Università di Trieste
LAUREA MAGISTRALE IN GEOSCIENZE SM62
Percorso Esplorazione Geologica

Anno accademico 2023 - 2024

Geologia Marina 953SM

Parte I

Modulo 1.2 Introduzione ai fondali oceanici oceani: Acqua oceanica, sedimento, e fluidi interstiziali

Docente
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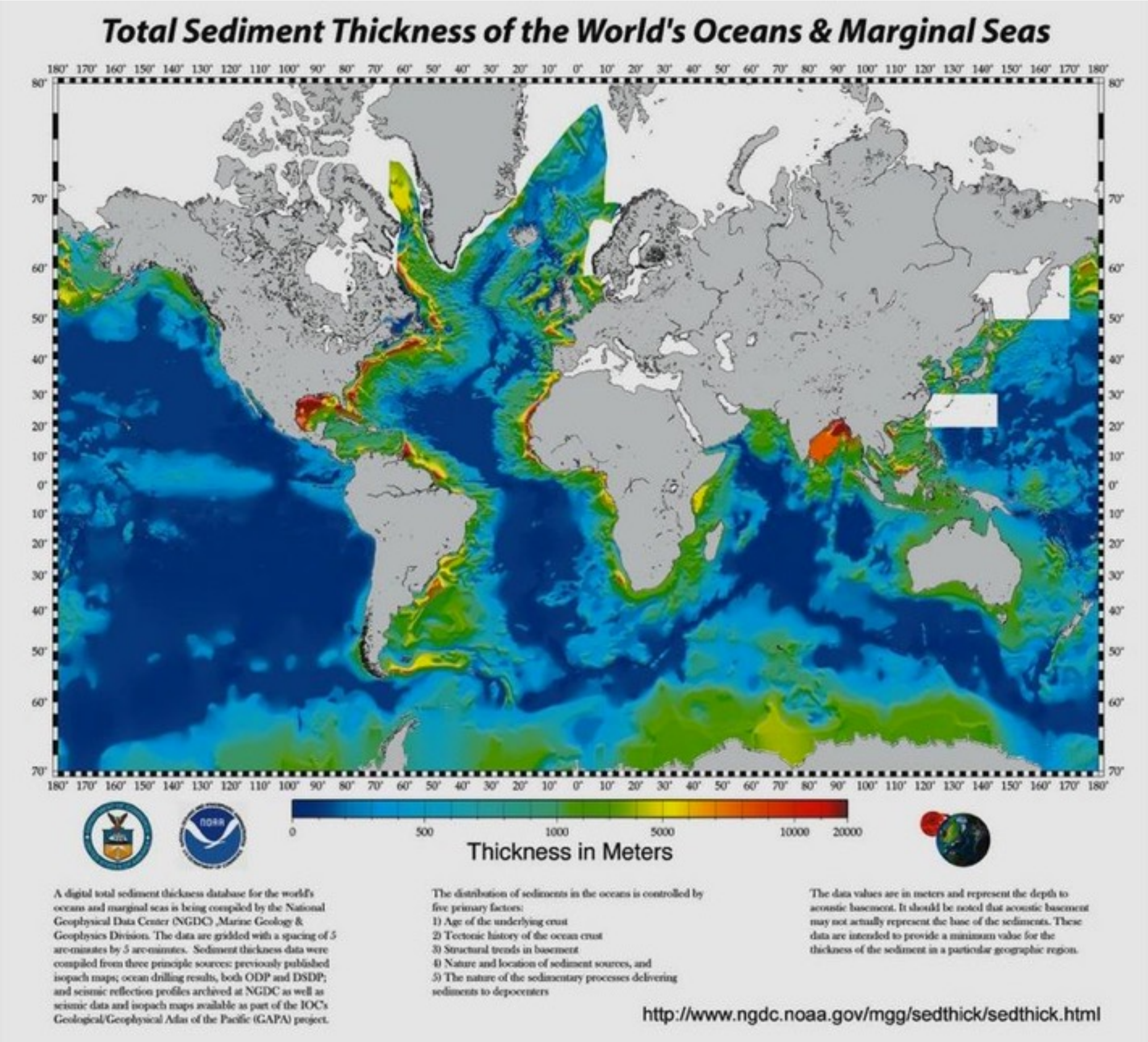
Oceans and Seas:

Global sinks of sediments eroded on continents



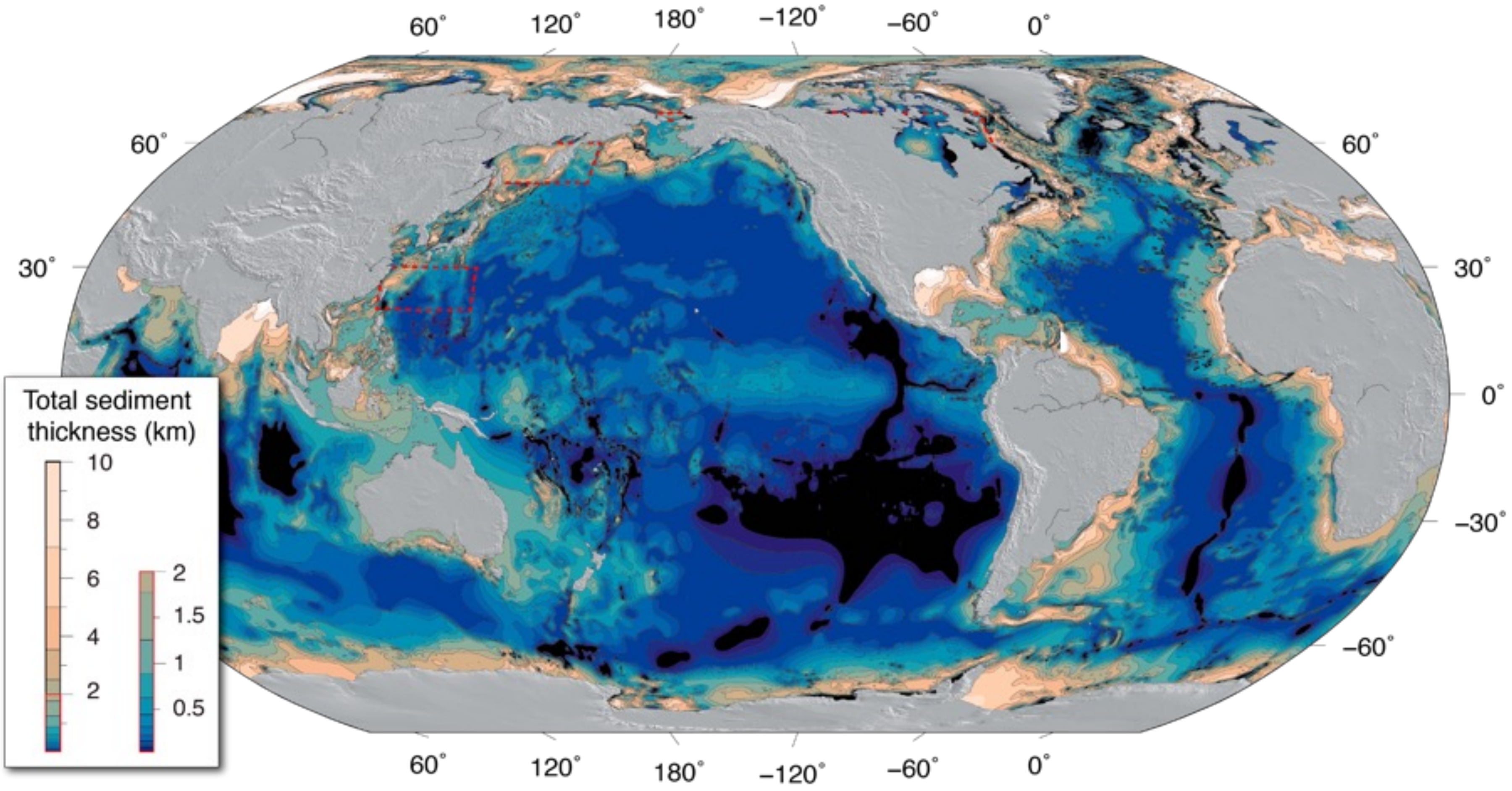
Total Sediment Thickness of the World's Oceans & Marginal Seas

A digital total sediment thickness database for the world's oceans and marginal seas is being compiled by the National Geophysical Data Center (NGDC) ,Marine Geology & Geophysics Division. The data are gridded with a spacing of 5 arc-minutes by 5 arc-minutes. Sediment thickness data were compiled from three principle sources: previously published isopach maps; ocean drilling results, both ODP and DSDP; and seismic reflection profiles archived at NGDC as well as seismic data and isopach maps available as part of the IOC's Geological/Geophysical Atlas of the Pacific (GAPA) project.

The distribution of sediments in the oceans is controlled by five primary factors:
1) Age of the underlying crust
2) Tectonic history of the ocean crust
3) Structural trends in basement
4) Nature and location of sediment sources, and
5) The nature of the sedimentary processes delivering sediments to depocenters

The data values are in meters and represent the depth to acoustic basement. It should be noted that acoustic basement may not actually represent the base of the sediments. These data are intended to provide a minimum value for the thickness of the sediment in a particular geographic region.

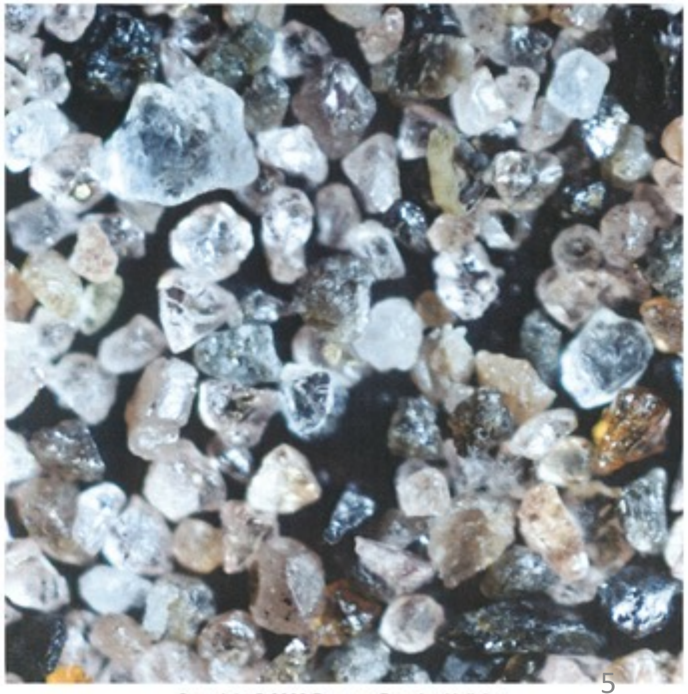
http://www.ngdc.noaa.gov/mgg/sedthick/sedthick.html



Straume et al., 2020. Geochemistry, Geophysics, Geosystems, 20, . DOI: 10.1029/2018GC008115

Terrigenous Sediments (also: *lithogenous*)

- Eroded rock fragments from land
- Transported from land by
  - Water (e.g., river-transported sediment)
  - Wind (e.g., windblown dust) - *aeolian transport*
  - Ice (e.g., ice-rafted rocks)
  - Gravity (e.g., turbidity currents)



Terrigenous Sediments (also: *lithogenous*)

CLAYS (hydrates alumosilicate mineral)

- Kaolinite
- Chlorite
- Illite
- Montmorillonite

- Particles are generally < 2 µm

Also generated by dissolution of calcareous plankton and benthos (red clays, or pelagic clays) below the **Carbonate Compensation Depth (CCD)** in the open ocean.

Terrigenous Sediments (also: *lithogenous*)

SILTS and SANDS

Silts (2 - 63 µm)

Sands (>63 µm)

Mainly transported by turbidity currents, debris flows, icebergs

Reflect composition of surrounding land masses

Biogenic Sediments (also: *biogenous*)

Hard remains of dead organisms

- Macroscopic (large remains)
  - Shells, bones, teeth
- Microscopic (small remains)
  - Tiny shells or tests settle through water column
  - Biogenic ooze (30% or more tests)
  - Mainly algae and protozoans

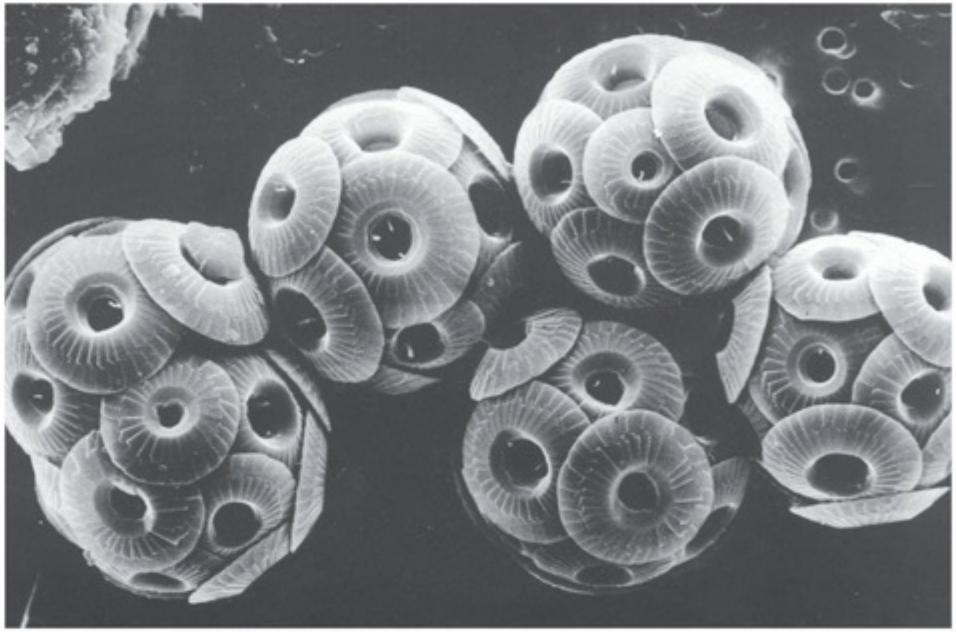
- Calcium carbonate ($CaCO_3$)
- Silica (SiO_2 or $SiO_2 \cdot nH_2O$)

Biogenic Sediments (also: *biogenous*) continued

Calcium carbonate in biogenous sediments

Coccolithophores (algae)

- Photosynthetic
- Coccoliths (nano-plankton)



(a)

Biogenic Sediments (also: *biogenous*) continued

Calcium carbonate in biogenous sediments

Foraminifera

(Benthic and Planktonic Protozoans)

Calcite

30µm - 1 mm

(c)

Biogenic Sediments (also: *biogenous*) continued

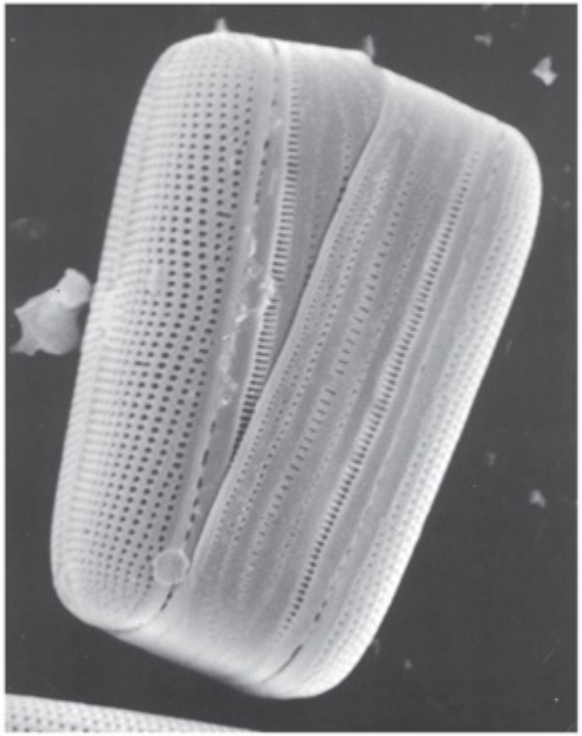
Pteropods
(planktonic gastropods molluscs)

Aragonite
(a variety of calcite, more soluble)

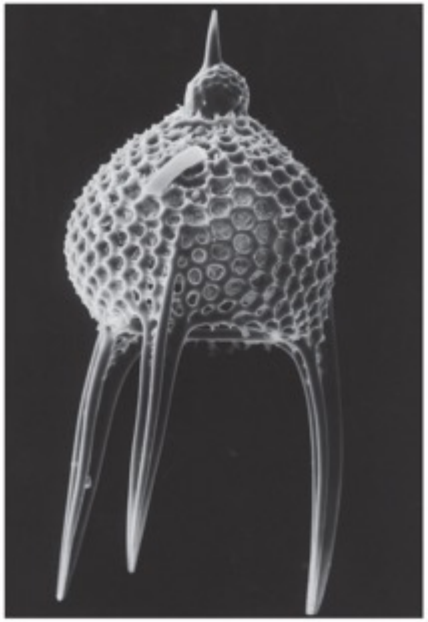
Biogenic Sediments (also: *biogenous*) continued

Silica in biogenic sediments

Diatoms (algae) < 200 µ m
Radiolarians (protozoans) 50-300 µm



(a)



(b)

(a)

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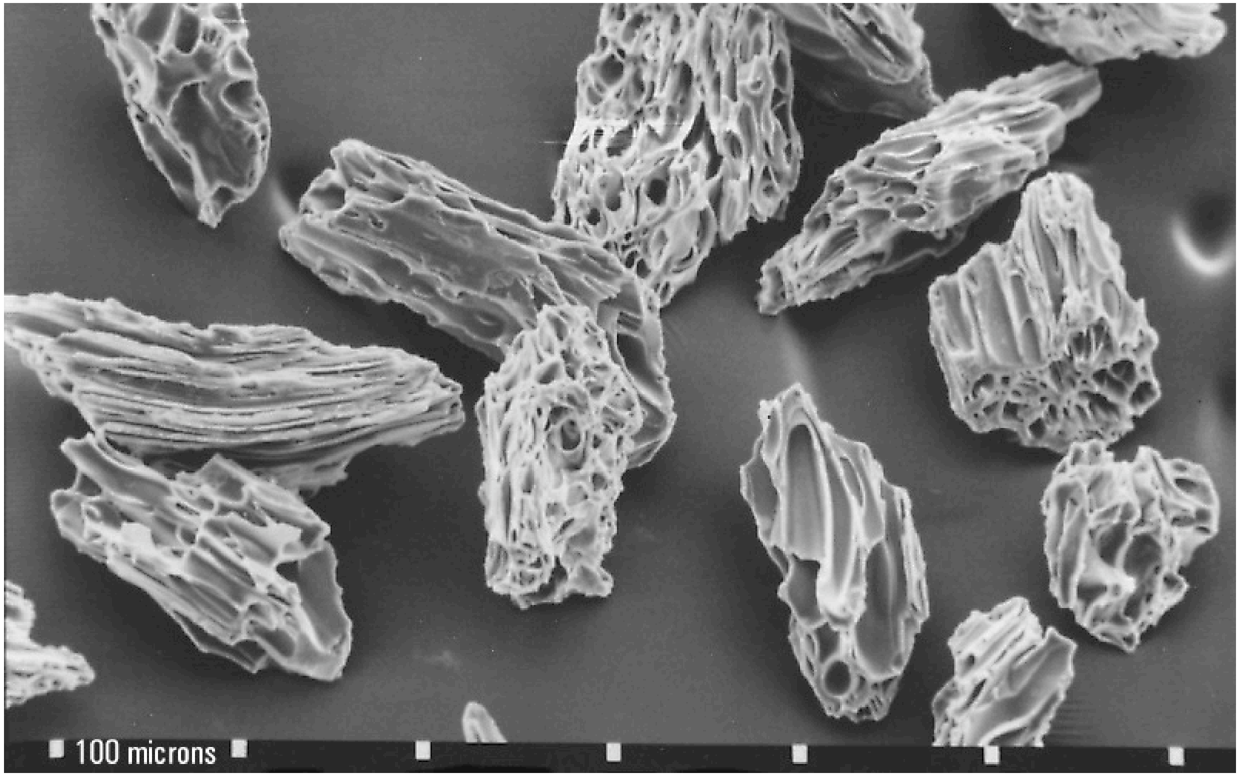
Authigenic Sediments (also: *Hydrogenous*)

- Minerals precipitate directly from seawater
    - Manganese nodules
    - Phosphates (beneath areas in surface ocean of ver high biological productivity)
    - Carbonates (Aragonite and calcite)
    - Metal sulfides (Associated with hydrothermal vents)
    - Evaporites (Minerals that form when seawater evaporates)

- Small proportion of marine sediments

Volcanogenic Sediments (also: *Hydrogenous*)

- Ash layers
- Lava basalts
- Tephra layers



Glass shards

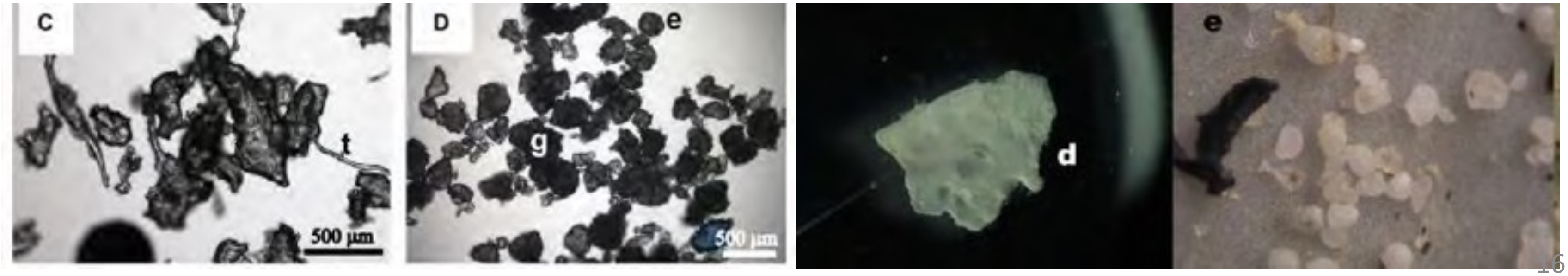
Cosmogenous Sediments

- Macroscopic meteor debris
- Microscopic iron-nickel and silicate spherules
- Tektites
- Space dust
- Overall, insignificant proportion of marine sediments

Microplastics

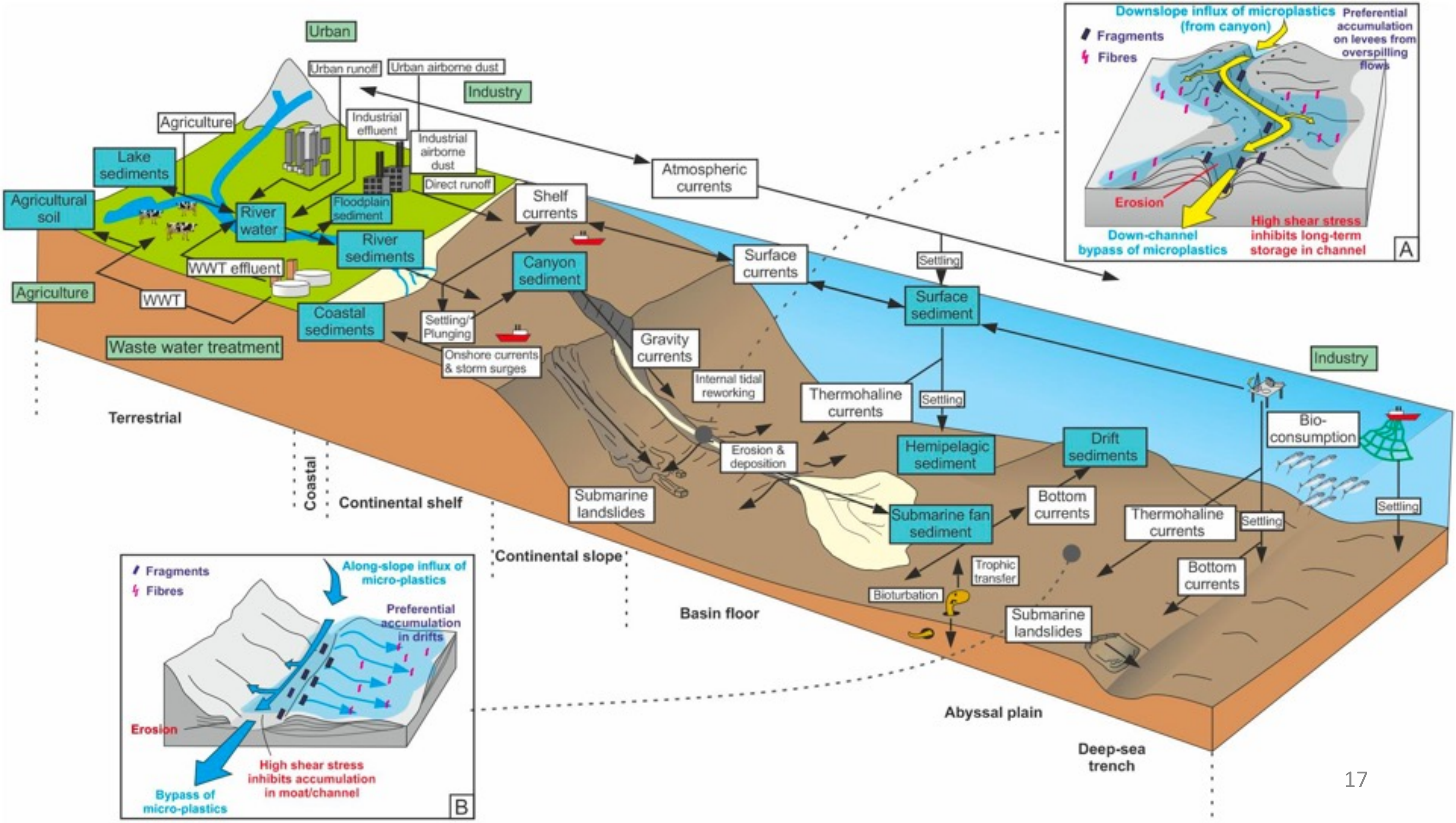
- "New and emerging issue" – GESAMP (Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) is an advisory body, established in 1969, that advises the United Nations (UN) system on the scientific aspects of marine environmental protection.

- Plastic particles < 5mm
- Primary microplastics are deliberately manufactured
- Secondary microplastics are break-down products of larger debris
- Most plastic derives from land-based sources
  - Household and industrial waste + wastewater
  - Fishing, aquaculture, shipping, tourism, etc.



Front. Earth Sci., 30 April 2019 | https://doi.org/10.3389/feart.2019.00080

Dispersion, Accumulation, and the Ultimate Fate of Microplastics in Deep-Marine Environments: A Review and Future Directions



MARINE SEDIMENTS

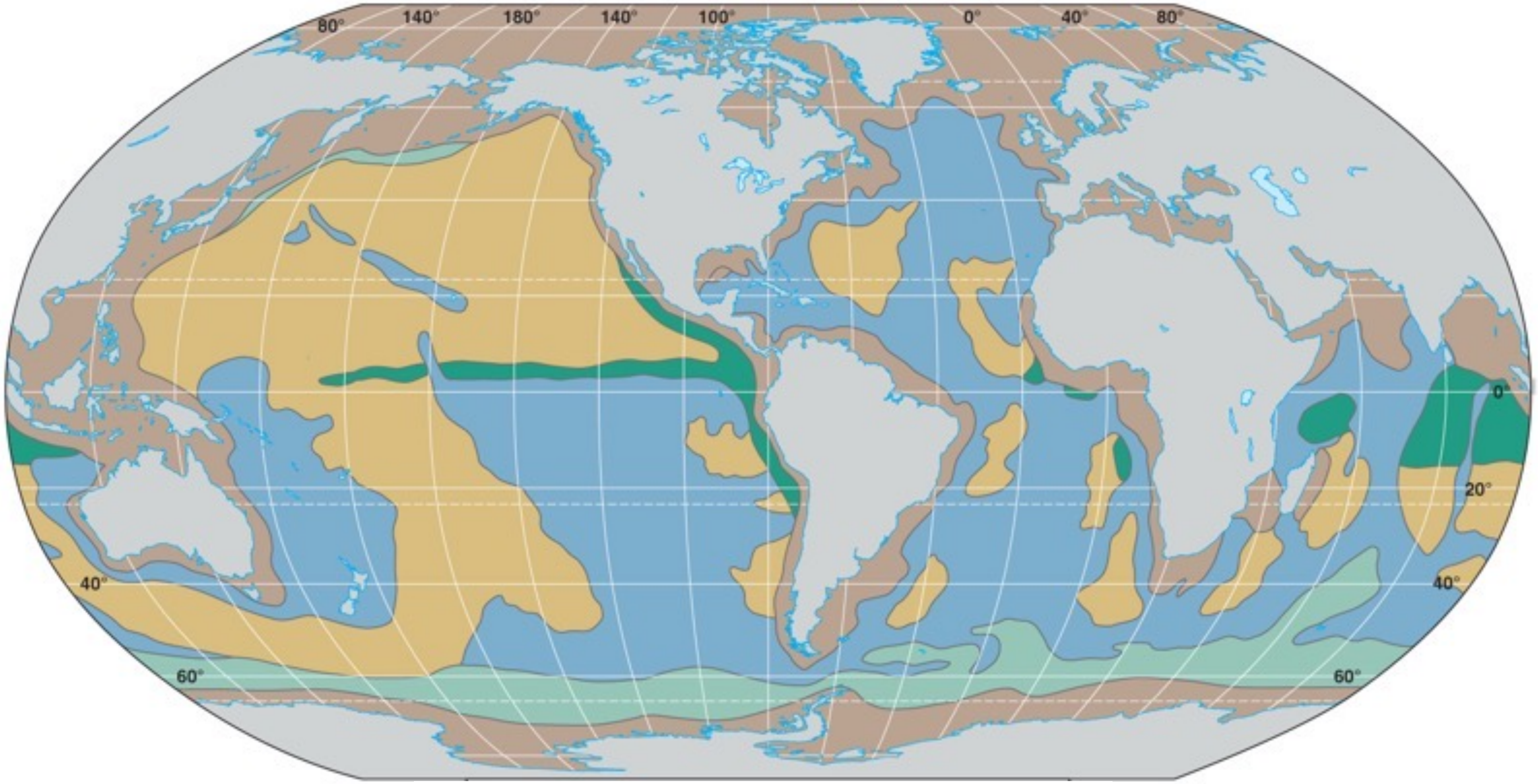
Distribution

Neritic

- Shallow water deposits
- Close to land
- Dominantly lithogenous
- Typically deposited quickly

Pelagic (Also Oceanic)

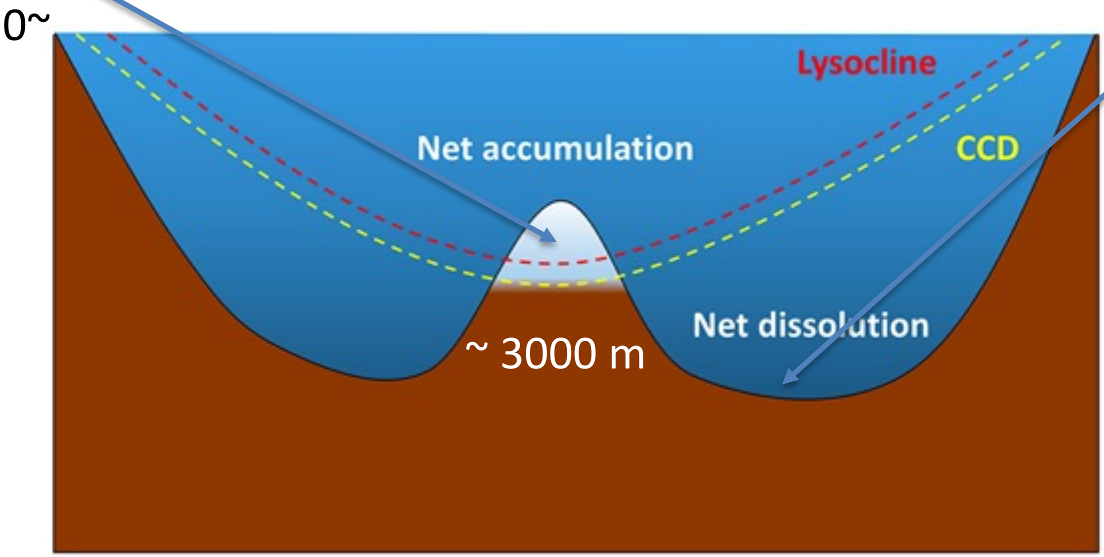
- Deeper water deposits
- Finer-grained sediments
- Deposited slowly



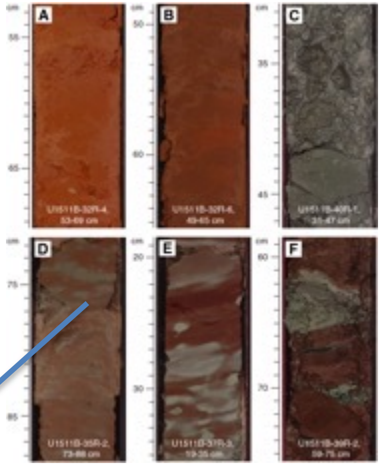
Neritic 🟫 **Oceanic** Abyssal clay 🟨 Calcareous Ooze 🟦 Siliceous Ooze ◩

Carbonate compensation depth (similar to snow-line on land)

Calcareous ooze
(Nannofossils,
forminifera)
Above the CCD



Southern high latitudes equator Northern high latitudes



Abyssal clays
Red clays
Below CCD

Calcareous sediment can only accumulate in depths shallower than the calcium carbonate compensation depth (CCD). Below the CCD, calcareous sediments dissolve and will not accumulate. The **lysocline** represents the depths where the rate of dissolution increases dramatically.

https://commons.wikimedia.org/wiki/File:Calcareous_sediment_in_the_ocean.png

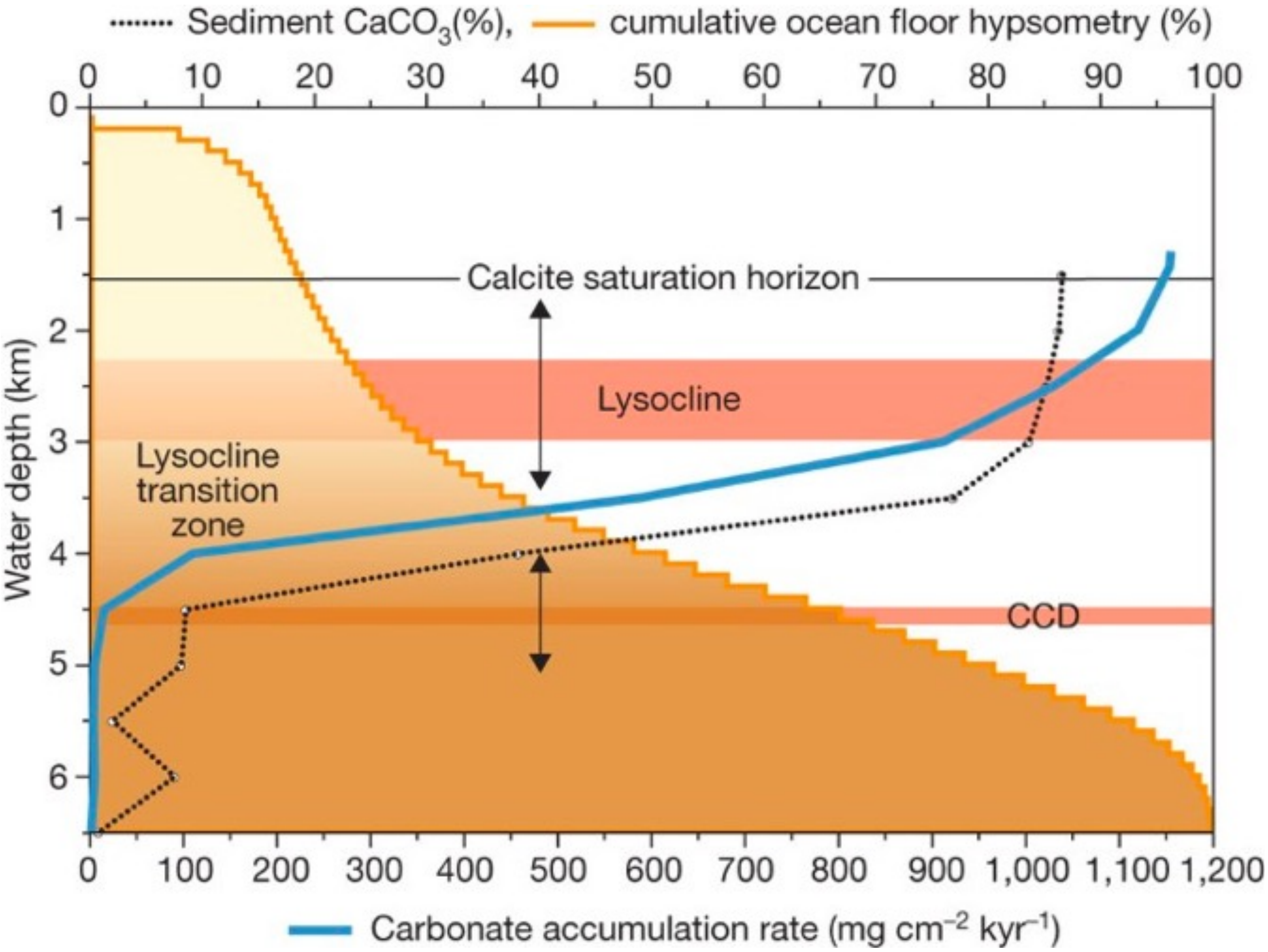
Within the water column, calcium (Ca^{2+}) content varies little, hence the calcium carbonate saturation state (CSS) is controlled by concentration of carbonate (CO_3^{2-}) ions, pH , water pressure, temperature , and salinity:

$CSS = (Ca^{2+}) \times (CO_3^{2-}) \div K'sp$

whereas K'sp is the equilibrium solubility product for the mineral phase of calcite or aragonite, respectively.

It is CSS: supersaturated > 1
saturated = 1
undersaturated < 1
with carbonate ions.
Position and thickness of the saturation horizon in the water column can be defined as the difference ΔCO_3^{2-} between the concentration of carbonate ions in situ and the concentration of saturated carbonate ion for the respective mineral phase.

https://www.encyclopedia.com/science-and-technology/astronomy-and-space-exploration/astronomy-general/ccd



Pälike et al., 2012, Nature

Distribution of pelagic sediment

Dominant component	**Composition**	**Atlantic**	**Pacific**	**Indian**	**Total %**
Foraminiferal and nannofossil ooze	Calcium carbonate	65	36	54	47
Pteropod ooze	Calcium carbonate	2	0.1	-	0.5
Diatom ooze	Silica (opal)	7	10	20	12
Radiolarian ooze	Silica (opal)	-	5	0.5	3
Red (actually brown) clay K, Fe	Al silicate	26	49	25	38

Source P.Pinet Invitation to Oceanography, 2000 2nd Edition, Jones and Barlett Publishers, Massachusetts

Take-home messages

Marine sediments are very heterogeneous material, whose solid component is made by a mixture of particles with different composition, shape and size

All of the inorganic solid components of marine sediments undergo some kind of chemical alteration through time essentially in consequence of the exposure to salt water

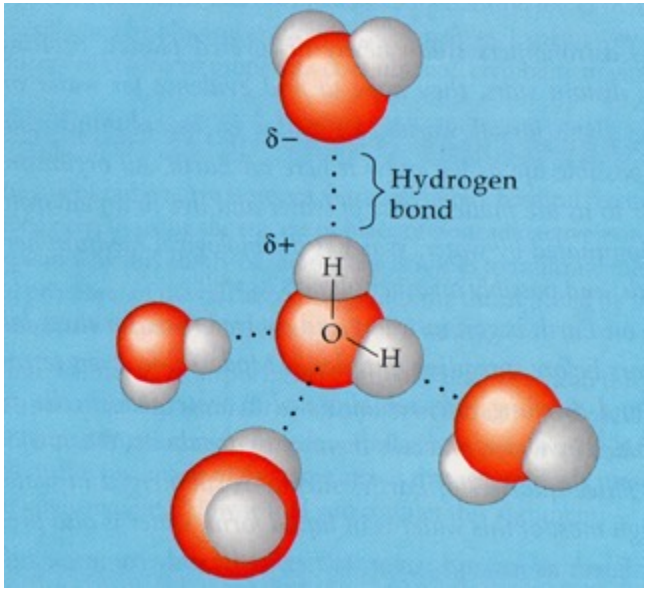
SEAWATER

Water has unique and unusual properties both in pure form and as a solvent.

These properties influence many of the chemical reactions taking place in the oceans.

“Distorted” tetrahedral arrangement, with 2 electrons in each lobe. Two lobes are used for O-H bonds and two lobes have free lone pairs of electrons.

The H-O-H tetrahedral angle of 105º, results in dipole moments, which means that this is a polar molecule.



Propensity to form hydrogen bonds. “Cooperative Bonding” in which the water molecules link together to form regions with structure.

SEAWATER

- SALINITY: dissolved ion content by weight.
- Average 3.5 % or 35 parts per thousands
- Varying between 3.1% and 3.8%
- Not uniform distribution (horizontal and vertical)

Seawater composition (by mass)

Element	**%**
Oxygen	**85.84**
Hydrogen	**10.82**
Chlorine	***1.94***
Sodium	**1.08**
Magnesium	**0.1292**
Sulfur	**0.091**
Calcium	**0.04**
Potassium	**0.04**
Bromine	**0.0067**
Carbon	**0.0028**

because salinity is directly proportional to the amount of chlorine in sea water, and because chlorine can be measured accurately by a simple chemical analysis, **salinity S is defined using chlorinity**

S (*o/oo*) = 1.80655 x Cl (*o/oo*)

Now Salinity is measured by Electroconductivity in Practical Salintiy Units (PSU)

Seawater composition

Marcet's Principle (constancy of composition):

X/Cl = constant

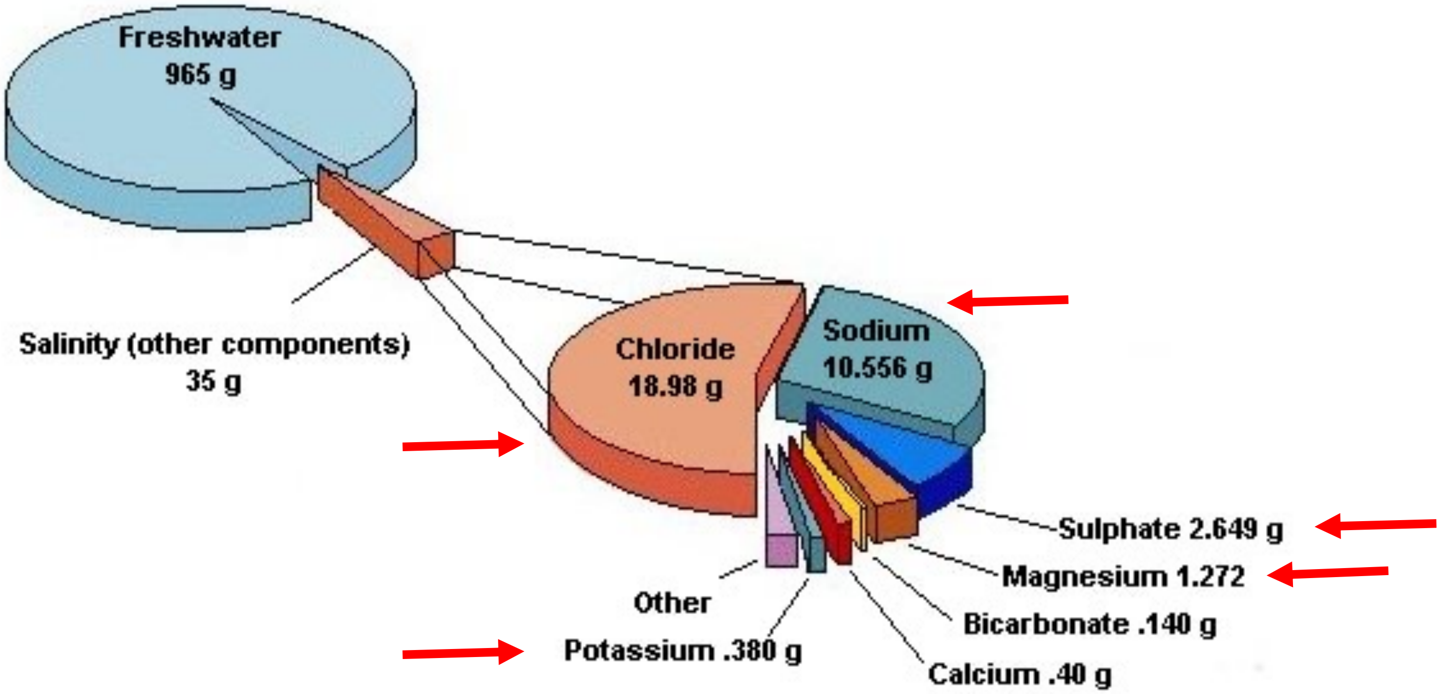
- True for ***conservative*** elements, which include most of the major ions in seawater (Na^+, K^+, SO_4^{-2}, and Cl^-).

- The concentration of this elements, normalized to salinity, is constant with depth and in the different oceans.

- The ratio of one conservative element to another will also be constant.

Seawater composition

→ Conservative elements



What does and what does not affect the constancy of composition of salt in seawater?

Does Not:

- Precipitation – evaporation
- Freezing – thawing
- Turbulent mixing between water masses

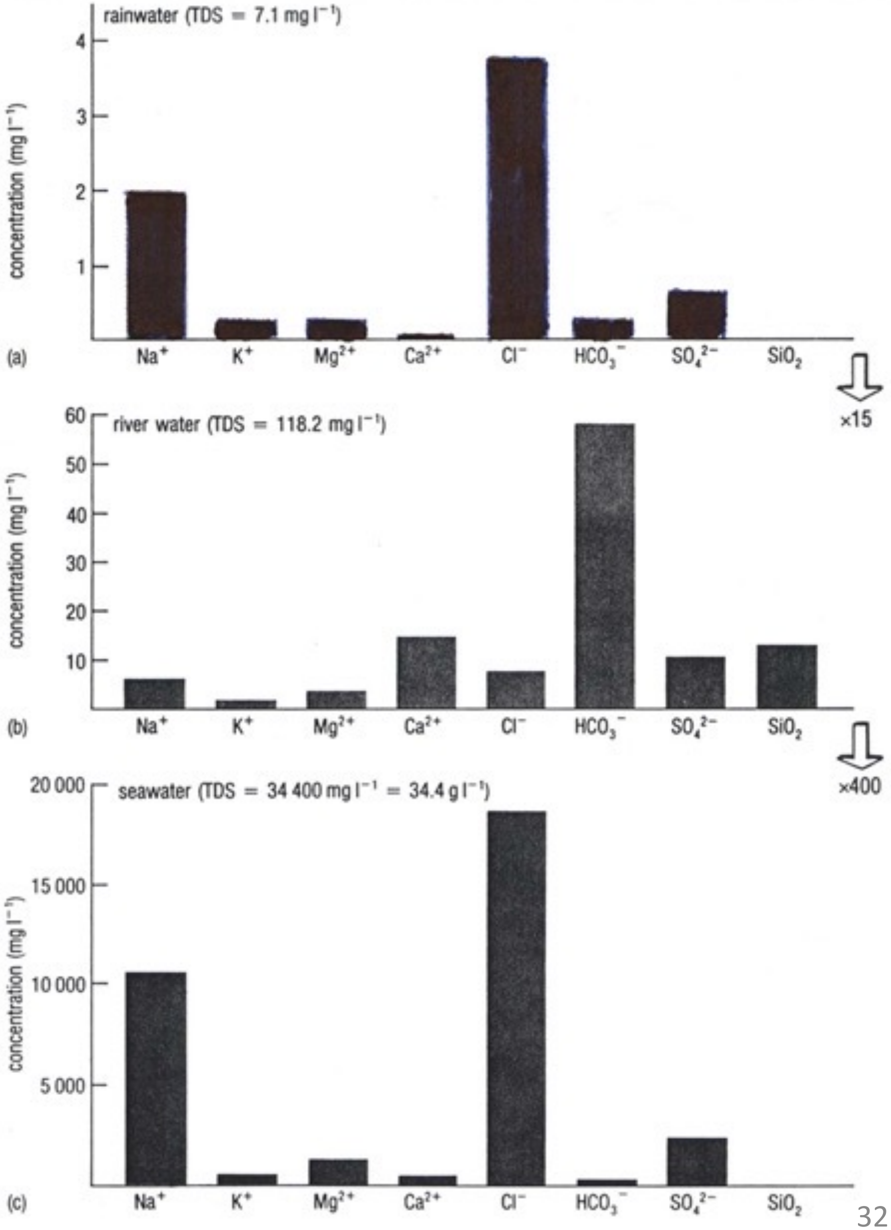
Does:

- Marginal seas receiving significant river runoff, e.g Baltic Sea
- Anoxic basins where sulfate reduction occurs, e.g. Black Sea
- Shallow water environments where significant inorganic aragonite (a form of $CaCO_3$) precipitation occurs – oolites
- Hydrothermal vents where seawater influx through hydrogeological processes causes low and high temperature alteration of basalts
- Evaporite basins, e.g. Dead Sea
- Interstitial waters of sediments

Origin of dissolved ions

rain water does not look like river water

seawater doesn't look like river water



Origin of dissolved ions

IGNEOUS ROCK + RAIN WATER >>>> SEDIMENTARY ROCK + RIVER WATER

Order of loss of cations during weathering of igneous rocks:

$$Ca^{++} > Na^{+} > Mg^{++} > K^{+} > Si^{++++} > Fe^{+++} > Al^{+++}$$

$Ca^{++} > Na^{+} > Mg^{++}$ are the most abundant cations in river water

K^{+} is retained in clay minerals and is not abundant in river water

FELDSPARS + H_2CO_3 >>>> CLAY + Ca, Na, K, H_4SiO_4

Origin of dissolved ions

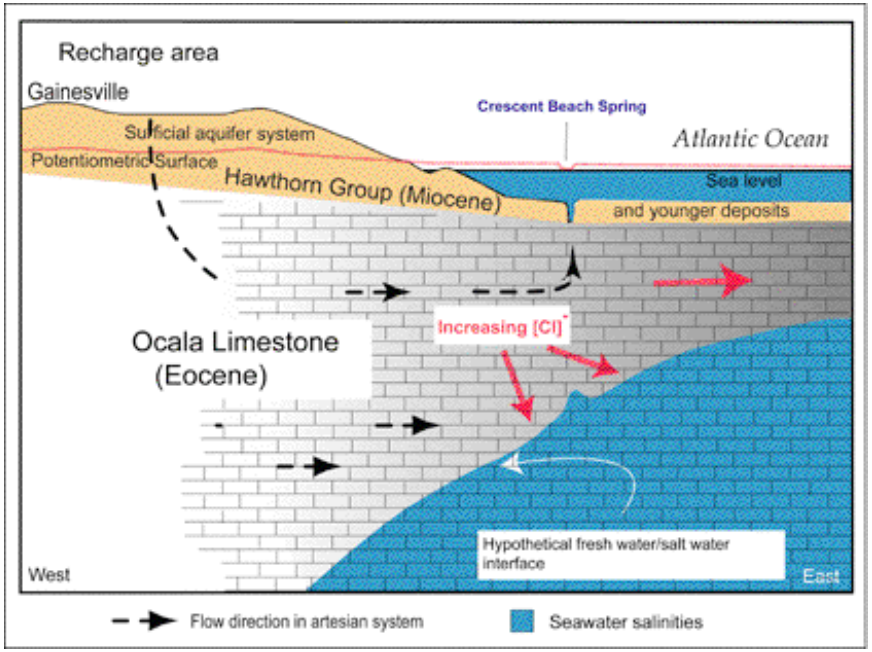
Product of alteration of igneous rocks:

LIMESTONES	5 - 15%
SANDSTONES	11 - 30%
SHALES	**65 - 80%**

MINOR COMPONENTS (evaporites, cements…)

Other input of ions to the oceans

Groundwaters



Around the world groundwater discharge was observed at several coastal regions

Considerable flow rates of more than 1000 liters per minute were measured for submarine springs in the northeastern Gulf of Mexico.

Using the enrichment of ^{226}Ra, Moore (1995) estimated that the groundwater flux to the coastal waters of South Atlantic Bay must be **~40% of the river-water flux** (LOCAL).

Leaky Coastal Margins working group, Florida 2001.
http://soundwaves.usgs.gov/2001/03/meetings5.html

Hydrothermal Systems

- Seawater is entrained at spreading centers and contributes to hydrothermal circulation.
- Rate of hydrothermal circulation 0.3 to 3% of river input.
- Reactions between seawater and basalt modify composition of the circulating fluids.

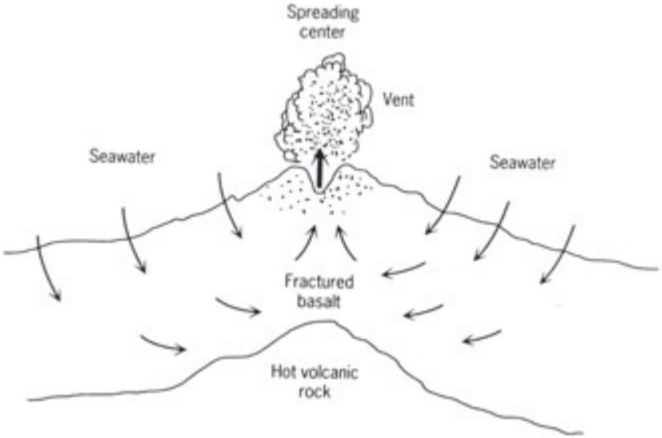
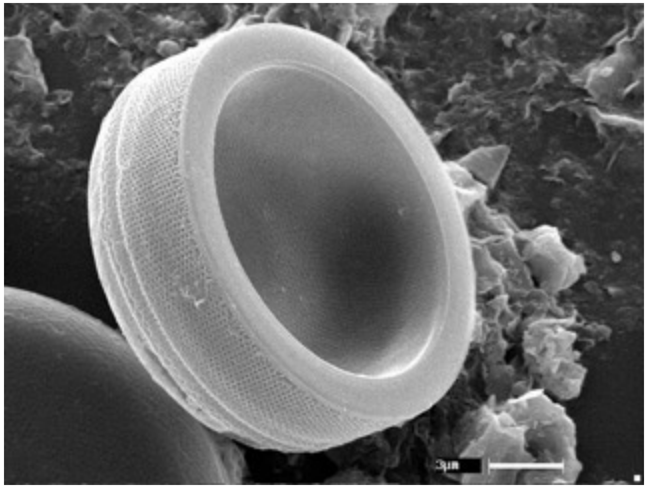


FIGURE 19.2. Hydrothermal convection cells.

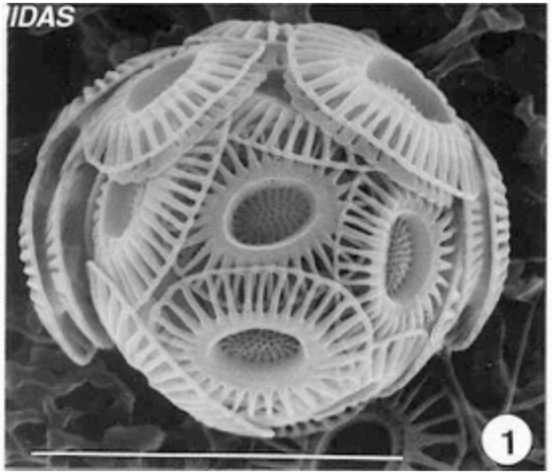
By **HIGH** and **LOW** temperature geochemistry

Salt sinks

Biological factors



Centric diatoms – an algae



Emiliania huxleyi, a coccolithorophorid

Make a skeleton based on the element Si – '**biogenic silica**' or SiO_2

Make skeletal material from **calcium carbonate** $CaCO_3$

Salt sinks

Microbiology: Sulfate reduction in anoxic basins

$SO_4^{--} + 2\ CH_2O. \longleftrightarrow H_2S + 2\ HCO_3^-$

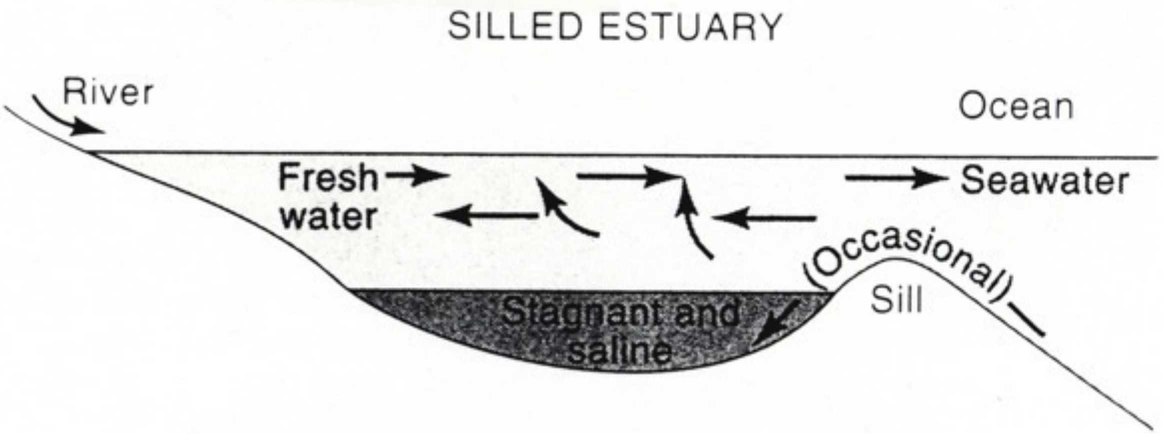
Organic matter   Increase in alkalinity

$2\ FeO \cdot OH + 3\ H_2S. \longleftrightarrow 2\ FeS + S^{--} + 4\ H_2O$

Pyrite

$Ca^{++} + 2\ HCO_3^- \longleftrightarrow 2\ CaCO_3 + 2\ H^+$

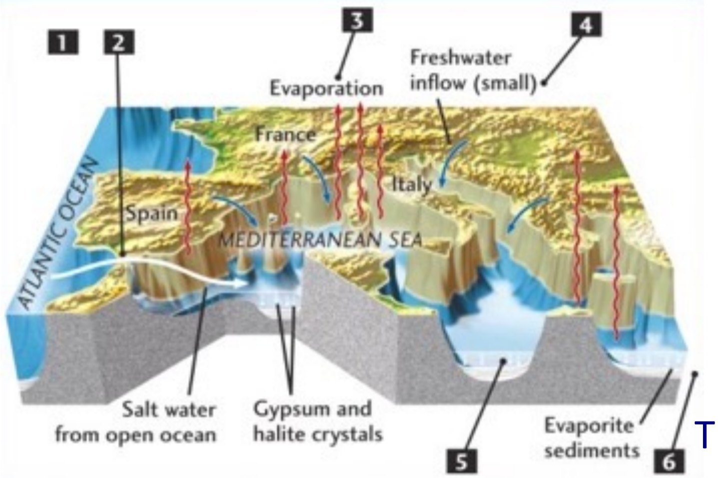
Calcite

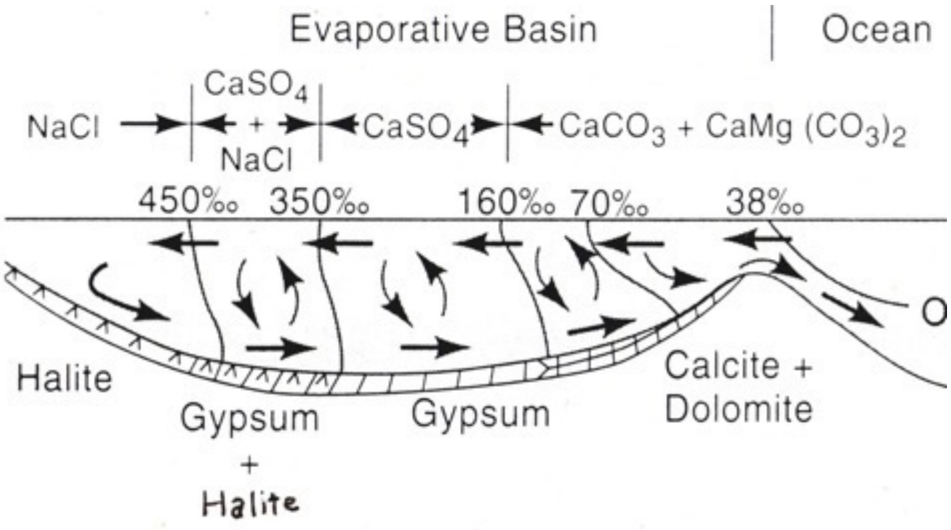


Black Sea

Salt sinks

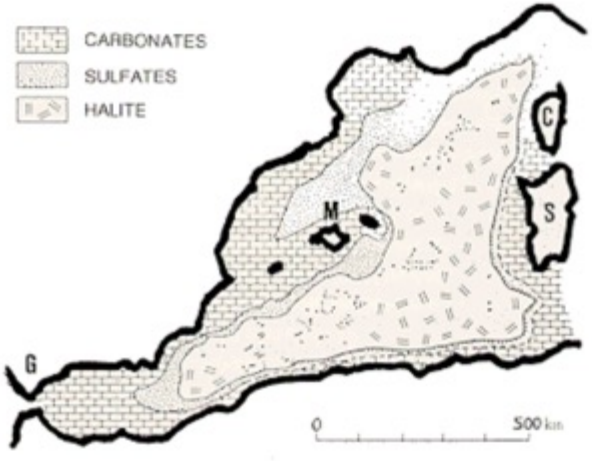
Evaporation





The minerals precipitate out of solution in the reverse order of their solubilities, such that the order of precipitation from sea water is:

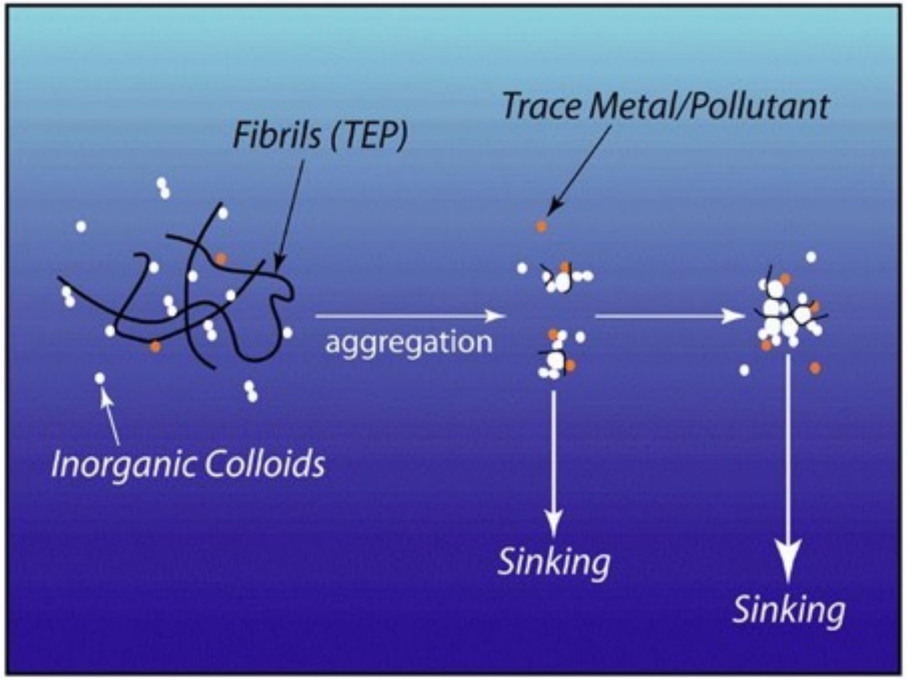
1 Calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$)
2 Gypsum ($CaSO_4 \cdot 2H_2O$) and anhydrite ($CaSO_4$)
3 Halite (i.e. common salt, NaCl)
4 Potassium and magnesium salts



Limestone (calcite) and dolomite are more common than gypsum, which is more common than halite, which is more common than potassium and magnesium salts.

Salt sinks

Extra-cellular polysaccharides may play a role in the formation of aggregates and transport of trace metals and pollutants in aquatic systems

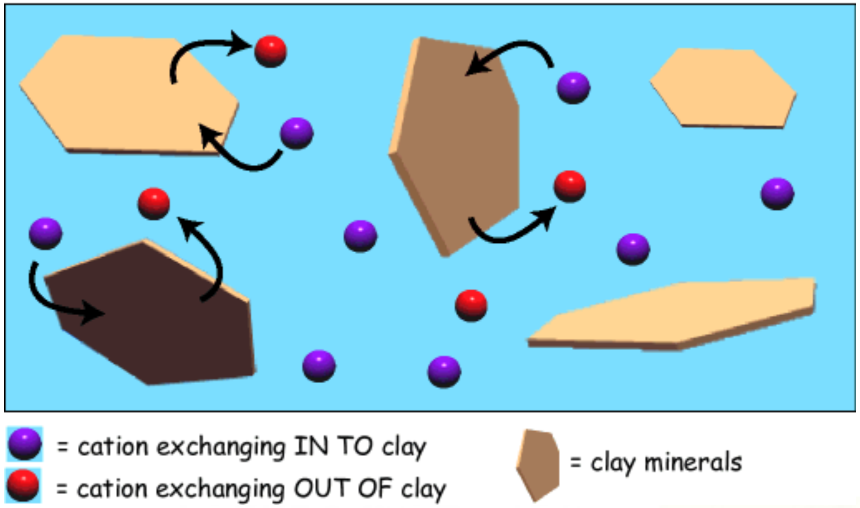


http://loer.tamug.tamu.edu/People/Santschi/santschi_research.htm

Salt sinks

Ion Exchange on Sedimentary Particles

Ca introduced in rivers is removed from clays at the expense of Na and K uptake



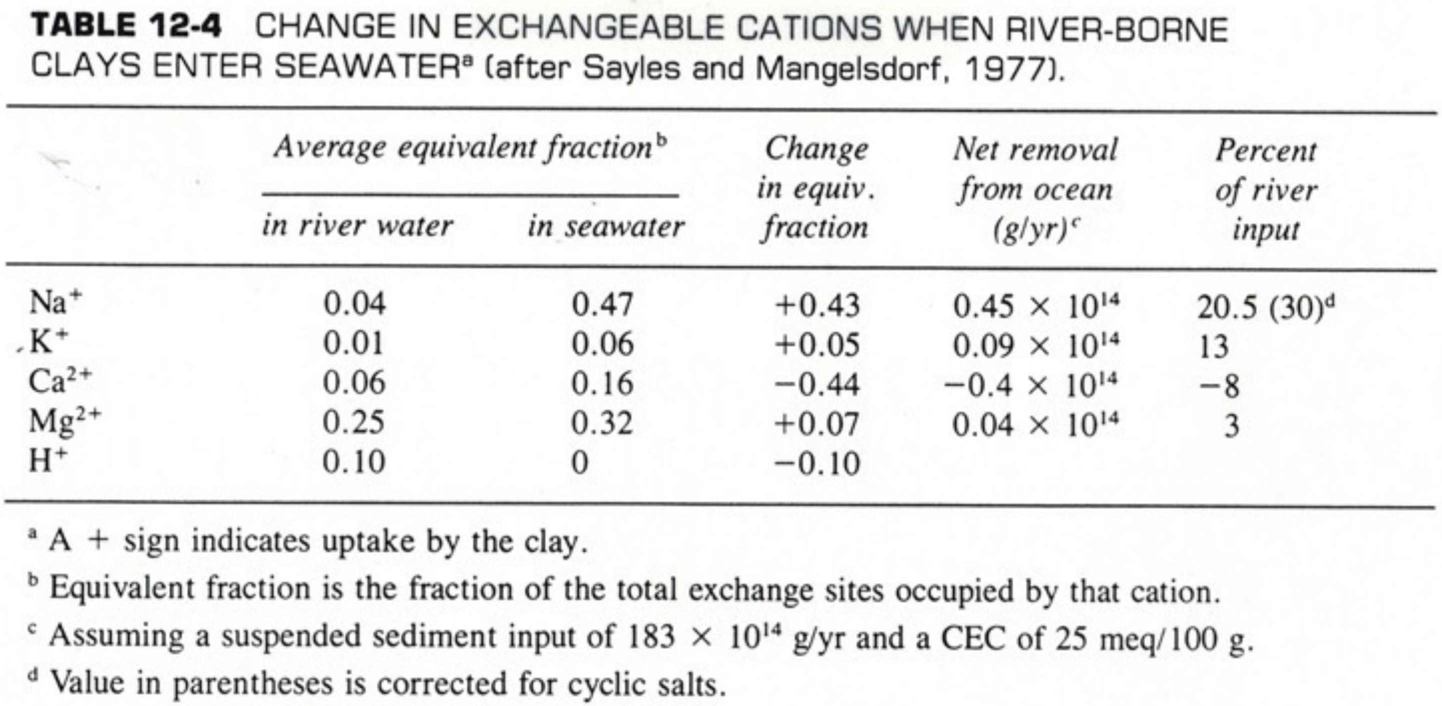


TABLE 12-4 CHANGE IN EXCHANGEABLE CATIONS WHEN RIVER-BORNE CLAYS ENTER SEAWATER[a] (after Sayles and Mangelsdorf, 1977).

	Average equivalent fraction[b]		*Change in equiv. fraction*	*Net removal from ocean (g/yr)*[c]	*Percent of river input*
	in river water	*in seawater*			
Na^+	0.04	0.47	+0.43	0.45×10^{14}	20.5 (30)[d]
K^+	0.01	0.06	+0.05	0.09×10^{14}	13
Ca^{2+}	0.06	0.16	−0.44	-0.4×10^{14}	−8
Mg^{2+}	0.25	0.32	+0.07	0.04×10^{14}	3
H^+	0.10	0	−0.10		

[a] A + sign indicates uptake by the clay.

[b] Equivalent fraction is the fraction of the total exchange sites occupied by that cation.

[c] Assuming a suspended sediment input of 183×10^{14} g/yr and a CEC of 25 meq/100 g.

[d] Value in parentheses is corrected for cyclic salts.

Salt sinks

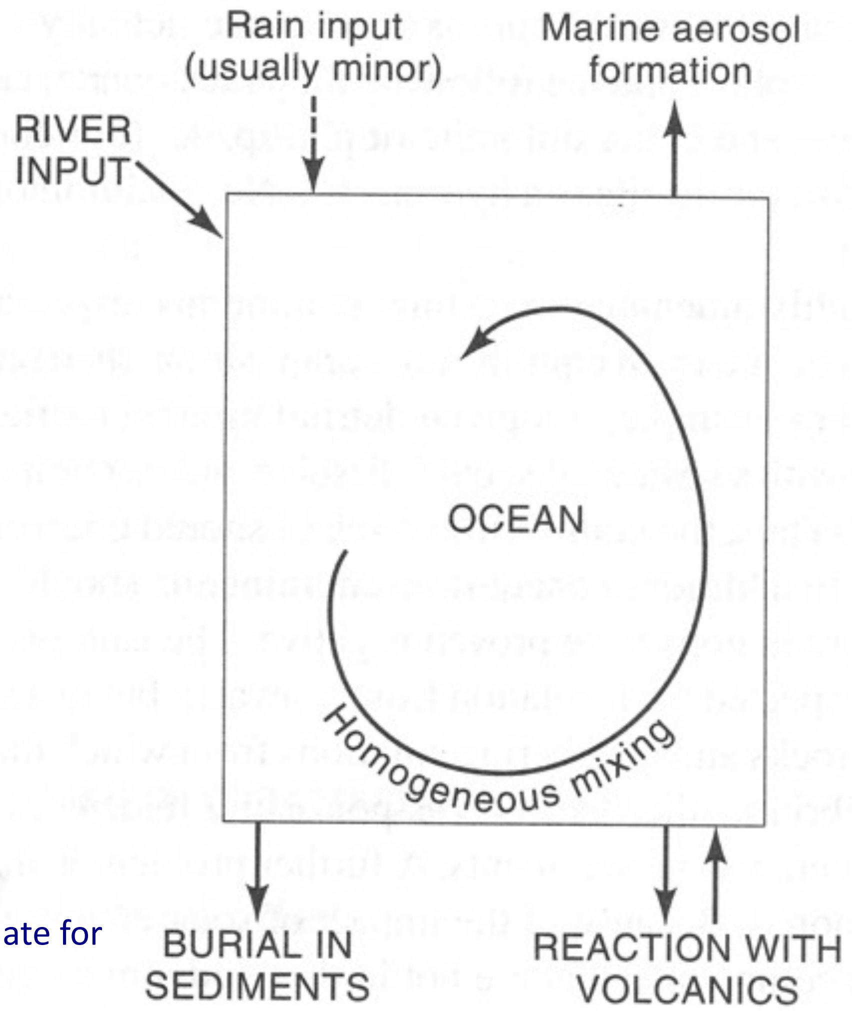
Hydrothermal systems

Basalt alteration at 200 ^{o}C

Source for Ca, sink for Mg, SO_4

Fresh Basalt + Mg^{++} + $2HC0_3^-$ = altered basalt + Ca-Silicate + $2CO_2$

Mass balance: Simple box models



From Berner and Berner. Box model appropriate for conservative elements in seawater.

Physical properties of sea water

In oceanography, the calculation of water movement requires measurements of density with an accuracy of a few parts per million. This is not easy.

Absolute Density of water can only be measured in special laboratories, and only with difficulty. The best accuracy is $1 : 2.5 \cdot 10^5 = 4$ parts per million.

To avoid the difficulty of working with absolute density, oceanographers use **density relative to density of pure water**. Density *r* (S, t, p) is now defined using Standard Mean Ocean Water of known isotopic composition, assuming saturation of dissolved atmospheric gasses.

Physical properties of sea water

S, t, p refer to salinity, temperature, and pressure.

In practice, **density is not measured**, **it is calculated** from in situ measurements of pressure, temperature, and conductivity using the **equation of state for sea water***. This can be done with an accuracy of two parts per million.

The International Equation of State (1980) published by the Joint Panel on Oceanographic Tables and Standards (1981) is now used. See also Millero and Poisson (1981) and Millero et al (1980).

Physical properties of sea water

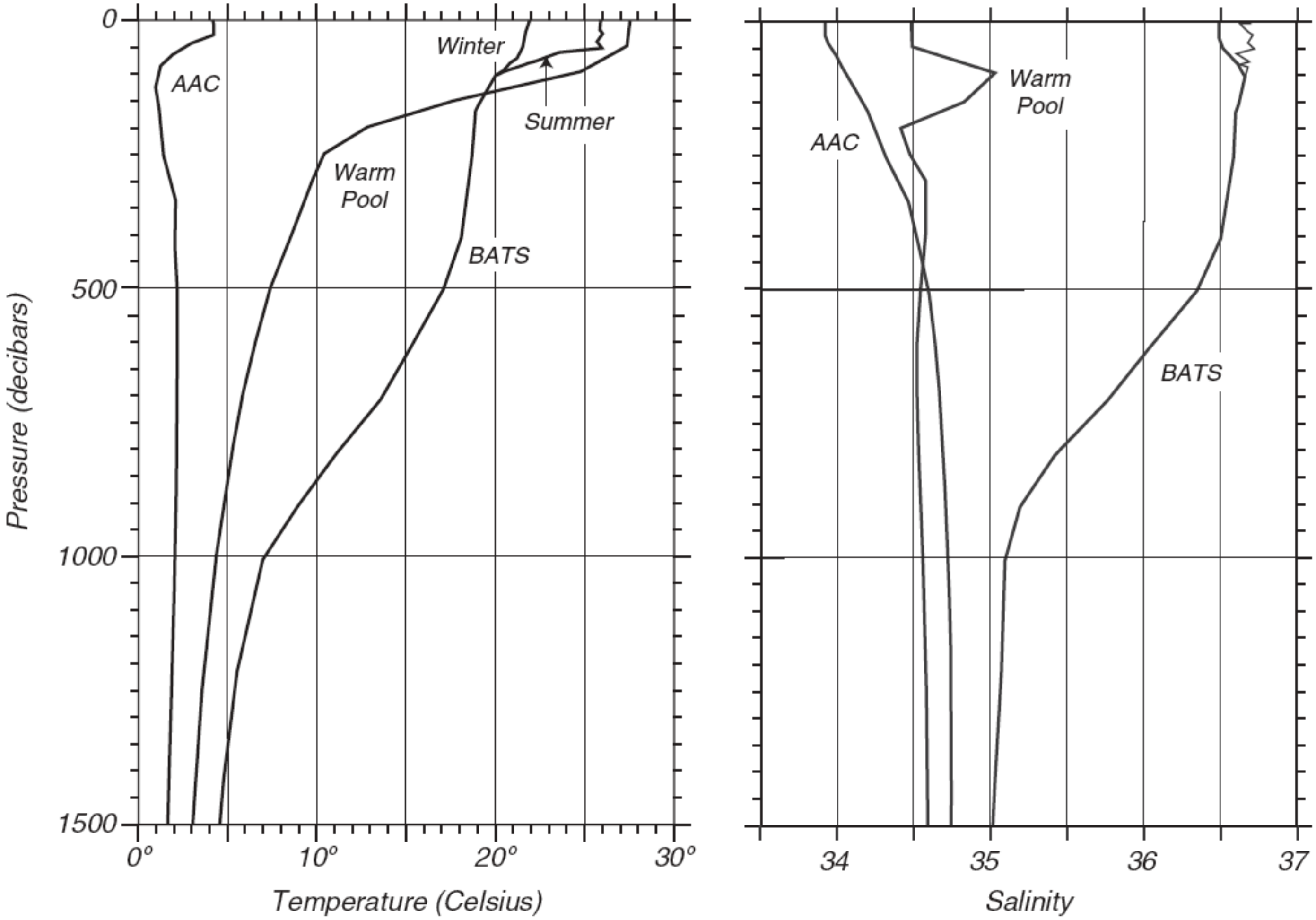
Density of water at the sea surface is typically 1027 kg m^{-3}.

For simplification, physical oceanographers often quote only the last 2 digits of the density, a quantity they call density anomaly or Sigma (S, t, p):

$$\sigma(S, t, p) = \rho(S, t, p) - 1000 \text{ kg m}^{-3}$$

T°C	Salinity (g kg $^{-1}$)				
	20	25	30	35	40
0	16.04	20.06	24.08	28.10	32.14
5	15.84	19.78	23.73	27.68	31.64
10	15.31	19.18	23.07	26.96	30.86
15	14.48	18.30	22.13	25.97	29.82
20	13.39	17.17	20.96	24.75	28.56
25	12.07	15.82	19.57	23.34	27.12

Vertical variability of seawater temperature and salinity



Typical temperature and salinity profiles in the open ocean. **AAC**: At 62.0. S, 170.0. E in the Antarctic Circumpolar Current on 16 January 1969 as measured by the R/V Hakuho Maru. **Warm Pool**: At 9.5. N 176.3. E in the tropical west Pacific **warm pool** on 12 March 1989 as measured by Bryden and Hall on the R/V Moana Wave. **BATS**: At 31.8. N 64.1. W near Bermuda on 17 April and 10 September 1990 as measured by the Bermuda Biological Station for Research, Inc.

Physical properties of sea water

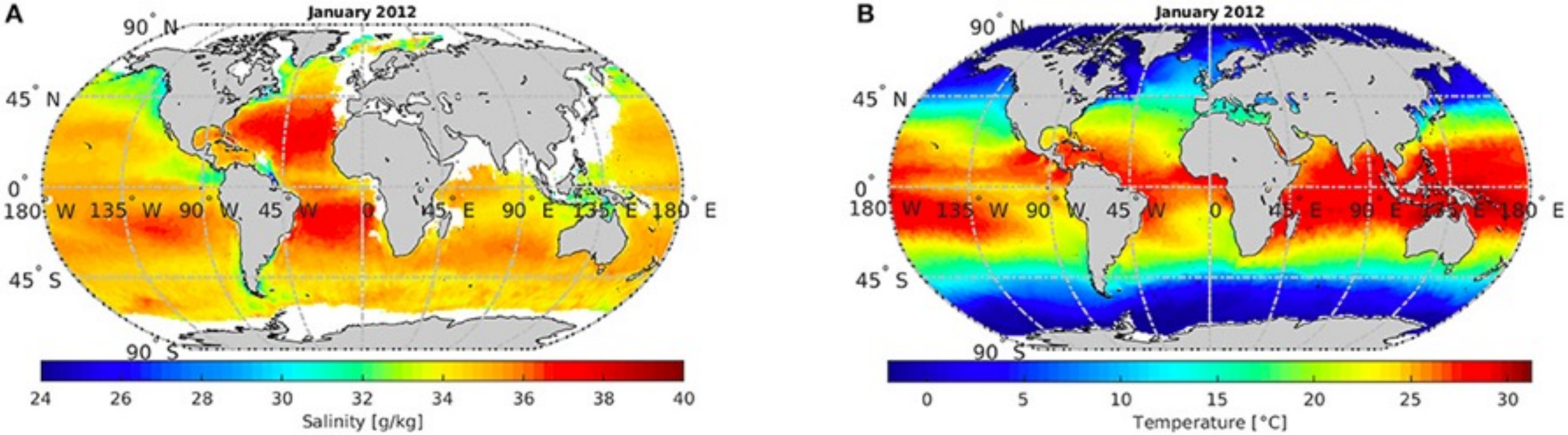
Potential Density

Potential density σ_t is the density a parcel of water would have if it were raised adiabatically to the surface without change in salinity. Written as sigma, $\sigma_t = \sigma(S, t, 0)$ Potential Density is especially useful because it is a conservative thermodynamic property.

Potential Temperature

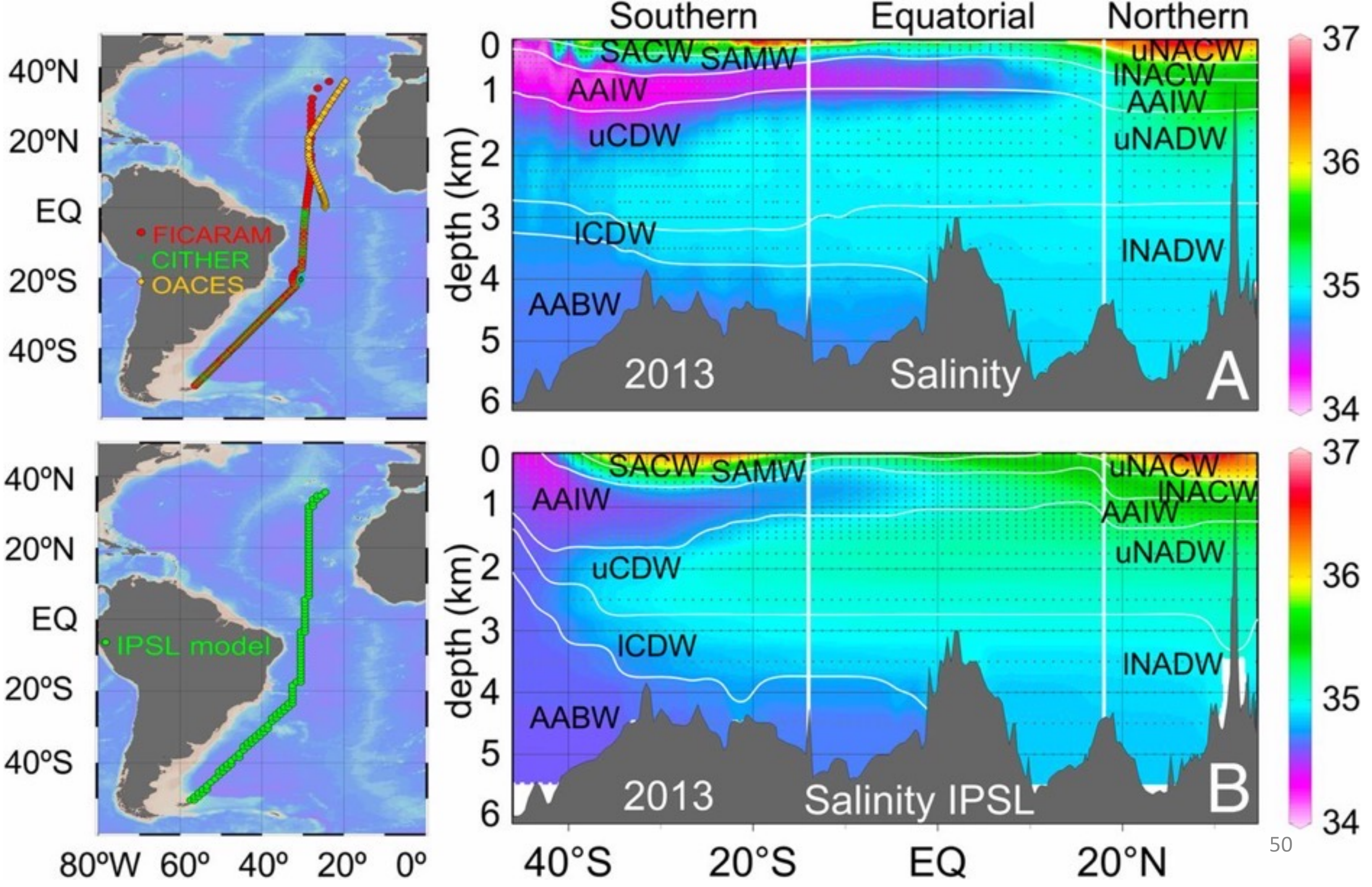
Potential temperature is defined as the temperature of a parcel of water at the sea surface after it has been raised adiabatically from some depth in the ocean. Raising the parcel adiabatically means that it is raised in an insulated container so it does not exchange heat with its surroundings.

Variability of seawater temperature and salinity



Piracha et al., 2019. Front. Mar. Sci., 04 October 2019 | https://doi.org/10.3389/fmars.2019.00589

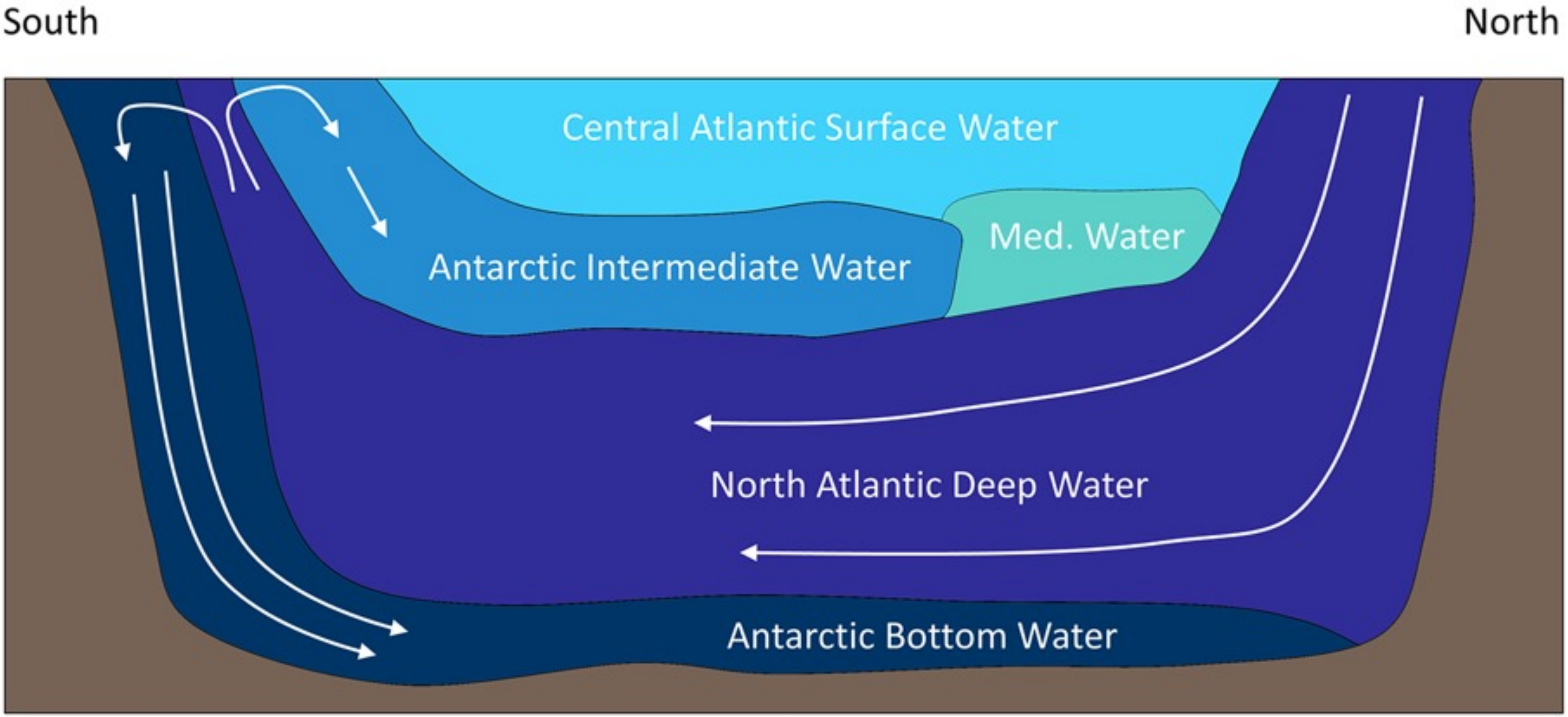
Variability of seawater density

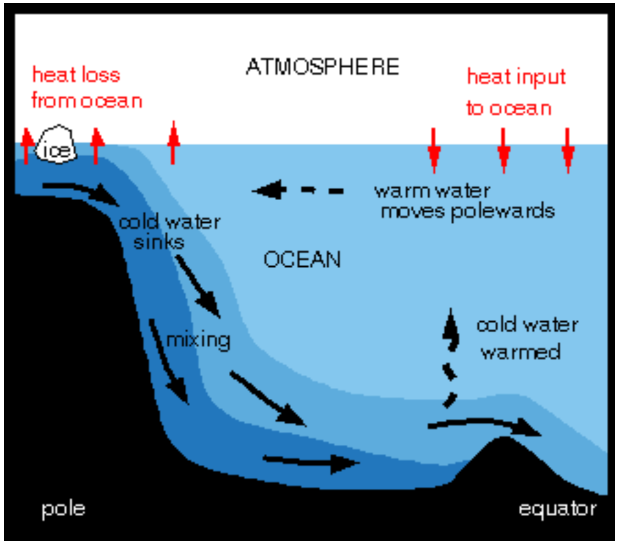


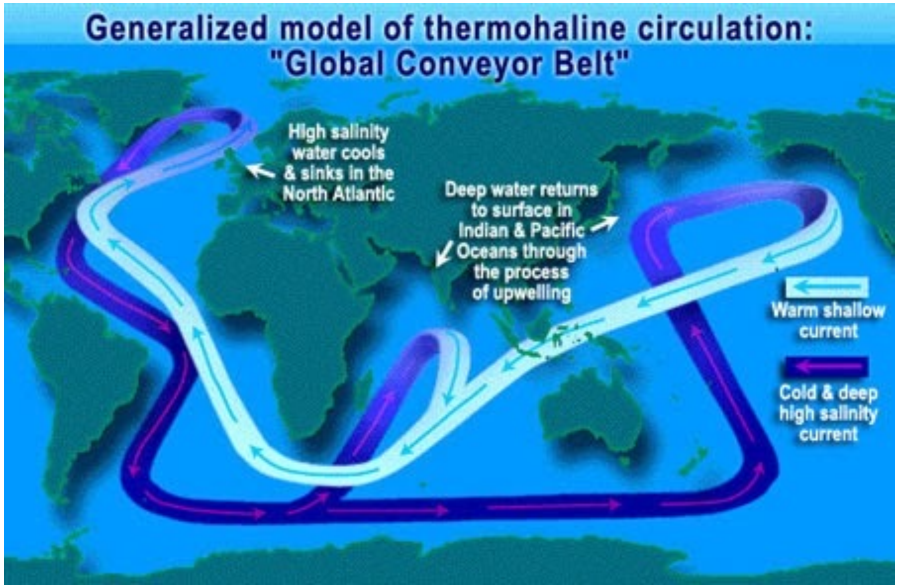
visualizzazioni NASA

https://svs.gsfc.nasa.gov/2630

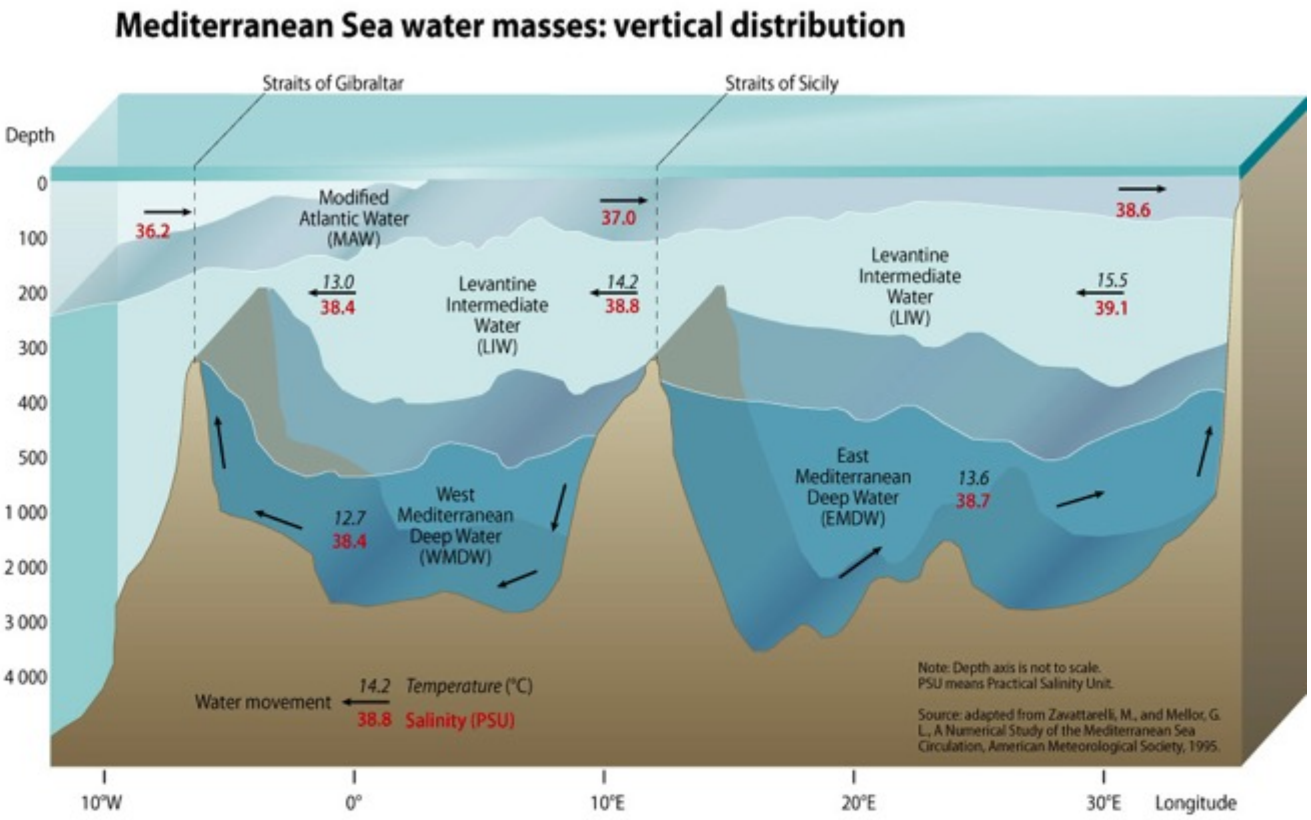
Thermohaline circulation







https://www.youtube.com/watch?v=p4pWafuvdrY



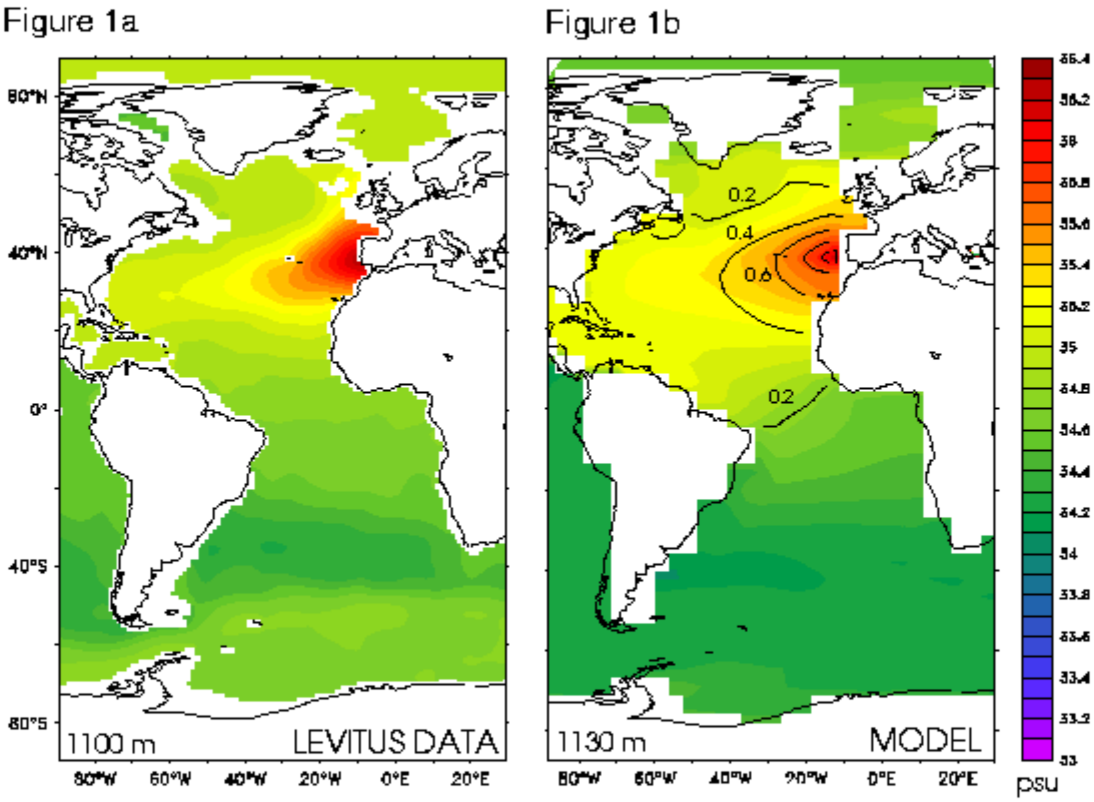
Mediterranean Sea water masses: vertical distribution

Note: Depth axis is not to scale.
PSU means Practical Salinity Unit.

Source: adapted from Zavattarelli, M., and Mellor, G. L., A Numerical Study of the Mediterranean Sea Circulation, American Meteorological Society, 1995.

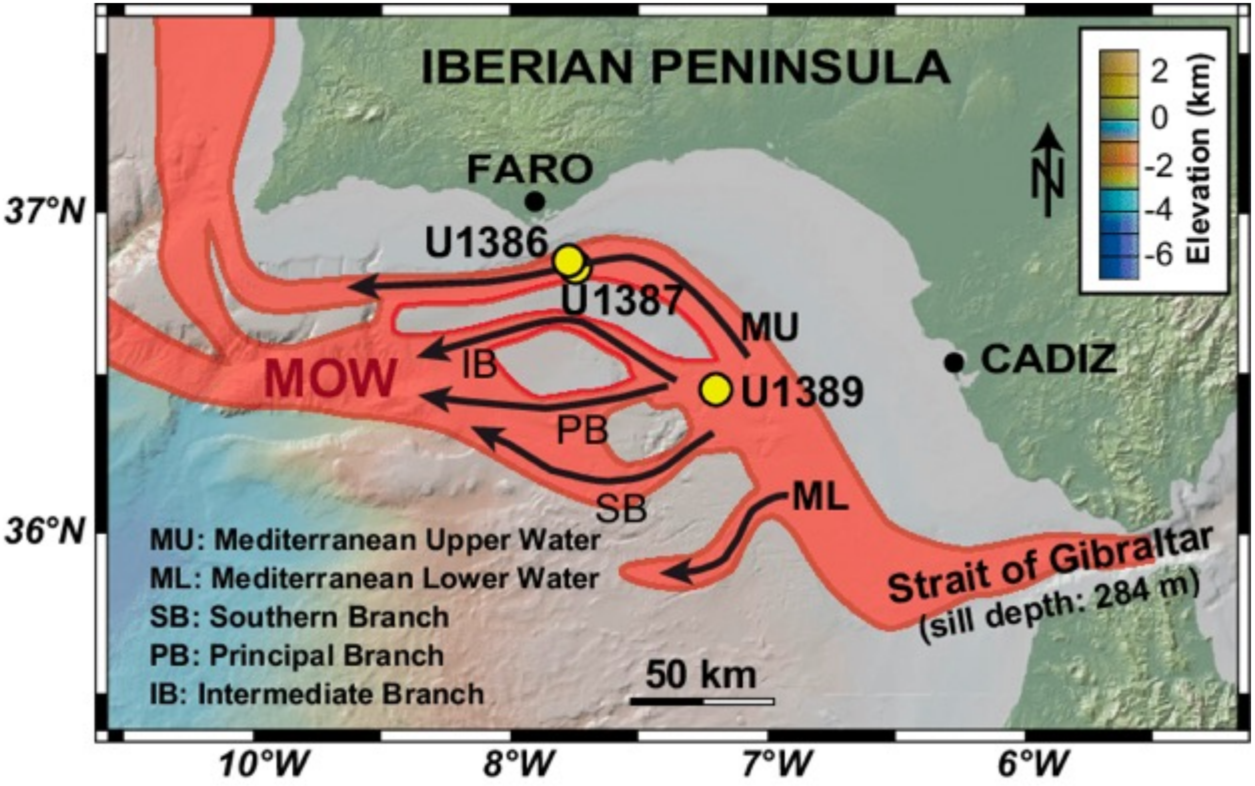
https://www.grida.no/resources/5885

Mediterranean Outflow Waters (MOW)



The tongue of saline water from the Mediterranean outflow in (a) the observations of Levitus, Burgett, and Boyer [1994] and (b) the model. Contours show the salinity anomaly (practical salinity units) relative to the control experiment without Mediterranean water.

http://www.pik-potsdam.de/~stefan/Publications/Journals/gibraltar.html

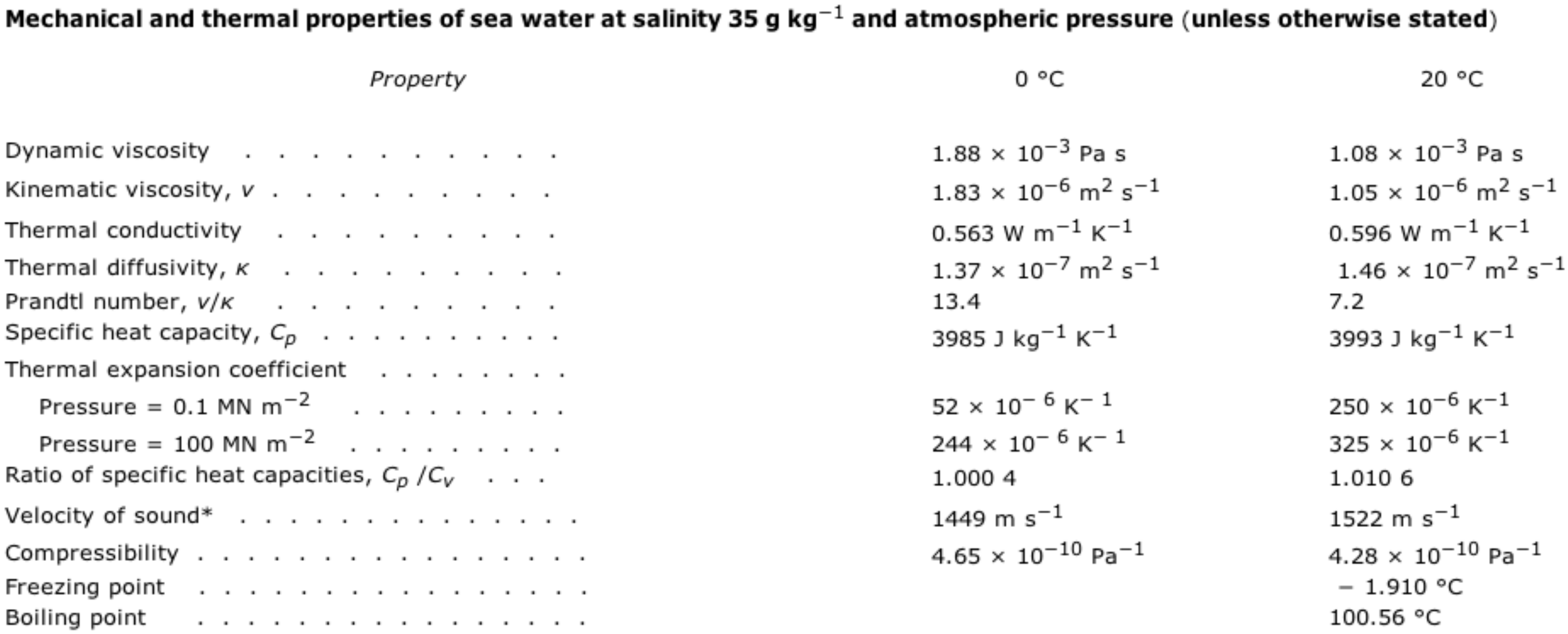


Main flow paths of Mediterranean Outflow Water (MOW) within Gulf of Cádiz (Hernández-Molina et al., 2014), including position of investigated Integrated Ocean Drilling Program (IODP) Expedition 339 sites.

Bahr, Andre & Kaboth-Bahr, Stefanie & Jiménez-Espejo, Francisco & Sierro, Francisco & Voelker, Antje & Lourens, Lucas & Röhl, Ursula & Reichart, Gert-Jan & Escutia, Carlota & Hernández-Molina, F. & Pross, Jörg & Friedrich, Oliver. (2015). Persistent monsoonal forcing of Mediterranean Outflow Water dynamics during the late Pleistocene. Geology. 43. 951-954. 10.1130/G37013.1.

Physical properties of sea water

(function of temperature, salinity and pressure)



Mechanical and thermal properties of sea water at salinity 35 g kg^{-1} and atmospheric pressure (unless otherwise stated)

Property	0 °C	20 °C
Dynamic viscosity	1.88×10^{-3} Pa s	1.08×10^{-3} Pa s
Kinematic viscosity, v	$1.83 \times 10^{-6}\ m^2\ s^{-1}$	$1.05 \times 10^{-6}\ m^2\ s^{-1}$
Thermal conductivity	$0.563\ W\ m^{-1}\ K^{-1}$	$0.596\ W\ m^{-1}\ K^{-1}$
Thermal diffusivity, κ	$1.37 \times 10^{-7}\ m^2\ s^{-1}$	$1.46 \times 10^{-7}\ m^2\ s^{-1}$
Prandtl number, v/κ	13.4	7.2
Specific heat capacity, C_p	$3985\ J\ kg^{-1}\ K^{-1}$	$3993\ J\ kg^{-1}\ K^{-1}$
Thermal expansion coefficient		
Pressure = $0.1\ MN\ m^{-2}$	$52 \times 10^{-6}\ K^{-1}$	$250 \times 10^{-6}\ K^{-1}$
Pressure = $100\ MN\ m^{-2}$	$244 \times 10^{-6}\ K^{-1}$	$325 \times 10^{-6}\ K^{-1}$
Ratio of specific heat capacities, C_p/C_v	1.000 4	1.010 6
Velocity of sound*	$1449\ m\ s^{-1}$	$1522\ m\ s^{-1}$
Compressibility	$4.65 \times 10^{-10}\ Pa^{-1}$	$4.28 \times 10^{-10}\ Pa^{-1}$
Freezing point		− 1.910 °C
Boiling point		100.56 °C

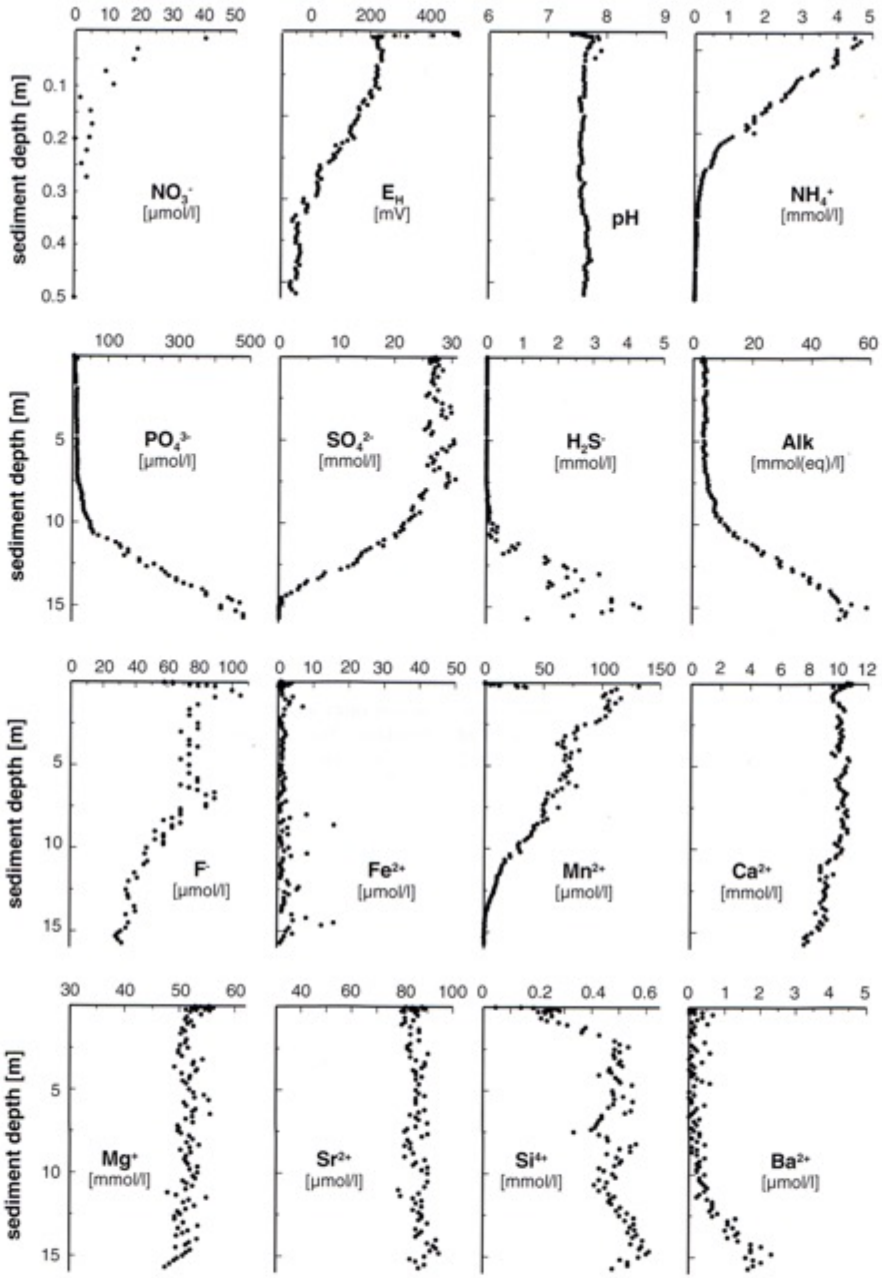
	Seawater (35‰)	Pure Water
Temperature of maximum density:	3.25ºC	3.98ºC
Freezing point	-1.91ºC	0.00ºC

Pore water in marine sediments

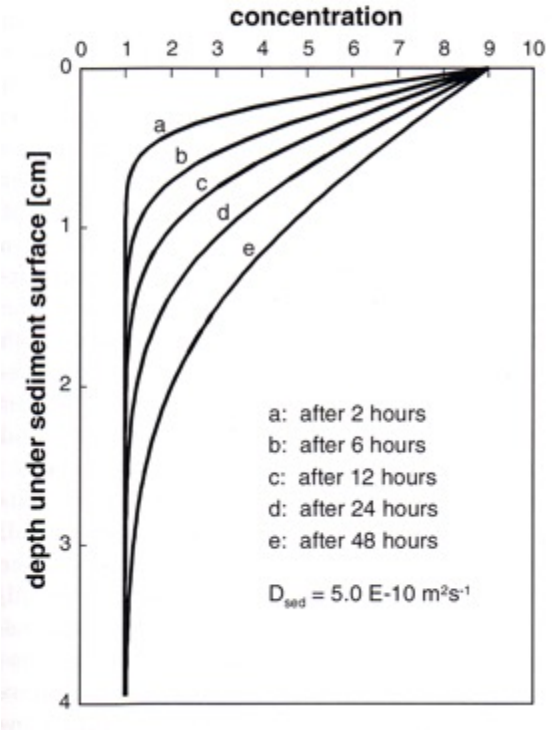
Chemically unstable sediment particles:

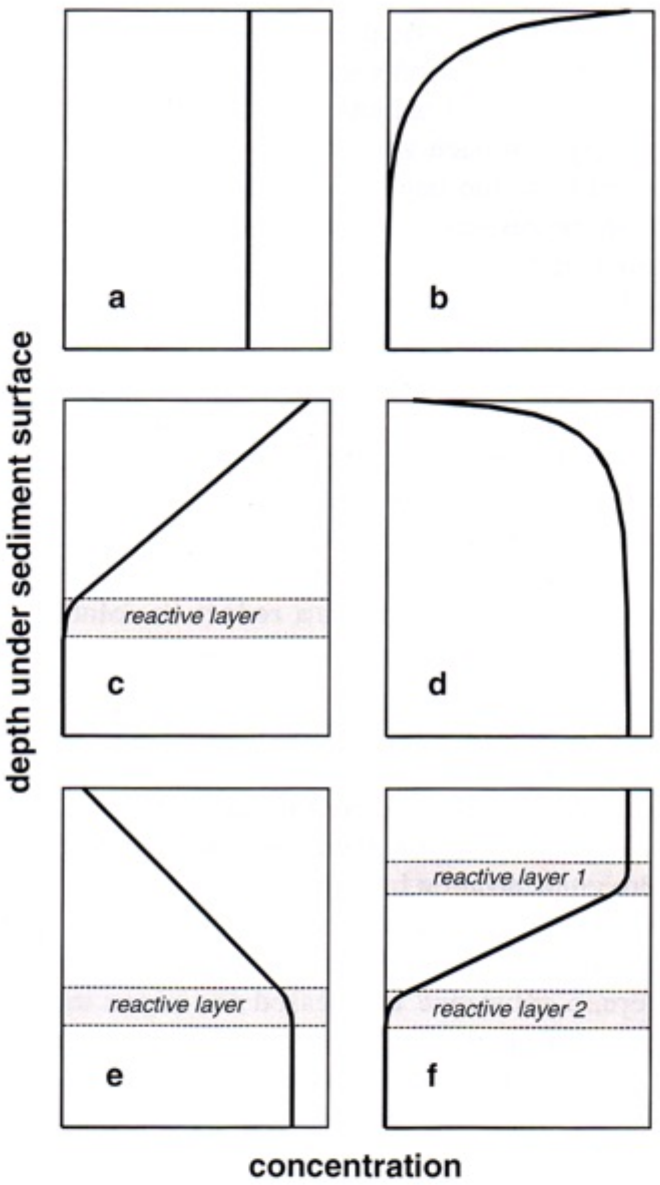
Igneous rock fragments
Amorphous material (e.g. opal)
Organic matter
Remnants of Organisms (bones, teeths)
Clay minerals
Aragonite and Mg Calcite

Pore water
in marine sediments

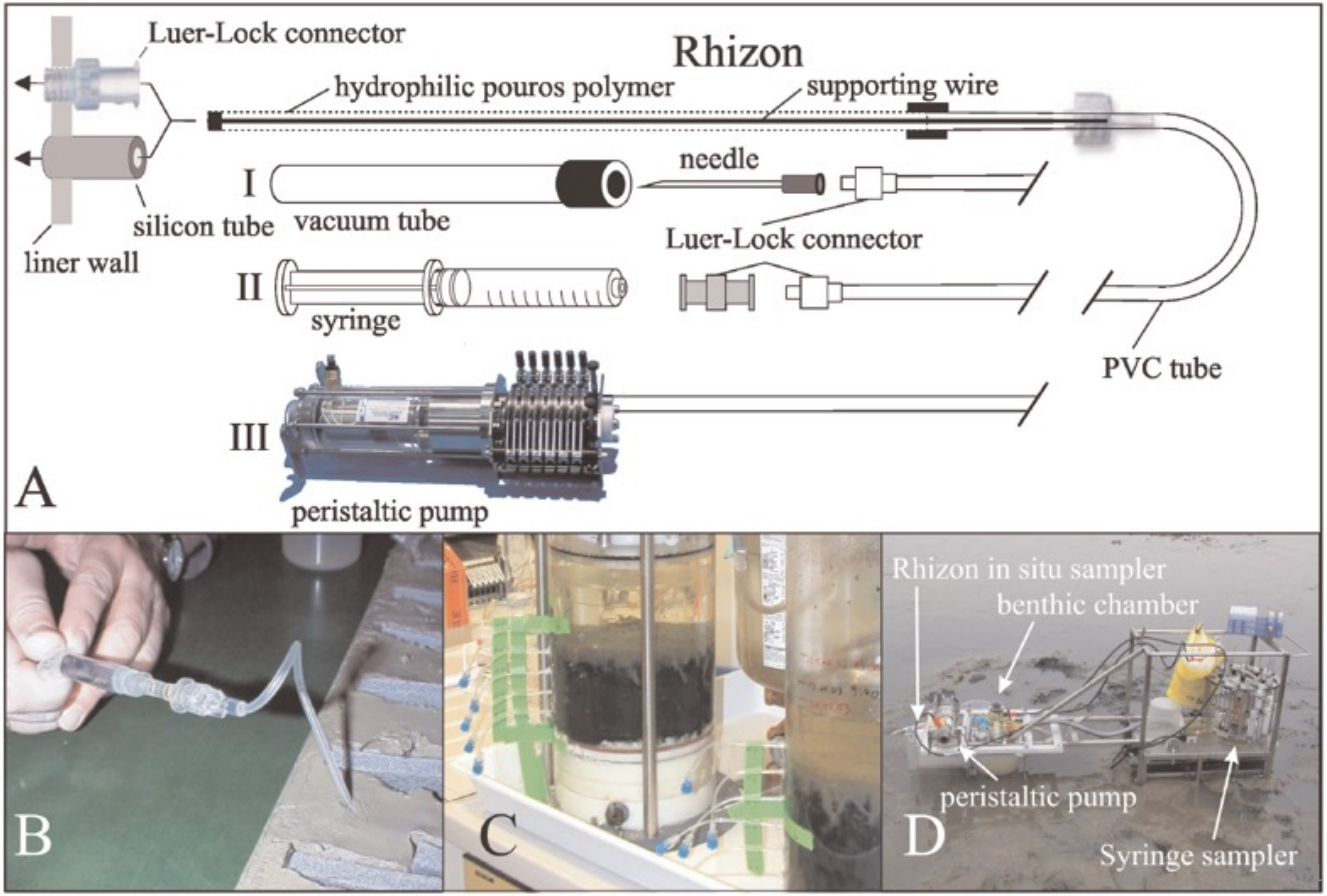


Pore water in marine sediments

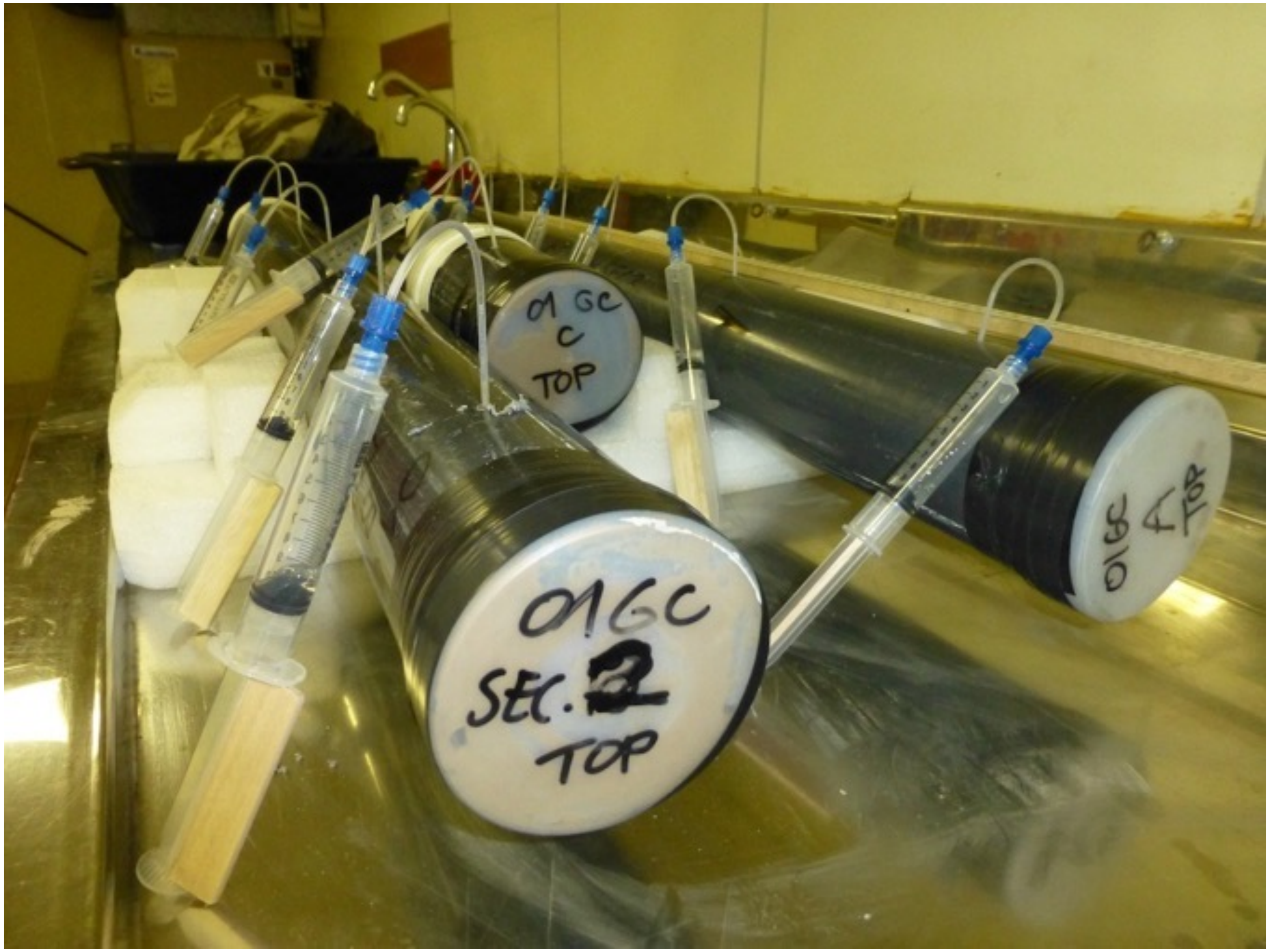




Pore water Sampling in marine sediments



Pore water Sampling in marine sediments



Pore water Sampling in marine sediments

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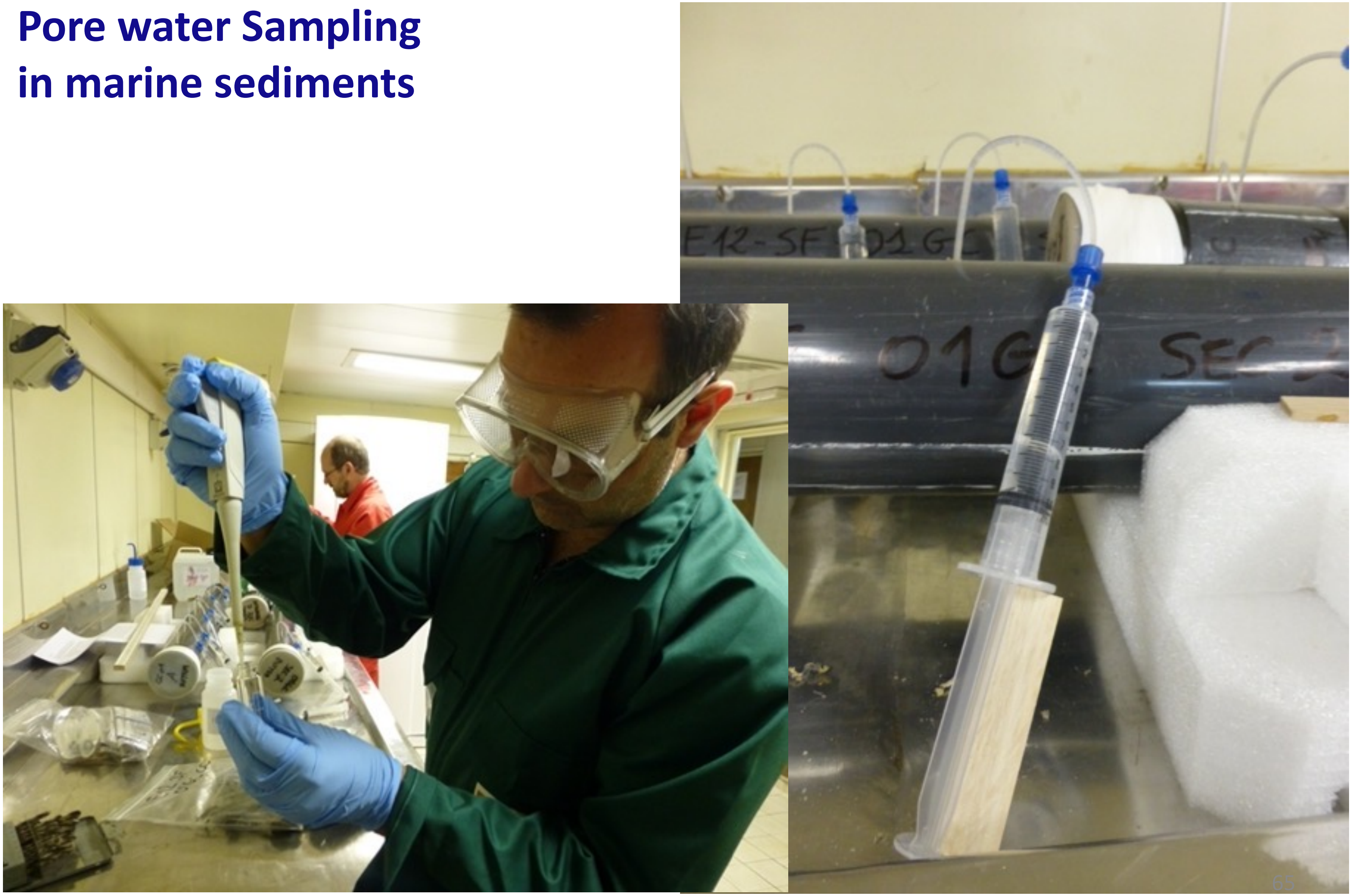

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Millero F.J., and A. Poisson. 1981. International one-atmosphere equation of state of seawater.Deep-Sea Research 28A (6): 625–629.

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