The Age of the Earth — NOT!

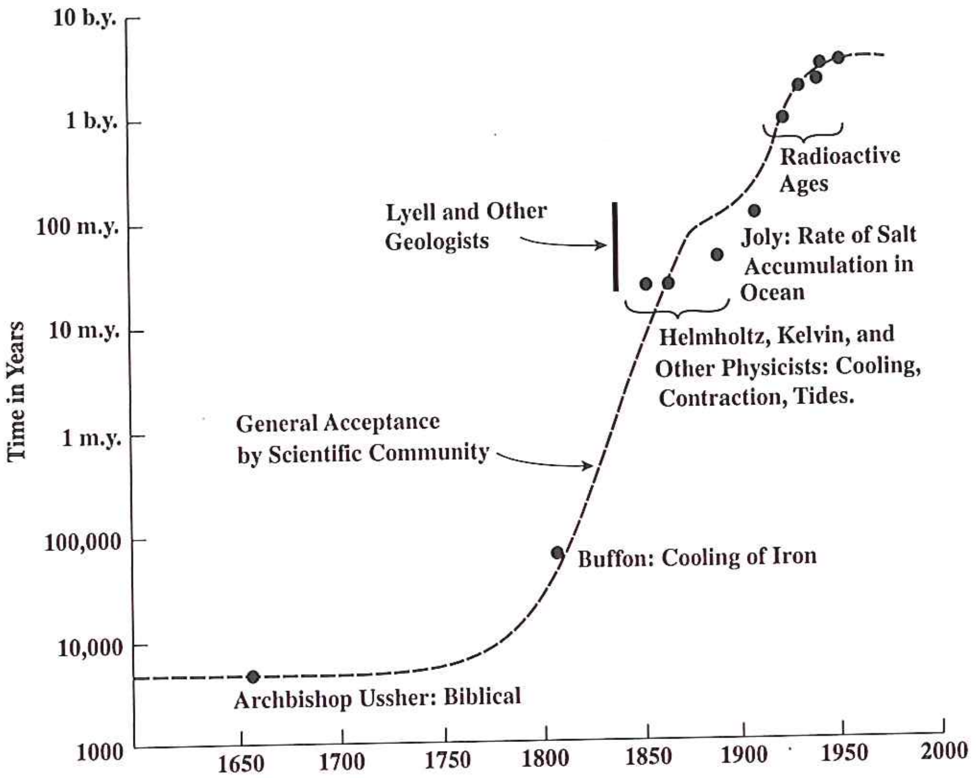


Figure 8.1. Age of Earth as estimated by various techniques since the Renaissance. Buffon tried to use rate of cooling of iron from a molten state to estimate the age of Earth, but the omission of as-yet undiscovered radioactive heating of Earth's interior (chapters 9 and 11) seriously shortened his cooling time. Joly worked out how long it would take to bring the oceans up to their current salinity based on the rate at which rivers carry salt to the sea; he ignored the precipitation of salt out of the ocean water into seafloor sediments. From Press and Siever (1978) by permission of W.H. Freeman and Company.

Lord Kelvin –
preeminent Victorian scientist
age of the Sun (1862)

Kelvin knew that the energy of the Sun could not be supplied by chemical combustion processes. Why?

Total energy radiated by Sun = $4 \cdot 10^{26}$ W ↙ ignores neutrinos

Combustion of coal releases $3 \cdot 10^{7}$ J/kg

How long could the Sun shine if its energy were supplied by burning coal?

$$t_{\text{coal}\,\odot} = \frac{(3\cdot10^{7}\ \text{J/kg})(\overset{\swarrow\ \text{mass of Sun}}{2\cdot10^{30}\ \text{kg}})}{4\cdot10^{26}\ \text{J/sec}} = 1.5\cdot10^{11}\ \text{sec}$$

= 4800 years only — pretty close to Archbishop Ussher!

Kelvin also dismissed cometary and meteoritic infall as source of Sun's energy — on basis of orbit of Mercury

Concluded that the Sun must have formed hot and was now <u>cooling off</u>.

Suppose the Sun has the same specific heat as H_2O : $c = 4000\ \text{J/kg}\ ^\circ\text{C}$

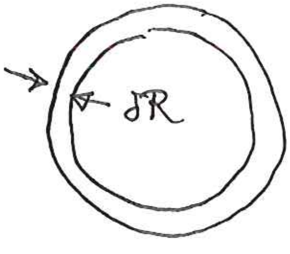
What would its cooling rate then be?

$$\left(4\cdot10^{26}\ \frac{\text{J}}{\text{sec}}\right)\left(3\cdot10^{7}\ \frac{\text{sec}}{\text{yr}}\right) = \underbrace{c_{H_2O}\left(\frac{\text{J}}{\text{kg}}\right) M_\odot(\text{kg})}_{\text{total specific heat of Sun}}\ \underset{\substack{\uparrow\\ \text{amount cooled in}\\ \text{one year}}}{dT}$$

$$dT = \frac{(4\cdot10^{26})(3\cdot10^{7})}{(4000)(2\cdot10^{30})}$$

$$= 1.5^\circ\text{C}/\text{year} \leftarrow \text{if } c_{\text{Sun}} = c_{H_2O}$$

This would result in a <u>thermal contraction</u>



$$\frac{\delta R}{R} = \underbrace{(10^{-4}\ \text{per}\ ^\circ\text{C})}_{\substack{\nearrow\\ \text{thermal}\\ \text{contraction coefficient}}}(1.5^\circ\text{C}) = 1.5\cdot10^{-4}/\text{yr}$$

1% shrinking in 70 years

Such a contraction could clearly be ruled out by past observations of solar radius R

Concluded that $c_{\text{solar material}} = (10^2 \text{ to } 10^4) \times c_{H_2O}$

Say $c_{Sun} = 1000 \times c_{H_2O} = 4 \cdot 10^6 \frac{J}{kg\,°C}$

Then cooling rate 1.5°/1000 years

Thermal contraction then imperceptible.

Kelvin estimated that the Sun had cooled from an initial temperature 15,000 °C hotter than its current temperature.

It's age would then be given by

$$\frac{(c_{Sun} M_{Sun})(15{,}000\,°C)}{age} = 4 \cdot 10^{26} \frac{J}{sec}$$

$$age = \frac{(4 \cdot 10^6 \frac{J}{kg\,°C})(2 \cdot 10^{30}\,kg)(15{,}000\,°C)}{4 \cdot 10^{26}\,J/sec}$$

$$= 3 \cdot 10^{14}\,sec = 10\text{ m.y.}$$

Kelvin thought $10^4 \times c_{H_2O}$ was an upper bound on $c_\odot \Rightarrow$ upper bound on age $\simeq \underline{\underline{100\text{ m.y.}}}$

Joly's salt clock (1899)

$$\text{age of } \oplus = \frac{\text{total Na}^+ \text{ in ocean}}{\text{annual Na}^+ \text{ influx from rivers}}$$

TABLE 8.1 Major Dissolved Components of Seawater for a Salinity of 35‰

Ion	Concentration g/kg	Concentration mM^a	Percent Free Ion
Cl^-	19.354	558	100
Na^+	10.77	479	98
Mg^{++}	1.290	54.3	89
SO_4^{--}	2.712	28.9	39
Ca^{++}	0.412	10.5	99
K^+	0.399	10.4	98
HCO_3^{-b}	0.12	2.0	80

[a] mM = millimoles per liter at 25°C.

[b] For pH = 8.1, P = 1 atm, T = 25°C.

Sources: Wilson 1975; Skirrow 1975; Millero and Schreiber 1982.

$$\text{Volume of ocean} = 4\pi\,(6371\ \text{km})^2\,(0.7)\,(\overset{\text{mean depth}}{4\ \text{km}})$$
$$= 1.4\cdot 10^9\ \text{km}^3 = 1.4\cdot 10^{27}\ \text{liters}$$

$$\text{Na}^+ \text{ in ocean} = (1.4\cdot 10^{27}\ \text{liters})\left(0.48\ \frac{\text{moles}}{\text{liter}}\right)$$
$$= 6.7\cdot 10^{20}\ \text{moles}$$

River influx = average concentration of Na^+ in river water × total discharge

$$= \left(2.3\cdot 10^{-4}\ \frac{\text{moles}}{\text{liter}}\right) \times$$
$$3.7\cdot 10^{16}\ \text{liters/year } H_2O$$
$$= 8.5\cdot 10^{12}\ \text{moles Na}^+/\text{year}$$

River	Location	Water (km³/yr)
1. Amazon	S. America	6300
2. Zaire (Congo)	Africa	1250
3. Orinoco	S. America	1100
4. Yangtze (Chiang)	Asia (China)	900
5. Brahmaputra	Asia	603
6. Mississippi	N. America	580
7. Yenisei	Asia (Russia)	560
8. Lena	Asia (Russia)	525
9. Mekong	Asia (Vietnam)	470
10. Ganges	Asia	450
11. St. Lawrence	N. America	447
12. Parana	S. America	429
13. Irrawaddy	Asia (Burma)	428
15. Mackenzie	N. America	306
17. Columbia	N. America	251
20. Indus	Asia (India)	238
Red (Hungho)	Asia (Vietnam)	123
Huanghe (Yellow)	Asia (China)	59

TABLE 5.6 Chemical Composition of Average River Water

	River Water Concentration[a] (mg/l)									Water Discharge (10^3 km^3/yr)	Runoff Ratio[b]
By Continent	Ca^{++}	Mg^{++}	Na^+	K^+	Cl^-	SO_4^{--}	HCO_3^-	SiO_2	TDS		
Africa:										3.41	0.28
Actual	5.7	2.2	4.4	1.4	4.1	4.2	26.9	12.0	60.5		
Natural	5.3	2.2	3.8	1.4	3.4	3.2	26.7	12.0	57.8		
Asia:										12.47	0.54
Actual	17.8	4.6	8.7	1.7	10.0	13.3	67.1	11.0	134.6		
Natural	16.6	4.3	6.6	1.6	7.6	9.7	66.2	11.0	123.5		
S. America:										11.04	0.41
Actual	6.3	1.4	3.3	1.0	4.1	3.8	24.4	10.3	54.6		
Natural	6.3	1.4	3.3	1.0	4.1	3.5	24.4	10.3	54.3		
N. America:										5.53	0.38
Actual	21.2	4.9	8.4	1.5	9.2	18.0	72.3	7.2	142.6		
Natural	20.1	4.9	6.5	1.5	7.0	14.9	71.4	7.2	133.5		
Europe:										2.56	0.42
Actual	31.7	6.7	16.5	1.8	20.0	35.5	86.0	6.8	212.8		
Natural	24.2	5.2	3.2	1.1	4.7	15.1	80.1	6.8	140.3		
Oceania:										2.40	—
Actual	15.2	3.8	7.6	1.1	6.8	7.7	65.6	16.3	125.3		
Natural	15.0	3.8	7.0	1.1	5.9	6.5	65.1	16.3	120.3		
World average:											
Actual	14.7	3.7	7.2	1.4	8.3	11.5	53.0	10.4	110.1	37.4	0.46
Natural (unpolluted)	13.4	3.4	5.2	1.3	5.8	8.3 (5.3)[c]	52.0	10.4	99.6	37.4	0.46
Pollution	1.3	0.3	2.0	0.1	2.5	3.2 (6.2)[c]	1.0	0	10.5	—	—
World % pollutive	9%	8%	28%	7%	30%	28% (54%)[c]	2%	0%	—	—	—

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[a] *Actual* concentrations include pollution. *Natural* concentrations are corrected for pollution.

[b] Runoff ratio = average runoff per unit area/average rainfall (calculated from Meybeck).

[c] We have raised pollutive contribution; see Table 5.11. (Our values are in parentheses.)

Source: All river water concentrations and discharge values from Meybeck (1979) except "actual" concentrations by continent, which were calculated from Meybeck's data. (M. Meybeck, "Concentrations des eaux fluviales en éléments majeurs et apports en solution aux oceans," *Rev. Géol. Dyn. Georgr. Phys.*, 21(3), 220, 227. Copyright © 1979. Reprinted by permission of the publisher.)

$$\text{age of } \oplus \text{ (Joly)} = \frac{6.7 \cdot 10^{20} \text{ moles}}{8.5 \cdot 10^{12} \text{ moles/yr}}$$

$$= 79 \cdot 10^{6} \text{ years}$$

Joly's mistake — ignored removal of Na^+ from oceans in evaporite deposits

e.g. $6.1 \cdot 10^{19}$ moles of NaCl in 1 km thick layer of salt beneath the Gulf of Mexico

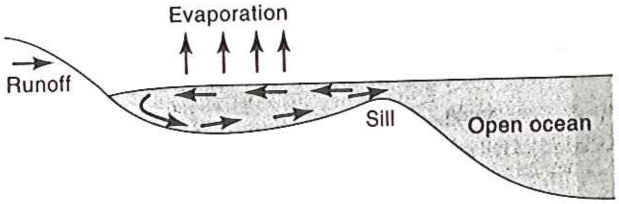


Figure 7.8. Antiestuarine circulation. Arrows indicate direction of water flow.

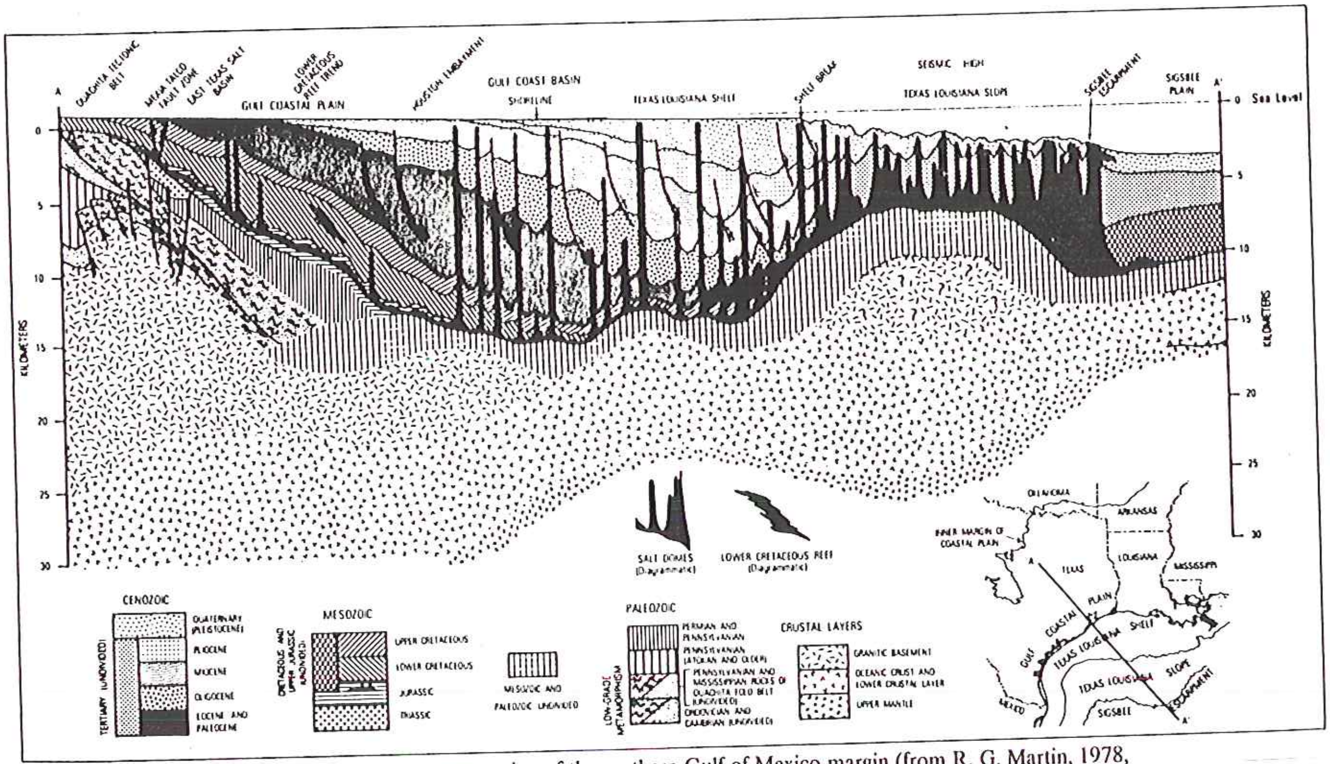


Figure 12. Generalized cross section of the northern Gulf of Mexico margin (from R. G. Martin, 1978, modified from earlier interpretations of Lehner, 1969; Dorman and others; 1972, Antoine and others, 1974; and Martin and Case, 1975).

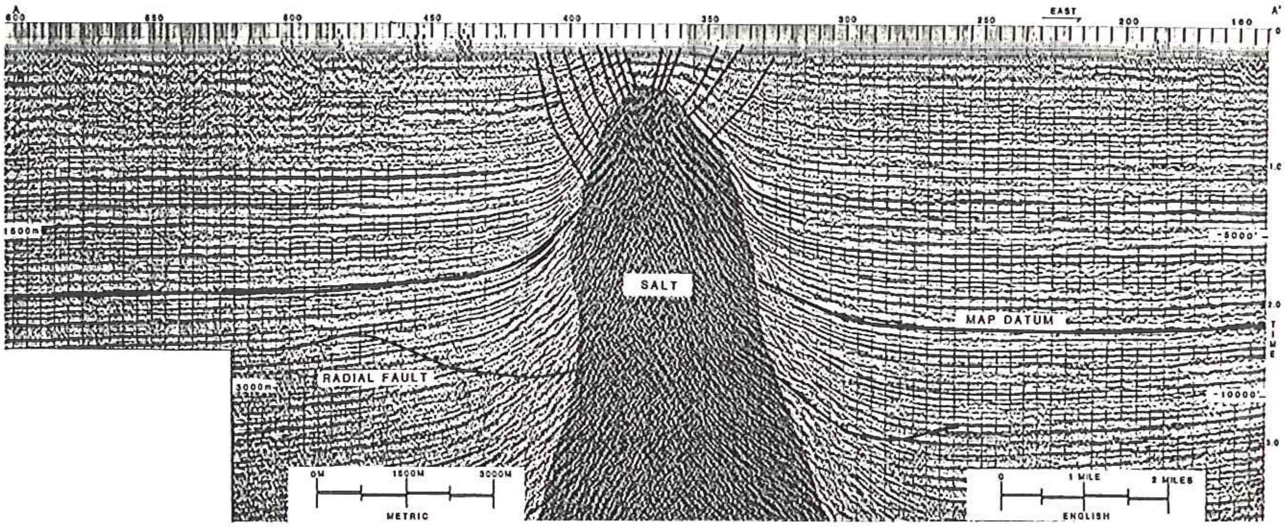


Fig. 8-31 (Sunwall et al., 1983)—Seismic line from offshore Louisiana, U. S. Gulf Coast, showing young salt diapir (characterized by reflection cut-outs) with superjacent normal faults and lower radial faults which strike parallel to seismic line. Salt configuration based on well control, gravity, and reflection and refraction seismic. Note that stratigraphic thinning toward diapir begins early (below 2 sec), but secondary rim synclines are not developed. Permission to publish by American Association of Petroleum Geologists.

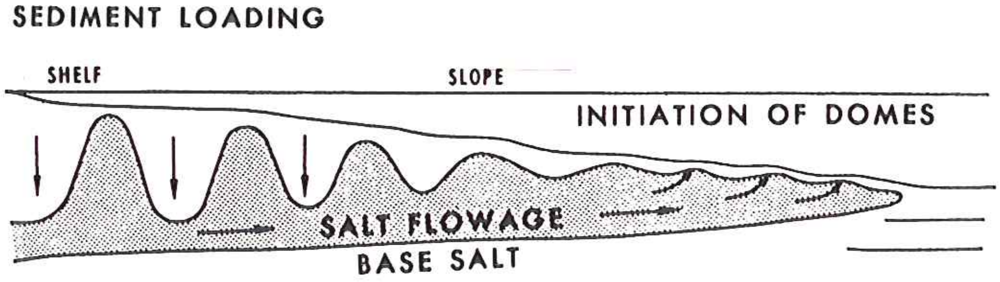
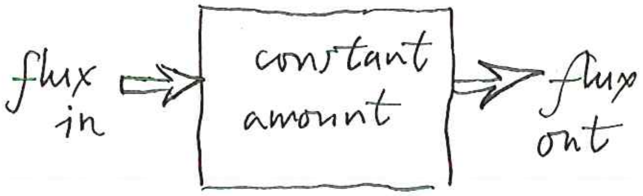


Figure 13. Diagrammatic representation of the initiation of salt dome growth on the continental slope as a result of sediment loading on the shelf–upper slope (from Humphris, 1978, 1979).

What Joly measured is the residence time of Na^+ in the oceans

Steady-state box model



$$\boxed{\text{residence time} = \frac{\text{amount in box}}{\text{flux in or out}}}$$

Example:
students at Princeton: $\text{residence time} = \frac{4400 \text{ students}}{1100 \text{ frosh/yr}} = 4 \text{ yrs}$

ocean overturn
time
~ 1000 yrs

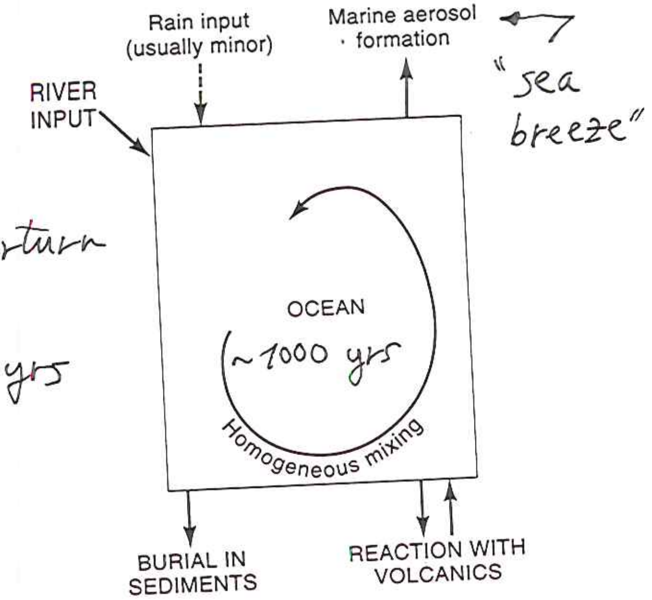


Figure 8.3. Simple box model appropriate for conservative elements in seawater. Note that, compared with the Sillèn model of Figure 8.2, fluxes enter and leave the box, and the atmosphere and sediments are considered to be outside the box. Also note that, in contrast to lakes, there is no outlet, so dissolved materials carried in by rivers can be removed only by sea–air transfer (marine aerosol formation), burial in sediments, or reaction with volcanics.

TABLE 8.3 Replacement Time with Respect to River Addition, τ_r, for Some Major and Minor Dissolved Species in Seawater

Component	Concentration (μM)		τ_r^a
	River Water	Seawater	(1,000 yr)
Cl	230	558,000	87,000
Na^+	315	479,000	55,000
Mg^{++}	150	54,300	13,000
SO_4^{--}	120	28,900	8,700
Ca^{++}	367	10,500	1,000
K^+	36	10,400	10,000
HCO_3^-	870	2,000	83
H_4SiO_4	170	100	21
NO_3^-	10	20	72
Orthophosphate	1.8[b]	2	40

[a] $\tau_r = ([SW]/[RW])\ \tau_w$, where τ_w = replacement (residence) time of H_2O = 36,000 yr; RW = river water; SW= seawater, and [ ] = concentration in μmoles per liter = μM.

[b] Includes input from solubilization of solids.

Sources: Based on Tables 8.1 and 8.2 and data of Meybeck (1979, 1982) for world average river water.

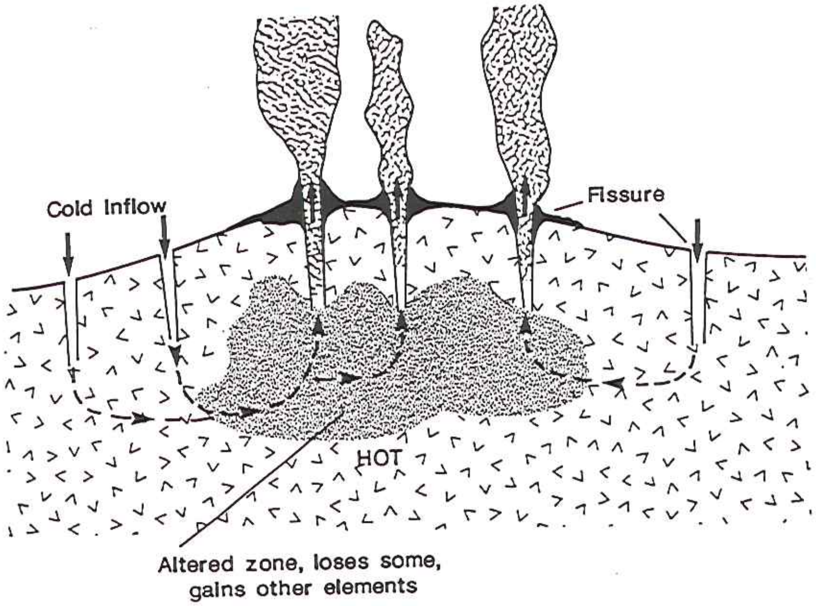


TABLE 8.8 Removal or Addition Fluxes of Some Major Seawater Constituents as a Result of Basalt-Seawater Reaction Near Midocean Ridges

Constituent	Flux (Tg/yr)		
	Edmond et al. (1979)	Thompson (1983)	Present Study
Mg^{++}	−187	−60	−119
Ca^{++}	140	73	191
K^+	51	−27	53
SO_4^{--} as S	−120	—	—[a]
H_4SiO_4 as Si	90	82	56

Note: Removal values shown as negative numbers. Tg = 10^{12}g.

[a] Less than 10% of Edmond et al. (1979) value

TABLE 4.7 Origin of Major Components of Groundwater (Major Processes Only)

Component	Origin
Na$^+$	NaCl dissolution (some pollutive)[a] Plagioclase weathering Rainwater addition
K$^+$	Biotite weathering K-feldspar weathering Biomass decreases Dissolution of trapped aerosols
Mg^{++}	Amphibole and pyroxene weathering Biotite(and chlorite) weathering Dolomite weathering Olivine weathering Rainwater addition
Ca^{++}	Calcite weathering Plagioclase weathering Dolomite weathering Dissolution of trapped aerosols Biomass decreases
HCO_3^-	Calcite and dolomite weathering Silicate weathering
SO_4^{--}	Pyrite weathering (some pollutive)[a] $CaSO_4$ dissolution Rainwater addition
Cl$^-$	NaCl dissolution (some pollutive)[a] Rainwater addition
H_4SiO_4	Silicate weathering

Note: Order presented is approximate order of decreasing importance.

TABLE 8.13 The Oceanic Chloride Budget (Rates in Tg Cl$^-$/yr)

Present-Day Budget			
Inputs		Outputs	
Rivers (natural)	215	Net sea–air transfer	40
Rivers (pollution)	93	Pore-water burial	25
Total	308	Total	65
Long-Term (Balanced) Budget			
Inputs		Outputs	
Rivers	215	NaCl evaporative deposition	163
		Net sea–air transfer	40
		Pore-water burial	12
		Total	215

Note: Tg = 10^{12} g. Replacement time for Cl$^-$ is 87 million years.

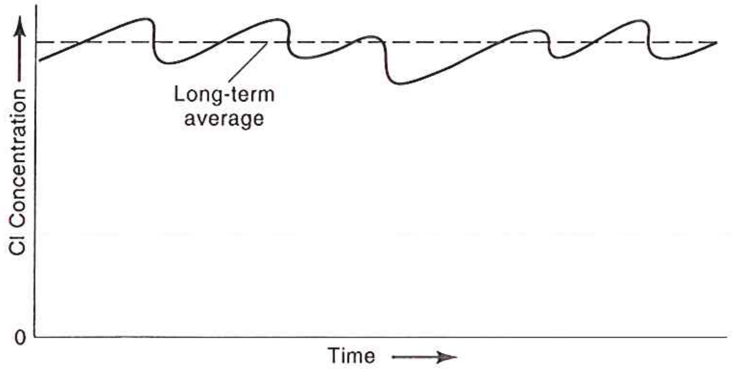


Figure 8.12. Schematic representation of change of chloride (Cl$^-$) concentration in seawater with geologic time. Sudden drops are due to the rapid precipitation of NaCl in evaporite basins.

TABLE 8.14 The Oceanic Sodium Budget (Rates in Tg Na^+/yr)

Present-Day Budget			
Inputs		Outputs	
Rivers (natural)	193	Cation exchange	42
Rivers (pollution)	76	Net sea–air transfer	21
		Pore-water burial	16
Total	269	Total	79
Long-Term Budget			
Inputs		Outputs	
Rivers	193	NaCl deposition	106
		Net sea–air transfer	21
		Cation exchange	21
		Pore-water burial	8
		Basalt–seawater reaction	37
		Total	193

Note: Tg = 10^{12} g. Replacement time for Na^+ is 55 million years.

TABLE 8.16 The Oceanic Magnesium Budget (Rates in Tg Mg^{++}/yr)

(Balanced) Budget for Past 100 Million Years			
Inputs		Outputs	
Rivers	137	Volcanic–seawater reaction	119
		In biogenic $CaCO_3$	15
		Net sea–air transfer	3
		Total	137

Note: Tg = 10^{12} g. Replacement time for Mg^{++} is 13 million years.

TABLE 8.18 The Oceanic Calcium Budget (Rates in Tg Ca^{++}/yr)

Present-Day Budget			
Inputs		Outputs	
Rivers	550	$CaCO_3$ deposition:	
Volcanic–seawater reaction	191	Shallow water	520
Cation exchance	37	Deep sea	440
Total	778	Total	960
Budget for Past 25 Million Years			
Inputs		Outputs	
Rivers	550	$CaCO_3$ deposition:	
Volcanic–seawater reaction	191	Shallow water	240
Cation exchance	19	Deep sea	440
		Evaporitic $CaSO_4$ deposition	49
Total	760	Total	729

Note: Tg = 10^{12} g. Replacement time (rivers only) for Ca^{++} is 1 million years.

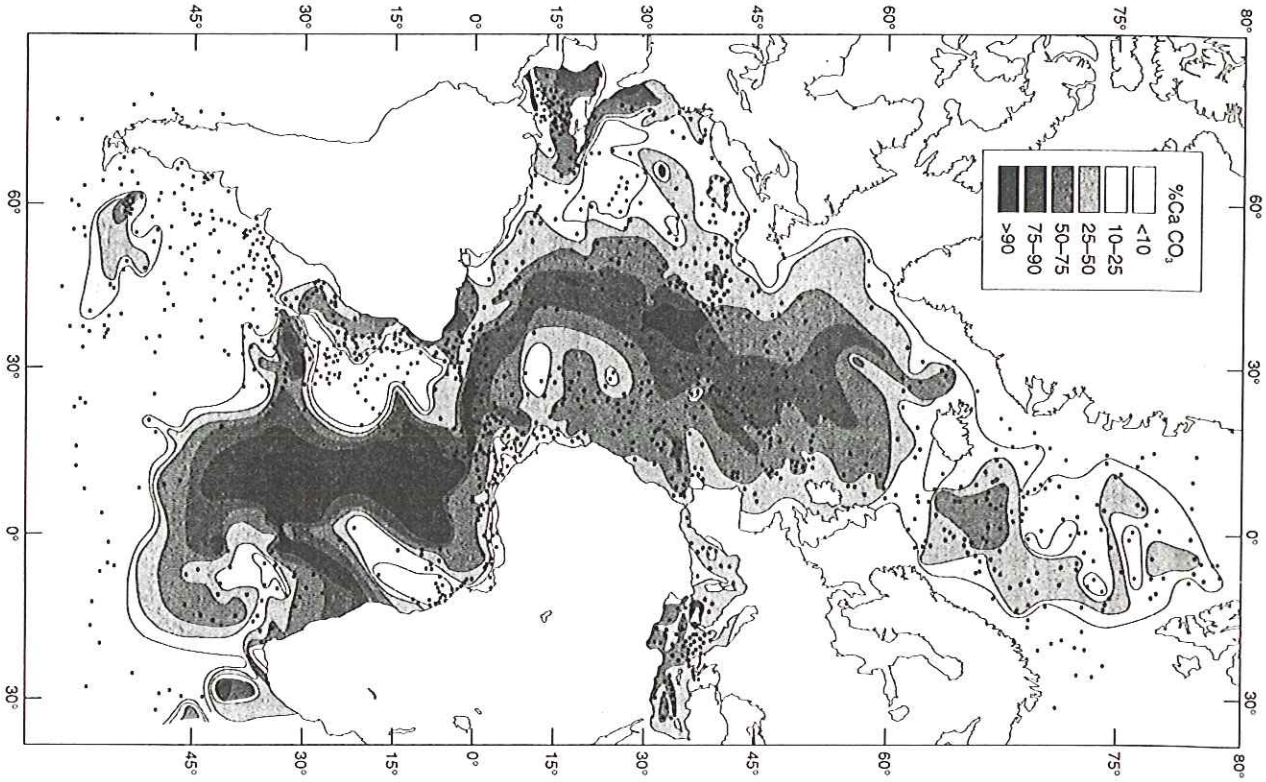
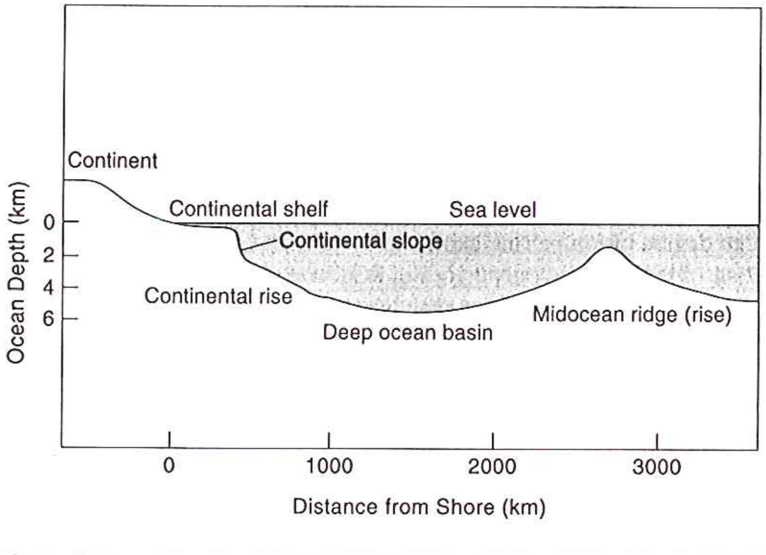


Figure 8.13. Distribution of $CaCO_3$ in deep-sea sediments of the Atlantic Ocean. Note that the highest concentrations are located at the shallowest depths atop the Mid-Atlantic Ridge. (After P. E. Biscaye, V. Kolla, and K. K. Turekian, "Distribution of Calcium Carbonate in Surface Sediments of the Altantic Ocean." *Journal of Geophysical Research* 81: 2596. Copyright © 1976 by the American Geophysical Union, reprinted by permission of the publisher.)



calcite compensation depth ~ 4 km

$CaCO_3$ shells dissolve below this depth

Figure 8.1. Generalized schematic cross section of the oceans showing major physiographic features. Note large differences in vertical and horizontal scales.