Università di Trieste

LAUREA MAGISTRALE IN GEOSCIENZE SM62A

Percorso Esplorazione Geologica

Anno accademico 2026 - 2027

Geologia Marina 953SM

Parte I

Modulo 1.3 Introduzione ai fondali oceanici oceani: circolazione oceanica

Docente
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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

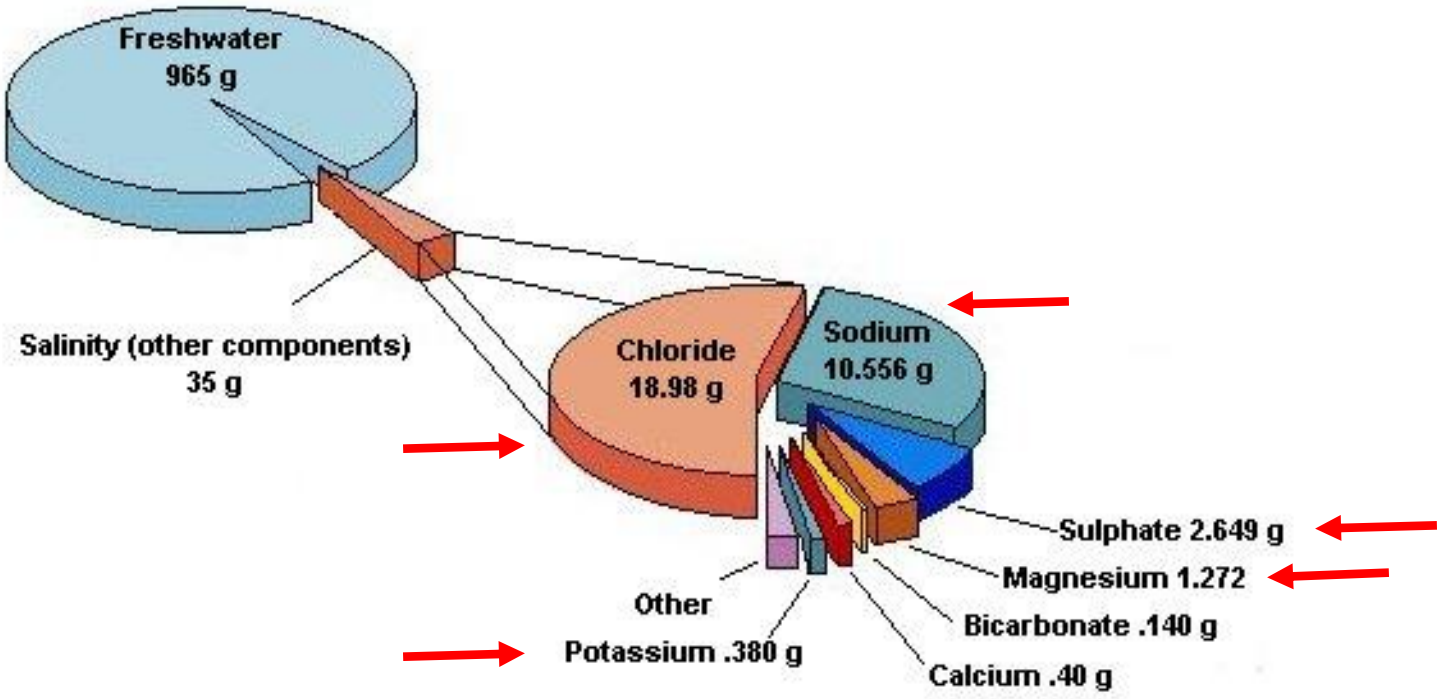
- True for **conservative elements**, which include most of the major ions in seawater (Na^+, K^+, SO_4^{-2}, and Cl^-).

- 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:

- Freezing – thawing
- Turbulent mixing between water masses

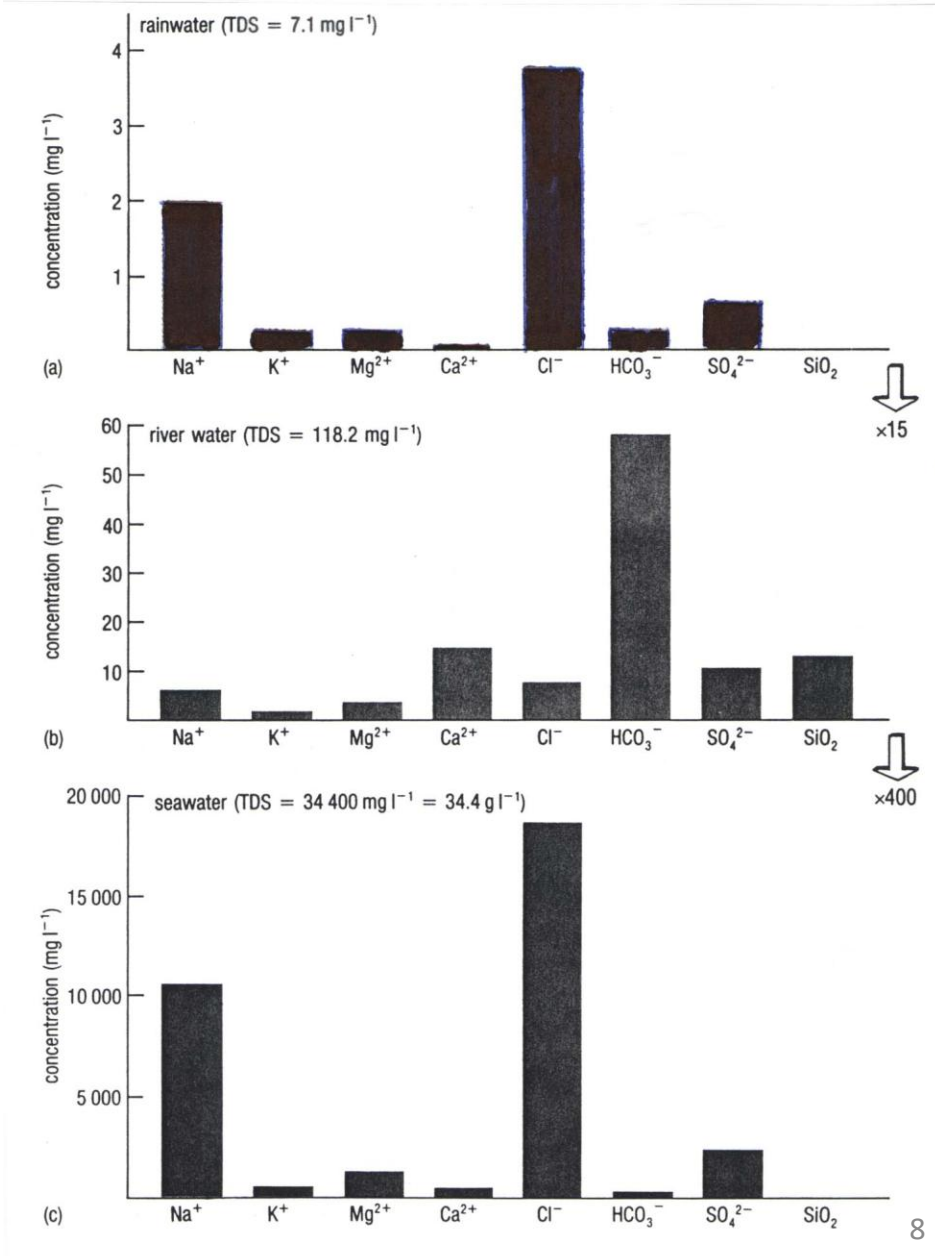
Does:

- 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
river water
seawater

are different



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

$$\text{FELDSPARS} + H_2CO_3 >>>> \text{CLAY} + Ca, Na, K, H_4SiO_4$$

Origin of dissolved ions

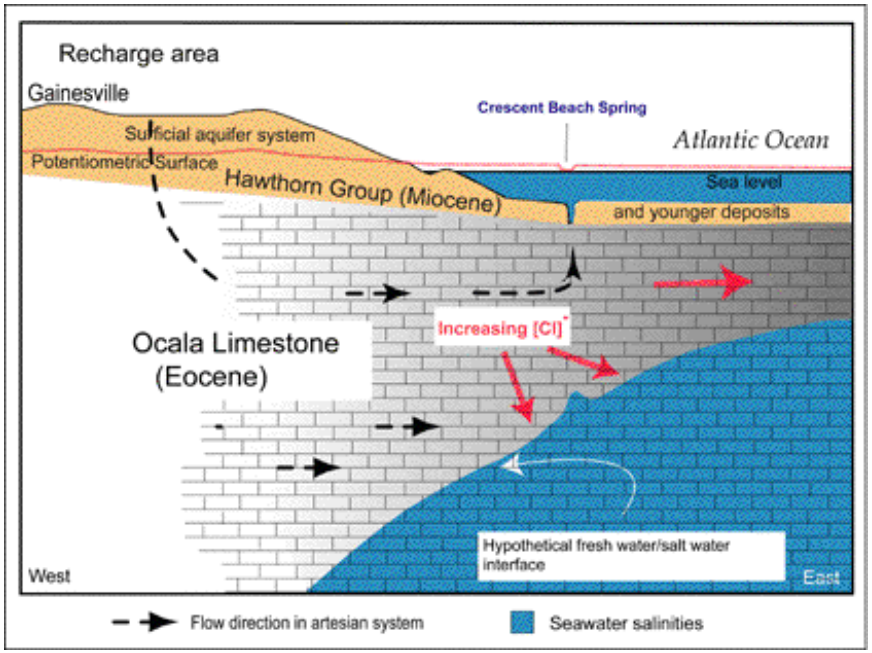
Product of alteration of igneous rocks:

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



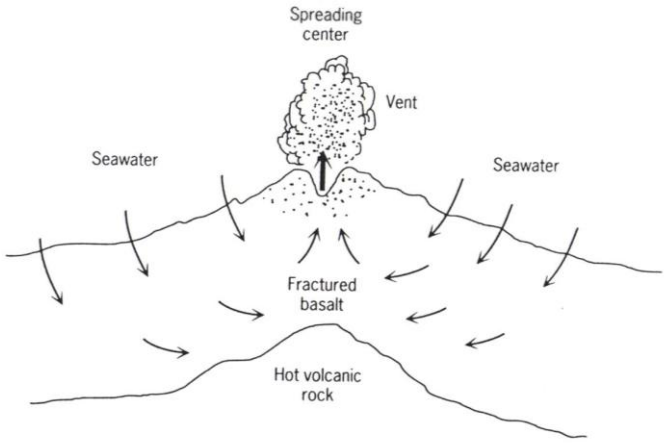


FIGURE 19.2. Hydrothermal convection cells.

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.

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

Salt sinks

Hydrothermal systems

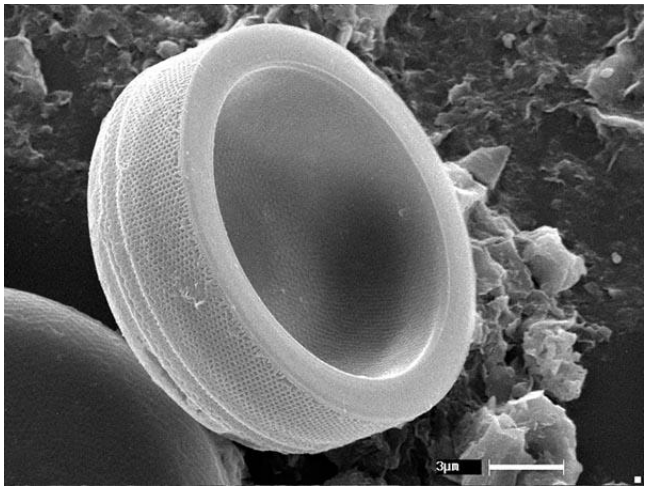
Basalt alteration at 200 ^{o}C

Source for Ca, sink for Mg, SO_4

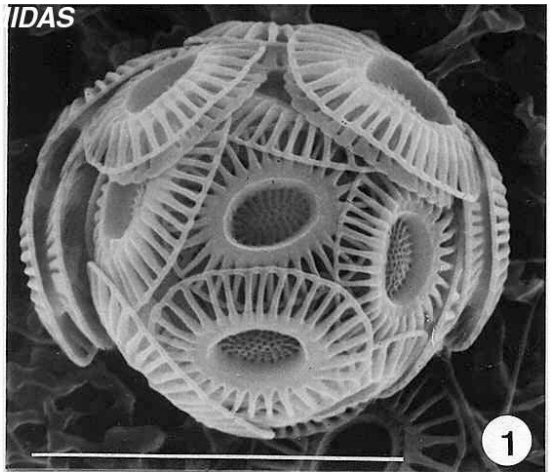
Fresh Basalt + Mg^{++} + $2HC0_3^-$ = altered basalt + Ca-Silicate + $2CO_2$

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

Microbiological processes of decomposition of organic matter in anoxic basins increase alkalinity:

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

Sulfate reduction

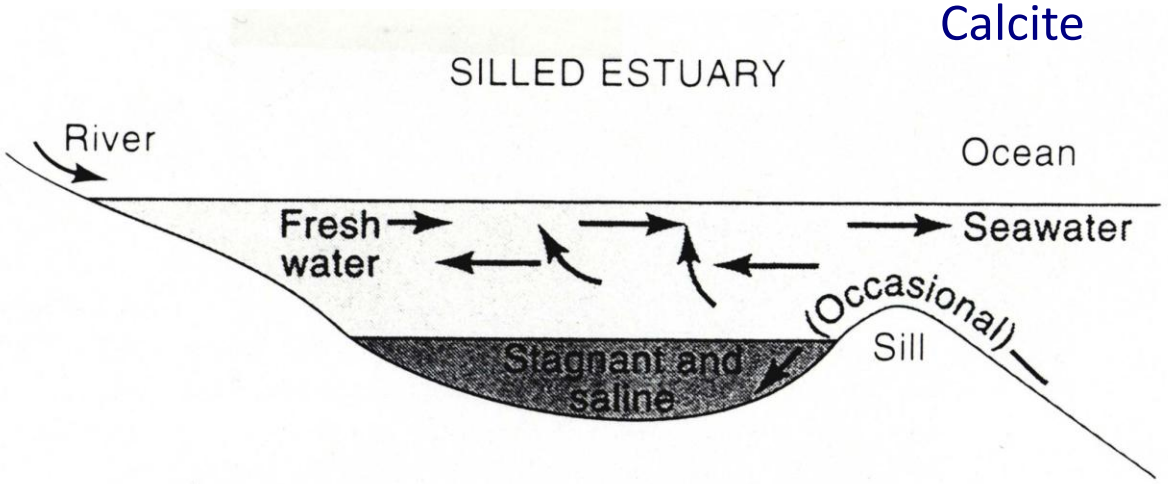
$$2\ FeO \cdot OH + 3\ H_2S. \longleftrightarrow 2\ FeS + S^{--} + 4\ H_2O$$

Pyrite

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

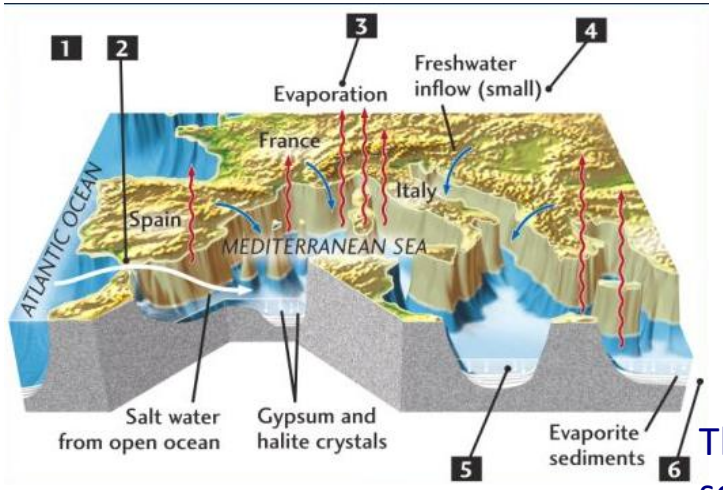
Calcite

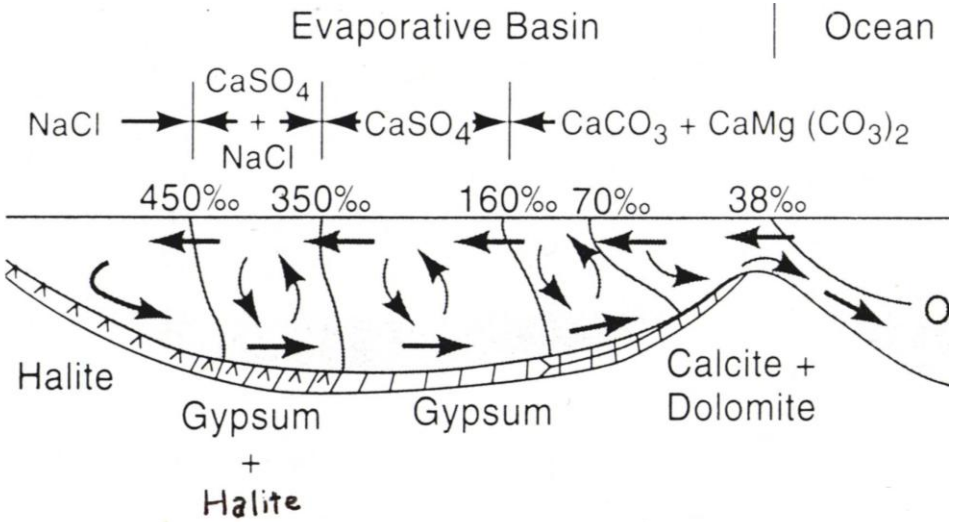
Black Sea



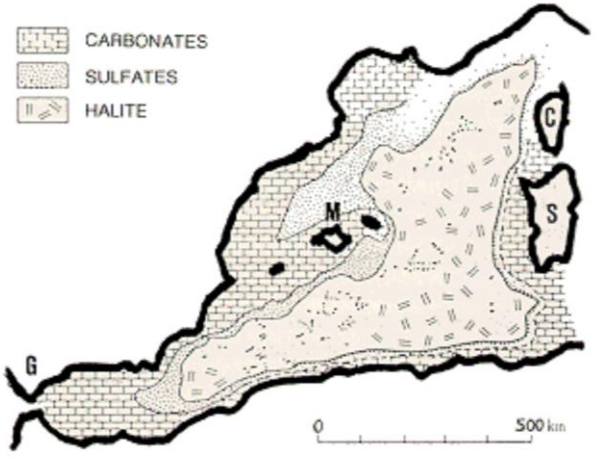
Salt sinks

Evaporation





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

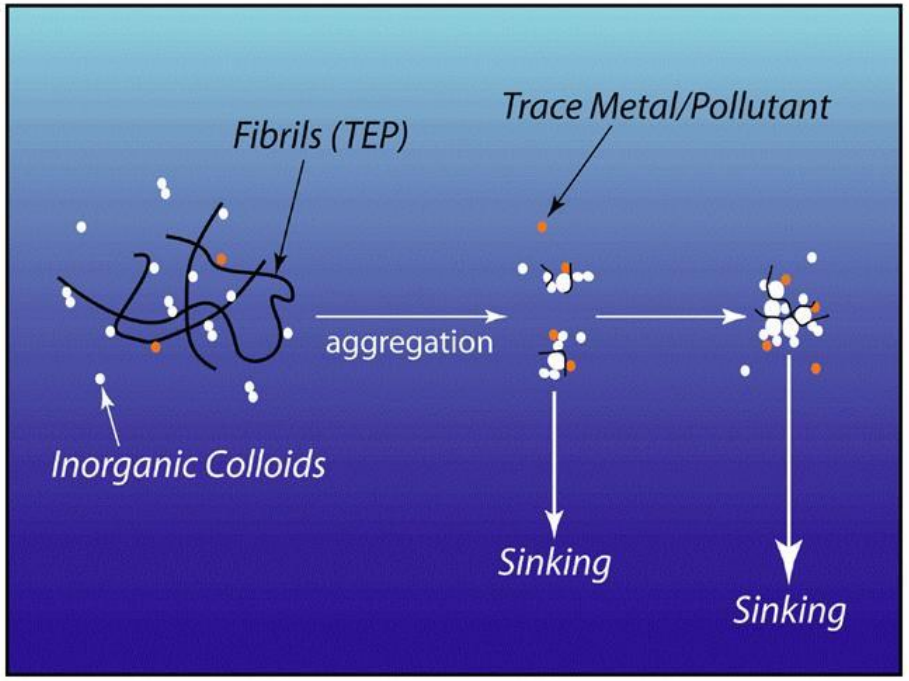


1. Calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$)
2. Gypsum ($CaSO_4 \cdot 2H_2O$) and anhydrite ($CaSO_4$)
3. Halite (i.e. common salt, NaCl)
4. Potassium and magnesium salts

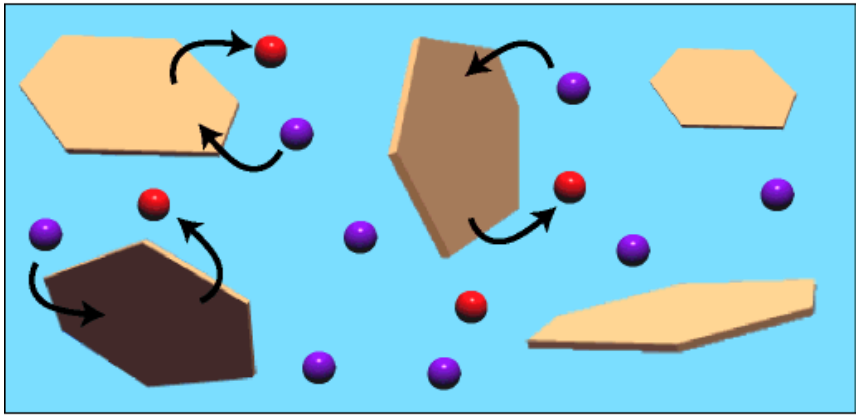
Limestone (calcite) and dolomite are more common than gypsum, which is more common than halite, which is more common than potassium and magnesium salts.

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 in clay minerals introduced in the Ocean by rivers is removed 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		

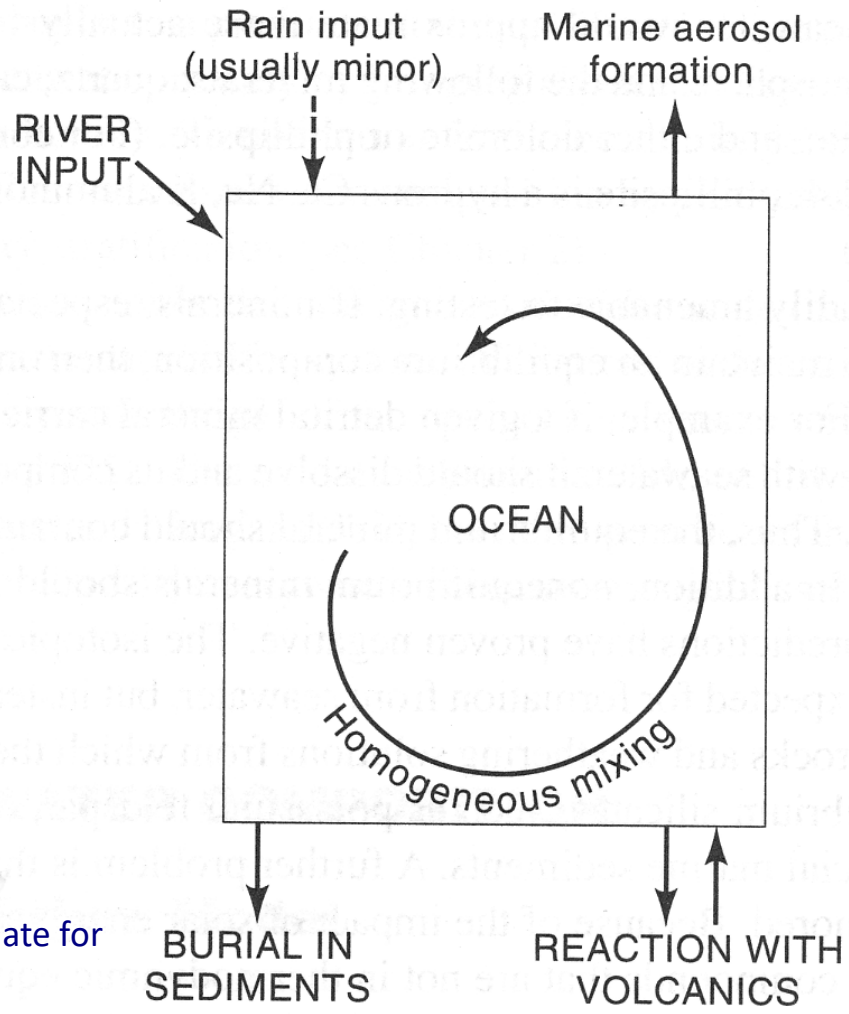
[a] A + sign indicates uptake by the clay.

[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.

Mass balance: Simple box models



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

Physical properties of sea water

Absolute Density of water can only be measured in special laboratories, and only with difficulty. The best accuracy is 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.

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

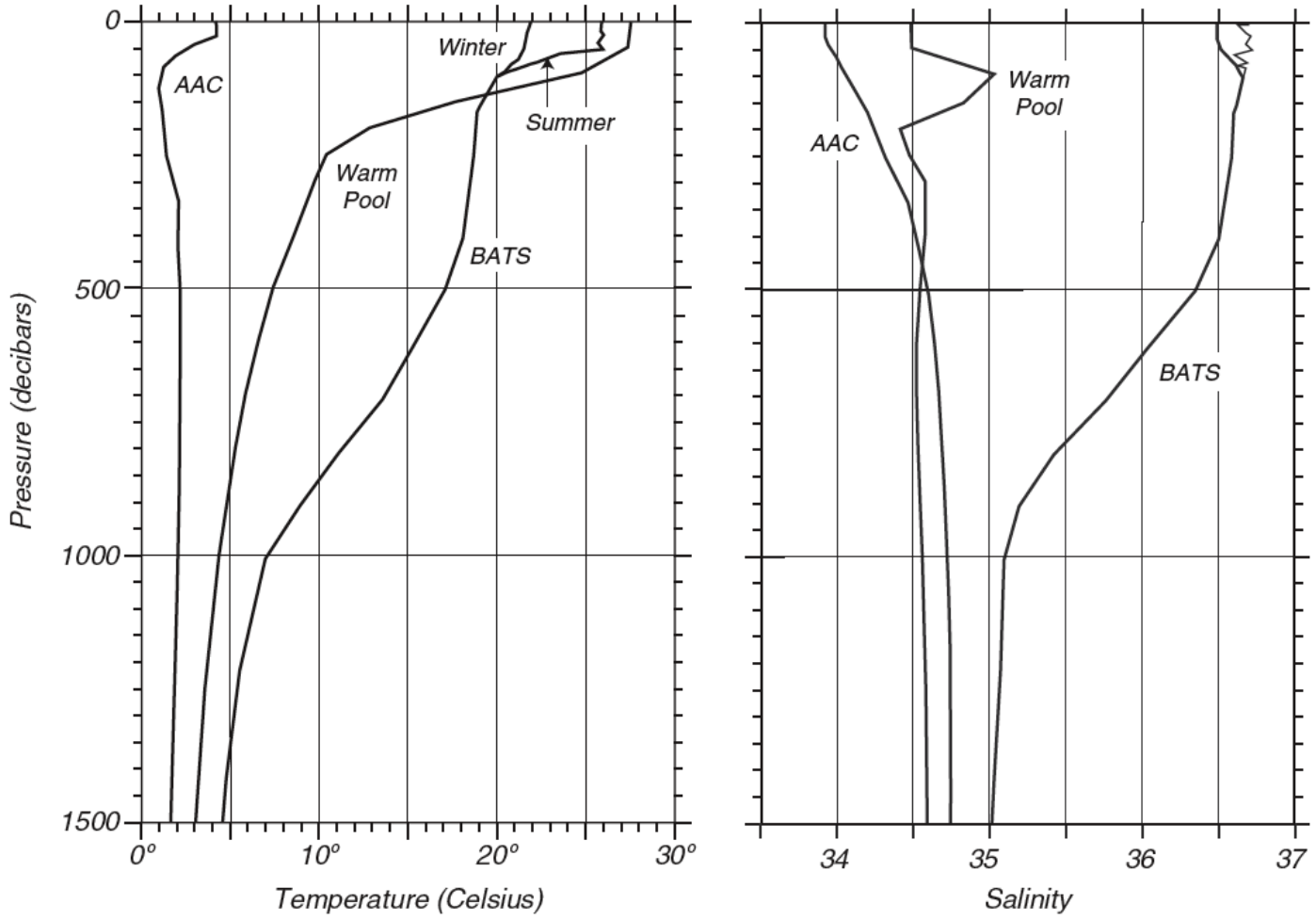
Density of water at the sea surface is typically 1027 kg m^{-3}.

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.

Insolation, evaporation, sea ice formation, and rain influence the distribution of **temperature and salinity** at the ocean surface.

Changes in temperature and salinity lead to changes in the density of water at the surface, which can lead to **convection and changes** in the deeper circulation of the ocean.

Once surface waters sink into the deeper ocean, they **retain a distinctive relationship between temperature and salinity** which helps oceanographers determine the source regions for subsurface water.

Currents are driven by density gradients.

Physical properties of sea water

Potential Density

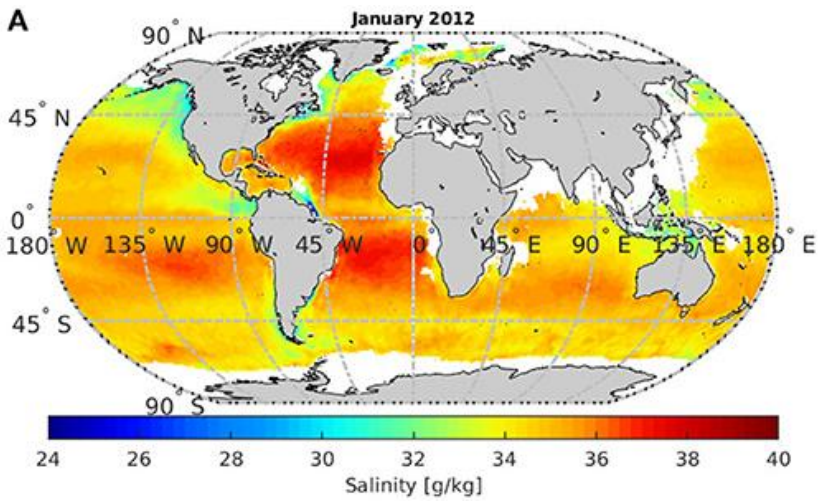
Potential density σ_t is the density a parcel of water would have if it were raised adiabatically to the surface without change in salinity. Written as sigma, $\sigma_t = \sigma(S, t, 0)$ Potential Density is especially useful because it is a conservative thermodynamic property.

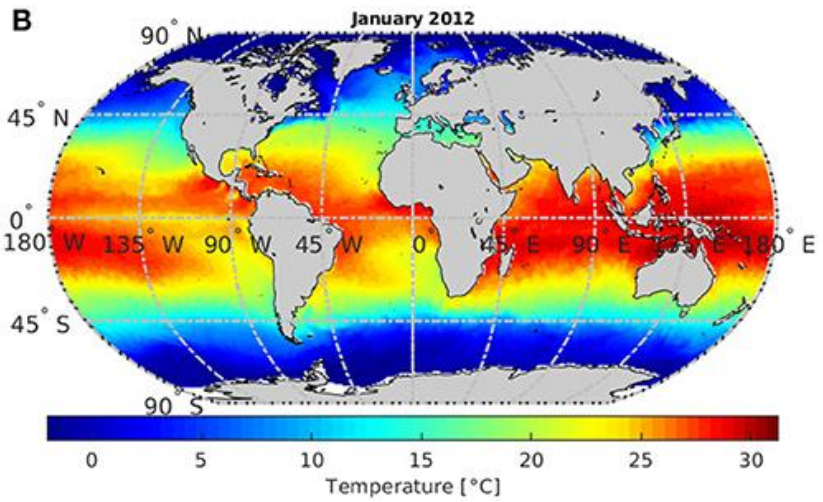
It removes the primary influence of pressure on density.
=> allows us to compare density of water samples from different depths.
=> Allows to measure water flow direction along the same potential density

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





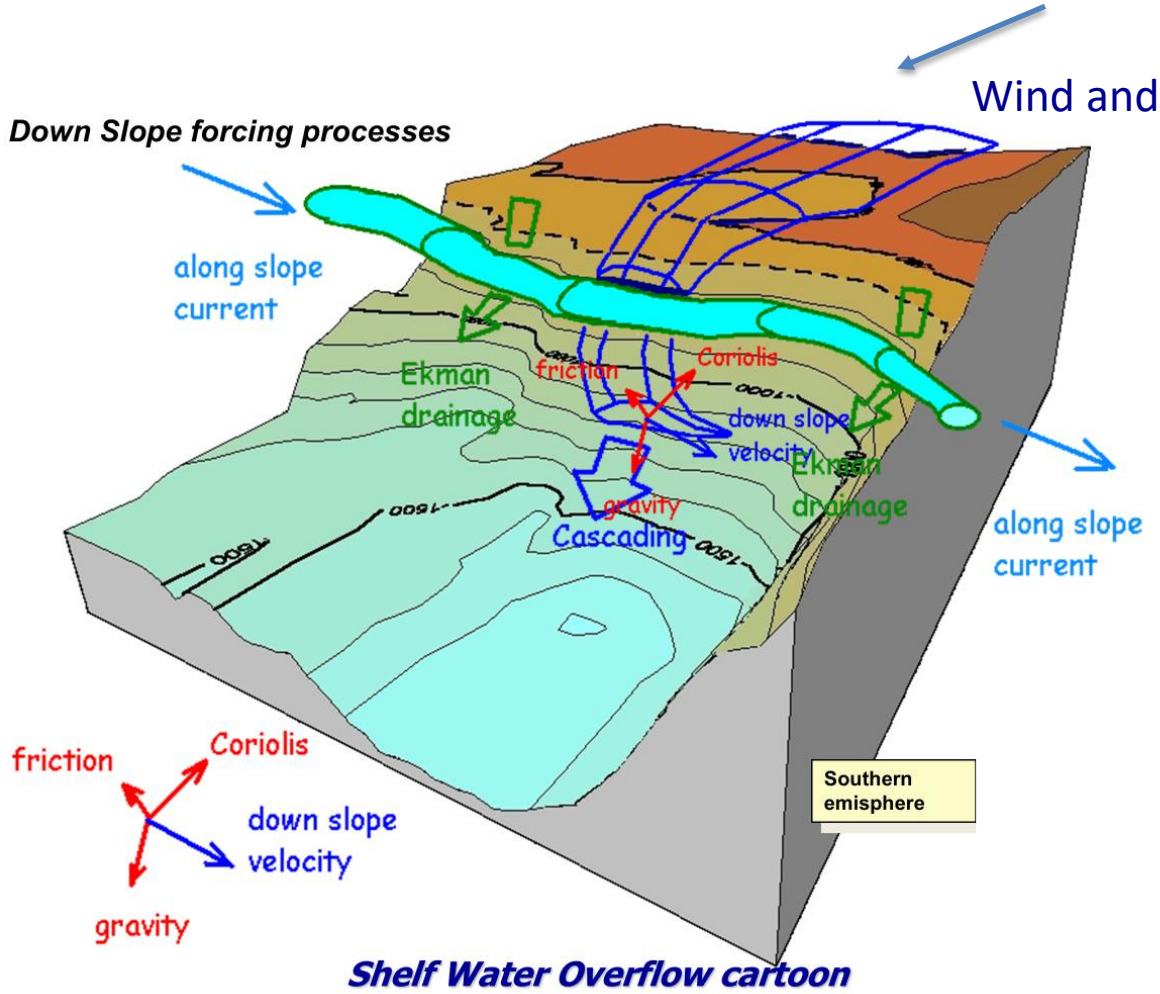
The saltiest waters are at mid-latitudes where evaporation is high.

Less salty waters are near the equator where rain freshens the surface water, and at high latitudes where melted sea ice freshens the surface waters

Warmest water is near the equator, coldest water is near the poles
North of 40° latitude, cooler waters tend to be on the western side

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

Wind and gravity driven dense water



Ekman transport is the net motion of fluid as the result of a balance between Coriolis and turbulent drag forces (the pressure gradient and friction)

Transport is 90◦ to the **right of the wind in the northern hemisphere**
Transport is 90◦ to the **left of the wind in the southern hemisphere**

Because the upwelled water is cold, the upwelling leads to a region of cold water at the surface along the coast. Upwelled water is richer in nutrients. The nutrients fertilize phytoplankton in the mixed layer, which are eaten by zooplankton, which are eaten by small fish, which are eaten by larger fish and so on to infinity.
=> upwelling regions are productive waters supporting the world's major fisheries. The important regions are offshore of Peru, California, Somalia, Morocco, and Namibia

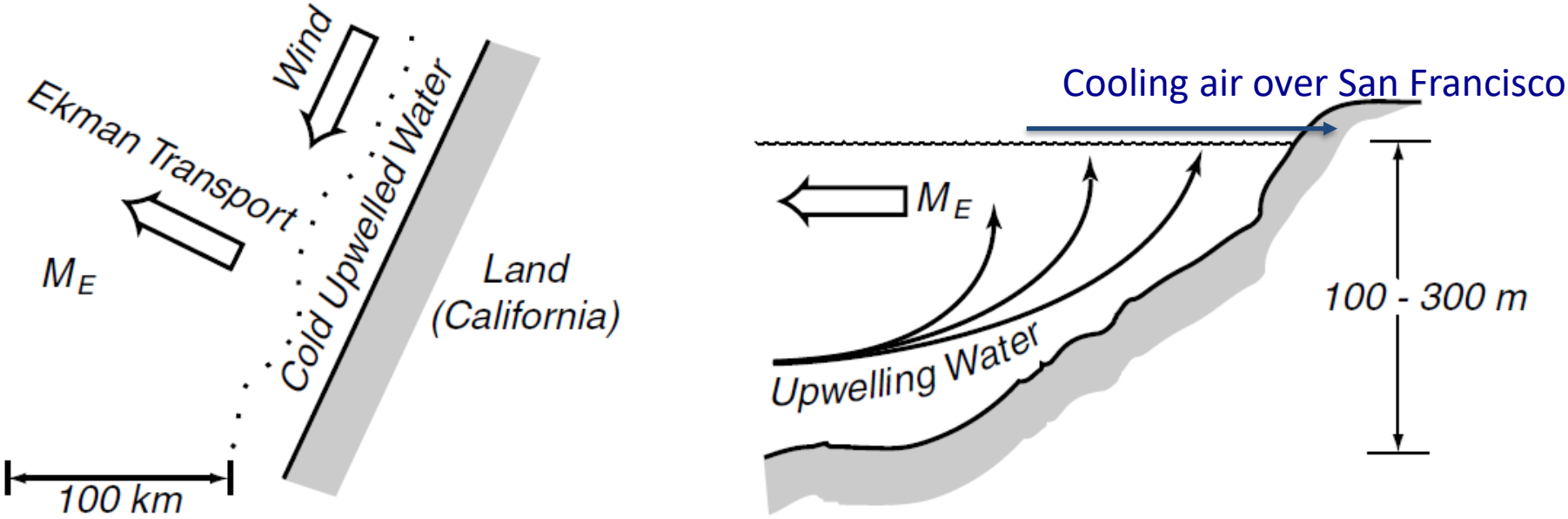
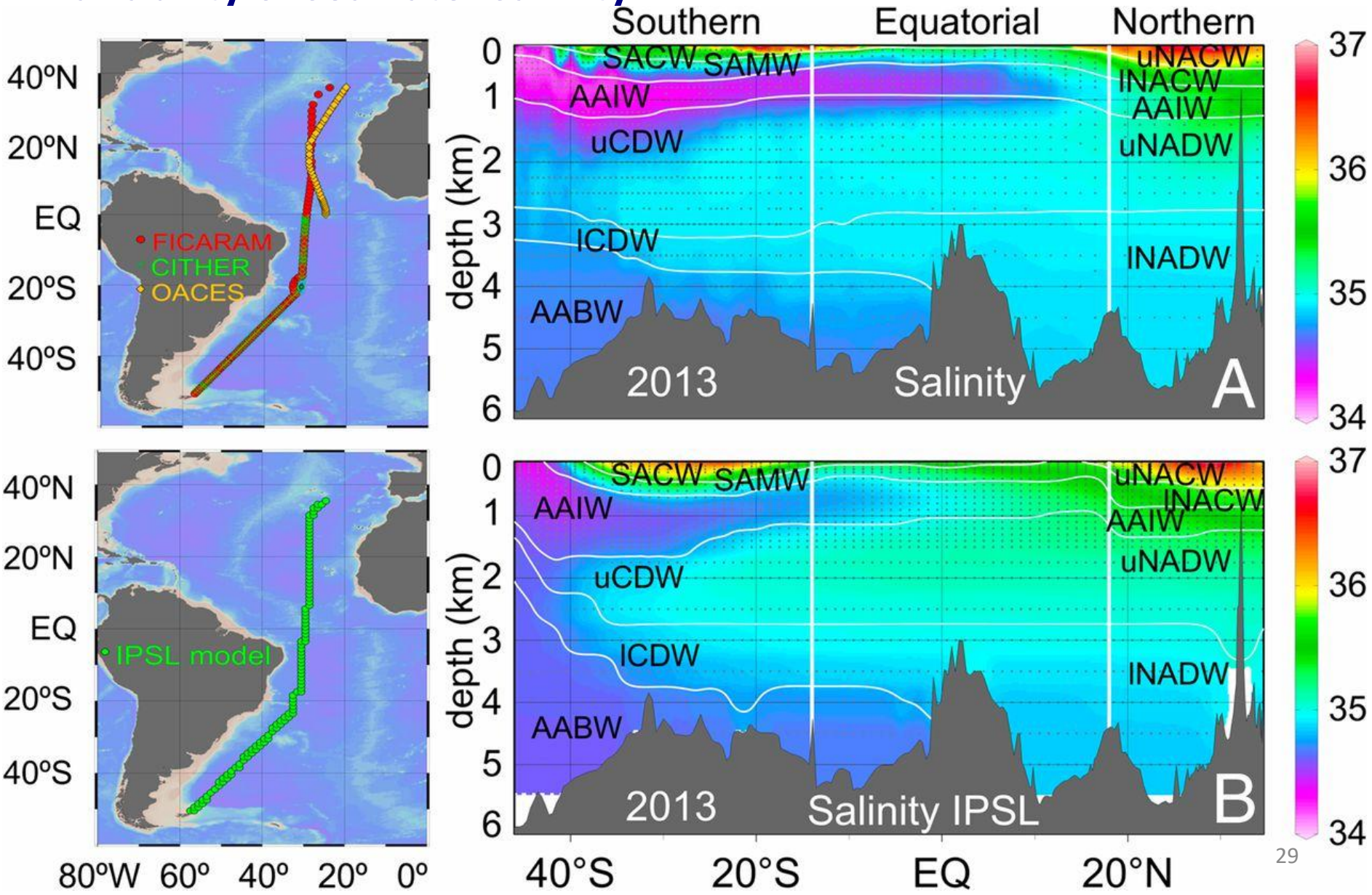


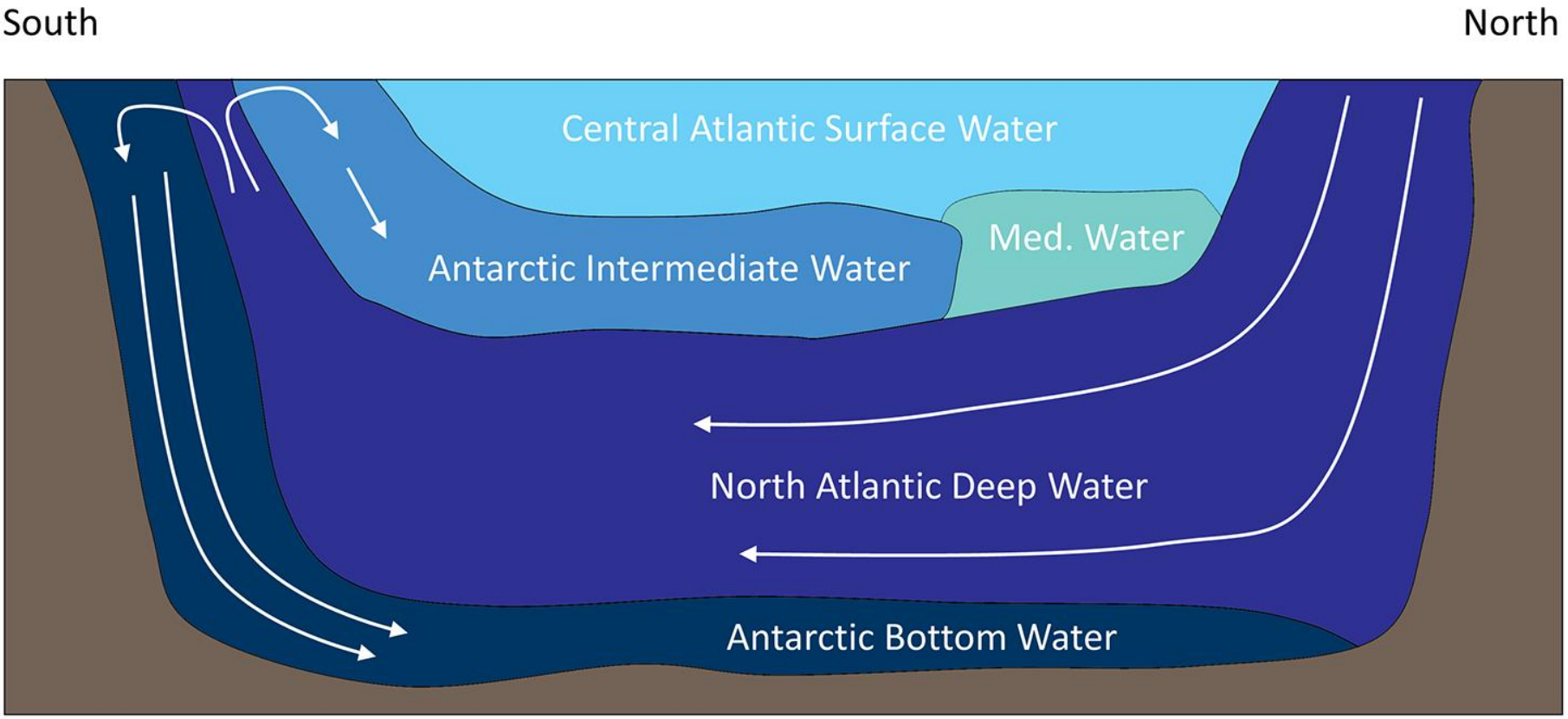
Figure 9.8 Sketch of Ekman transport along a coast leading to upwelling of cold water along the coast. **Left:** Cross section. The water transported offshore must be replaced by water upwelling from below the mixed layer. **Right:** Plan view. North winds along a west coast in the northern hemisphere cause Ekman transports away from the shore.

Stewart, R.D., 2007. Introduction To Physical Oceanography. Texas A & M University, Department of Oceanography, 345 pp.
http://oceanworld.tamu.edu/resources/ocng_textbook/PDF_files/book_pdf_files.html

Variability of seawater salinity

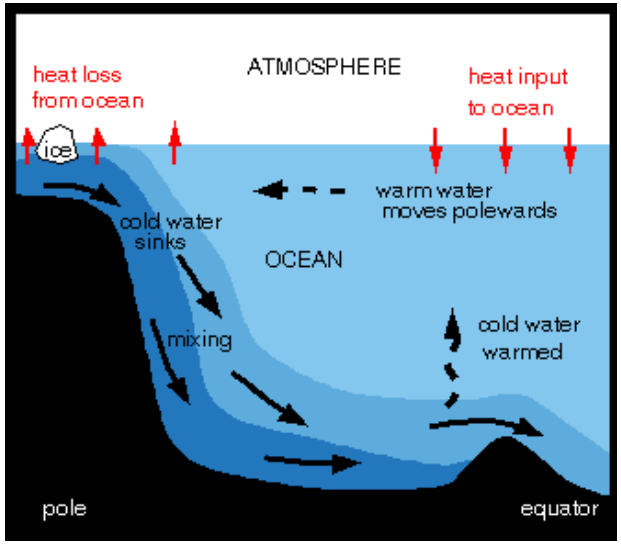


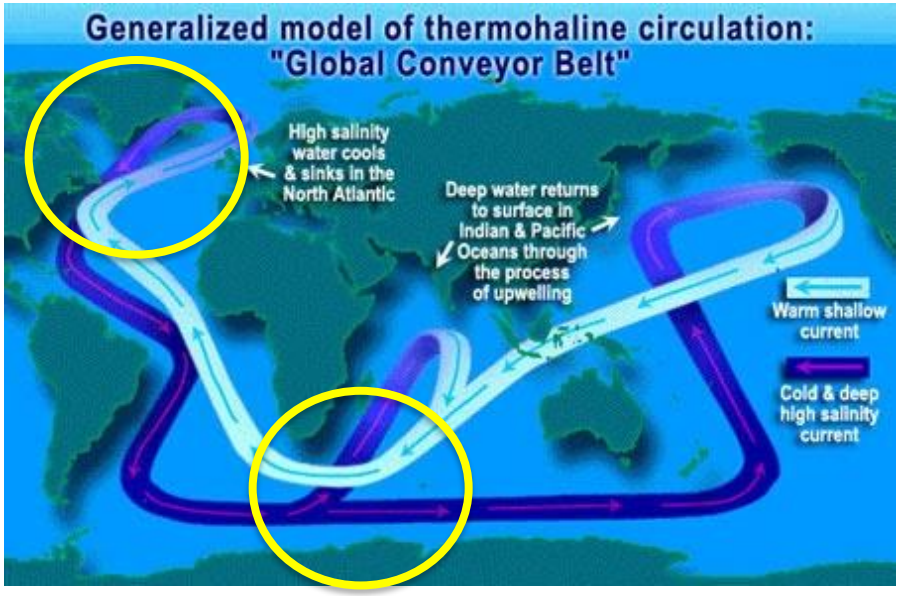
Thermohaline circulation



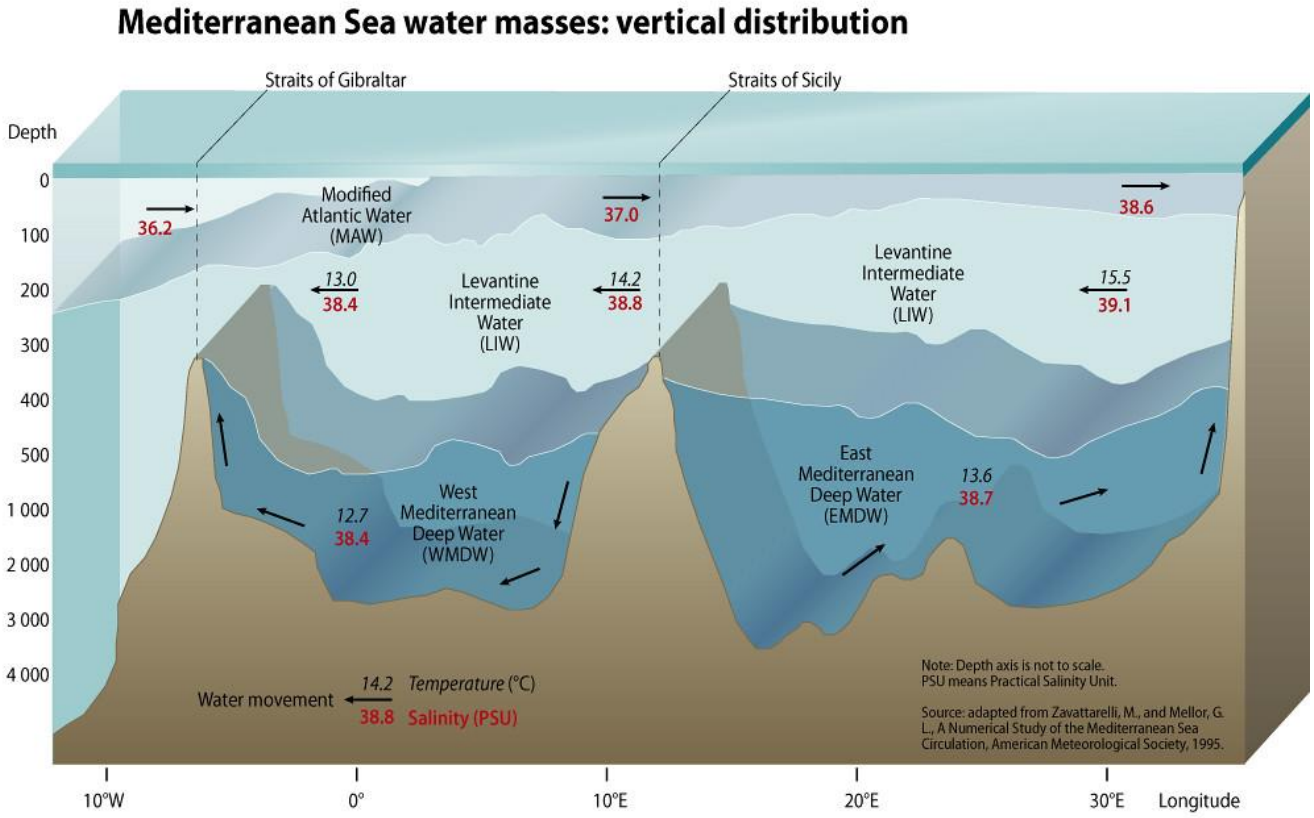
visualizzazioni NASA

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



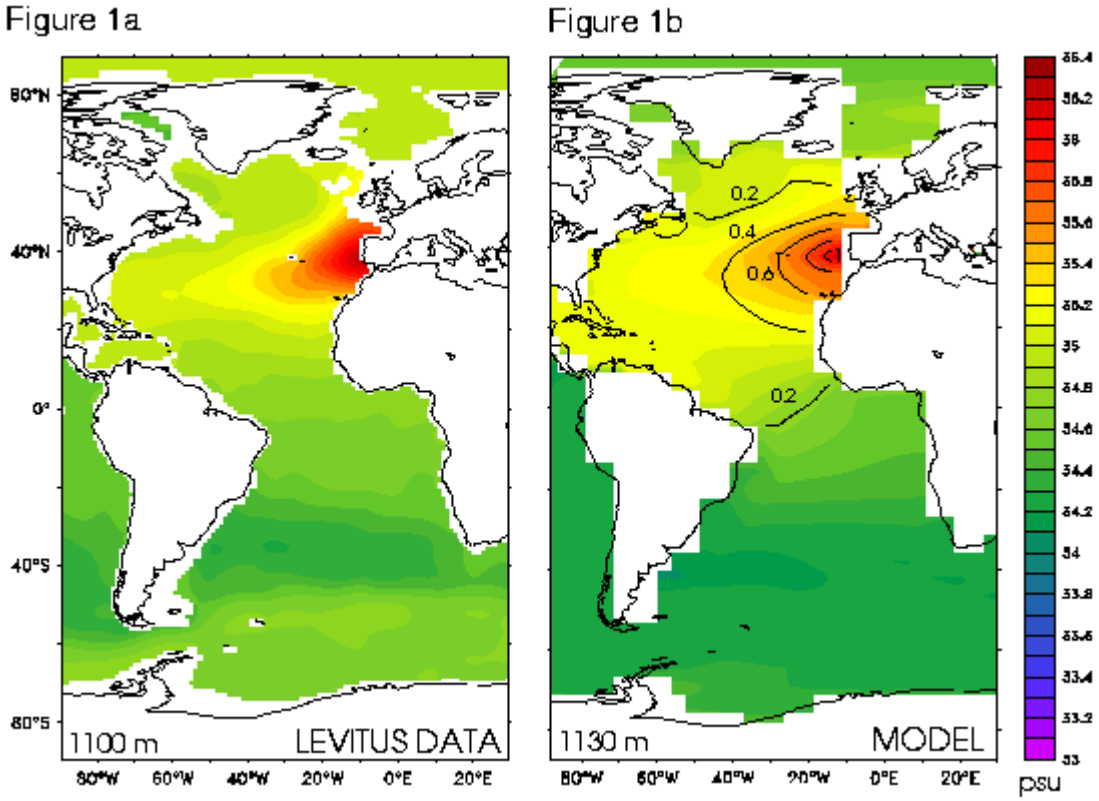


https://www.youtube.com/watch?v=p4pWafuvdrY



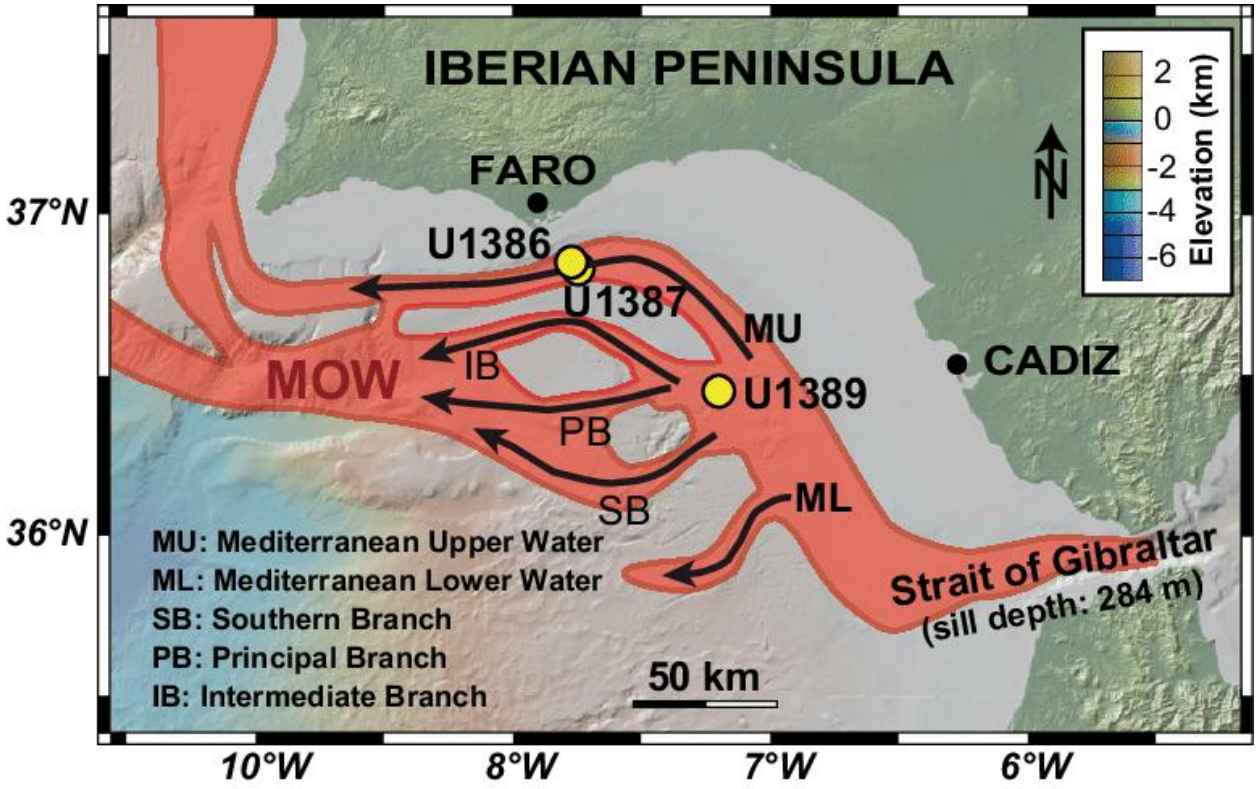
https://www.grida.no/resources/5885

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, ν	1.83 × 10^{-6} m^2 s^{-1}	1.05 × 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 × 10^{-7} m^2 s^{-1}	1.46 × 10^{-7} m^2 s^{-1}
Prandtl number, ν/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 × 10^{-6} K^{-1}	250 × 10^{-6} K^{-1}
Pressure = 100 MN m^{-2}	244 × 10^{-6} K^{-1}	325 × 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 × 10^{-10} Pa^{-1}	4.28 × 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

References

Worthington L.V. 1981. The water masses of the World Ocean: Some results of a fine-scale census. In: Evolution of Physical Oceanography: Scientific surveys in honor of Henry Stommel. Edited by B. A. Warren and C. Wunsch. 42–69. Cambridge: Massachusetts Institute of Technology.

Millero F.J., C.-T. Chen, A. Bradshaw, and K. Schleicher. 1980. A new high pressure equation of state for seawater. Deep-Sea Research 27A: 255–264.

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

JPOTS Joint Panel on Oceanographic Tables and Standards. 1981. The practical salinity scale 1978 and the international equation of state of seawater 1980. Paris: unesco Technical Papers in Marine Science 36: 25.

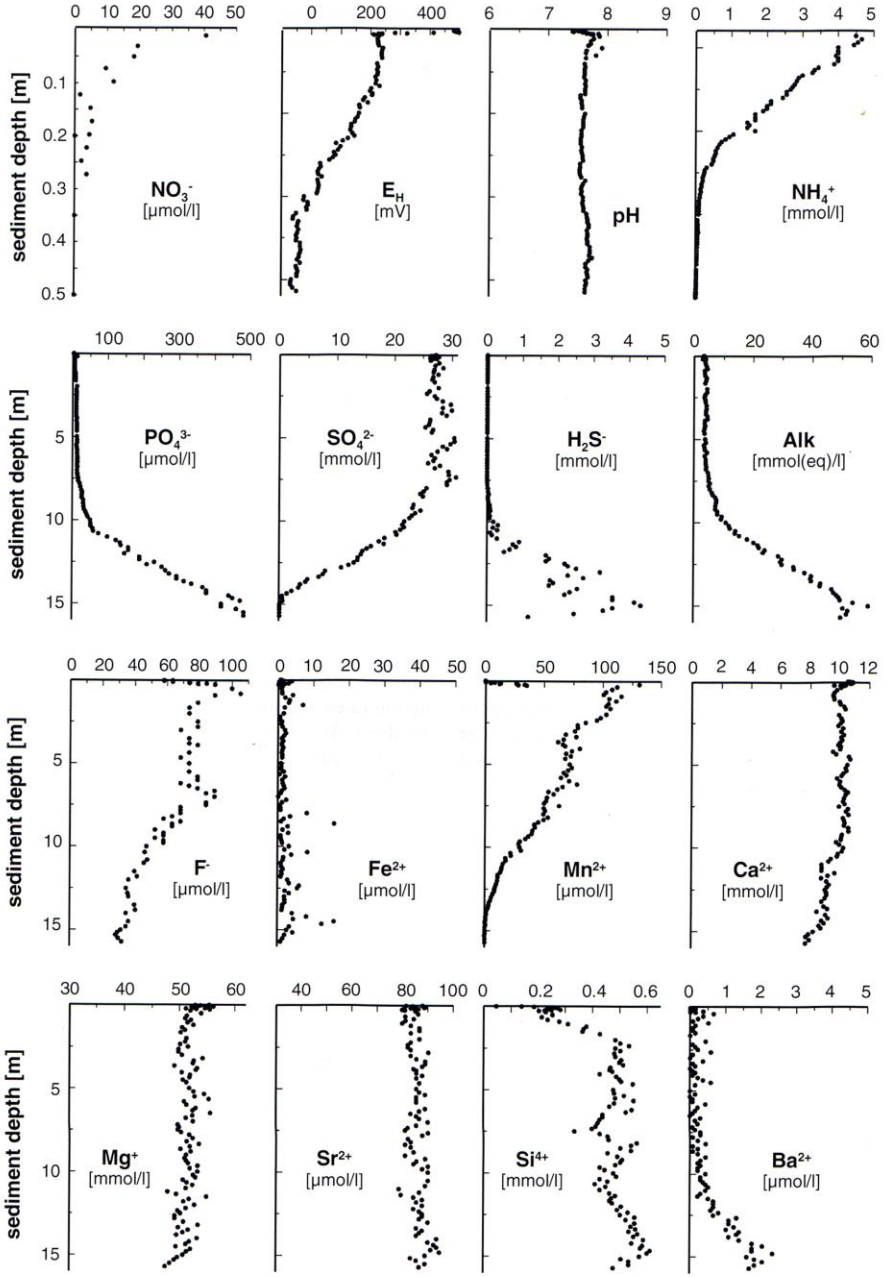
Stewart, R.D., 2007. Introduction To Physical Oceanography. Texas A & M University, Department of Oceanography, 345 pp. http://oceanworld.tamu.edu/resources/ocng_textbook/PDF_files/book_pdf_files.html

Pore water in marine sediments

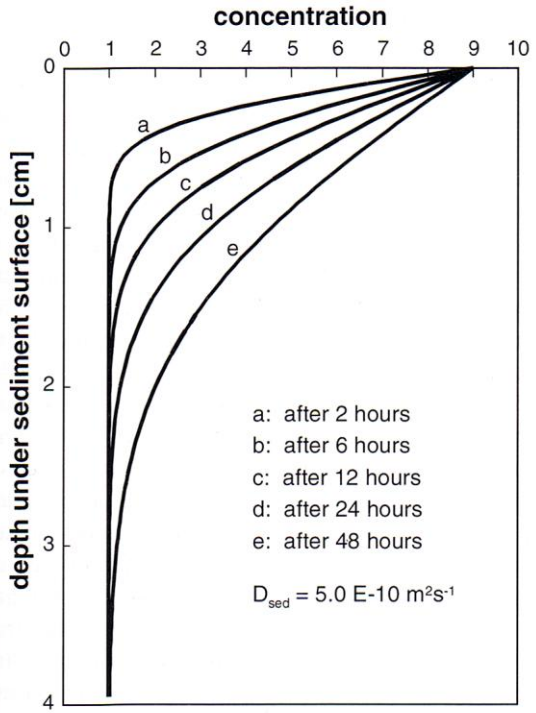
Chemically unstable sediment particles:

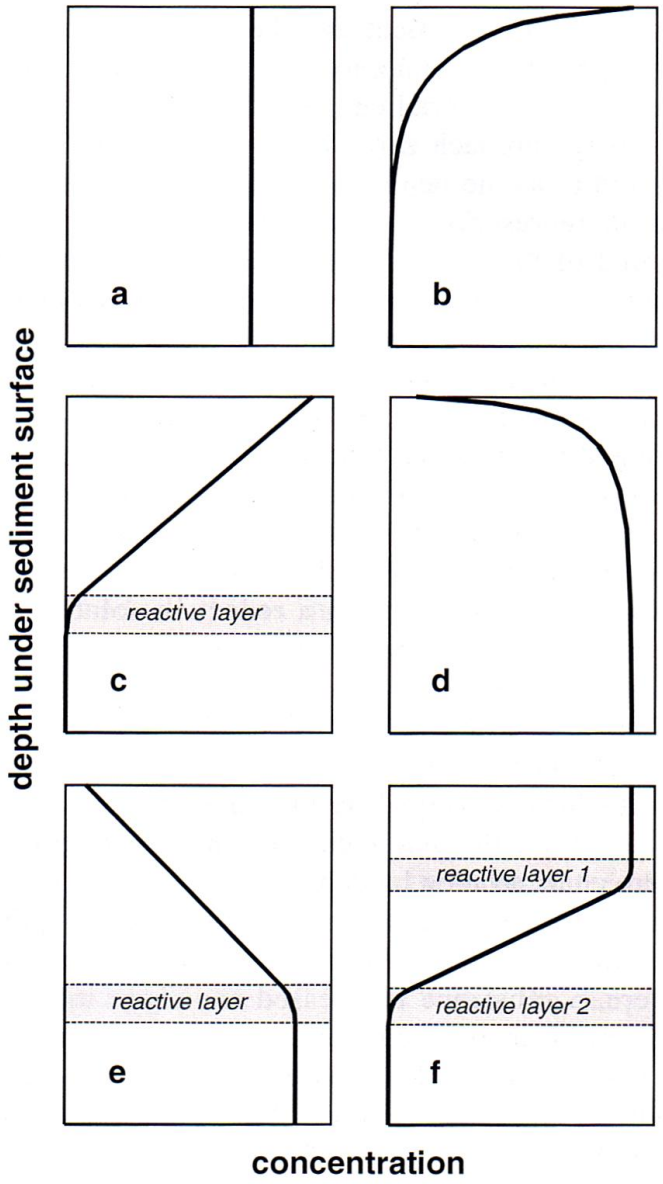
Igneous rock fragments
Amorphous material (e.g. opal)
Organic matter
Remnants of Organisms (bones, teeths)
Clay minerals
Aragonite and Mg Calcite

Pore water in marine sediments

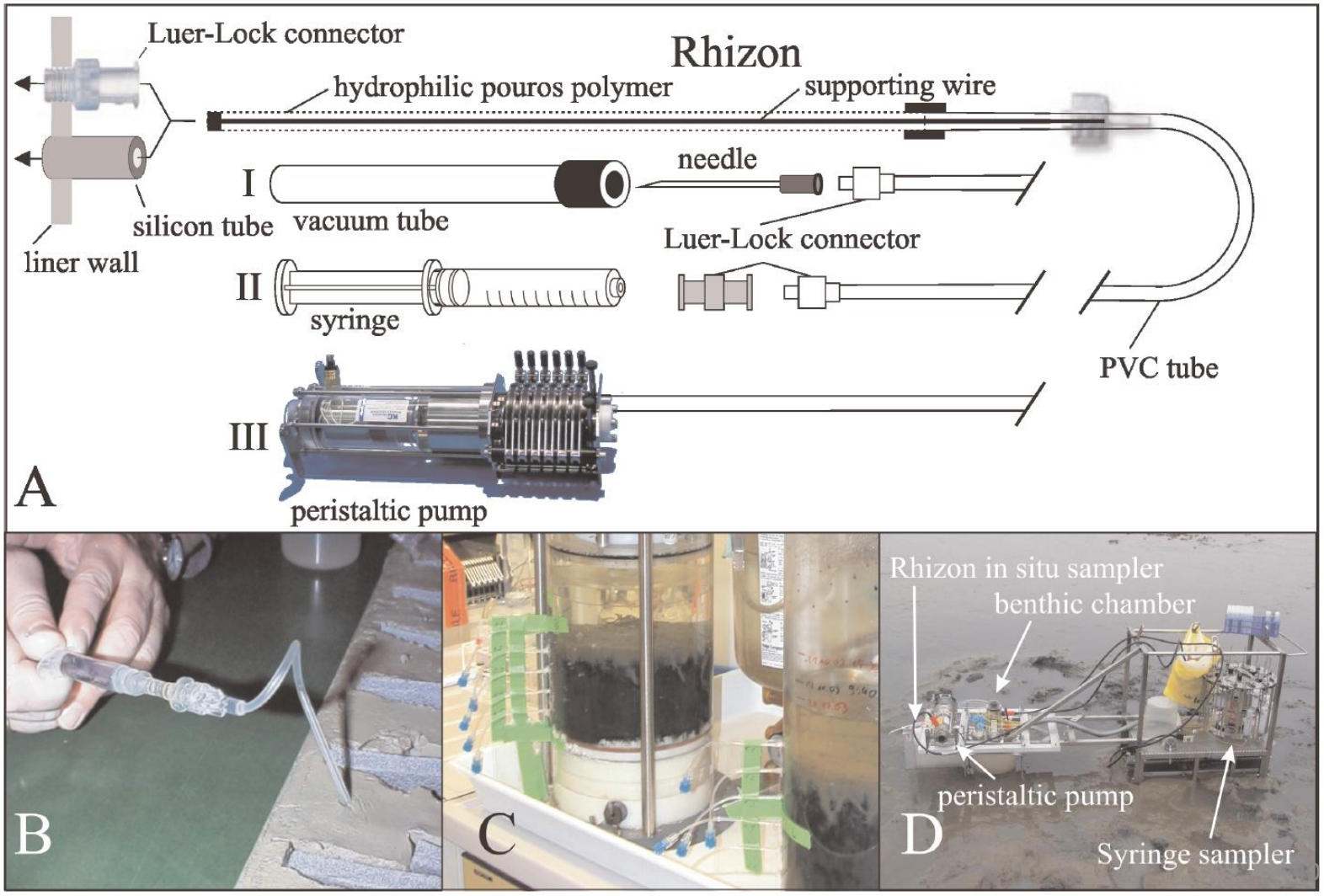


Pore water in marine sediments

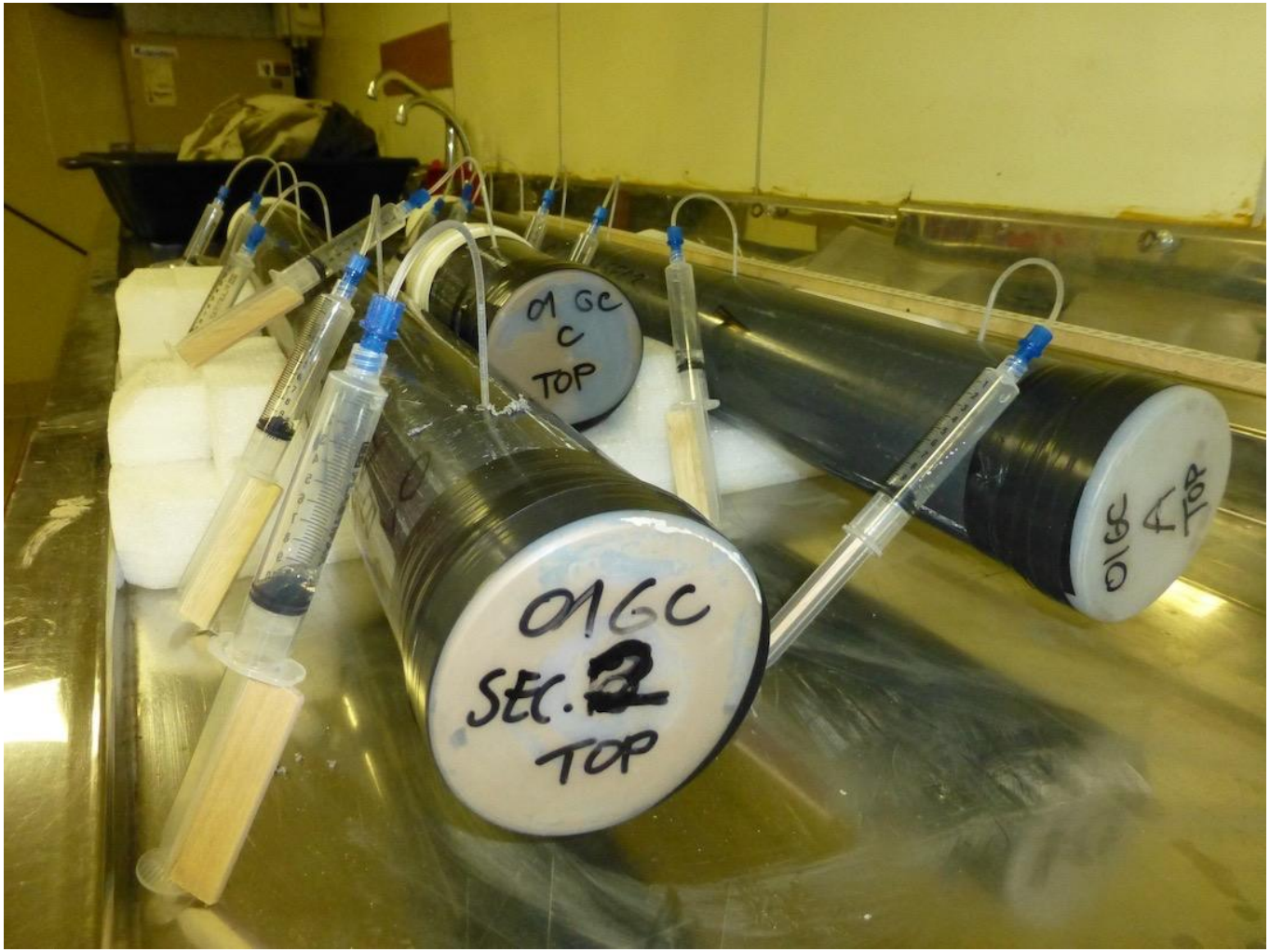




Pore water Sampling in marine sediments



Pore water Sampling in marine sediments



Pore water Sampling in marine sediments



Pore water Sampling in marine sediments

