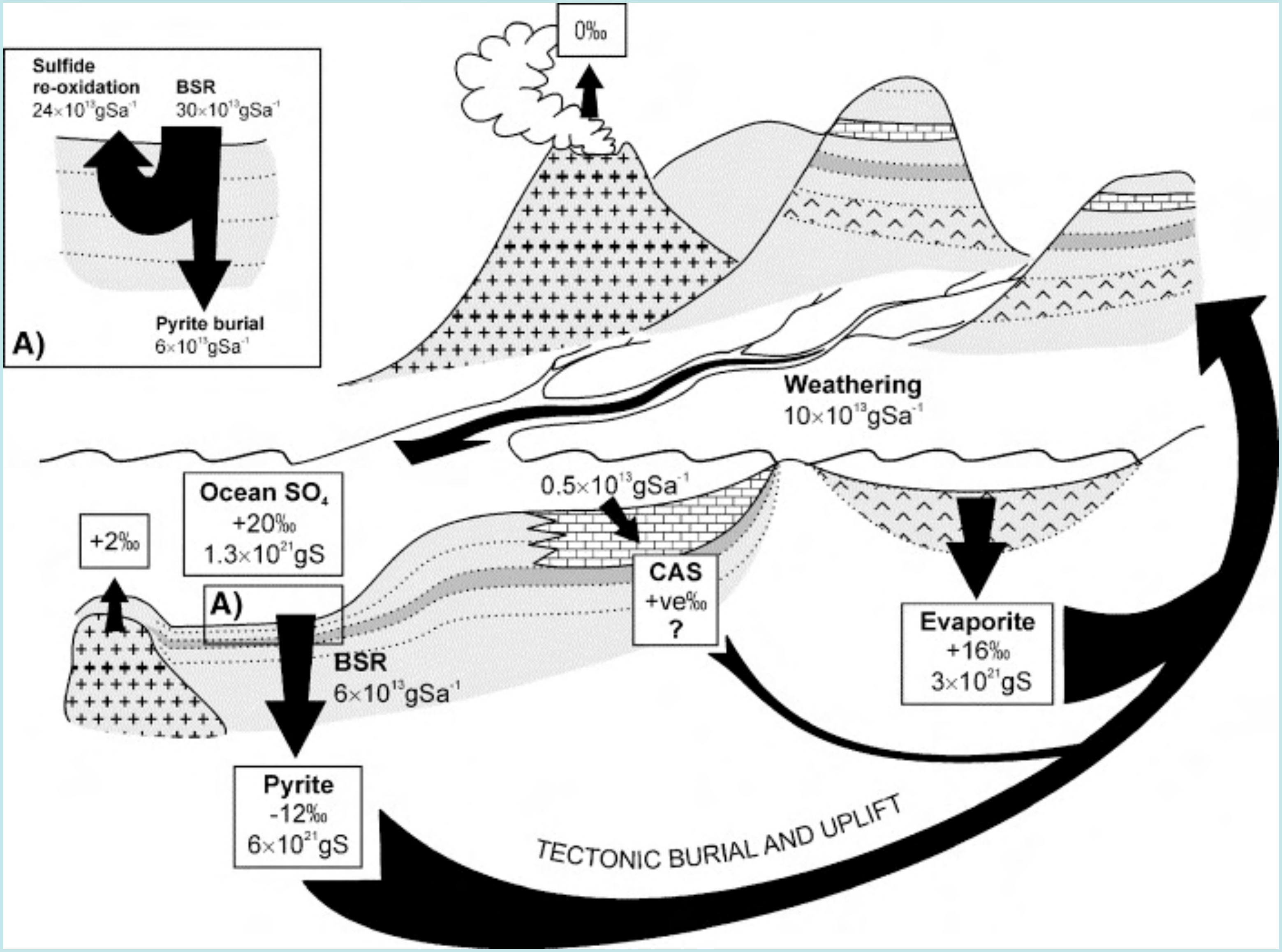


Teragrams of sulfur

The Sulfur Cycle



The Sulfur Cycle



A Representation of the Sulfur Cycle

volcanic 10, 3

weathering
72
0 to +10 (5.7)

uplift

seawater
+21, 128^{7}Tg

burial
gypsum 44, +21
pyrite 28, -16

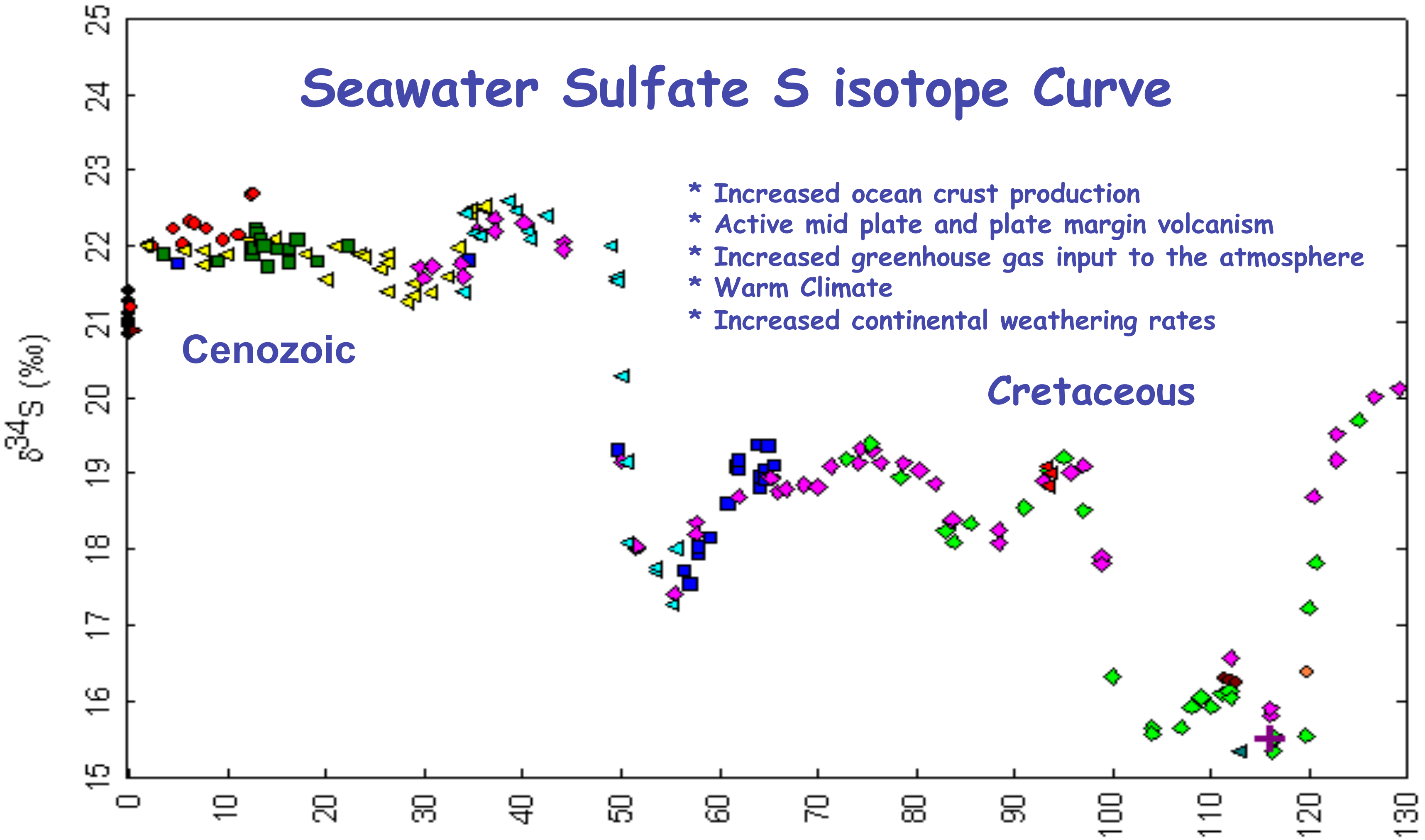
10, 3.5
hydrothermal

subduction

fluxes in units of Tg (S) yr^{-1}, isotope ratios in ‰ CDT

Arthur et al., 1990

The Sulfur Cycle



Seawater Sulfate S isotope Curve

* Increased ocean crust production
* Active mid plate and plate margin volcanism
* Increased greenhouse gas input to the atmosphere
* Warm Climate
* Increased continental weathering rates

steady state mass and isotope balance model

δ^{34}S of input

δ^{34}S of seawater

S input flux

$$F_{py} = \frac{(\delta^{34}S_{in} - \underline{\delta^{34}S_{SO4}}) * F_{in}}{\Delta^{34}S_{sw-py}}$$

pyrite burial flux

seawater-pyrite isotopic difference

Evaluate the change in each of the model parameters needed to explain the difference in $\delta^{34}S_{SO4}$.

Kump 1989

The biogeochemicals cycles of S and C are intimately linked with the principal processes that control the level of atmospheric oxygen.

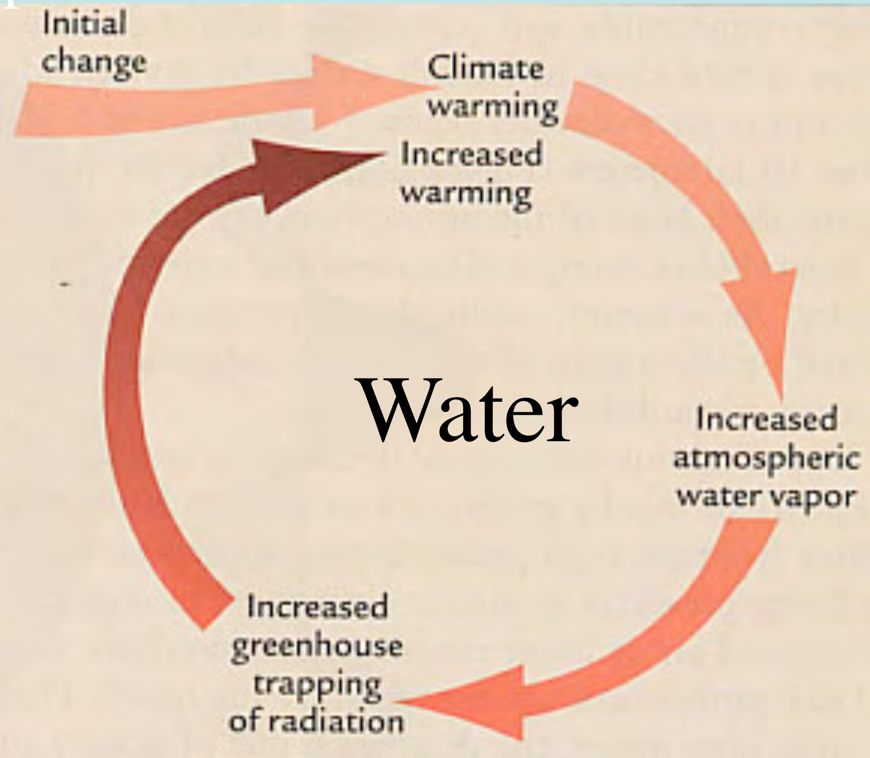
$$CO_2 + H_2O = CH_2O + O_2$$

$$2Fe_2O_3 + 16Ca^{2+} + 16HCO_3^- + 8SO_4^{2-} = 4FeS_2 + 16CaCO_3 + 8H_2O + 15O_2$$

To maintain constant oxygen an periods of organic C burial should be compensated by less pyrite burial resulting in an inverse isotopic relation

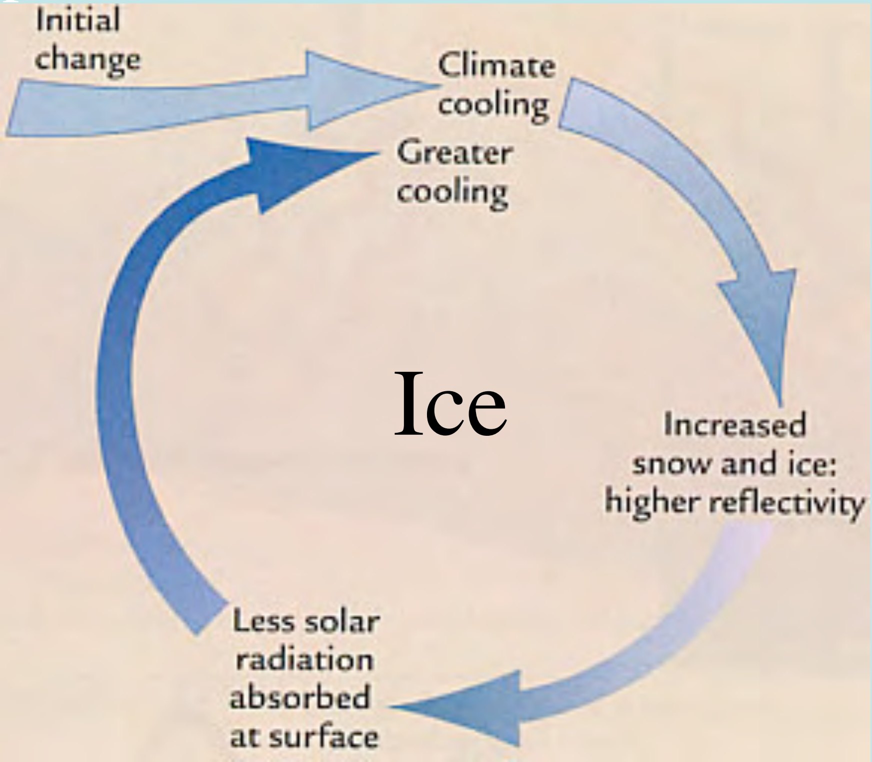
Feedbacks in the Climate System

Forcing/
perturbation



Water

Forcing/
perturbation



Ice

CO_2 ↑ → Temperature ↑

Precipitation ↑

Weathering ↑

River solute load ↑

Biological Productivity ↑

CO_2 ↓

Mountain Uplift ↑

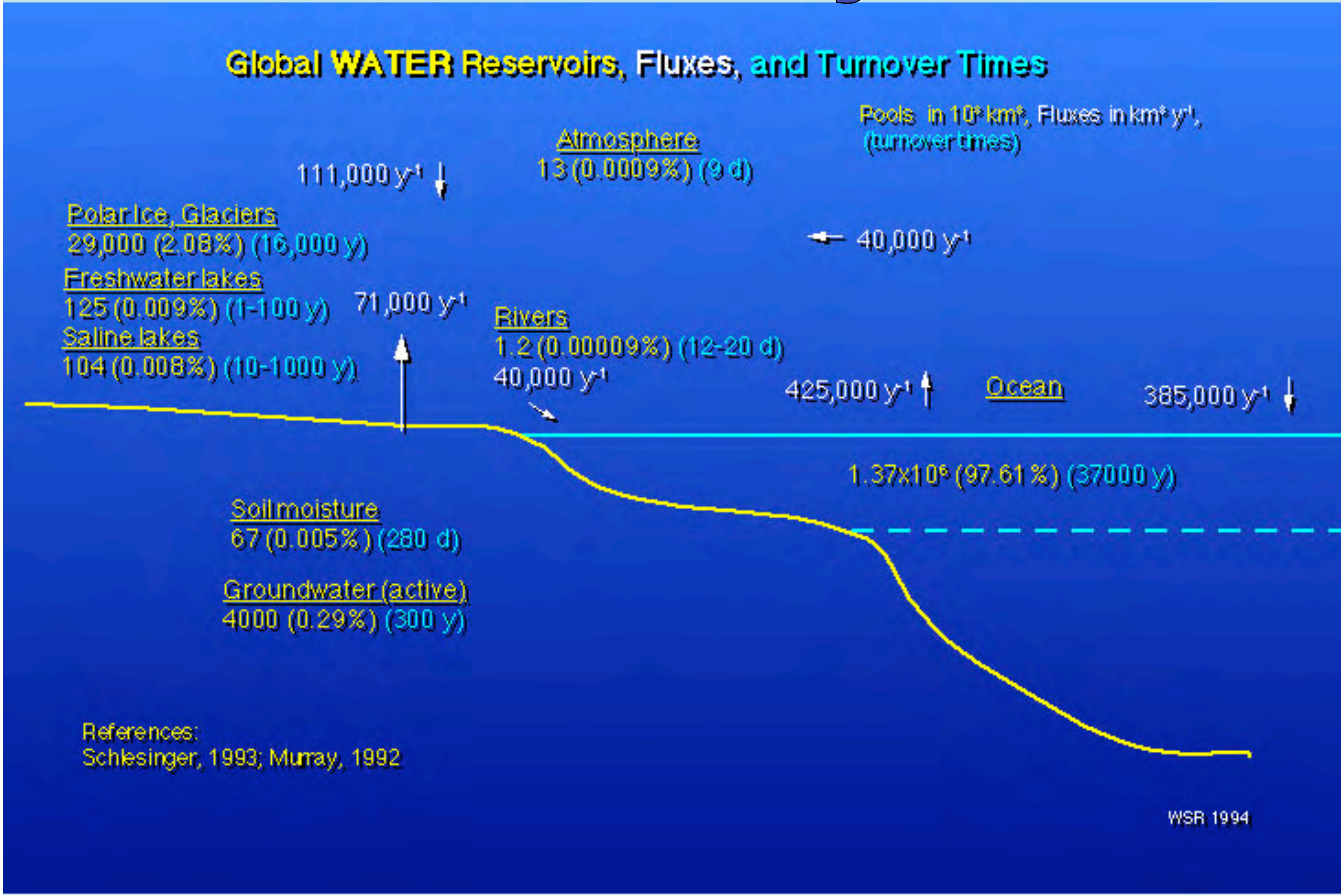
Weathering ↑

CO_2 ↓

Temperature ↓

Weathering ↓

The Water Cycle



Global WATER Reservoirs, Fluxes, and Turnover Times

Pools in 10^3 km^3, Fluxes in km^3 y^{-1}, (turnover times)

<u>Atmosphere</u>
13 (0.0009%) (9 d)

<u>Polar Ice, Glaciers</u>
29,000 (2.08%) (16,000 y)

<u>Freshwater lakes</u>
125 (0.009%) (1-100 y)

<u>Saline lakes</u>
104 (0.008%) (10-1000 y)

<u>Rivers</u>
1.2 (0.00009%) (12-20 d)

<u>Ocean</u>
1.37x10^6 (97.61 %) (37000 y)

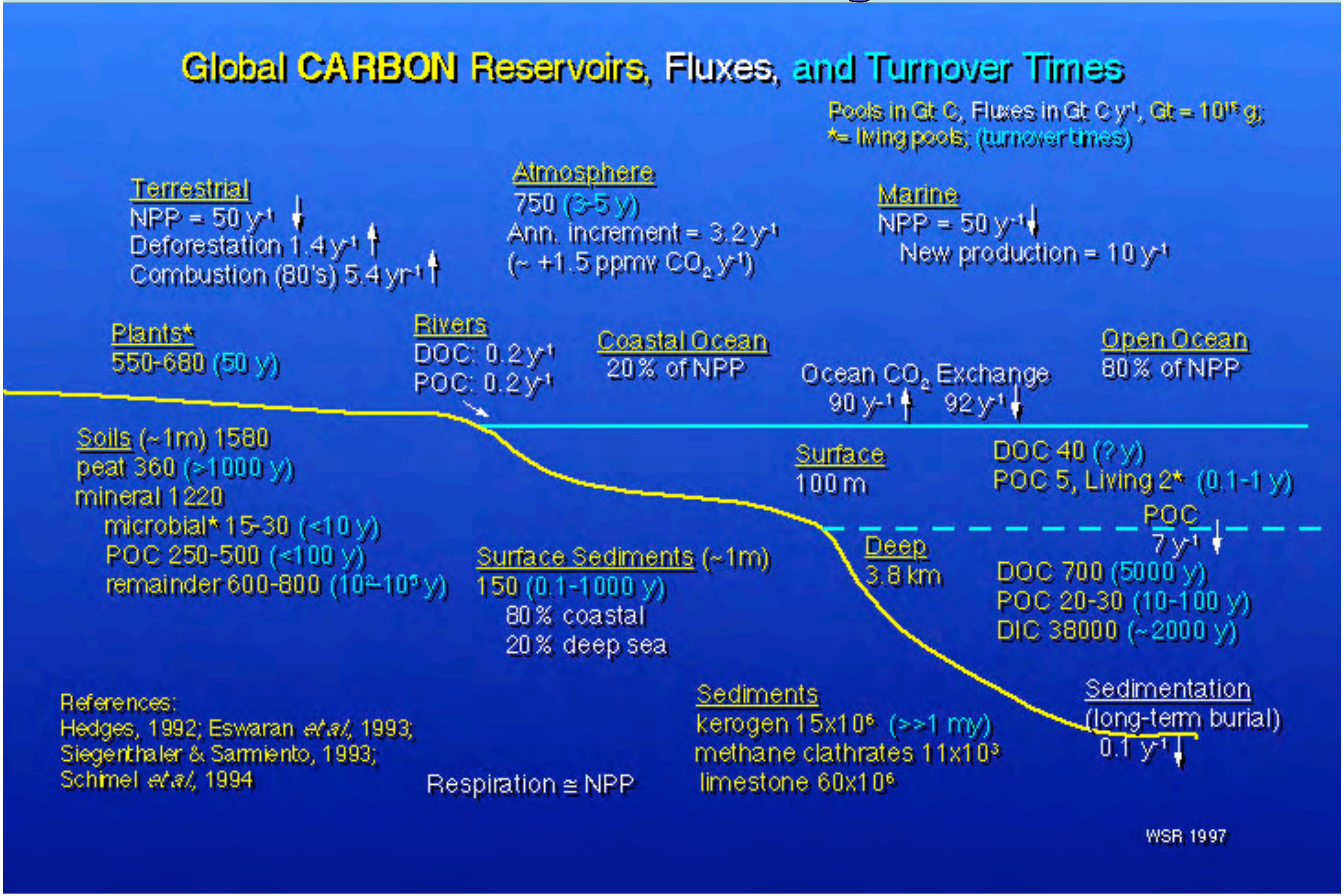
<u>Soil moisture</u>
67 (0.005%) (280 d)

<u>Groundwater (active)</u>
4000 (0.29%) (300 y)

References:
Schlesinger, 1993; Murray, 1992

WSR 1994

The Carbon Cycle



Global CARBON Reservoirs, Fluxes, and Turnover Times

Pools in Gt C, Fluxes in Gt C y^{-1}, Gt = 10^{15} g;
*= living pools; (turnover times)

Terrestrial
NPP = 50 y^{-1} ↓
Deforestation 1.4 y^{-1} ↑
Combustion (80's) 5.4 yr^{-1} ↑

Atmosphere
750 (3-5 y)
Ann. increment = 3.2 y^{-1}
(~ +1.5 ppmv CO_2 y^{-1})

Marine
NPP = 50 y^{-1} ↓
New production = 10 y^{-1}

Plants*
550-680 (50 y)

Rivers
DOC: 0.2 y^{-1}
POC: 0.2 y^{-1}

Coastal Ocean
20% of NPP

Ocean CO_2 Exchange
90 y^{-1} ↑ 92 y^{-1} ↓

Open Ocean
80% of NPP

Soils (~1m) 1580
peat 360 (>1000 y)
mineral 1220
microbial* 15-30 (<10 y)
POC 250-500 (<100 y)
remainder 600-800 (10^2–10^5 y)

Surface
100 m

DOC 40 (? y)
POC 5, Living 2* (0.1-1 y)

POC
7 y^{-1} ↓

Surface Sediments (~1m)
150 (0.1-1000 y)
80% coastal
20% deep sea

Deep
3.8 km

DOC 700 (5000 y)
POC 20-30 (10-100 y)
DIC 38000 (~2000 y)

Sediments
kerogen 15x10^6 (>>1 my)
methane clathrates 11x10^3
limestone 60x10^6

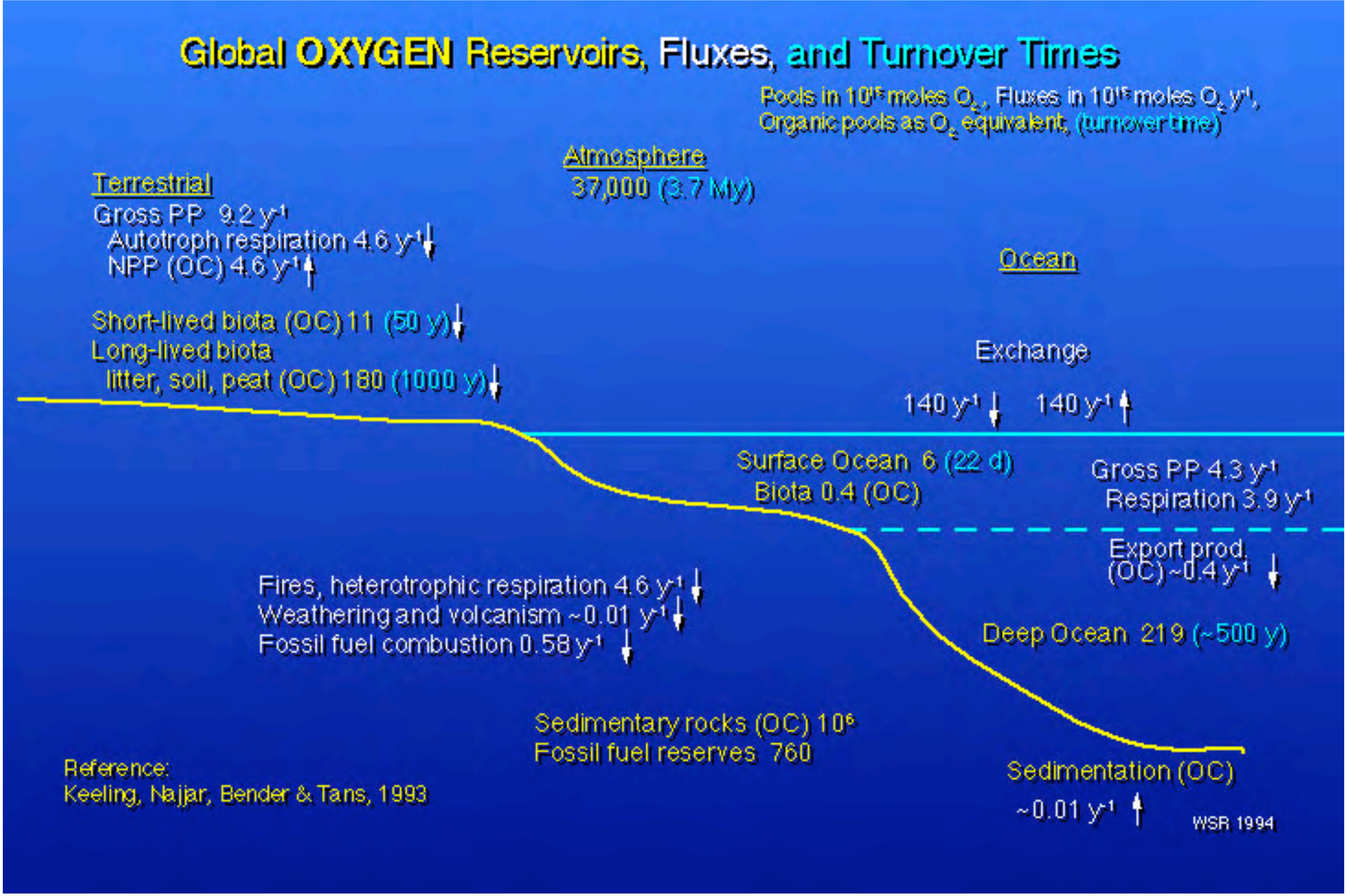
Sedimentation
(long-term burial)
0.1 y^{-1} ↓

References:
Hedges, 1992; Eswaran *et al.*, 1993;
Siegenthaler & Sarmiento, 1993;
Schimel *et al.*, 1994

Respiration ≅ NPP

WSR 1997

The Oxygen Cycle



Global OXYGEN Reservoirs, Fluxes, and Turnover Times

Pools in 10^{15} moles O_2, Fluxes in 10^{15} moles O_2 y^{-1},
Organic pools as O_2 equivalent, (turnover time)

Atmosphere
37,000 (3.7 My)

Terrestrial
Gross PP 9.2 y^{-1}
Autotroph respiration 4.6 y^{-1} ↓
NPP (OC) 4.6 y^{-1} ↑

Short-lived biota (OC) 11 (50 y) ↓
Long-lived biota
litter, soil, peat (OC) 180 (1000 y) ↓

Ocean

Exchange

140 y^{-1} ↓ 140 y^{-1} ↑

Surface Ocean 6 (22 d)
Biota 0.4 (OC)

Gross PP 4.3 y^{-1}
Respiration 3.9 y^{-1}

Export prod.
(OC) ~0.4 y^{-1} ↓

Fires, heterotrophic respiration 4.6 y^{-1} ↓
Weathering and volcanism ~0.01 y^{-1} ↓
Fossil fuel combustion 0.58 y^{-1} ↓

Deep Ocean 219 (~500 y)

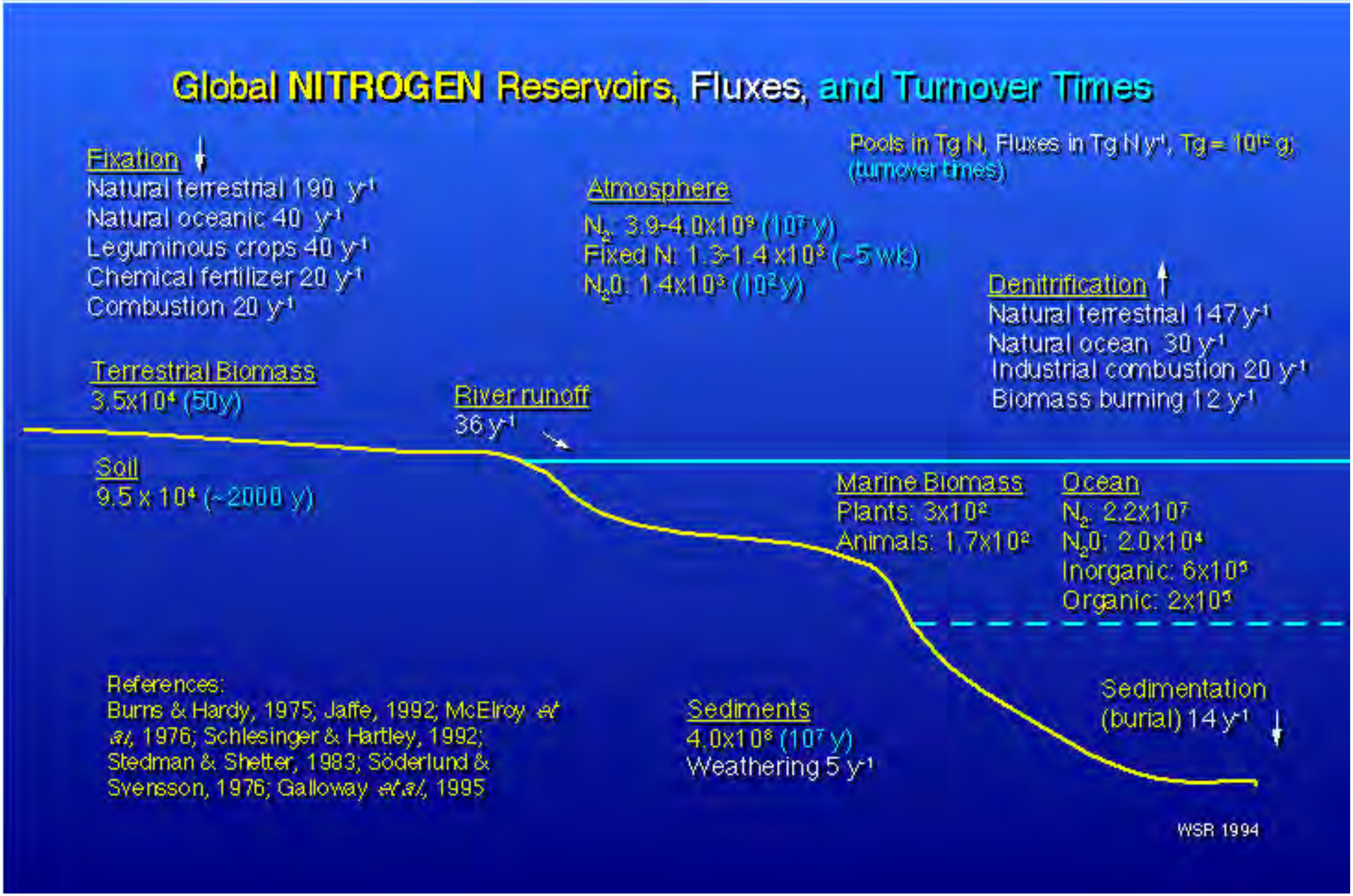
Sedimentary rocks (OC) 10^6
Fossil fuel reserves 760

Sedimentation (OC)
~0.01 y^{-1} ↑

Reference:
Keeling, Najjar, Bender & Tans, 1993

WSR 1994

The Nitrogen Cycle



Global NITROGEN Reservoirs, Fluxes, and Turnover Times

Pools in Tg N, Fluxes in Tg N y^{-1}, Tg = 10^{12} g;
(turnover times)

Fixation ↓
Natural terrestrial 190 y^{-1}
Natural oceanic 40 y^{-1}
Leguminous crops 40 y^{-1}
Chemical fertilizer 20 y^{-1}
Combustion 20 y^{-1}

Atmosphere
N_2: 3.9-4.0x10^9 (10^7 y)
Fixed N: 1.3-1.4 x10^3 (~5 wk)
N_2O: 1.4x10^3 (10^2 y)

Denitrification ↑
Natural terrestrial 147 y^{-1}
Natural ocean 30 y^{-1}
Industrial combustion 20 y^{-1}
Biomass burning 12 y^{-1}

Terrestrial Biomass
3.5x10^4 (50y)

River runoff
36 y^{-1}

Soil
9.5 x 10^4 (~2000 y)

Marine Biomass
Plants: 3x10^2
Animals: 1.7x10^2

Ocean
N_2: 2.2x10^7
N_2O: 2.0x10^4
Inorganic: 6x10^5
Organic: 2x10^5

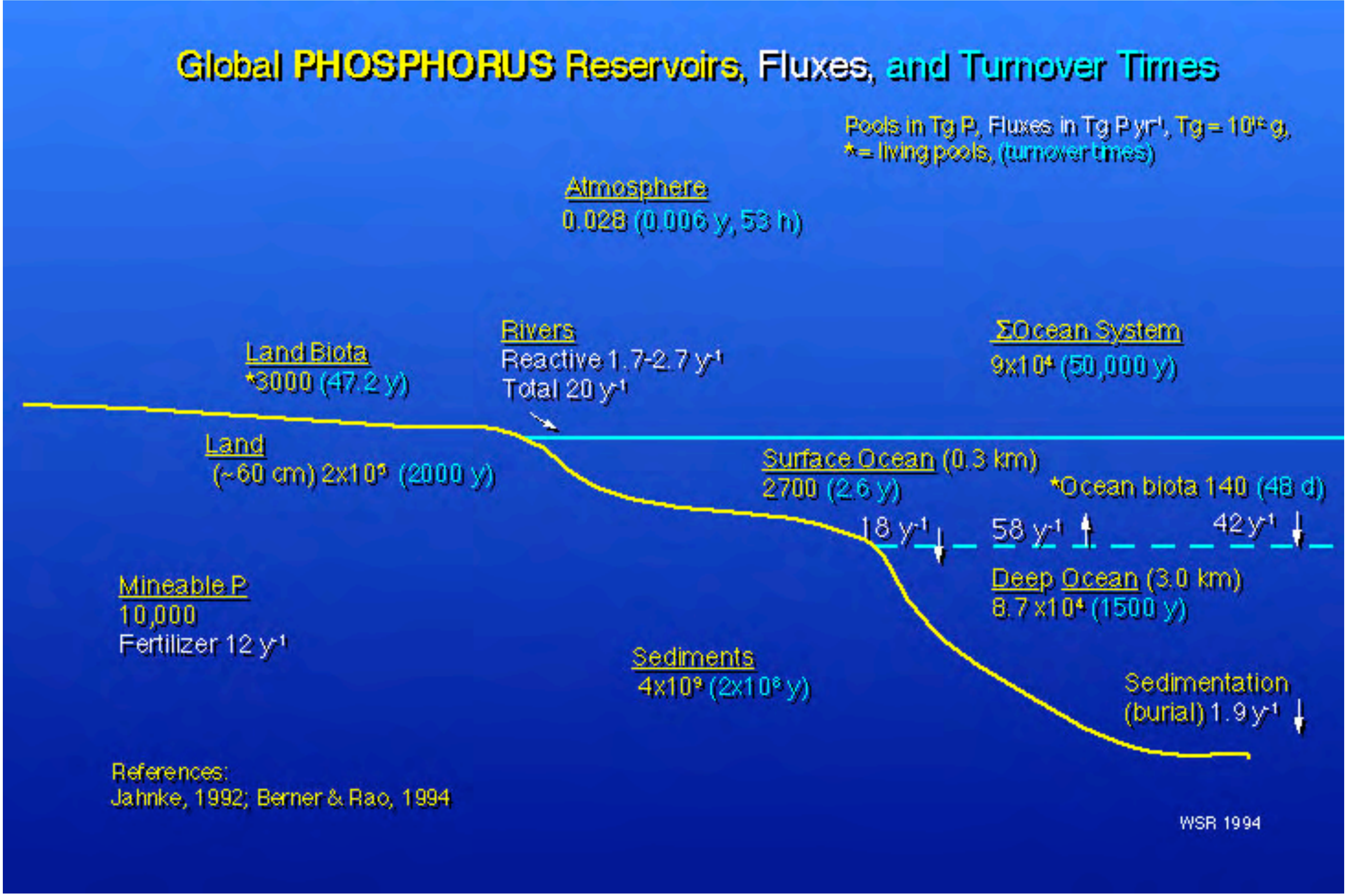
Sediments
4.0x10^8 (10^7 y)
Weathering 5 y^{-1}

Sedimentation
(burial) 14 y^{-1} ↓

References:
Burns & Hardy, 1975; Jaffe, 1992; McElroy *et al.*, 1976; Schlesinger & Hartley, 1992; Stedman & Shetter, 1983; Söderlund & Svensson, 1976; Galloway *et al.*, 1995

WSR 1994

The Phosphorus Cycle



Global PHOSPHORUS Reservoirs, Fluxes, and Turnover Times

Pools in Tg P, Fluxes in Tg P yr^{-1}, Tg = 10^{12} g,
* = living pools, (turnover times)

<u>Atmosphere</u>
0.028 (0.006 y, 53 h)

<u>Land Biota</u>
*3000 (47.2 y)

<u>Rivers</u>
Reactive 1.7-2.7 y^{-1}
Total 20 y^{-1}

<u>ΣOcean System</u>
9×10^4 (50,000 y)

<u>Land</u>
(~60 cm) 2×10^5 (2000 y)

<u>Surface Ocean</u> (0.3 km)
2700 (2.6 y)

*Ocean biota 140 (48 d)

18 y^{-1} ↓

58 y^{-1} ↑

42 y^{-1} ↓

<u>Deep Ocean</u> (3.0 km)
8.7×10^4 (1500 y)

<u>Mineable P</u>
10,000
Fertilizer 12 y^{-1}

<u>Sediments</u>
4×10^9 (2×10^8 y)

Sedimentation
(burial) 1.9 y^{-1} ↓

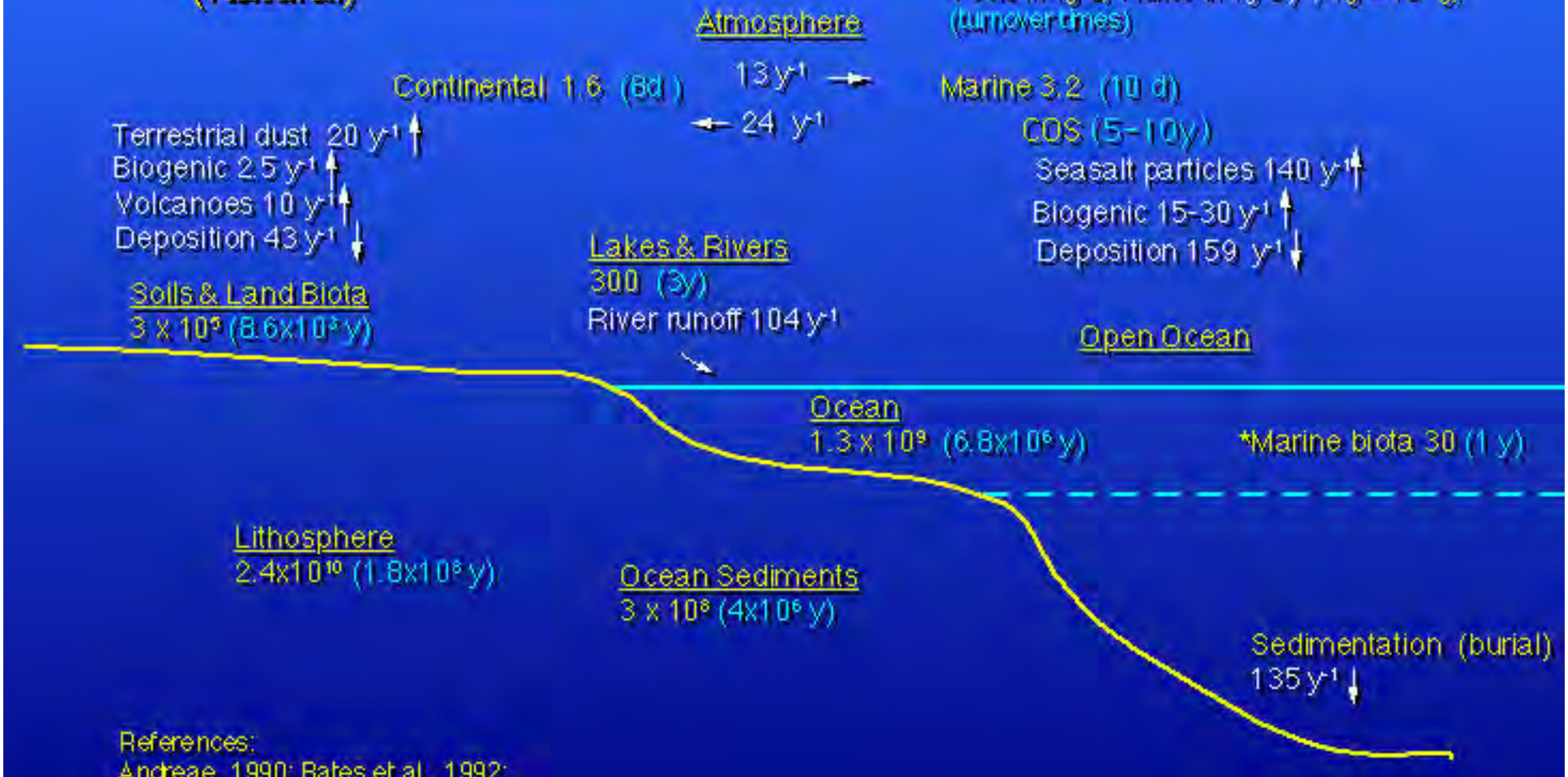
References:
Jahnke, 1992; Berner & Rao, 1994

WSR 1994

The Sulfur Cycle Pre-Industrial

Global SULFUR Reservoirs, Fluxes, and Turnover Times (Natural)

Pools in Tg S, Fluxes in Tg S y^{-1}, Tg = 10^{12} g;
(turnover times)



Atmosphere

Continental 1.6 (8d)
13 y^{-1} →
← 24 y^{-1}
Marine 3.2 (10 d)
COS (5-10y)

Terrestrial dust 20 y^{-1} ↑
Biogenic 2.5 y^{-1} ↑
Volcanoes 10 y^{-1} ↑
Deposition 43 y^{-1} ↓

Seasalt particles 140 y^{-1} ↑
Biogenic 15-30 y^{-1} ↑
Deposition 159 y^{-1} ↓

Soils & Land Biota
3 x 10^5 (8.6x10^3 y)

Lakes & Rivers
300 (3y)
River runoff 104 y^{-1}

Open Ocean

Ocean
1.3 x 10^9 (6.8x10^6 y)

*Marine biota 30 (1 y)

Lithosphere
2.4x10^{10} (1.8x10^8 y)

Ocean Sediments
3 x 10^8 (4x10^6 y)

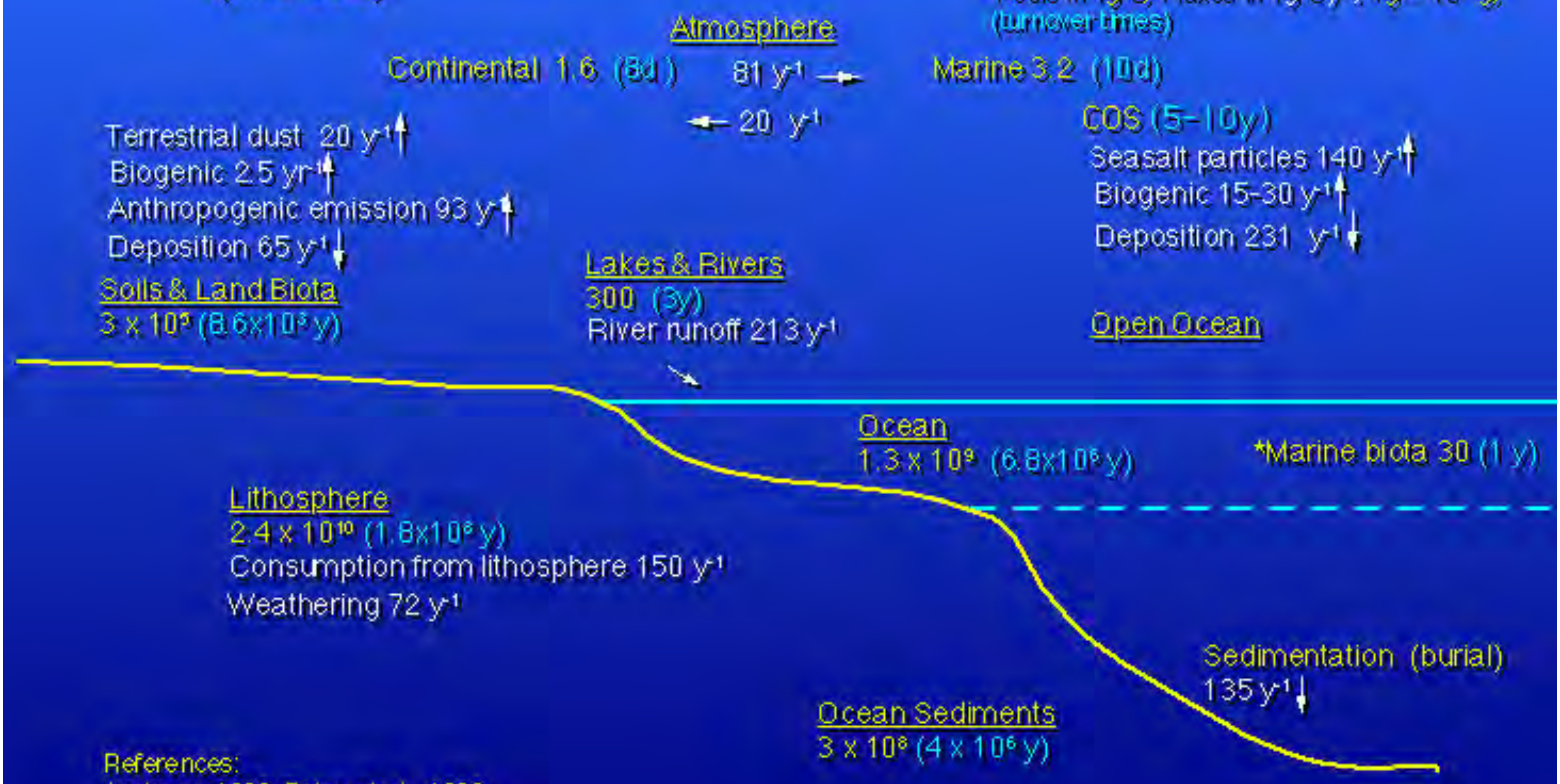
Sedimentation (burial)
135 y^{-1} ↓

References:
Andreae, 1990; Bates et al., 1992;
Charlson, Anderson & McDuff, 1992

WSR 1994

The Sulfur Cycle (mid 1980's)

Global **SULFUR** Reservoirs, Fluxes, and Turnover Times (mid-80's)



Pools in Tg S, Fluxes in Tg S y^{-1}, Tg = 10^{12} g; (turnover times)

Atmosphere

Continental 1.6 (8d) 81 y^{-1} → Marine 3.2 (10d)

← 20 y^{-1}

COS (5-10y)

Terrestrial dust 20 y^{-1} ↑

Biogenic 2.5 yr^{-1} ↑

Anthropogenic emission 93 y^{-1} ↑

Deposition 65 y^{-1} ↓

Soils & Land Biota

3 x 10^5 (8.6x10^3 y)

Seasalt particles 140 y^{-1} ↑

Biogenic 15-30 y^{-1} ↑

Deposition 231 y^{-1} ↓

Lakes & Rivers

300 (3y)

River runoff 213 y^{-1}

Open Ocean

Ocean

1.3 x 10^9 (6.8x10^6 y)

*Marine biota 30 (1 y)

Lithosphere

2.4 x 10^{10} (1.8x10^8 y)

Consumption from lithosphere 150 y^{-1}

Weathering 72 y^{-1}

Sedimentation (burial)

135 y^{-1} ↓

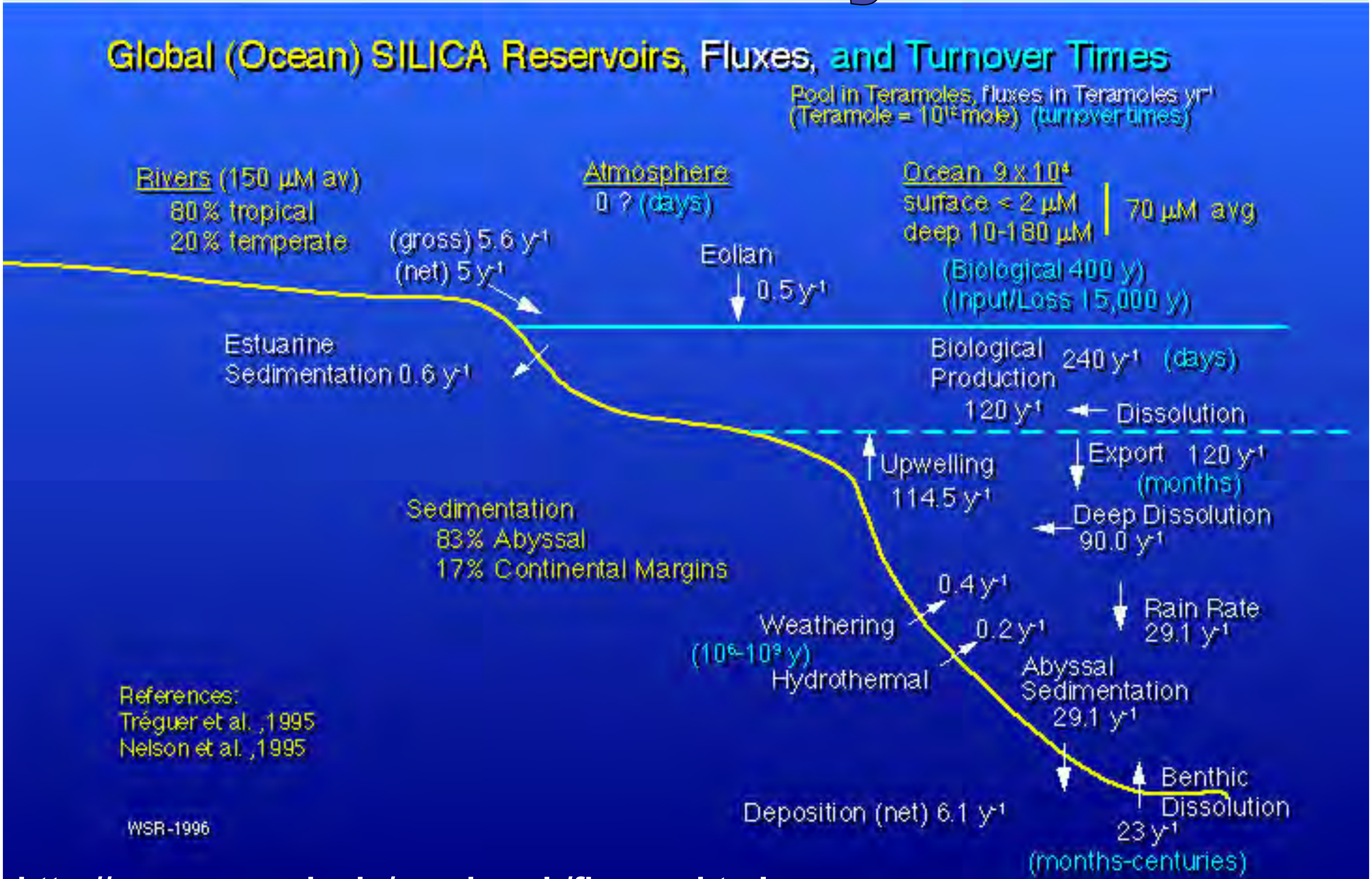
Ocean Sediments

3 x 10^8 (4 x 10^6 y)

References:
Andreae, 1990; Bates et al., 1992;
Charlson, Anderson & McDuff, 1992

WSR 1994

The Silica Cycle



http://www.ess.uci.edu/~reeburgh/figures.html