An Introduction to Ocean Science

Edited by Jason Birt

Front cover: Launching a dive RIB into the surf at Tofo, Mozambique (© Jason Birt)

Rear cover: A vellela-eating pelagic nudibranch (© Jason Birt)

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Chapter 1: Basic Chemistry

Elements

Elements are base chemicals and cannot be further broken down without using heavy nuclear weaponry. Examples of elements include hydrogen, oxygen and iron.

Atoms, sub-atomic particles and ions

Atoms are the smallest non-divisible units of an element. OK, that's by conventional chemistry and you can split them if you're gonna go nuclear but generally the atom is the smallest unit in most situations. Atoms consist of...

> **Protons**: These are found in the nucleus (centre) of the atom, have a mass of 1 and a positive charge, +1.
>
> **Neutrons**: These are also found in the nucleus and help keep the protons apart (like charges repel). They have no charge (hence their name: neutron = neutral) but have a mass of 1.
>
> **Electrons**: These have no mass (alright, not strictly true but it is *tiny*) but have a negative charge, denoted -1. Electrons balance the charge of protons rendering the atom electrically neutral. They do not reside in the nucleus and instead orbit the nucleus in a cloud (see later).

There are smaller sub-atomic particles that make up these sub-atomic particles but we'll leave them to crazed atom smashers busy creating black holes under Switzerland...

Ions: These are charged atoms. The charge is given by the atom having 1, 2 or 3 fewer electrons than protons, giving the ion a positive charge or having 1, 2 or 3 electrons more than protons, giving the ion a negative charge. Why do elements do this? To achieve stability, as we'll see later. In a dry state, these ions usually bond together (ionically, as it so happens) and in complementary pairs (e.g., sodium ions have a positive charge (+1) and chloride ions have a negative charge (-1); together they form sodium chloride - or salt).

Atomic number, atomic mass and isotopes

We now go up a level.

Atomic number refers to the number of **protons** are in the nucleus.

Atomic mass refers to the number of **protons and neutrons** in the nucleus. This gives an element a mass given the unit **grammes**. A **molar mass** of a substance is given the unit **g** $\mathbf{mol^{-1}}$ (grammes per mole - we'll come to moles at some point).

Isotopes refer to the variations in mass for a given element. An element's name is determined by its atomic number, that is, the number of protons it has. But the number of neutrons can vary, producing different atomic masses and therefore different isotopes. Some isotopes of elements can be unstable and hence **radioactive**. This means that the elements breakdown or give off highly energised components to achieve stability. Oxygen comes in different isotopes: the most common is ^{16}O but there are a few oxygen atoms that are ^{18}O. Incidentally, the ratio of ^{18}O to ^{16}O is used as a proxy (indirect marker) of temperature for paleoclimatology.

Molecular mass

Molecular mass is like atomic mass only in this case you simply add the atomic masses of the constituent elements in the compound or molecule.

Periodic table

Up until the mid-nineteenth century, the number of elements known wasn't massive and they were about as organised as a teenage boy's bedroom. Then a massive expansion of chemical knowledge initiated by local lad Humphry Davy led to the need for some sort of organisation. Many attempts were made but the Russian Dmitri Mendeleev came up with today's accepted version: the periodic table. It truly is a work of genius. The elements are laid out in terms of their chemical behaviour so that when looking at the left hand side, the elements become progressively more volatile down the column and on the right hand side, one column in, they become progressively more placid. The furthest column to the right are elements termed noble gases because they really have to be forced to bond with anything and more often than not don't. Horizontally, elements are laid out according to the number of electrons in each of their "shells", a concept we are about to move on to next.

Shells, orbits and clouds

Oh boy, now we're onto something... Shells, orbits and clouds are all different models for explaining how electrons are arranged around the nucleus. Clouds refers to the latest idea and we'll come to that in a minute. Shells and orbits refer to different energy levels from the nucleus. It is generally accepted that each of these shells and orbits have a capacity that needs to be filled with electrons before the next orbit or shell can be filled. The inner most shell has a capacity for two electrons, the next has a capacity for eight electrons, the next has eight and the next has, er, more. Look at the periodic table and you can see the the arrangement.

This now gives a hint about the formation of ions, an important concept in marine chemistry. Those elements with only 1, 2 or 3 electrons in the outermost shell are not that stable and "want" to give those away so that their outermost shell is full. Those elements with 1, 2 or 3 spaces in their outermost shell "want" to fill those spaces. For some reason, a full outer shell is the most stable. So what happens is that those elements with spaces to fill will bond with those elements with electrons to give away... you can see why now hopefully!

Chemists and physicists more recently have discovered that atoms are not solar systems with a nuclear "sun" with orbiting "planetary" electrons. Rather, electrons orbit the nucleus in weird and wonderfully shaped clouds, with each cloud having a particular energy level. A cloud is defined as a region of space around the nucleus where there is a 96% probability of finding the electrons.

Electrons can jump clouds (or, in the older sense, orbits or shells) when energy is given to them. When they fall back to their previous cloud (or orbit) they emit energy, usually in the form of light. This property is exploited in street lamps: electricity is applied to sodium and as the electrons in sodium fall back to their normal place they emit orange light. Xenon does the same and is used in car headlight bulbs for this reason.

Valence electrons

This term refers to those electrons in the outermost shell. Why are they important? Because these electrons are the ones that interact with other atoms or ions and are therefore important in **bonding**. The number of **valence electrons** indicates - roughly - how many "partner" atoms that atom can have. Those with 1, 2 or 3 electrons in the outermost shell tend to form bonds with 1, 2 or 3 other atoms respectively. Those with 1, 2 or 3 spaces tend to form the same number of bonds. However, it also depends on how the spare electrons match the spare spaces. For example, Magnesium has 2 electrons in its outer shell and can either form 2 bonds with 2 chloride ions (forming $MgCl_2$ because Cl has one space so one space for one Mg electron) or it can form 1 bond with an oxygen ion (forming MgO because oxygen has 2 spaces and can therefore accommodate the 2 spare Mg electrons). Carbon and sulphur and a few others are exceptions and can form 4 or more bonds, depending on the element.

Covalent bonding

There are different forms of bonding and this depends on whether the component elements have a tendency to "grab" electrons off others or share them. The closer elements are to each other in the periodic table, the more likely they are to share those electrons as we'll see later.

Covalent bonds are those where electrons are shared. Carbon has four spaces in its outer shell and with hydrogen, hydrogen's one electron fills one of those spaces. Four hydrogens bonded to carbon gives carbon a full outer shell. Hydrogen doesn't want to lose that electron (it's the only one it's got!) and to have another gives it a full outer shell. Carbon would find it hard to lose 4 electrons to give it a full outer shell so with those four hydrogens and all electrons shared, everyone is happy.

Polar covalent bonding

In certain circumstances, one of the component elements in a bond will be slightly more "possessive" of the bond electrons. This induces a slight negative charge to the element that gets these and a slight positive charge to the element which is losing them. This is a vitally important bond in marine science and biology: watch this space...

Ionic bonding

This is the whole shebang: one element takes the electrons from the other and the main strength of the bond is through opposite charges attraction. This bond tends to form with elements at some distance from each other in the periodic table.

Compounds and molecules

Compounds and **molecules** are often used interchangeably and generally mean the same thing. In the strict chemical definition, “a **molecule** is defined as a sufficiently stable electrically neutral group of at least two atoms in a definite arrangement held together by very strong chemical bonds. It can also be defined as a unit of two or more atoms held together by covalent bonds.” (IUPAC, 1994). In biochemistry and biology, the definition is looser and often molecules may have charges.

For example:

- Na is the element sodium
- NaCl is the compound sodium chloride
- O_2 is the oxygen molecule
- CH_4 is the methane molecule

Body centred cubic

Whilst many covalently bonded compounds form crystal structures, these structures are best associated with ionic bonds. Body centred cubic is so termed because one of the atoms (ions) is in the centre of a cubic arrangement with eight atoms surrounding (one at each corner). 10% of elements in compounds form this arrangement.

Face centred cubic

This arrangement has an ion at each corner plus one in the middle of each face of the cube.

20% of elements in compounds form this arrangement.

Simple cubic

Only polonium compounds form this arrangement: one ion in each corner of the cube.

Chapter 2: Water Physics and Chemistry

The properties of water

The **bond angle** of the water molecule is **104.45 degrees** and the **bond lengths** are 95.84 pm (0.00000000009584 metres!). This bond angle is critical because it dictates a number of the biological properties of water.

Water molecules display **polarity** because oxygen is more **electronegative** than hydrogen so gains greater possession of the bonding electrons. These polar covalent bonds give oxygen a slightly negative charge and the hydrogens a slightly positive charge.

These slight charges generate temporary bonds between the oxygen of one water molecule and the hydrogen of another. These temporary bonds are quite strong and are called **hydrogen bonds**. Hydrogen bonds are pervasive through nature in organic molecules and are responsible for the shapes of complex organic molecules. In water, though, these bonds are responsible for water being liquid at room temperature and a number of water's properties.

Fresh water has a **melting** or **freezing point** of 0 °C at 1 atm.

Fresh water has a **boiling point** of 100 °C at 1 atm.

Reduced pressure reduces the boiling point. At 8000 m, water boils at 69 °C. It is unclear as to whether reduced pressure affects melting point. Some sources say that in pure circumstances, the reduced pressure found at high altitude leads to liquid water droplets still being present despite the air temperature being 40 °C below.
Adding **salt depresses** the melting point, hence its use on roads.

Fresh water is at its **densest** at 4 °C.

Fresh water becomes *less* dense as the temperature drops below this. This is useful because this allows water to freeze from the **top down** rather than the bottom up.

Ice is *less* dense than liquid water and this is unusual for a solid. Why? Well, the bond angle of water allows the molecules of water to form an arrangement that traps **air** into the structure. This trapped air makes ice less dense and allows it to float. Again, this is useful because the floating ice insulates the water from the cold atmosphere and slows deeper freezing.

Ice requires a **seed** to form. This can be salt, dust, dirt, etc.

The **specific heat capacity** of water is 4184 kJ kg^{-1} K^{-1}. This is high and indicates that water needs a lot of energy to heat up and gives off a lot to cool down. This makes water a great buffer to regulate the Earth's climate. Whilst the atmosphere can be very variable in terms of temperature, the oceans change temperature slowly. There is also a lag in monthly temperatures between atmosphere and ocean.

The **latent heat of fusion** (between ice and liquid water) is 334 J g^{-1}.

The **latent heat of vaporisation** (between liquid water and water vapour) is 2500 J g^{-1}. This is quite high and means that evaporation can remove a lot of heat from a surface (hence why you feel cold when drying). Incidentally, hot water freezes quicker than cold water. Apparently. Try it and let me know! (I accept **NO** responsibility for damage to your freezer...)

Other properties of water make it key for biological activity. The hydrogen bonds that make water liquid at room temperature also make it "sticky". The water molecules are attracted to each other and also to other substances. This allows water to adhere (**adhesion**) to the walls of tubes like xylem in plants, allowing **capillary action**. Similarly, **surface tension** allows a **miniscus** to form and this can allow organisms to skim along the surface.

Water is also deemed a **universal solvent**. This is not completely true because it doesn't mix at all well with organic compounds like fats. However, with inorganic salts, given time it will dissolve most things. With **sodium chloride**, the solvating powers of water are again due to the slightly polar nature of water. The hydrogens of water align closest to chloride ions (opposite charges attract) and keep them separated and in solution from sodium ions, which are surrounded by water molecules with the oxygen closest to them.

Water as a solvent: moles and concentration

Molecular mass

Molecular mass is like **atomic mass** only in this case you simply add the atomic masses of the constituent elements in the compound or molecule.

Knowing **molecular mass** (**M**) allows us to then calculate the **amount** (**n**) of a substance (the number of molecules actually present) from the **mass** (**m**) presented to you and from that, the concentration (**C**) of that substance if it is to be dissolved in water and you know the **volume** (**V**). And marine chemistry features a lot that is dissolved. After all, the principle of salinity is the concentration of salts dissolved in water and pH is a number that represents the concentration of acid ions (H^+ ions, hydrogen ions) in water... And don't get me started on nutrient concentrations...

The Mole

Time for a coffee before this one... Chemists do not use the term **amount** for weight or concentration or mass, they use **amount** to refer to the number of atoms being present. There are 6.02×10^{23} atoms per mole of a substance: this is a constant referred to as Avogadro's number. A **molar quantity** of a substance or its **molar mass** is the mass per mole. For example, a **mole** of carbon weighs 12 grams, in other words carbon has a molar mass of 12 g mol^{-1}. If you had 6 g of carbon (say, graphite, a form of carbon) then your amount of carbon would be 0.5 mol (6 g / 12 g mol^{-1} = 0.5 mol). If you had 24 g mass you would have 2 moles of carbon. Generally:

$n=m/M$

where m is mass of the substance on your balance, M is the molar mass and n is the amount in moles (or mol).

Concentration

This brings us onto **concentration**. Concentration is the **amount** per **volume** or moles per litre. Only chemists don't use litres - they use decimetres cubed or dm^3 (Why? Who the hell knows – they're chemists! By the way, have you noticed that there are no chemists on TV? Brian what'shisname (the one with the suspiciously young face) – physicist, that Scottish bloke on extremely niche programming channel BBC4 waffling on about how Earth was made – geologist, Kate Humble, who appears at the opening of an envelope marked FAO Science – celebrity scientist. Why is that? Is chemistry so boring? I spy a TV niche for myself... Know any production companies? Yes? My mobile number is 078[CENSORED BY REBECCA ALLEN]5). So chemical concentration is denoted mol dm^{-3}. You can calculate concentration by dividing amount by volume or:

$c=n/V$

where c is concentration, n is amount and V is volume. For example, if we had 6 g of carbon and let's say for sake of argument it dissolved completely in 500 ml of water (or 0.5 dm^3) then the concentration of carbon would be:

6 g / 12 g mol^{-1} = 0.5 mol

0.5 mol / 0.5 dm^3 = 1 mol dm^{-3} or 1M

Why 1M? Because M is shorthand for mol dm^{-3}.

Electronegativity, redox and pH

Electronegativity

Electronegativity is a measure of how electron "grabbing" an element is. The further up a group the element is, the more electronegative. The further to the right of a period an element is, the more electronegative. Therefore, fluorine is the most electronegative and francium or caesium is the least. The units of electronegativity are relative and referred to as Pauling Units. The greater the difference in electronegativity elements in a compound are, the more likely that the bonding is going to be ionic. The more similar, the more covalent it is.

Reduction and oxidation

This process refers to the loss or gain of electrons. An element that gains electrons (e.g., chlorine becoming a chloride ion) is said to be **reduced**. An element that loses electrons (e.g., sodium atom to sodium ion) is said to be **oxidised**. This is a key process in the marine environment.

Half equations

Oxidation and reduction processes often occur together, with one part of a **reaction** playing the role of the **reducing agent** and the other, the role of the **oxidising agent**. One way of displaying the passage of electrons is to show the reaction in terms of half equations. Each component is shown either side of a reaction, with the equation showing whether it is losing electrons (shown as e^- on the right hand side of the equation) or gaining electrons (e^- shown on the left).

Redox in the marine environment

Examples of **redox** in the marine environment include:

- Most biological reactions.
- The use of zinc anodes attached to ships to prevent rusting.
- The change in conditions at the top of sediment in a mud flat to deeper down, as shown by the **Redox Potential Discontinuity Layer (RPDL)**.

RPDL?

This band of sediment is seen going from brown (oxidised) through grey to black (reduced). The colouration is based on the change of iron compound. There are accompanying smells.

In polluted environments, this layer may be close to the surface but in biologically active environments with lots of **macrofauna**, the **RPDL** (the layer that marks the change from oxidised to reduced conditions) may be a lot deeper because of burrowing activity bringing in oxygenated water and oxidising the sediment around the burrow. This encourages more biological activity.

pH

pH is shorthand for the **concentration of hydrogen ions** in a solution. pH stands for **“potential of hydrogen”**. It is derived from the equation: **$pH = -\log_{10} [H^+]$**. pHs of **1-6.9** are deemed **acidic** and those pHs of **7.1-14** are deemed **basic** or **alkaline**. pH **7** is **neutral**.

Of course, pH can also give the hydrogen ion concentration. You can do this by using the equation: **$[H^+] = 10^{-pH}$**. This is done using your **10^x button** on your calculators. You enter the pH, then press the +/- button and then 10^x. Some calculators may be different. Incidentally, the **[ ]** brackets are shorthand for **concentration**.

So what common compounds are what? Well **concentrated hydrochloric acid** is around about **pH 2** whereas **acetic acid** is more likely to be **pH 5**. The stronger the acid, the more likely it is to donate its **H^+ ion**. **Sodium hydroxide** is usually **pH 10-12**. It donates **OH^- ions** to water. An **OH^- ion** will combine to spare **H^+** ions to form…

…**H_2O**. As a very general rule of thumb compounds with H at the beginning will tend to be acidic (H_2SO_4 – sulphuric acid) and those with OH at the end will be alkaline (NaOH – sodium hydroxide). There are many exceptions, though.

Measuring pH can be achieved by either using **litmus paper**, which reacts with substances to give different colours that equate to different pHs, **indicator solutions** (like **neutral red**), which do much the same thing or **electronic pH meters**. Indicator solutions can be universal, that is, covering a wide range of pHs – the trade-off being inaccuracy – or specific, covering a narrow range of pHs. Meters can give the most accurate values but need a lot of care and careful **calibration** (adjusting with a solution with a known pH) with **buffer solutions** (those that are able to control their pH within a very tight band of pHs).

Hydrological cycle

The hydrological cycle describes the movement of water throughout all the major pathways. Apart from a little that escapes into space, most water is recirculated, although the time it takes can vary remarkably. There are “reservoirs” within the system – groundwater, glaciers and ice flows, atmosphere and ocean (see figure 1).

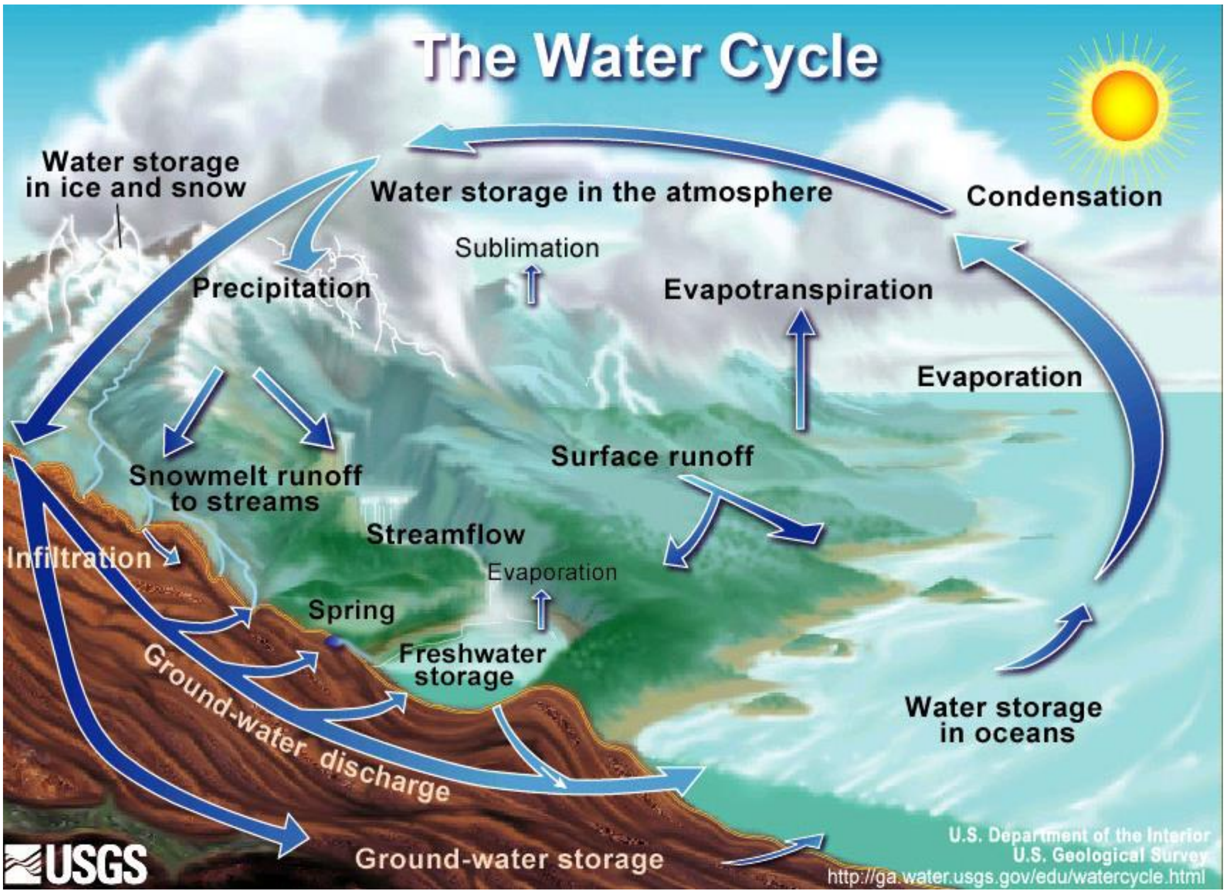


Figure 1. Hydrological cycle simplified. This should be used in conjunction with that created in your lecture notes (From USGS, 2009).

Water passes through the system through a variety of routes. See below for those sourced from Wikipedia:

"Precipitation

Condensed water vapour that falls to the Earth's surface. Most precipitation occurs as rain, but also includes snow, hail, fog drip, graupel, and sleet. Approximately 505,000 km^3 of water fall as precipitation each year, 398,000 km^3 of it over the oceans.

Canopy interception

The precipitation that is intercepted by plant foliage and eventually evaporates back to the atmosphere rather than falling to the ground.

Snowmelt

The runoff produced by melting snow.

Runoff

The variety of ways by which water moves across the land. This includes both surface runoff and channel runoff. As it flows, the water may infiltrate into the ground, evaporate into the air, become stored in lakes or reservoirs, or be extracted for agricultural or other human uses.

Infiltration

The flow of water from the ground surface into the ground. Once infiltrated, the water becomes soil moisture or groundwater.

Subsurface Flow

The flow of water underground, in the vadose zone and aquifers. Subsurface water may return to the surface (eg. as a spring or by being pumped) or eventually seep into the oceans. Water returns to the land surface at lower elevation than where it infiltrated, under the force of gravity or gravity induced pressures. Groundwater tends to move slowly, and is replenished slowly, so it can remain in aquifers for thousands of years.

Evaporation

The transformation of water from liquid to gas phases as it moves from the ground or bodies of water into the overlying atmosphere. The source of energy for evaporation is primarily solar radiation. Evaporation often implicitly includes transpiration from plants, though together they are specifically referred to as evapotranspiration. Total annual evapotranspiration amounts to approximately 505,000 km^3 of water, 434,000 km^3 of which evaporates from the oceans.

Sublimation

The state change directly from solid water (snow or ice) to water vapor.

Advection

The movement of water — in solid, liquid, or vapour states — through the atmosphere. Without advection, water that evaporated over the oceans could not precipitate over land.

Condensation

The transformation of water vapour to liquid water droplets in the air, producing clouds and fog."

Table 1. Residence time of water in different reservoirs (From Wikipedia, 2009).

Reservoir	Average residence time
Oceans	3,200 years
Glaciers	20 to 100 years
Seasonal snow cover	2 to 6 months
Soil moisture	1 to 2 months
Groundwater: shallow	100 to 200 years
Groundwater: deep	10,000 years
Lakes	50 to 100 years
Rivers	2 to 6 months
Atmosphere	9 days

Chapter 3: Salinity

Composition of salts in seawater

Seawater isn't just about sodium and chloride – almost all naturally occurring elements can be found dissolved in seawater and contributing to saltiness. The units of salinity are variously g kg^{-1}, mol kg^{-1}, ‰ and PSU or practical salinity units. The most recent definition of salinity involves the use of a reference standard to calibrate against so technically salinity is now viewed as a ratio and therefore unit-less. Marine biologists feel uncomfortable about that so often still use ‰. See below for a table of composition.

Table 2. Composition of the major salts in seawater of 35 ‰ (From Wikipedia, 2009).

Component	Concentration (mol/kg)
Cl^-	0.546
Na^+	0.469
Mg^{2+}	0.0528
SO_4^{2-}	0.0282
Ca^{2+}	0.0103
K^+	0.0102
C_T	0.00206
Br^-	0.000844
B_T	0.000416
Sr^{2+}	0.000091
F^-	0.000068

Marcet's principle of constancy of composition

This principle states that there is no variance in the composition of seawater regardless of the overall level of salinity. That is, whilst their concentration will drop in lower salinity seawater, the proportions between one ion and another will not. There are, however, some exceptions.

Deviations from constancy of composition

Marginal seas – those that are shallow, have restricted basins or high river influx with a particularly high load of dissolved mineral.

Anoxic basins – these have very low or no dissolved oxygen so become reducing environments. This will change the solubility of certain elements causing them to drop out of solution and therefore change the composition of the seawater.

Formation of sea ice – the speed of formation may cause selective uptake of certain elements into the ice and are therefore removed from the seawater.

Deposition of calcareous shells – the formation of shells or coral will cause a disproportionate removal of calcium and carbonate from the seawater. Below 4500m, the resolubilisation of seawater will cause a relative increase in the concentration of calcium and carbonate.

Hydrothermal vents – these are major suppliers of salts into the oceans but are also major sinks (see below). Depending on the temperature of the vent, there will be differences in supply and removal, leading to local variations in the composition of seawater.

Evaporites – evaporites are rocks and sediments formed from salts left by evaporation. Faster evaporation will selectively remove some elements more than others. This will create local variations. The resolubilisation of these rocks will therefore create further deviations.

Air-Sea interface – this very thin layer can have differences of composition caused by the effects of evaporation as described above.

Interstitial waters – this is the water between sediment grains. Sediment grains may well have high concentrations of certain element that then diffuse into the interstitial water. Interstitial water will mix with seawater overlying it.

It must be stated that whilst there are a number of situations listed, these form a very small proportion of the global ocean volume.

Sources and sinks

Sources – rivers, groundwater, precipitation, hydrothermal vents, aeolian transport, volcanoes, sea ice.
Sinks – interstitial water exchange, subduction, evaporation, hydrothermal vents, sea ice, evaporite formation.

Residence time

Quite simply the amount of time an element or compound spends in a reservoir. This includes pollutants. The equation is:

$$R_t = \frac{Volume\ of\ reservoir}{Volume\ of\ inflow\ or\ outflow\ per\ unit\ time}$$

The unit of time depends on the unit used in the volume of inflow/outflow.

Measurement of salinity

Salinity used to be measured chemically, using burettes (tall glass pipettes) to measure the amount of the constituent salts. This was simplified to just measuring the amount of chloride present, a measure called chlorinity. This measurement can be converted to salinity using the following formula:

$$S = 1.8655\ chlorinity$$

Then it was realised that salts in seawater conducted electricity. The more salt in seawater, the greater the conductivity and the lower the resistance. Whilst very accurate measurements of salinity can be made using a salinometer, which uses a reference cell, most measurements nowadays use a TS (temperature-salinity) probe that uses conductivity or resistance. These give quick readings and often also record depth.

Temperature and salinity profiles

Temperature and salinity are often plotted against depth to ascertain oceanic structure. Unlike normal scientific graphs, the known value (in this case depth, Z) is on the y-axis not the x-axis. Therefore, temperature or salinity is on the x-axis. Additionally, the x-axis runs along the top not the bottom of the graph. For an example, see figures 2 and 3.

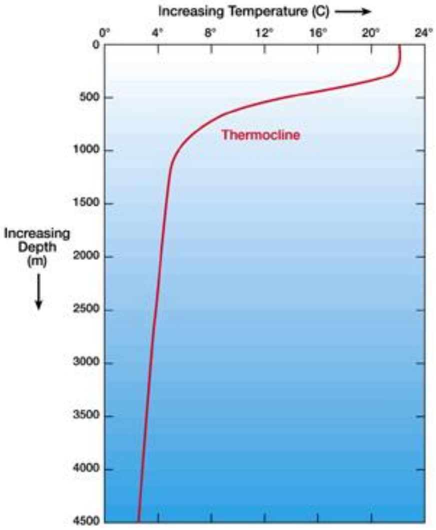


Figure 2. Temperature profile. Note that there is a stable upper layer and a stable lower layer. In-between the two is a sudden change in temperature with depth called a **thermocline** (From University of Carolina, 2009).

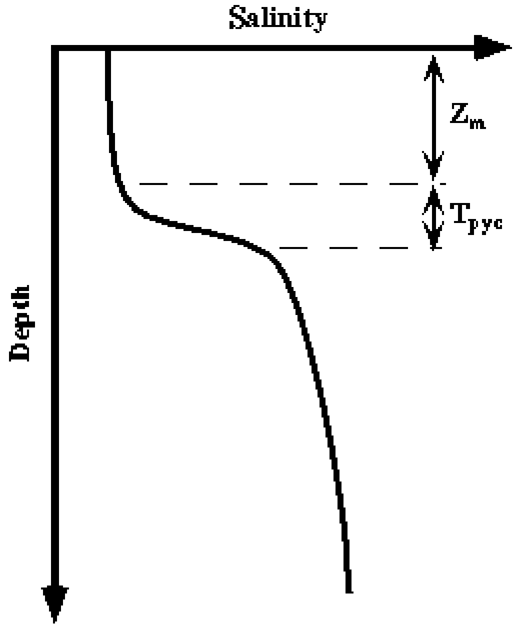


Figure 3. This is a salinity profile of a typical estuary. The sudden change in salinity with depth is called a **halocline**. The stable upper layer is river-derived water and the stable lower layer is tidal water (From Lucas *et al.*, 1998).

Density and the equation of state

The warmer a water body is, the less dense it is. The more salty water is, the denser it is. Therefore, cold, salty water is most dense and warm, fresher water is least dense. This leads to the arrangement and structure of estuaries and other water masses, usually from least dense at the surface to most dense at depth. This sorting is by gravity as dense water per unit volume weighs more than less dense water. The unit of density is kg m^{-3}. The relationship between temperature and salinity to produce density is not a simple one as the figure below will demonstrate:

$$\rho(T,S,P) = \frac{\rho(T,S,0)}{1 - \dfrac{P}{K(T,S,P)}}$$

Figure 4. Equation of state for calculating seawater from temperature and density. The NOAA website where this figure was obtained states: "ρ is the density of seawater in kg/m^3, T is the temperature in C, S is the salinity in psu, P is the pressure, and K(T,S,P) is the secant bulk modulus. The empirically based UES equation is given over a three-dimensional domain for D = { -2 < T < 40C, 0 < S < 40 psu, and 0 < P < 10000 decibars}. This domain represents all possible combinations of T, S, and Z which are encountered globally. Mathematically, the functions (T,S,0) and K(T,S,P) are represented by multidimensional polynomials and, as a result, the density (1) is the ratio of two, three-dimensional polynomials which contain more than 40 parameters." Thankfully, there is software to do this!

Density profiles

Combining temperature and salinity data using the Cox equation will produce a profile of density against depth. Such a profile may feature a pycnocline – a sudden change in density with depth. This may well occur where there is thermocline, as in the middle of ocean gyres or where there is a halocline, in salt-wedge estuaries.

T-S plots

T-S plots produce a signature for a water body. They range temperature on the y-axis against salinity on the x-axis. The points usually have the depth they were recorded at placed next to them. See below:

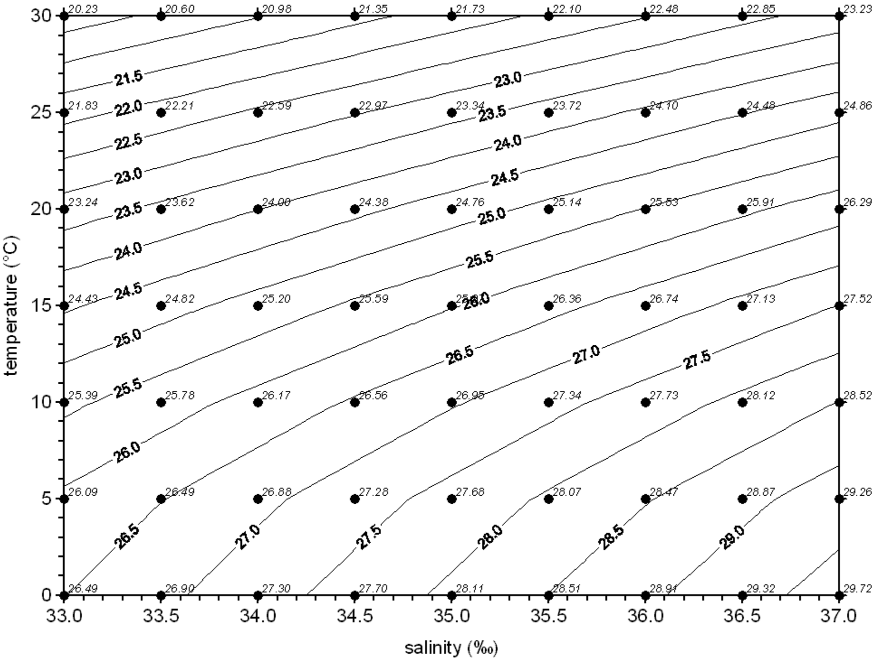


Figure 5. An example blank T-S plot ready for plotting. Note the contours of density. They are expressed as sigma-t. For an explanation of this unit see below (From University of Carolina, 2009).

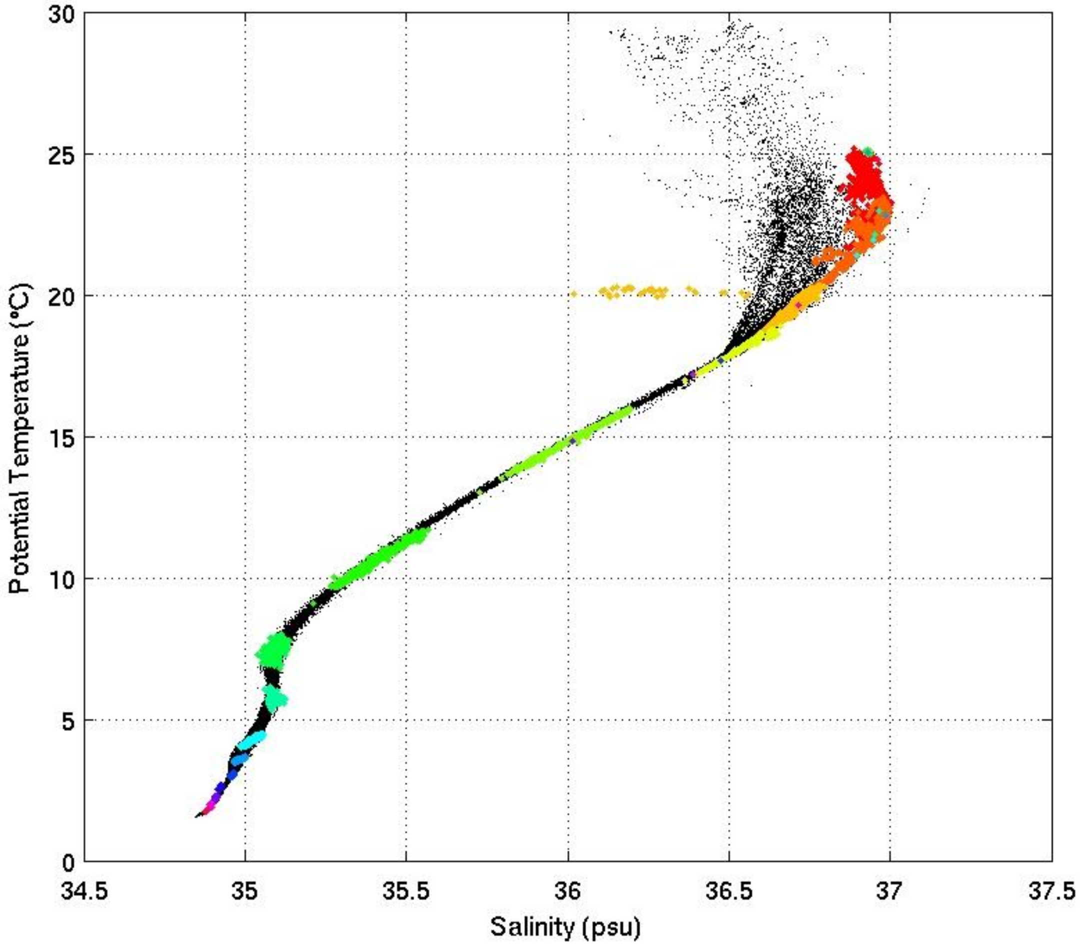


Figure 6. A plot generated by a computer from a buoy moored in the Atlantic to measure the Atlantic Meridional Overturning Circulation. Though no depths are indicated, you can see this water body has a defined signature. Potential temperature takes into account pressure changes (From University of Miami, 2009).

Sigma-t

Density can be measured to a high degree of accuracy. Generally, seawater will have a density greater than 1000 kg m^{-3}. If the density was measured to be 1027.3456 kg m^{-3} that would be a bit wordy so oceanographers came up with the concept of doing away with the start. Using this equation:

$$\sigma_t = \rho - 1000$$

where ρ is density and σ_t is sigma-t you can produce the value 27.3456, which is easier to handle.

Water masses

OK, so there are differences in salinity and temperature and these produce signatures.

Water masses have particular signatures and these are determined by where they were "created". So salty water flowing in the Gulf Stream that meets ice will be very salty and very cold. Such a water mass would be termed North Atlantic bottom water if formed in the Atlantic Arctic. See below for some other water masses:

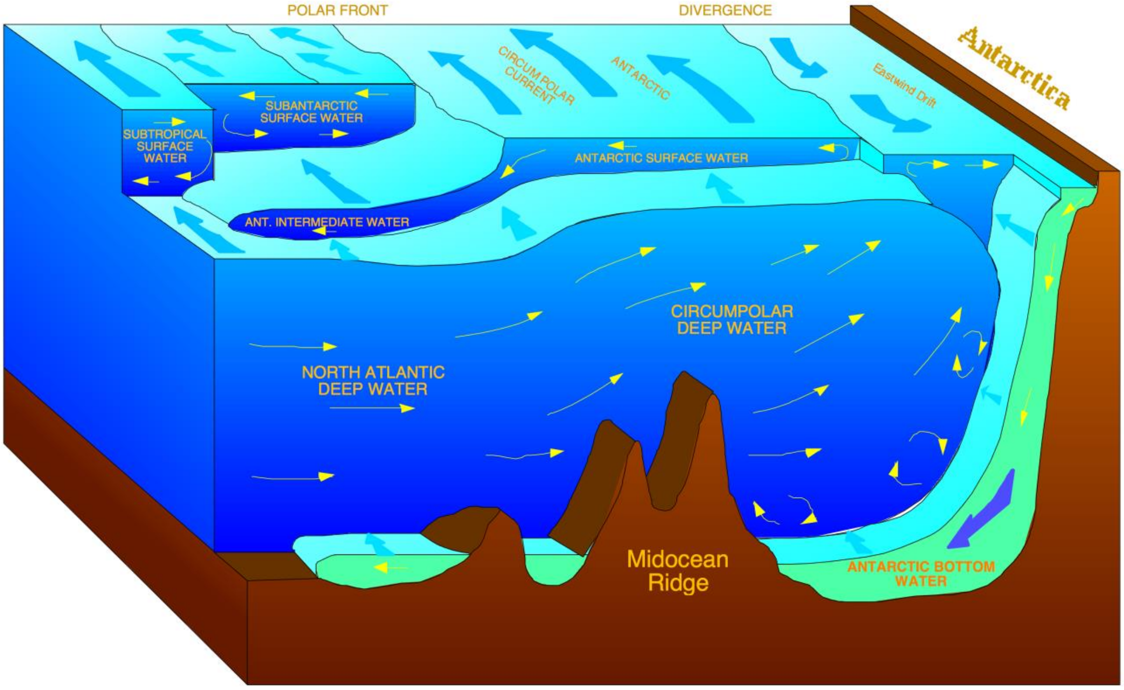


Figure 7. A selection of other water masses and their locations in the South Atlantic (From Wikipedia, 2009).

We can use data to generate T-S plots that help us to identify certain water masses, how they slide around each other and how they slowly intermingle:

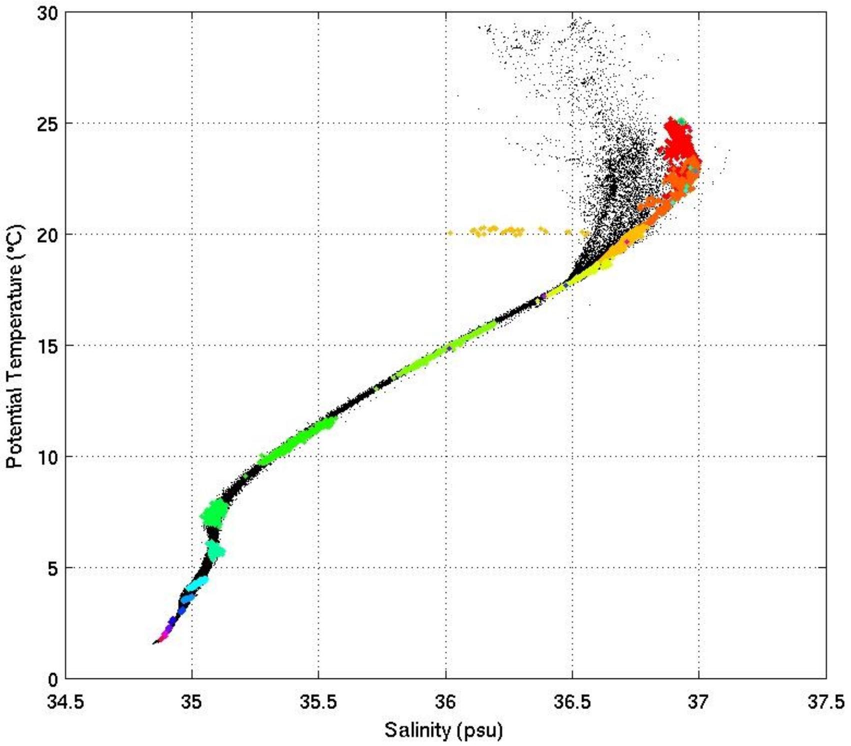
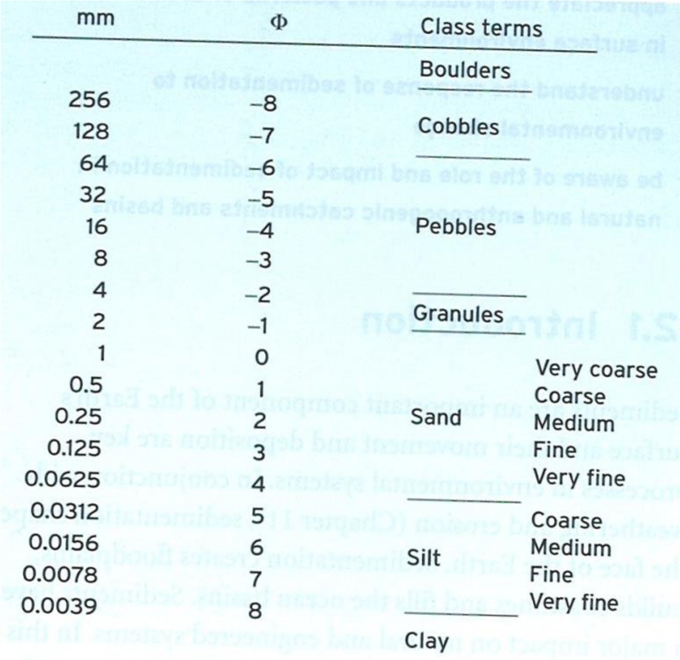


Figure 8. With this T-S plot we can see there are two, possible three water masses. Top-right there is surface water. This merges into a large stable middle section that slowly changes temperature and salinity. Note the abrupt change in the bottom-left. This indicates a boundary between one mass and another (From University of Miami, 2009).

Chapter 4: Sedimentology

Sediment size classification

Sediments can be classed on the Udden-Wentworth scale, which is best described using the diagram in figure 9. Grain size in millimetres needs to be converted into phi, using the equation phi (ϕ) = $\log_2$ (size in mm).



mm	Φ	Class terms	
		Boulders	
256	−8		
128	−7	Cobbles	
64	−6		
32	−5		
16	−4	Pebbles	
8	−3		
4	−2		
2	−1	Granules	
1	0		Very coarse
0.5	1		Coarse
0.25	2	Sand	Medium
0.125	3		Fine
0.0625	4		Very fine
0.0312	5		Coarse
0.0156	6	Silt	Medium
0.0078	7		Fine
0.0039	8		Very fine
		Clay	

Figure 9. Udden-Wentworth scale for sediment size (From Holden, 2010).

Grain shape

Grain shape is also important as the size will dictate properties like water drag across the surface of the grain, the way it interacts with other grains, settlement rates and electrical charge distributions. This can be best described using the diagram in figure 10 below.

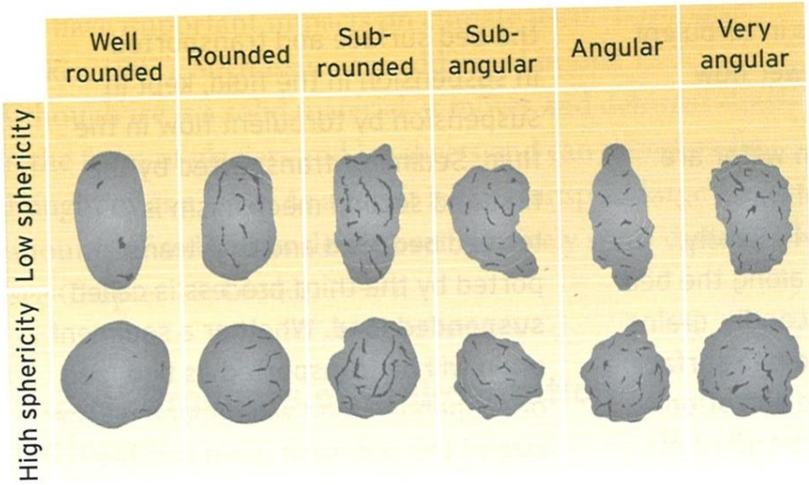


Figure 10. Roundness and sphericity for grains (From Pettijohn et al., 1987 in Holden, 2010).

Sediment transport

Rolling

The grains roll along the river/sea bed without losing contact. Usually a transport mode of large or heavy grains or environments of lower energy flow (see figure 11).

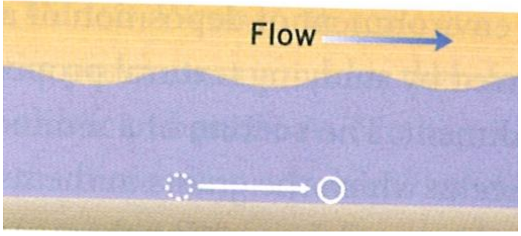


Figure 11. Rolling, rolling, rolling... (From Holden, 2010).

Saltation

Usually in environments with more energy or with smaller/lighter grains, the sediment bounces along the bed (see figure 12).

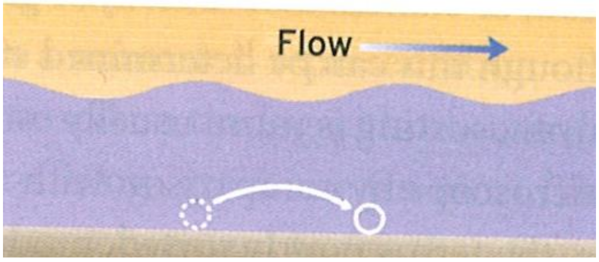


Figure 12. Saltatory transport. Like kangaroos and nervous conduction (From Holden 2010).

Suspension

Very high energy flow or, more likely, very small/light grains. No contact is made with the bed and the grain is carried along with the flow (see figure 13).

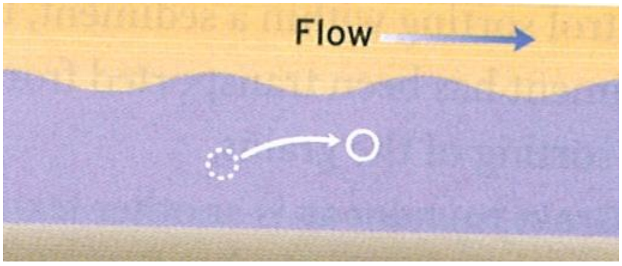


Figure 13. Suspension of materials too light to sink (From Holden, 2010).

Flocculation

This is an electrical process by which very small grains clump together to form larger grains, which can then settle. For example, clay particles in freshwater might all have the same charge. As they enter a region of increasing salinity, electrical charges change but not all of the grains will change at the same time and not all of each grain may change charge at the same time. Remember that like charges repel and opposite charges attract. So in freshwater these grains will repel each other and remain in suspension but in these changing charge environments will attract and clump together. Mudflats are formed. Any grains making their way out of this environment will separate as all the charges become the same (but different from when they were in freshwater) and they will go into suspension.

Hjulstroms curve

Hjulstroms curve best indicates the relationship between size of grain, speed of current flow and the type of material being transported (see figure 14 below).

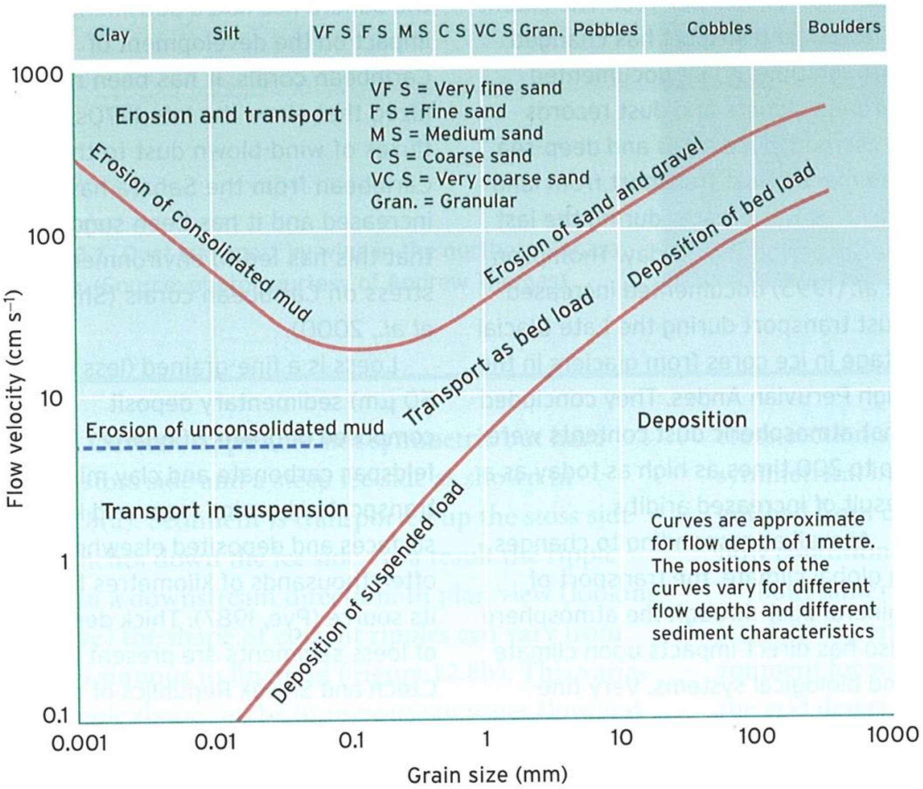


Figure 14. Hjulstrom's curve of sedimentary transport. Hjulstrom has two dots above the o. I can’t bother to insert that symbol so if it worries you pen them in. Basically, the red lines denote threshold current velocities between modes of sedimentary movement (From Press and Siever, 1986 in Holden, 2010).

Bedform flow

The transport of materials and the interaction of water flow over the bed can be best described using a bedform flow diagram, which can be seen in figure 15 below.

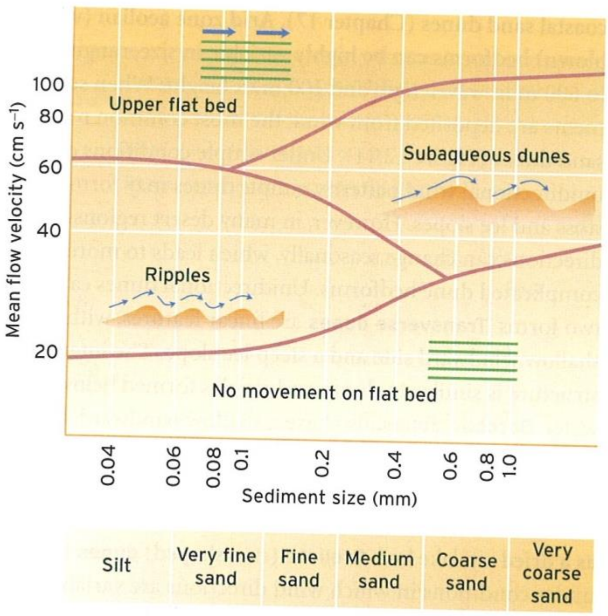


Figure 15. Bedforms and their relationship to current speed and sediment size. At intermediate current flows, ripples (if sediment size is small) or dunes (if sediment size is large). Notice that at low speeds, sediment doesn't move and at high speeds it shifts the sediment along the surface (From Nicholls, 1999 in Holden, 2010).

Ripple formation

That interaction between water movement and sediments leads to the production of seabed/riverbed features that can be seen in figures 16 and 17.

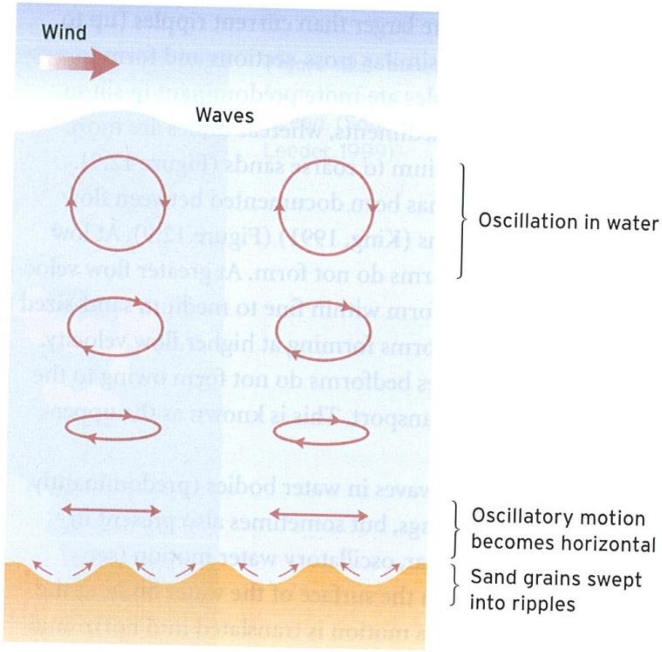


Figure 16. Shallow water wave interactions with the seabed. Hopefully you can see how the oscillatory water movement sorts the sand grains into ripples (From Nicholls, 1999 in Holden, 2010).

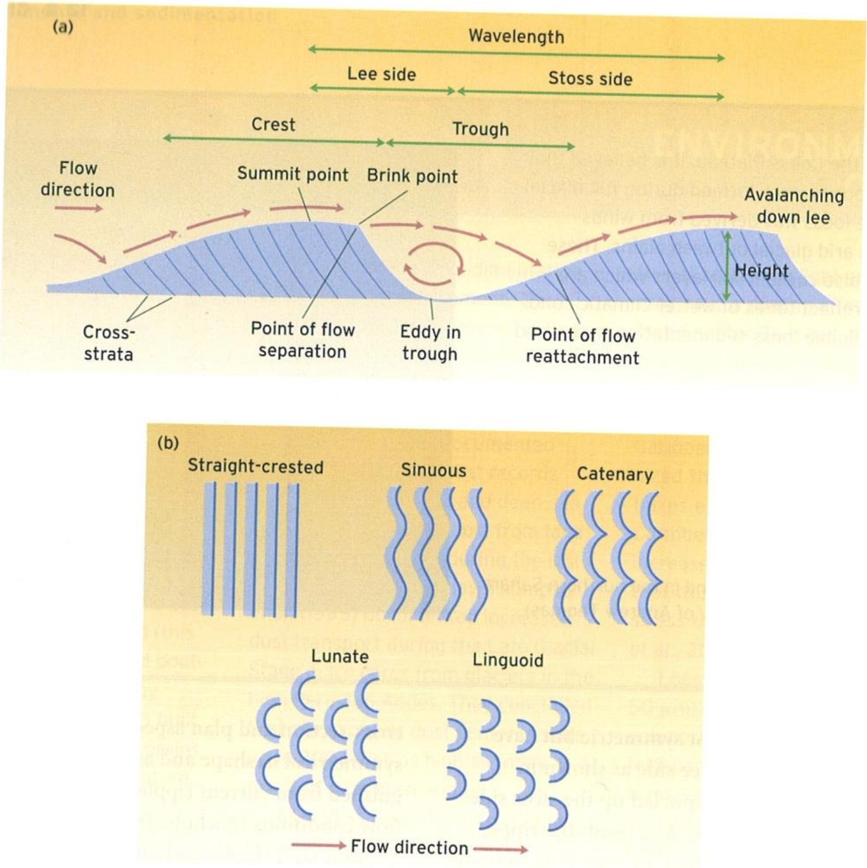


Figure 17. Current and wave formation of ripples. In the case of (a) (top) take note of the anatomy of ripples and the different terms used. Assume current flow is from left to right. These terms can also be applied to aquatic dunes. In (b) (bottom) the transition of ripples and dunes from straight to lunate and linguoid depends on current speed and depth (From Tucker, 1981 in Holden, 2010).

Gross scale movements of sediments can lead to the formation of features like bars, barrier islands, sandbanks and spits. I refer you to the relevant chapters of a range of oceanography textbooks for information on those features.

Sand dunes

Sand dunes are formed by Aeolian transport processes, that is, by the wind. There are a variety of dune shapes and they are influenced by wind direction, largely the predominant wind direction. See figure 18 for more details.

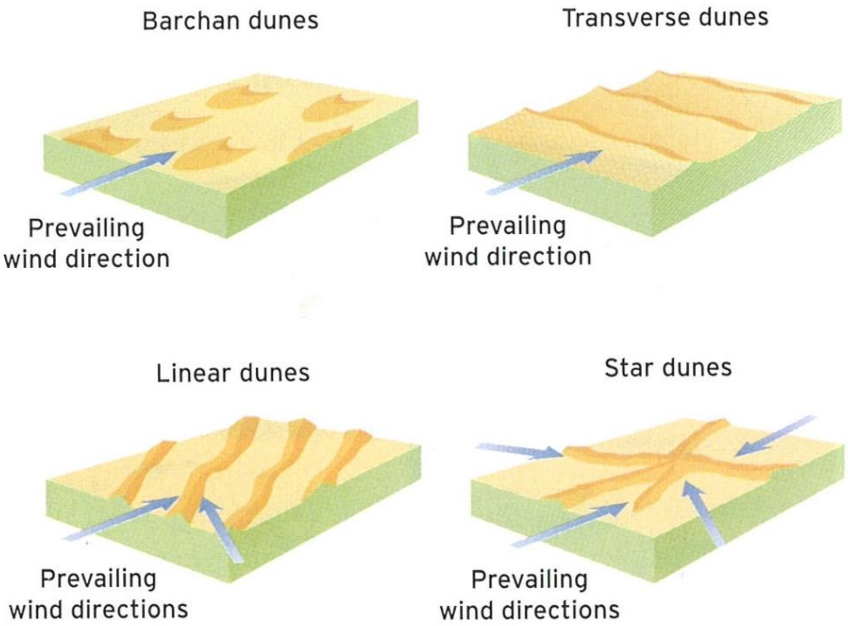


Figure 18. Sand dunes come in a variety of shapes and it depends on predominant wind direction (From Nicholls, 1999 in Holden 2010).

Chapter 5: Geology

The material in this chapter is NOT written by me. It is reprinted from a variety of sources, which will be indicated as the material is used. This is due to time constraints and the desire to get this out to you whilst it is still useful – that is, before your exams. Future versions will hopefully have this chapter written by me. So make the most of this period whilst the material below still makes sense.

Rock cycle (from the Open University)

For humankind, rocks and minerals have great economic value, whether it is good hard stone for building, or minerals and metals for weapons and jewellery. All the Earth's processes depend on the properties of rocks and minerals in some way.

Most of the Earth's major events, such as volcanic eruptions, mountain building, weathering, erosion and even earthquakes involve rock and minerals. So a knowledge of the Earth's basic building blocks is essential to understanding the Earth.

Every rock contains clues about the environment in which it formed. If a rock is made up of small fossil shell fragments, that tells us it was formed in a shallow marine environment.

Other rocks may contain clues that show they were formed by a volcanic eruption, or deep within the Earth during mountain building. Rocks provide a record of events that occurred during the 4.5 billion years of the Earth's life.

The rocks of the Earth are constantly being transformed into new types of rock and recycled by a number of processes which together make up the rock cycle (see figure 19).

Magma

Some rocks form by the hardening of molten rock or “magma”. This can happen either at the Earth's surface after a volcanic eruption, where magma might flow out onto the surface to form lava, or beneath the Earth's surface where the magma slowly crystallizes to form granite. These kinds of rocks are known as **igneous** rocks.

Sediment

New rocks, however, can also form by the Earth's processes acting on existing rocks. Weathering and erosion by wind, water and ice produce vast quantities of rock and mineral particles called sediment, which is subsequently deposited on the Earth’s surface or in the oceans. Over time sediments become buried and compressed to form sedimentary rocks.

Sedimentary Rocks

These sedimentary rocks can themselves become eroded to form new sediments. Completely new sedimentary rocks can form from biological processes such as the accumulation of shells or the growth of coral reefs.

Metamorphic rocks

Igneous and sedimentary rocks can be changed or altered by high temperature and pressure into metamorphic rocks. This often happens at the boundaries of the Earth's tectonic plates, where for example, two continents may collide forming new mountain ranges. Under very extreme conditions, metamorphic rocks can begin to melt and produce new magma.

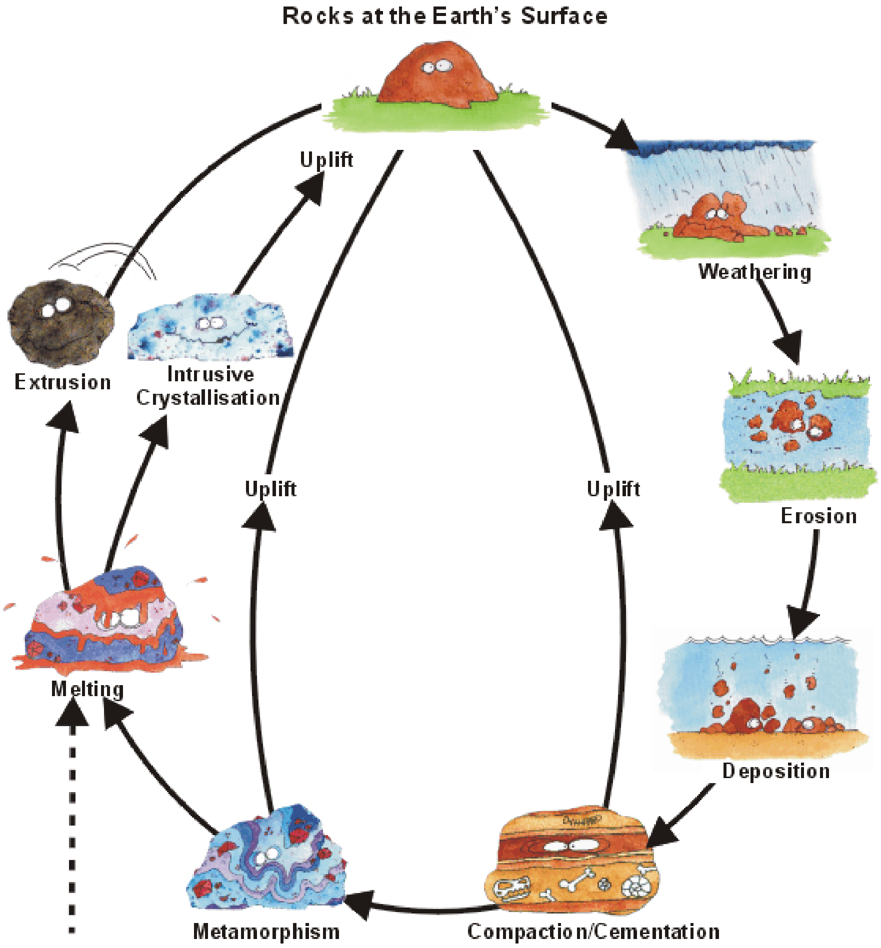


Figure 19. This diagram encapsulates the rock cycle (if you ignore the eyes on the rocks). Remember this cycle will take place over millions of years (From Oxford University Museum of Natural History, n.d.).

Rock types (from Open University)

Rocks can be divided into three broad categories - igneous, metamorphic and sedimentary (see figure 20).

Igneous Rocks

All igneous rocks have solidified from a molten state, either inside the Earth or on the surface. The lavas and molten fragments (pyroclasts) and ash produced by volcanoes are called extrusive igneous rocks, because they are formed by the extrusion of magma on to the Earth's surface. Other igneous rocks such as granite formed deep underground; these are called intrusive igneous rocks formed where magmas have cooled within the Earth.

Intrusive Igneous Rocks

Intrusive igneous rocks represent batches of magmas that didn't make it to the Earth's surface before cooling and solidifying. They form by the slow crystallisation of magmas, either at depth (several km below the Earth's surface) as large irregular intrusions or plutons, or nearer the surface in cracks and fractures as shallow minor intrusions such as dykes or sills.

Extrusive Igneous Rocks

Extrusive igneous rocks (sometimes called volcanic rocks) are formed when magma erupts at the surface. When magma reaches the surface it may spill out as a lava flow, either on land such as in Hawaii, or beneath the sea, such as on mid-oceanic ridges. Alternatively it may erupt explosively producing fragmental debris (pyroclasts) which eventually deposit on the surface, forming a pyroclastic rock. Differences in composition, mineralogy and crystallisation temperature of different magmas influence their eruptive style.

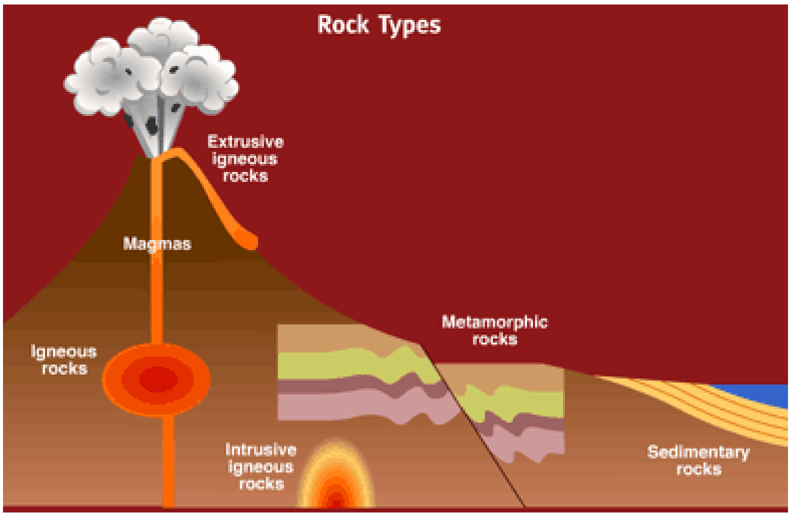


Figure 20. Example of the formation of different types of rocks (From Open University, 2006).

Magmas

Magmas are complex chemical mixtures, containing many elements that organise themselves into several minerals as the magma crystallises. Each mineral in an igneous rock usually begins to crystallise at a different temperature. The fundamental control on the mineral composition of an igneous rock is the chemistry of the magma from which it crystallises. But chemistry is not the only thing that makes igneous rocks look different.

Various rocks will all have exactly the same chemical composition, but appear different because of the size of the crystals. The number and size of the crystals depends on the amount of time they have to grow. For extrusive rocks this can be seconds, for a small fragment of magma flying through the air, to a few years for the middle of a thick lava flow (e.g. basalt). This kind of rapid cooling results in small crystals because they have very little time to grow. For intrusive igneous rocks, the cooling rate is much slower (probably several thousand years!) and the magma has time to grow larger crystals (e.g. Gabbro). Generally speaking the slower the cooling, the bigger the crystals.

Sedimentary Rocks

Sedimentary rocks form under a great variety of circumstances, such as glacial environments, deserts, rivers and coral reefs. They are formed by the laying down, or deposition of tiny grains which form layers of sediment. When sediment is transported by water in rivers or seas, it can settle to the bottom like tea leaves settle to the bottom of a cup. You can see sediment being deposited today in rivers and on beaches.

Where does all the sediment come from?

Sedimentary grains are formed when rocks at the Earth’s surface are weathered or broken up by water, wind, frost and ice. The tiny fragments and individual mineral grains are usually transported from one place to another by wind or water before being deposited as roughly horizontal layers of sediment.

With time these layers of sediment may themselves get washed or blown away, or they may be buried by yet more sediment and compacted. When this happens and water is squeezed out of the sediment, new minerals may grow in the spaces between the grains and the loose sediment grains become cemented together forming a solid sedimentary rock such as sandstone. Layers of sedimentary rocks are called beds.

Fossils

Some sedimentary rocks contain fossils of plants or animals which were living at the time the sedimentary grains were deposited. Accumulations of shells and the calcite skeletons of marine organisms like corals make up a rock called limestone.

Sedimentary rocks are often porous. The individual pore spaces are connected with each other. This means that liquids and gasses can move through the rock, so often reservoirs of water, oil and gas are contained within sedimentary rocks like sandstone.

Metamorphic Rocks

Metamorphic are existing sedimentary and igneous rocks that have changed form. Any type of rock can undergo a change of form, becoming metamorphic rock, if it is heated to temperatures of several hundreds of degrees Celsius, and/or if subject to high pressure (because of the weight of overlying rocks).

An increase in pressure and temperature will come about if a rock becomes more deeply buried in the Earth as a result of earth movements, or if it is covered by a deepening layer of sedimentary deposits. Igneous and metamorphic rocks both have a crystalline texture and both form at high temperatures, but an important distinction is that metamorphism occurs in the solid state, whereas igneous rocks form from liquid (molten) rock.

During metamorphism, the atoms in the minerals making up the rock become reorganised, sometimes resulting in the regrowth of existing minerals (crystals), or in the formation of new minerals. As a result, the new rock may look very different from the original rock. The overall chemical composition of the rock normally remains about the same, however, with elements just rearranging themselves into new minerals that are more suited to the new temperature and pressure conditions. This is what happens during recrystallisation and can often result in banding or alignment of crystals in the rock.

You may already know of two metamorphic rocks, slate and marble. Although the terms slate and marble are often used to describe construction and ornamental stones, the colloquial use of 'slate' and 'marble' covers a much wider range of materials than is covered by the strict definitions of these metamorphic rocks. Slate is a metamorphic rock with an extremely fine grain size; it is difficult to make out individual crystals even with a hand lens. It was originally laid down as a soft mud, but it has been recrystallied and the result is a hard, water-resistant rock that can be split into thin sheets.

Marble is a metamorphic rock formed from limestone, but unlike schist and slate, marble doesn't always have a banded structure. This is because marble usually contains only one mineral, calcite, so there cannot be alternating bands of different minerals. This means that marble doesn't break along preferred directions like metamorphic rocks that contain minerals arranged in parallel bands. It therefore makes a good material for statues, as smooth surfaces can be carved in any direction. Any impurities in the marble tend to result in a mottled appearance.

Weathering and erosion (from National Geographic)

Weathering and erosion slowly chisel, polish, and buff Earth's rock into ever evolving works of art—and then wash the remains into the sea.

The processes are definitively independent, but not exclusive. **Weathering** is the mechanical and chemical hammer that breaks down and sculpts the rocks. **Erosion** transports the fragments away.

Working together they create and reveal marvels of nature from tumbling boulders high in the mountains to sandstone arches in the parched desert to polished cliffs braced against violent seas.

Water is nature's most versatile tool. For example, take rain on a frigid day. The water pools in cracks and crevices. Then, at night, the temperature drops and the water expands as it turns to ice, splitting the rock like a sledgehammer to a wedge. The next day, under the beating sun, the ice melts and trickles the cracked fragments away.

Repeated **swings in temperature** can also weaken and eventually fragment rock, which expands when hot and shrinks when cold. Such pulsing slowly turns stones in the arid desert to sand. Likewise, constant cycles from wet to dry will crumble clay.

Bits of sand are picked up and carried off by the **wind**, which can then blast the sides of nearby rocks, buffing and polishing them smooth. On the seashore, the action of waves chips away at cliffs and rakes the fragments back and forth into fine sand.

Plants and animals also take a heavy toll on Earth's hardened minerals. Lichens and mosses can squeeze into cracks and crevices, where they take root. As they grow, so do the cracks, eventually splitting into bits and pieces. Critters big and small trample, crush, and plow rocks as they scurry across the surface and burrow underground. Plants and animals also produce acids that mix with rainwater, a combination that eats away at rocks.

Rainwater also mixes with chemicals as it falls from the sky, forming an acidic concoction that dissolves rock. For example, acid rain dissolves limestone to form karst, a type of terrain filled with fissures, underground streams, and caves like the cenotes of Mexico's Yucatán Peninsula.

Back up on the mountains, snow and ice buildup into **glaciers** that weigh on the rocks beneath and slowly push them downhill under the force of gravity. Together with advancing ice, the rocks carve out a path as the glacier slumps down the mountain. When the glacier begins to melt, it deposits its cargo of soil and rock, transporting the rocky debris toward the sea. Every year, rivers deposit millions of tons of sediment into the oceans.

Without the erosive forces of water, wind, and ice, rock debris would simply pile up where it forms and obscure from view nature's weathered sculptures. Although erosion is a natural process, abusive land-use practices such as **deforestation** and **overgrazing** can expedite erosion and strip the land of soils needed for food to grow.

Plate tectonics (from NASA)

History of plate tectonics

Plate tectonic theory had its beginnings in 1915 when Alfred Wegener proposed his theory of "continental drift." Wegener proposed that the continents plowed through crust of ocean basins, which would explain why the outlines of many coastlines (like South America and Africa) look like they fit together like a puzzle. Wegener was not the first to notice this puzzle-like fit of the continents (Magellan and other early explorers also noticed this on their maps), but he was one of the first to realize that the Earth's surface has changed through time, and that continents that are separated now may have been joined together at one point in the past.

Paleontologists had also found that there were fossils of similar species found on continents that are now separated by great geographic distance. Paleoclimate studies, which concerns examining the climate in Earth's past, revealed that glaciers covered large areas of the world which also are now separated by great geographic distances. These observations seemed to indicate that the Earth's **lithosphere** had been moving over geologic time.

Wegener's ideas were very controversial because he didn't have an explanation for why the continents moved, just that there was observational evidence that they had. At the time, many geologists believed that the features of the Earth were the result of the Earth going through cycles of heating and cooling, which causes expansion and contraction of the land masses. People who believed this were called the anti-mobilists. The mobilists were in the opposite camp and supported Wegener's ideas, since many of them had seen evidence for continental motion, especially in the Alps.

Although Wegener's "continental drift" theory was later disproved, it was one of the first times that the idea of crustal movement had been introduced to the scientific community; and it laid the groundwork for the development of modern **plate tectonics**. As years passed, more and more evidence was uncovered to support the idea that the plates move constantly over geologic time.

Paleomagnetic studies, which examine the Earth's past magnetic field, showed that the magnetic north pole seemingly wandered all over the globe. This meant that either the plates were moving, or else the north pole was. Since the north pole is essentially fixed, except during periods of magnetic reversals, this piece of evidence strongly supports the idea of plate tectonics.

Following World War II, even more evidence was uncovered which supports the theory of plate tectonics. In the 1960's a world-wide array of seismometers were installed to monitor nuclear testing, and these instruments revealed a startling geological phenomenon. It showed that earthquakes, volcanoes, and other active geologic features for the most part aligned along distinct belts around the world, and those belts defined the edges of tectonic plates.

In addition, further paleomagnetic studies revealed a striped pattern of magnetic reversals in the crust of the ocean basins. Basalt contains a fair amount of magnetic minerals called magnetite. When the lava from spreading centres in the oceans forms and cools, these minerals align to the north pole. The Earth has undegone several magnetic reversals in the past, in which the north and south poles are reversed for a period of time. When geologists and geophysicists discovered that the crust in the ocean recorded these reversals, it was even more positive proof that the lithosphere had to be in motion, otherwise there would be no "stripes" of normal and reversed polarity crust.

These were some of the final pieces of the puzzle that led to the development of modern plate tectonic theory. Since its emergence in the 1960's, plate tectonic theory has gained wide-spread acceptance as the model of Earth processes.

Plates

Plate tectonics deals with the study of the motion and **deformation** of the Earth's crust. This type of study is based on the theory that the lithosphere is divided into seven major and several minor **plates** that are all moving in relation to each other as well as in relation to fixed "hot spots," which are areas of upwelling **mantle** material. Plate tectonic theory tries to account for the movement of the crust throughout geologic time. Motion of the crust is that of a **rigid body**, which accounts for the style of deformation we see.

Plate tectonic theory is based on several assumptions about tectonic processes: 1) that new material is generated by sea-floor spreading at the mid-ocean ridges, which once formed become part of a plate, 2) that surface area is conserved, therefore plate material must be destroyed through another process, and 3) motion of plates is accommodated only along plate boundaries (Fowler,1990).

Plates are rigid bodies of rock that essentially float atop a region of partial melt called the **asthenosphere**. The plates comprise the **lithosphere**, composed of the crust (which is the rigid, outermost layer of the Earth) and the solid portion of the upper mantle. The crust is of two basic types, continental and oceanic, that differ on the basis of composition.

Continental crust is mostly of granitic composition. This means that the rocks contain an abundance of quartz and feldspars, which are called felsic (meaning light-colored) minerals. Oceanic crust, on the other hand, is of basaltic composition. Basalts contain minerals such as olivine and plagioclase feldspar, which are called mafic (meaning dark- colored) minerals. The two different types of crust differ in density and thickness as well as in composition--continental crust (avg. density = 2.8 g cm^{-3}) is much less dense than oceanic crust (avg. density = 3.3 g cm^{-3}). Oceanic crust is 7-10 km thick, while continental crust is 35-70 km thick.

Plate boundaries

Plate boundaries are found at the edge of the lithospheric plates and are of three types, **convergent**, **divergent** and **conservative**. Wide zones of deformation are usually characteristic of plate boundaries because of the interaction between two plates. The three boundaries are characterized by their distinct motions.

The first sort of plate boundary is called a divergent boundary, or spreading center. At these boundaries, two plates move away from one another. As the two move apart, mid-ocean ridges are created as **magma** from the mantle upwells through a crack in the oceanic crust and cools. This, in turn, causes the growth of oceanic crust on either side of the vents. As the plates continue to move, and more crust is formed, the ocean basin expands and a ridge system is created. Divergent boundaries are responsible in part for driving the motion of the plates.

As you can imagine, the formation of the new crust on either side of the vents would act to push plates apart, as we see at the Mid-Atlantic Ridge, which helps to move North America and Europe further and further apart. Mid-ocean ridges are vast mountain chains in the ocean and are as tall if not taller than mountain chains on land. The process which actually drives the motion at these ridges is known as convection. Magma is pushed upwards through the ridge cracks by convection currents. As some magma erupts out through the crust, the magma which does not erupt continues to move under the crust with the current away from the ridge crest. These continual convection currents, called convection cells, help to move the plates away from each other to allow more crust to be created and the sea floor to grow. This phenomenon is known as sea-floor spreading.

The mid-ocean ridges also play a very crucial role in the development of plate tectonic theory, because of the unique quality that minerals within the basalt possess. Basalt contains a fair amount of magnetic minerals, which align to the Earth's magnetic field upon crystallization. In the past, Earth's magnetic field has been known to change polarity, causing a reversal in the magnetic field, which is preserved when the crystals form. The alignment of these magnetic minerals can be used to date the crust, since they can be correlated with ages of known magnetic reversals in Earth's history. This plays a key role in the development of plate tectonic theory because it was the first positive proof that the plates were indeed moving and had been for most of geologic time. By using the magnetic reversal information preserved in the minerals of the mid-ocean ridge basalts, scientists were able to prove that the plates were moving, and that new crust was being formed and old crust was being destroyed in a continuous process that had been going on for most of Earth's history. The oldest crust in the ocean dates back to the early **Cretaceous**, 100-65 million years ago, which is relatively recent in geologic time.

If this is the case, where did all the rest of the crust go?

This leads us to the second type of plate boundary, which is called a convergent boundary or subduction zone. These are plate margins where one plate is overriding another, thereby forcing the other into the mantle beneath it. These boundaries are in the form of trench and island arc systems. All the old oceanic crust is going into these systems as new crust is formed at the spreading centres. Convergent boundaries also explain why crust older than the Cretaceous cannot be found in any ocean basin-- it has already been destroyed by the process of subduction.

Subduction zones are the location of very strong earthquakes, which occur because the action of the down going slab interacts with the overriding slab. The "Ring of Fire" around the margins of the Pacific Ocean is due precisely to the subduction zones found around the edges of the Pacific plate. Subduction also is the cause of the volcanic activity in places like Japan: as the downgoing slab goes deeper beneath the overriding plate, it becomes hotter and hotter because of its proximity to the mantle. This causes the slab to melt and form magma, which moves upward through the crust and eventually forms volcanoes (island arcs) in oceanic crust or huge intrusive masses (plutons and batholiths) in continental crust. The Aleutian Islands are another example of a surface expression of subduction (see figure 21).

Figure 21. Surface expression of subduction zone in the Aleutian Islands of Alaska (From NASA, n.d.).

Sometimes, when there is a convergent boundary between two continental plates, subduction cannot occur. Since continental crust is more buoyant, or less dense, than oceanic crust, one plate does not easily override the other. Instead, the plates crumple as they plough into one another, and a very high mountain range is created. This is a special type of convergent boundary called a collisional boundary. The Himalayas in India are the result of two continental plates (the Indo-Australian and Eurasian plates) colliding head on (see figure 22).

Figure 22. The Himalayas are a result of the direct collision of two continental plates (From NASA, n.d.).

The third type of plate boundary is called a conservative or transform boundary. It is called conservative because plate material is neither created nor destroyed at these boundaries, but rather plates slide past each other. The classic example of a transform plate boundary is the San Andreas fault in California. The North American and Pacific Plates are moving past each other at this boundary, which is the location of many earthquakes. These earthquakes are caused by the accumulation and release of strain as the two plates slide past each other. Another example of a transform boundary is seen at the mid-ocean ridges, where the spreading centres are offset by transform faults anywhere from a few meters to several kilometres in length.

Forces in the Earth

There are three main forces that drive deformation within the Earth. These forces create **stress**, and they act to change the shape and/or volume of a material. The following diagrams show the three main types of stress: compressional, tensional, and shear. Stress causes the build up of **strain**, which causes the deformation of rocks and the Earth's crust.

Compressional stresses cause a rock to shorten. **Tensional** stresses cause a rock to elongate, or pull apart. **Shear** stresses causes rocks to slip past each other.

Chapter 6: Waves

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Definition of a wave

A wave is a disturbance that moves along or beneath the sea surface and that can be described by **wave height**, **amplitude**, **wavelength** and **wave period**.

Types and dimension of wave

The dimensions of a wind-generated wave are dependent on wind speed and duration, **fetch**, and the original sea state. Large waves are generated by strong winds that blow for a long period of time across an expansive fetch. Waves with a wave period less than 0.1 s are referred to as **capillary waves** because the returning force (the force that returns the water to a flat surface) is the surface or capillary tension of the water surface. Waves with a longer period than 0.1 s are referred to as **gravity waves** because gravity is the returning force. **Chop** has a period of 1-10 s, **swell** 10-30 s, **tsunamis** 10 min – 1 hour and **seiches** 10 min – 10 hr.

It isn’t only wave period that is determined by factors like fetch: wave height is too. Wave height is often analysed using **significant wave height**, which is the average of the highest one-third of all the waves estimated from the variance of the wave spectrum. Wave generation is caused by the friction of the wind passing over the surface of the water. At wind speeds greater than 2.5 m/s waves become large enough to interfere with the flow of the wind, creating high pressure on the windward side of the waves and low pressure in the lee of the wave crests. This promotes growth in the wave by increasing the height of the crest and deepening the trough.

Wave orbitals and mass transport

Two kinds of motion are associated with sea waves: the propagation of the wave form and the orbital motions of the water particles beneath the wave. The diameter of the water particle orbits decreases systematically to a depth that is equivalent to one-half the wavelength, below which wave motion is no longer evident. There is a creep of water particles with successive orbits. Whilst the waves appears to move quickly, the actual water particles only move forward slowly, a process called **mass transport**.

Wave equations

Waves travelling in water **deeper** than **one-half of the wavelength** are called **deep-water waves**; their speed, or **celerity** (**C**), is proportional to their wavelength or wave period. Generally, waves conform to the equation:

$$C = \sqrt{\frac{gL}{2\pi} tanh\left(\frac{2\pi d}{L}\right)}$$

where L is wavelength, g is gravity and d is water depth. Incidentally, the whole equation to the right should be under the square root sign, not just the first part. This equation can describe all waves but can be simplified for deep and shallow water.

Deep water waves can be calculated using the simple equations:

$$C = \sqrt{\frac{gL}{2\pi}} \text{ and } L = \frac{gT^2}{2\pi}$$

which can be simplified to…

$$C = 1.56T = 1.25\sqrt{L}$$

where T is the wave period and L the wavelength.

Waves in water shallower than one-twentieth of the wavelength are called **shallow-water waves**, because they interact with the sea bottom; their celerity diminishes systematically with decreasing water depth and can be calculated using the equation:

$$C = \sqrt{gd}$$

where g is gravity and d the depth of the water column the wave is travelling through. **Intermediate waves** have a **ratio of depth:wavelength** (**d:L**) between one-twentieth and one-half the wavelength and possess complicated transitional characteristics that are a function of both wavelength and water depth. These follow the first equation given.

Wave interaction with the coast

As waves enter shallow water, their period remains constant, their celerity and wavelength decrease, and their wave height increases as water depths diminish. Also, the orbital motion of water changes from a circular shape beneath deep-water waves to an elliptical shape beneath shallow-water waves. If the wave approaches at an oblique angle, the part of the wave crest nearest the shore slows down as it enters shallower water whereas the part of the crest that is furthest continues at its normal speed. This bends the wave so that it ends up parallel to the shore, a process called **refraction**. On headlands and bays, as waves approach, they are refracted into areas of high energy at headlands, where erosion occurs, and areas of low energy, where deposition occurs. As waves enter shallower water they also increase in height as they slow down, because the front of the wave slows down comparative to the back of the wave still in deeper water. Depending on the type of shore, at least three types of breaker are generated:

a. **Spilling breaker** – the upper crest becomes over-steepened and cascades or spills down the front of the wave. This happens on shallow gradient beaches.

b. **Plunging breaker** – the wave front steepens, curls and collapses or plunges forward, releasing much of its energy instantaneously. This happens on steeper gradient beaches.

c. **Surging breaker** – the flat, low waves do not become over-steepened or actually break: instead, they move smoothly up and then down the face of the beach, reflecting much of their energy seaward. These are found on the steepest gradient beaches.

Standing waves

Standing waves are stationary wave forms that oscillate up and down about a fixed point, the **node**. Standing waves in estuaries and harbours, called **seiches**, have natural periods of oscillation that are directly proportional to the basin length and inversely proportional to the square root of water depth. Amplification of a seiche, a phenomenon termed **resonance**, occurs when the period of the forcing element, such as a tide, approximates the natural period of oscillation of the basin.

Internal waves

Internal waves are submarine disturbances that travel along density discontinuities in the water column, such as thermoclines and haloclines. They have much longer periods than wind-generated surface waves. Their celerity can be calculated by the equation:

$$C = \sqrt{gh\frac{\rho_2 - \rho_1}{\rho_2}}$$

where g is gravity, h is height of the internal wave, ρ_2 is the density of water below the thermocline and ρ_1 is the density of the water layer above the thermocline.

Tsunamis

A **tsunami** is a seismic sea wave containing tremendous amounts of energy as a result of its mode of formation (usually a submarine landslide, a shifting of rocks triggered by an earthquake or a volcanic explosion). Tsunamis are flat waves with long periods and long wavelengths; they grow in height in shallow water and flood the shoreline, sometimes causing catastrophic destruction.

Chapter 7: Currents

Wind circulation

The Earth has a number of wind circulation cells that are generated by solar heat inputs. These set up semi-permanent air circulation systems of alternating areas of high pressure and low pressure called **Hadley Cells, Ferrel Cells** and **Polar Cells**. On the surface, there are semi-permanent wind systems set up as a result, so that air is moved into areas where it is heated and where it subsequently rises. This semi-permanent wind causes…

… Surface current formation

Wind drags along the surface of water due to friction, creating waves (see next session) and currents. Due to Coriolis deflection, the direction of surface currents produced is not in line with the wind but 10-20° to the right (NH) or left (SH). The surface currents produced can lead to the formation of…

… Gyres

Gyres are circular systems of currents found in the major ocean basins, rotating clockwise in the northern hemisphere and anti-clockwise in the southern hemisphere. The one we will concentrate on will be the North Atlantic gyre, which consists of the **Gulf Stream**, **North Atlantic Drift**, **Canary Current** and the **North Equatorial Current**.

Coriolis force influence on surface currents

As these currents around the North Atlantic gyre move, they create a clockwise rotation. This is set up by the following mechanism. As the currents move, they are deflected to the right by Coriolis force and pile up in the middle. The middle of the North Atlantic gyre is actually nearly a metre higher than at the edges (see, water can flow uphill!). This leads to…

… Pressure gradient force

The resultant “hill” in the middle of the gyre has a higher pressure than the edges and fluids move from regions of high pressure to regions of low pressure, due to an apparent force called the **pressure gradient force**. In this case, the water will move from the middle to the edges, aided by gravity as the water is flowing downhill. This movement of water is influenced and deflected by Coriolis force and is pushed to the right. This resultant current is called…

… Geostrophic flow

Geostrophic flow is the result of the fluid movement induced by pressure gradient force combining with wind-driven circulation. This gives the circulation a momentum meaning that periodic drops in wind speed do not lead to an immediate or observable impact on current speed.

Western intensification

Water is only held on the Earth's surface by gravity and moves with the Earth's rotation by frictional drag. However, there is a bit of a lag with the water's rotation with that of the Earth's and this causes the ocean to pile up on the eastern seaboards of oceans. This piling rebounds back into the ocean but does result in the "hill" of water in the middle of the gyre not being in the middle of the North Atlantic but to the west, so that there is a steeper slope on the western side and more gradual slope on the eastern side. This **western intensification** causes the Gulf Stream to be deeper, narrower and faster and the Canary current to be shallower, wider and slower. Western intensification also corrects some anomalies that occur with the preservation of **angular momentum** and **vorticity** by inducing additional vorticity through **frictional sheer**. However, that is a heavily complicated and mathematical subject best suited to another sheet (one day).

Ekman spiral

Ekman was a clever chap. He took Coriolis's work and applied it fully to oceanography. We have already seen that surface currents are deflected by a few degrees to the right in the northern hemisphere from the direction of the wind that starts it. If one now assumes that the surface layer of water induced to move also moves the one below, also deflected by a few degrees and that, due to frictional losses, that one moves more slowly but induces the next layer down, also deflected by a few degrees and moving even more slowly, we will see a spiral form. That spiral will eventually peter out. The resultant movement of water is called…

… Ekman transport

This **Ekman transport** will be at 90° to the right of the wind current in the north and to the left in the south. Ekman transport leads to two processes of real biological importance…

… Upwelling

This is where a wind current inducing a surface current moving along the coast has its mass transport due to Ekman transport moving away from the coast. As there cannot be a hole in water, deep, nutrient-rich water **upwells** to the surface and fuels major biological productivity. This also occurs in the equatorial regions where water currents run parallel to each other in each hemisphere causing **divergence**. The opposite causes…

… Downwelling

When a wind current induces a surface current that runs along the coast in such a way that Ekman transport moves water onto the coast, this water piles up and sinks down, pushing deep water down. Such a situation brings about lower productivity.

Chapter 8: Tides

Coriolis force

Coriolis force was first described by Gaspard-Gustave Coriolis in 1835. It is an apparent force in response to circular motion and depends on your frame of reference. It is best described using an example.

Imagine you are viewing the Earth from above the North Pole. The Earth is rotating anti-clockwise. Now picture a missile being launched from Spain towards London. It is travelling in a straight line with reference to itself through the air but the land is rotating underneath it. Without correction, London would have moved to the west and instead of London would be, say, Berlin. So instead of hitting London, the missile, without correction would hit Berlin. You, observing from above, would see the missile curve in its flight to the right. The slower the object moves, the more the deflection to the right. In the northern hemisphere, objects moving independently of the Earth's surface (like air and water) are forced to the right.

In the southern hemisphere, where the observer above the South Pole would observe clockwise rotation, objects appear to move to the left. Bear this in mind for some of the following.

Tides

Equilibrium tidal theory

Equilibrium tidal theory makes certain assumptions about the Earth. It assumes that the Earth is perfectly spherical, has water of uniform depth and that there are no continents to impede the movement of water. Not very like Earth then… However, what equilibrium tidal theory does do well is describe the gross, global forces acting on water to bring about tides.

The main forces acting on water are the Sun and the Moon. The moon has the greatest influence despite its small mass (and hence gravitational attraction) because of its greater proximity. When the Sun and Moon are aligned, the tidal range is at its greatest because the two bulges of water created on the Earth's surface are larger (one bulge is created because of the gravitational attraction, the other because of Newton's law regarding equal and opposite forces). Such an arrangement is called a **spring tide**. When the Moon and Sun are at right angles to each other, the tidal variation between high and low tides is smaller. This is a **neap tide**. The high and low tides are created by the Earth rotating through the bulges of water.

Longer period variations are caused by variations in the Earth's orbit around the Sun, the angle of tilt, orbital variation of the moon, etc. These can be on a period of weeks to year. Therefore, any given state of tide is a result of many different waveforms from these variations in forces adding together to produce the tidal waveform.

Dynamic tidal theory

Of course the Earth does have variable depths, is not perfectly spherical and has continents. Therefore, we have to take into account these by applying the gross forces as described in the equilibrium theory to local areas. This is called dynamic tidal theory. Let's take a given tidal basin like the North Sea.

As the global tidal wave reaches this location water piles up on the coast of the Netherlands and then, due to gravity is pulled down. The resulting water movement is deflected to the right due to Coriolis Force and then it piles on the German coast. Same thing again but this time deflected right to the northern North Sea, where it piles against another rotatory system and down and to the right against the UK. A full rotation takes about 12 hours. So although the deflection of water movement is to the right, the resulting circulation of the tidal wave is anti-clockwise in the northern hemisphere.

This rotatory system is called an **amphidromic system** and technically, it has zero amplitude of tidal variation in the middle. In reality, the water sloshing around the system means that there is tidal variation but that variation is small. As you move further out from the centre, the tidal range increases. Points of equal tidal range are joined together by **co-range** lines. Locations that have high tide in the amphidromic systems are joined by lines of **co-tide**. More complex forms of dynamic tidal theory explain why some estuarine systems have such large tidal ranges.

Chapter 9: Thermohaline Circulation

Formation

The warmer water is, the less dense it is. The saltier water is, the denser it is. Therefore, cold, salty water will be very dense. In the North Atlantic, the Gulf Stream is salty (increases density) but this is more than overridden by its warmth (temperature has more influence than salinity). As it passes north, the ice of the Arctic cools the water and it becomes cold and salty: it sinks. This forms bottom water that passes around the ocean basins. This is supplemented by similar processes in the Antarctic.

Global movement

This movement of **thermohaline** water forms a series of currents around the bottom of the oceans. Some of it comes to the surface in the Caribbean and feeds the Gulf Stream, forming the **Mid-Atlantic Meridional Overturning Circulation**, also known as the Atlantic Conveyor. The rest passes around the globe, upwelling at places where upwelling occurs, like the Peruvian upwelling zone. It then makes its way back to points of deepwater formation like the Arctic. In all, it takes a molecule of water about 2000 years to make its way back to the start.

The **Thermohaline Circulation** has a major role in the distribution of nutrients, gases and heat. Furthermore, it uptakes and transports a lot of carbon dioxide, having a major role in climate change.

Chapter 10: Light and Sound in the Ocean

The source of the quotes is that reviled black hole of referencing, Wikipedia. Or it could be that Paul Pinet oceanography book cited earlier. Can't really remember…

Light transmission in water

Reflection

"Reflection is the returning of light or sound waves after falling on another medium."
The equation for reflection is: $\theta_i = \theta_r$. θ is the angle of light to the normal (perpendicular to the surface of reflection.

Refraction

"**Refraction** is the change in direction of a wave due to a change in its speed."
The equation is: $\text{Sin } \theta_1 \text{ (or }_i)/\sin \theta_2 \text{ (or }_r) = v_1 \text{ (or }_i)/v_2 \text{ (or }_r) = n_2/n_1$

Dispersion

"A phenomenon that causes the separation of a wave into components of varying frequency."

Scattering

"**Scattering** is a general physical process whereby some forms of radiation, such as light, for example, are forced to deviate from a straight trajectory by one or more localized non-uniformities in the medium through which they pass."

Sound transmission in water

Longitudinal waves

"**Longitudinal waves** are waves that have vibrations along or parallel to their direction of travel; that is, waves in which the motion of the medium is in the same direction as the motion of the wave. Mechanical longitudinal waves have been also referred to as **compressional waves** or **compression waves**."

Rarefaction refers to where the waves are less compressed and compression refers to where they are more compressed.

Refraction

“**Refraction** is the change in direction of a wave due to a change in its speed.”
The equation is: Sin θ_1 (or $_i$)/sin θ_2 (or $_r$) = v_1 (or $_i$)/v_2 (or $_r$) = n_2/n_1

Spreading loss

The loss of intensity of sound by it expanding into an increasing volume of water, therefore an increasing surface area. Intensity is defined as the amplitude per unit surface area.

Attenuation: Absorbance

The conversion of sound into heat by the longitudinal wave being taken up by constituents in the water.

Scattering

“**Scattering** is a general physical process whereby some forms of radiation, such as sound, for example, are forced to deviate from a straight trajectory by one or more localized non-uniformities in the medium through which they pass.”

Impedance

The **acoustic impedance (Z)** of a material is defined as the product of its **density (ρ)** and **acoustic velocity (V)**. Acoustic impedance is given by the equation **$Z = \rho V$**.

Sofar

“The **SOFAR channel** (Sound Fixing And Ranging channel), or **deep sound channel** (DSC), is a horizontal layer of water in the ocean centered around the depth at which the speed of sound is minimum. The SOFAR channel acts as a waveguide for sound, and low frequency sound waves within the channel may travel thousands of miles before dissipating.”

Sonar

“**Sonar** (which started as an acronym for **sound navigation and ranging**) is a technique that uses sound propagation (usually underwater) to navigate, communicate or to detect other vessels.” There are **Passive** types, which involve listening only and **active** types, which involve emission of a sound and listening for its reflection.

Side Scan Sonar

“Side-scan sonar (also sometimes called **side scan sonar**, **sidescan sonar**, **side looking sonar**, **side-looking sonar** and **bottom classification sonar**) is a category of sonar system that is used to create efficiently an image of large areas of the sea floor.”

ADCP

“An **Acoustic Doppler Current Profiler** (**ADCP or ADP**) is a type of sonar that attempts to produce a record of water current velocities over a range of depths.”

Hydrophones

“A **hydrophone** is a microphone designed to be used underwater for recording or listening to underwater sound. Most hydrophones are based on a piezoelectric transducer that generates electricity when subjected to a pressure change.”