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Understanding Sea Level Changes

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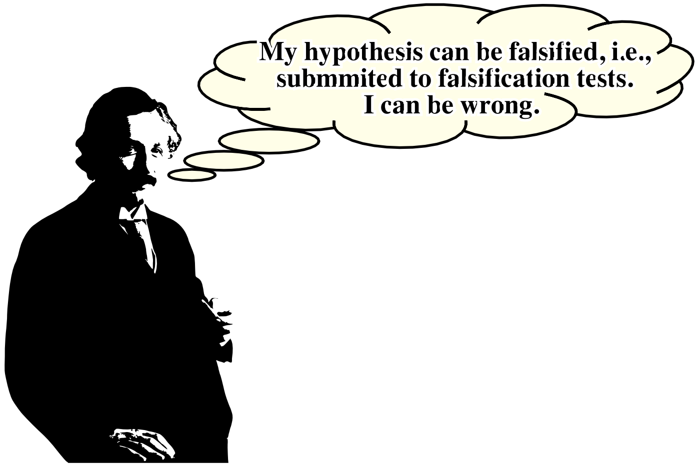
Nisi Utile Et Quod Facimus Stulta Est Gloria

Introduction

The dramatic sea level rise announced by the media and politicians, is, for the people, in general, the most known and dangerous consequence of climate change. However, talk about sea level changes without specifying the reference surface and in what the place of the Earth's surface does not make sense. Saying that sea level will rise 4 cm (Al Gore in his book "*An Inconvenient Truth " says: "6 meters") until the end of the century without telling what sea level is taking into account is a lie by omission. On this subject, the opening remarks of President J. Chirac in the 6th conference of parties to Kyoto (Hague, November 2000): "Kyoto is the first component of an authentic global governance", are highly significant. In this lecture, after a small introduction and a reminder of the basic conjectures, we will review the different sea level types, how we can measure them and with what precision, as well as, the main sea level changes drivers. Sea level and climate changes, implies a categorization. Taking into both the duration and magnitude of the sea level and climate drivers, Vigneau, J. P. (2005) in Climatologie proposed the following hierarchization, which should always be taking into account when talking about climate or sea level changes : (i) Pulsations (4th order climate drivers), lasting a few years or a few decades and which are, perfectly, reversible (e.g., series of years of raining or drought) ; (ii) Oscillations, (3rd order) lasting from a few centuries to a few millennia, but are reversible (e.g., the Little Ice Age) ; (iii) Fluctuations, (2nd order) spreading out over tens, hundreds of thousands of years and have mark cyclic character (e.g., the evolution of the Quaternary) ; (iv) Mutations (1st order), lasted millions, tens or hundreds of millions of years that have a irreversible character (e.g., irreversible upheavals of the Earth's surface).

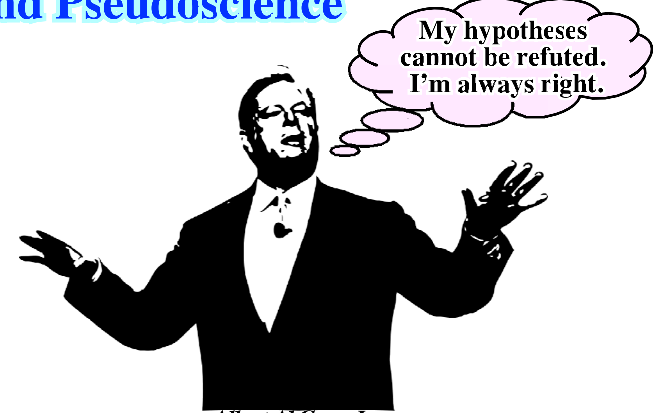
Falsification Criterion

Demarcation between Science and Pseudoscience



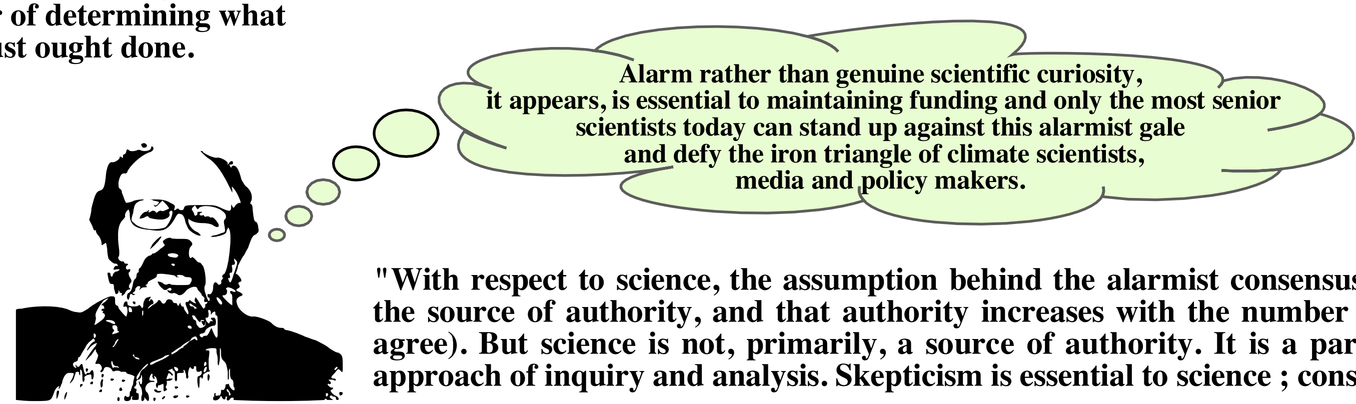
Albert Einstein
(1879 - 1955)

Scientists acquire knowledge by facts, but they do not give them the power of determining what must ought done.



Albert Al Gore, Jr
(1948 -)

Pseudoscientists, never criticize their hypotheses and commit, generally, naturalistic paralogisms (realistic fallacies), i.e., they slip from a speech declining on the mode of "it is" to a speech based on the affirmation "it is necessary or we need to"



"With respect to science, the assumption behind the alarmist consensus is that science is the source of authority, and that authority increases with the number of scientists (who agree). But science is not, primarily, a source of authority. It is a particularly effective approach of inquiry and analysis. Skepticism is essential to science ; consensus is foreign".

Ptof. Richard Sigmund Lindzen
(born in 1940)

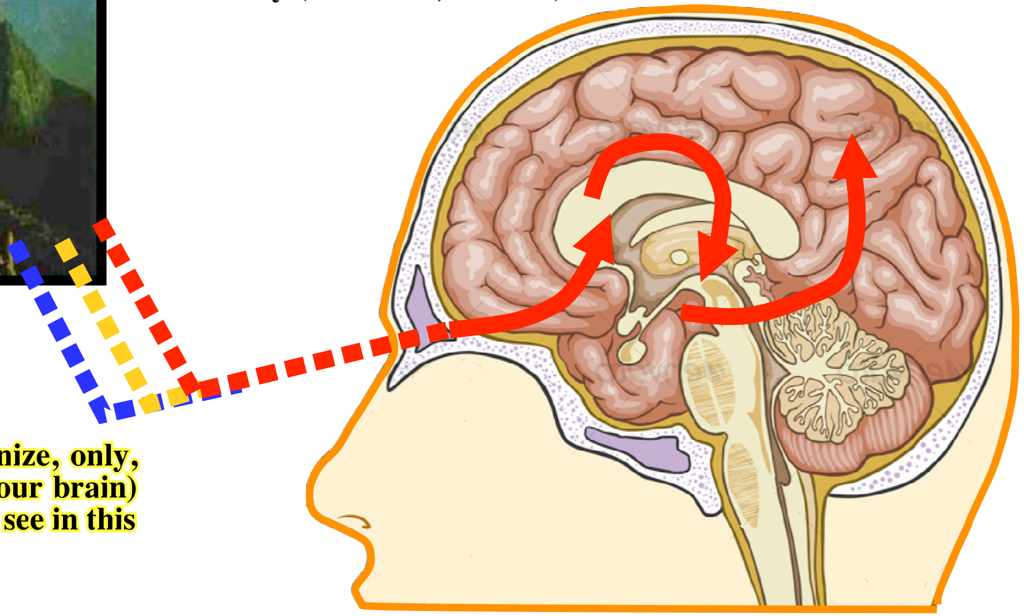
In Science truth does not exist. Rationalism and criticism are preponderant. Scientific statements can just be refuted, corroborated or validated, but never verified (in Latin *verus* means true). Observation can validate a hypothesis, but not verify it. Scientific knowledge progresses by trial and errors. Science is a never-ending cycle, in which a proposed hypothesis is falsified and then another hypothesis is offered in place, which becomes a new candidate for falsification and so on. In pseudoscience metaphysical states (unfalsifiable) and verificationism are paramount. Pseudoscientists, often, use "consensus" (a political concept alien to the scientific method) to justify their hypothesis: "The entire global scientific community has a consensus on the question that human beings are responsible for the warming and President Bush has today again expressed personal doubts that is true" (Al Gore, USA Today, May 23, 2006). However, scientists know, in Science, by definition, consensus is an impossibility, as well suggested in Paul Valery: "Ce qui est dit partout, par tous et toujours a toutes les chances d'être faux".

Theory Preceeds Observation

(Karl Popper, 1934)

There is not such things as uninterpreted observation. All observations are theory impregnated. In addition, we do not see with ours eyes but with ours brains.

Electromagnetic waves in the form of white light illuminates this photo. Part of the white light is absorbed and part reflected. Specific wavelengths enter your eyes, stimulated retinal cells, causing complex chemical and electrical changes in your brain and end up at the visual centre at rear of your brain. So, you see with your brain an internal representation of the picture and not the reality (Robinson, D. 2005).

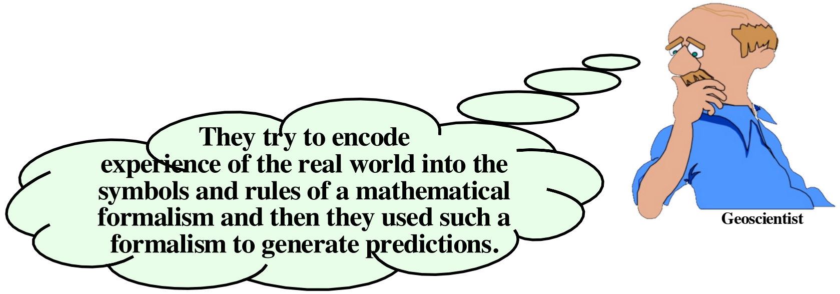


When you look at a landscape, you recognize, only, what you know (having an image of it in your brain) and what you expect to see. If you expect to see in this photo a human image you will see it easily.

A geoscientist, like anyone else, sees just what he knows and and what he expect to find. If you don't know what is a "rip current" you never find it, even if you spend hours looking at the sea. If you know that a "rip current" is a transverse or oblique current to the shoreline directed toward the open sea affecting the mass of superficial seawater, you have a chance to recognize it. After visiting the Machu Pichus (Peru), you have a chance to recognize, in the photo above, the beauty of the architecture of the Peruvian old city. However, another person turning the photo 90° rightward, recognizes something different. The most appealing subject of the K. Popper's philosophy is the idea of theory-laden observation, i.e., whenever you are making an observation-statement to question some theory, you are relying on some background theory which shapes your observation. Any observation is, inherently, theory-laden. You cannot, simply, speak of observation as true, since the background theory that shapes it can be false. Each theory or scientific hypothesis is assisted by observations and observations are controlled by the theory.

Scientific Model

Representation of an idea, process or system that is used to describe and explain phenomena that cannot be experienced directly



La Trahison des Images

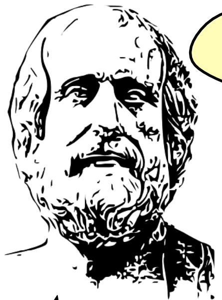
(1928-1929, oil painting on canvas 59 x 65 cm)

René Magritte

The work of art of the Belgian surrealist René Magritte: La Trahison des Images ("Ceci n'est pas pipe") is very illustrative on model subject. Magritte's purpose was to make people aware that an image or model is not to be confused with real thing it represents. "Being" and "Representing" (Wynn, C. M. et al.,1997) is not the same thing. Contrary to the idea that observations in geosciences are the facts upon which scientific hypotheses are based, it must be said the majority of hypotheses in geosciences were formulated *a priori* in order to explain problems raised by observations. They have not been built from a collection of detailed observations using an inductive approach ("Observing details may be entertaining and fascinating, but we learn from generalities". ... wrote P. Bak (1996).

Geoscientist sees just what he knows and what he expect to find. Scientific hypothesis are formulated *a priori* in order to explain problems raised by observations and are not built from a collection of detailed observation using an inductive approach. Models and simulations, generally, reveal the general mechanisms. The reference ellipsoid, for instance, is just a simplified model of the world around us, i.e., a smoothed mathematic representation of Earth sea level surface ignoring the effects of tides, seasonal currents and waves. Such a reference surface forms the mathematical surface that would be taken by sea level if the land was crossed by channels in all directions. The prime tasks of modern geoscientist are to separate the local signals from the global ones, to plot the relationships of global patterns both to time and to each other, and to search the forces driving the varied processes. The success of certain models is just the result of incessant propaganda in educational systems. What is and is not scientific is a time-dependent phenomenon. Scientific rules, laws or models are not absolute as a lot of geologists would like to believe.

Thermodynamics' Laws



Nothing is born or perishes,
but already existing things combine
and then separate again.

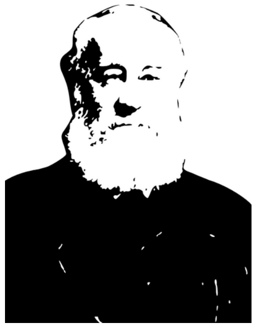
Anaxagore
(c. 510 - c. 428 BC)

Nothing is lost,
nothing is created,
everything is transformed.

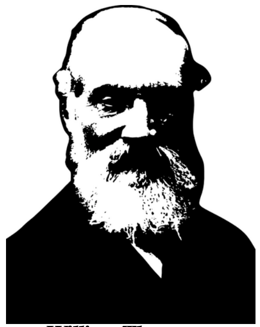
Lavoisier
(1743 - 1794)

Father's of Thermodynamics

Sadi Carnot
(1796 - 1832)



James Joule
(1818 - 1889)



William Thompson
(1824 - 1907)

Rudolf Clausius
(1822 - 1888)

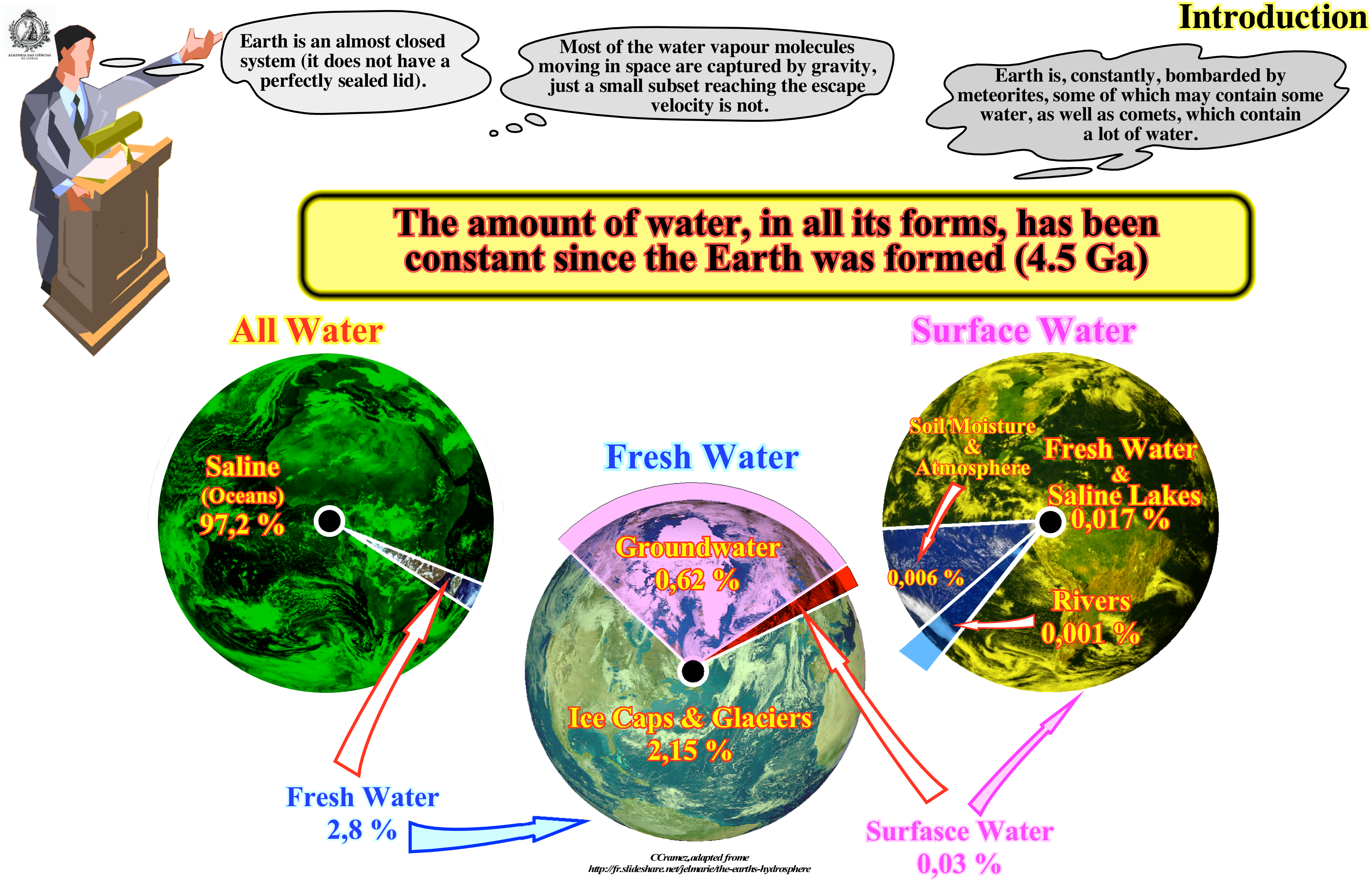
In classic physics, the Thermodynamics, i.e., how heats moves is governed by three laws

1) The first law or law of energy conservation says whatever happens, the energy of the Universe is constant (it can not be created or destroyed, but only change one form in another).

2) The second law says the entropy (measure of the part of the energy that can not be exploited in any way) of an isolated systems always increases.

3) The third law says that when the temperature of a system reaches the absolute zero (-273.15 °), all natural processes ceases to occur and entropy reaches its minimum.

A fourth law can be considered: If two thermodynamic systems are each in thermal equilibrium with a third, then they are in thermal equilibrium with each other. In science, work is accomplished every time an object is displaced by a force. More an object is displaced the greater is the work. Greater is the force more the work is important. Energy is the ability to do a work. Neither the heat nor work is an energy forms. Both are methods to transfer energy from one place to another. Work is a method ; heat is another. There are just three forms of energy: a) Kinetic, i.e., the ability to do work through the movement ; b) Potential, i.e., the ability to do work through the position and c) Electromagnetic radiation, such as the energy of light transported from Sun to Earth. Electrical, chemical and nuclear energies are things that do not exist. They are just abbreviations for specific combinations of kinetic and potential energy. The electrical energy, for instance, is just the potential energy of negative charge electrons in the presence of positive charges. So, there are not renewable energies. What is renewable are the processes of energy transformation.



The understanding of absolute (eustatic) and relative (absolute + tectonics) sea level changes can only be approached if the amount of water, under its all forms (liquid, solid and gaseous), is constant since Earth's formation. Such a conjecture, which is assumed by the large majority of geoscientists, has not been falsified yet. However, over time, the percentage of each of its forms varies. For the same volume of oceanic basins, if the amount of liquid water decrease, due to a glaciation, the level of the oceans (± 97% of all water) falls. On the contrary, if the volume of the oceanic basin decreases, for the same amount of saline water, the sea level rises. Most of the water on Earth is either salty or inaccessible to humans. Only 3% is fresh, of that, just about 32% is unfrozen (groundwater ± 30 % and surface water around 2%). The distribution of water on the Earth is : (i) Ocean, 1,350 x 10^{15} m^3 (97.3 % of the total) ; (ii) Cryosphere, 29 x 10^{15} m^3 (2.1 %) ; (iii) Underground, 8.4 x 10^{15} m^3 (0.6 %) ; (iv) Lakes and Rivers, 0.2 x 10^{15} m^3 (0.01 %) ; (v) Atmosphere, 0,013 x 10^{15} m^3 (0.001 %) and (vi) Biosphere, 0.0006 x 10^{15} m^3 (4 x 10-5 %).

Shoreline Displacements

Benoit de Maillet (1658-1738) and Antoine de Lavoisier (1734-1794) hypothesize the shoreline displacements were caused by sea level changes.

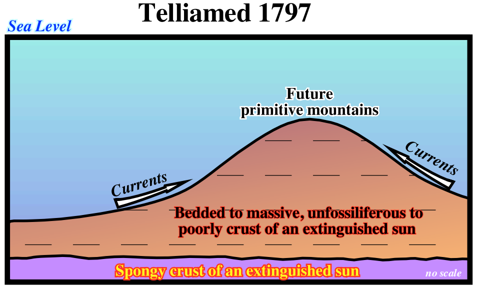
During thousands of years of diminution of the sea was, entirely, responsible for all physiographic, lithologic and structural features of the Earth's crust.

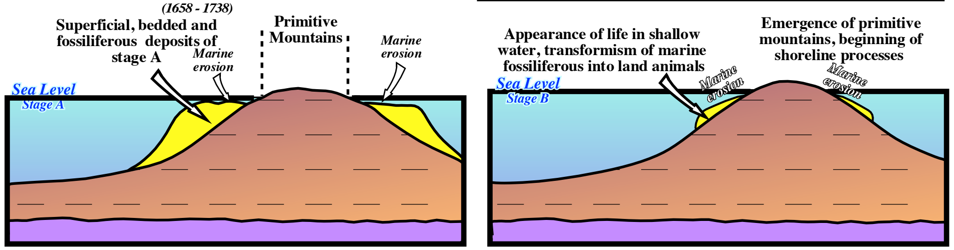
The formation of littoral banks is due to very slow successive rises of the sea level.

Benoit de Maillet
(1658 - 1738)

Diminution of the Sea

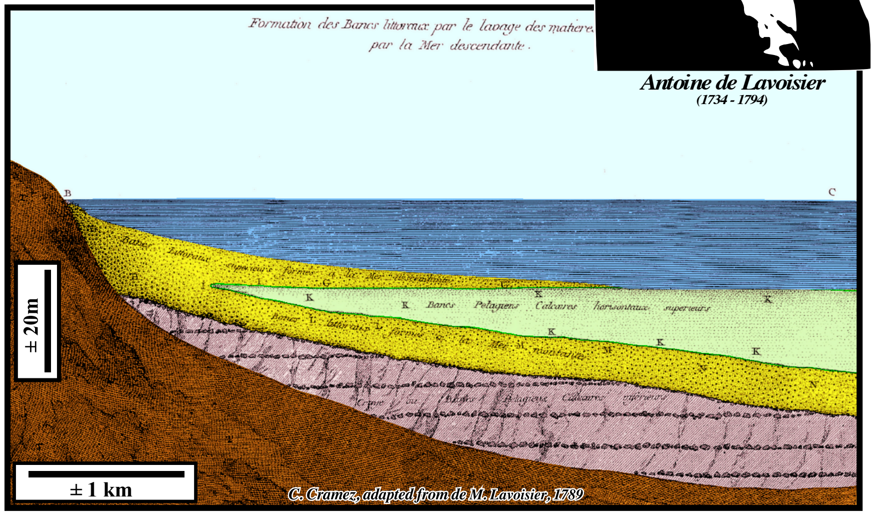
Telliamed 1797





CCramez, adapted from A. Carozzi, 1992

Formation of Littoral Banks



C. Cramez, adapted from de M. Lavoisier, 1789

Antoine de Lavoisier
(1734 - 1794)

A. de Lavoisier (1789) was, after the French ambassador to Egypt, De Maillet, was one of the first scientists to consider sea level changes as the main factor of the cyclicity of sedimentary deposits. Lavoisier interpreted the coastal sandstones of the Paris geographic basin as retrogradational sandstones deposited in association with successive relative sea level rises (marine ingressions). As illustrated, the geometry of these sandstones, strongly, suggests a landward displacement of depositional coastal break (± the shoreline) of the depositional surface at each relative sea level increment. In sequential stratigraphy, relative sea level rise, marine ingression and eustatic paracycle are synonymous. Between two consecutive relative sea level rises (without relative sea level fall between them), the sediments are deposited during the stability period of relative sea level occurring after each marine ingression. They are bounded by ravinement surfaces. They form a sequence-paracycle, which, generally, has an progradational internal configuration and is formed by one or more progradational sedimentary systems tracts.

In geoscience exists a certain circularity. Geoscientists need data to develop hypotheses and, conversely, they need hypotheses to guide observation. Geoscientists do not start from nothing. The knowledge of basics conjecture is indispensable. Observations are, usually, presented as the basis of science. In reality, geoscientists think with ideas and not with observations. Observations do not create ideas. Ideas create observations. Ideas are integrated patterns that derive from experience not from observations. A scientific idea will emerge in a scientific team just after the team knowledge evolves to the necessary minimum level of knowledge to support the cognition of a given idea. Scientists do not always find what they expect. Their predictions do not always work out. The payoff is the understanding that the hypothesis on which the prediction was based needs to be modified. Scientists must study problems that are complete unknown for them. Even in such cases, they do not start from nothing. A certain number of conjectures are known since longtime. A lot of data is available and as a large a large bibliography on such a problems.

Epeirogeny & Sea Level

Suess (1888) believed the displacements of shorelines were caused by sea level changes, induced by vertical tectonic global mouvements (eustatic movements).

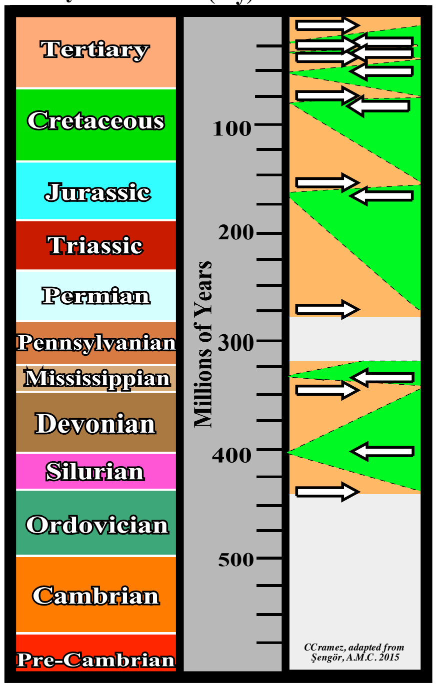
Veränderung...
welche annähernd ingleicer Hohe, in positivem oder in negativen Sinne über die ganze Erdesich äussern, und bezeichnen diese Gruppe von Bewegungen als
eustatisch Bewegungen

Edoard Suess
(1832 - 1914)

Negative movements, inducing rise of the sea level, are caused by spasmodic subsidence of the sea floor as consequence of global contraction (epirogeny).

Positive movements, inducing sea level rise, are more continuous and caused by displacement of sea water by ocean floor sedimentation.

Shoreline Displacements



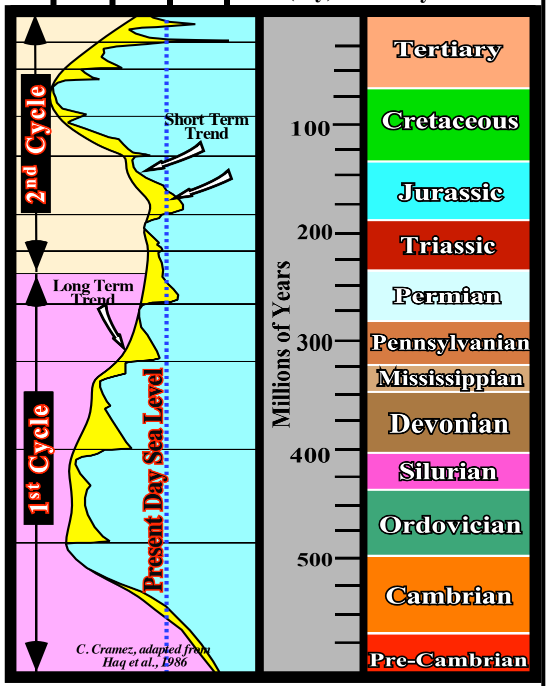
Using the mapping of coastal onlaps, Exxon's geoscientits calculated the amplitude of the rises and falls of the sea level in reference to the present time sea level.

Peter Vail
(Born 1930)

Suess's transgressions / regressions cycles (shoreline displacements fit quite well with the Exxon's curve of the short term sea level change.

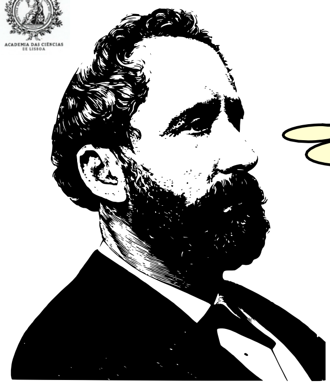
Two long term sea level cycles are recognized in the Phanerozoic with a global rise and fall of the sea level in each 1st order eustatic cycle.

Sea Level Changes



E. Suess dealt with the phenomenon of displaced shorelines and look for explanations for their genesis and controlling factors. He propose several important shoreline displacements, created by sea level falls and rises (without proposing any amplitude), induced by epeirogenic movements ("epeiros" mainland and "genesis" birth, in Greek), i.e., vertical movements due to the activity in the underlying mantle. In 1888, he introduced the term "eustatic movements" referring to the global synchroneity of marker events in marine successions of the Earth history. Suess' idea of sea level variations was based on observations of continent floodings (marine ingressions and regressions). Originally, Suess coined eustasy the crustal subsidence and sediment deposition. He believed the Earth's surface was formed by a homogeneous and solid crust and the landforms (topographic reliefs) were induced, mainly, by vertical movements due to thermal contraction of the Earth. According the thermal contraction theory, vertical movements lead to the formation of mountain ranges and collapse of continental bridges that give birth to the oceans.

Epeirogeny & Orogeny



Eduard Suess
(1831 - 1914)

Sea level changes are global are synchronous. The falls are the result of subsidence of the ocean floor due to the Earth contraction. The rises are due to the upward displacement of the sea water by sedimentation on the ocean floor

Émile Haug
(1861 - 1927)

Transgressions and regressions in geosynclines are not simultaneous with those of the continents. In fact, regressions on the continents correlate with regressions in geosynclines and vice versa.

Amadeus William Grabau
(1870 - 1946)

The long epeirogenic and orogenic processes, proposed by Haarmann (oscillations), can be replaced by rhythmic pulsations, involving rise and fall of the sea level as the primary controlling factor, with land movements effecting secondary modifications. Unconformities are relative with sea level fluctuations

Anthony Hallam
(1933 - 2017)

Oceanographic studies had revealed the existence of a mid oceanic ridge system, and the growth and decline of such ridges provided a ready mechanism for changing the cubic capacity of the ocean basins and hence of causing long-term changes of the sea level.

The term orogeny is, here, employed in the Gilbert's sense, i.e., for the processes of mountain building as distinguished from epeirogeny. Before Plate Tectonics advent, the Suess's eustatic concept, with time, became unpopular. The thermal cooling and contracting Earth theory, with sea floor subsidence causing falls of the sea level, while the continent remained, virtually, rigid and unchanging in level, was refuted. Transgression / Regression cycles studies showed they did not correlate, globally, and they were, mainly, due to local uplift and subsidence. The thermal contraction theory, finally, was falsified. The hypothesis of lateral tectonic movements (transfer of matter) under the zones of uplift, which provide the terrigeneous influx to fill the basin, began to have a lot of adepts. The understanding of sea level falls and rises began to change since the 60's as a consequence of the oceanographic and biostratigraphy studies. The Agassiz's Glacial Theory (1937), which disrupted the scientific world, strongly suggested the formation and thaw of glaciers and ice caps could cause significant sea level changes, independently of any tectonic movement.

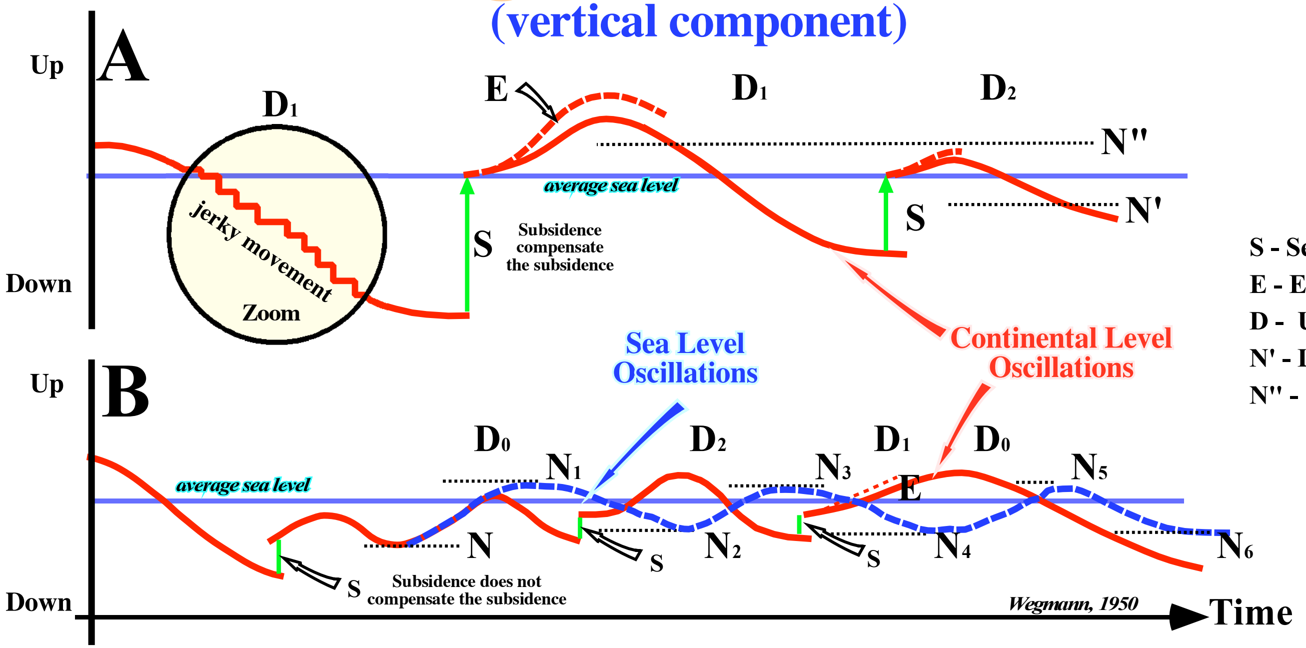
Continent & Sea Level Oscillations

At a given location, sea-level oscillations can be analyzed according to two components: (i) One corresponding to continental deformations and (ii) Sea level variations of all seas and oceans, which are called eustatic variations.

Wegmann C. Eugène
(1886 - 1982)

The major movements of the Earth's crust are associated with important transfert of material of the same order that are spread over long periods. In narrow orogenic zones, the vertical component has a large amplitude, whereas it is weaker in the vast extent of shields.

Orogenic Movements
(vertical component)



S - Sedimentation
E - Erosion
D - Unconformity
N' - Lower limit of sea level
N'' - Upper limit of sea level

The movements of the continent and those of the sea level can evolve in the same direction or be opposed. It is, particularly, in this last context that the formation of unconformities is most likely. In situation A, sedimentation and subsidence are more or less in equilibrium. The unconformity D_1 on the descendant part of the curve of the continent movement does not, necessarily, belong to a synchronous set. The unconformity D_2, lying between the extremes of an sea level oscillation, belongs everywhere to a synchronous set because the oscillation is in all simultaneous points. In situation B, sedimentation is not strong enough to compensate for subsidence. Some examples of possible cases are represented by the N_1, N_2, N_3, N_4, N_5 and N_6 which are successive eustatic levels. D_0 represents the top of the continental level fluctuation curve, on which there is no unconformity, due to a simultaneous sea level rise (N-N1). As the continent and sea level move in the opposite direction (N_2-N_3), the D_2 mismatch is tightly limited in time. The D_1 mismatch occurs while the continent is rising while the sea level (N_3-N_4) is falling. At D_0, the continent and the sea level (N_5-N_6) fall at the same time and their relative position thus remains more or less stationary.

Eustasy

Today, the term Eustasy, is used in a quite different sense of the original Suess' definition (crustal subsidence and sediment deposition). It is often, defined as " worldwide simultaneous changes in sea level, as distinguished from local and relative sea level changes.

Since 1977, the definition of Eustasy more difficult to falsify is:

Vertical Sea Level Changes, regardless their Causes

Alex Mörner
(born in 1938)

The main causes of Sea Level Changes are:

(i) Epeiro-Eustasy (Subsidence or Uplift of Sea Floor),
control the space available for sediments (accommodation) ;

(ii) Glacio-Eustasy,
controlled by variations in ocean water volume ;

(iii) Tectono-Eustasy,
controlled by changes in ocean basin volume ;

(iv) Geoidal-Eustasy,
controlled by ocean water distribution caused by variations in terrestrial gravity field ;

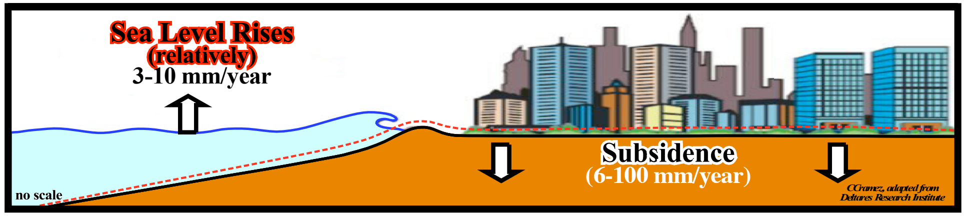
(v) Ocean Thermal Expansion or Thermosteric Sea Level Rise,
if ocean temperature rise, water density decreases, and for a constant mass, the volume increases.

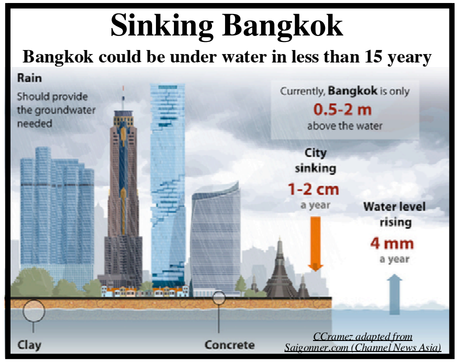
Glacio-Eustasy and Tectono-Eustasy are eustatic variations that are, sometimes considered, globally, and uniform. However, for many geoscientists, they can be neither global nor uniform, since any cause of sea level affects, also, the terrestrial geoid. If this is true, no eustatic curve is valid globally. During the thawing of the ice caps, in response to the charge of water added to the ocean basins, sea level will be depressed and in response to the removed charge, the continent will be raised. The redistribution of material within the Earth is affected by overload and will further force ocean surface variations (induced by gravity anomalies) and thus further water redistributions will be necessary to try to equalize gravitational potential. This continuous gravitational retroactive processes between ice caps, oceans and continent, are the process that determines, ultimately, the relative sea level signatures that are observed everywhere the continent and the ocean meet. Only glacio-eustasy changes are both important (> 10 m) and rapid (<1 My).

(i.a) Subsidence

(Sea level rises relatively)

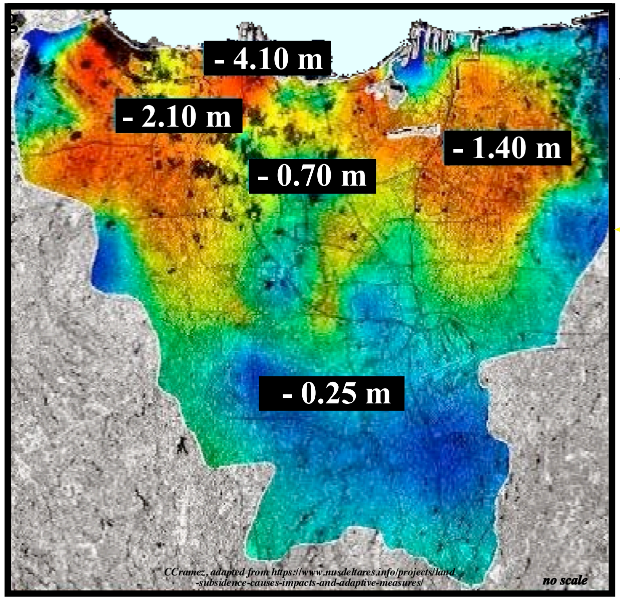
Subsidence increases the space available for sediments (accommodation)





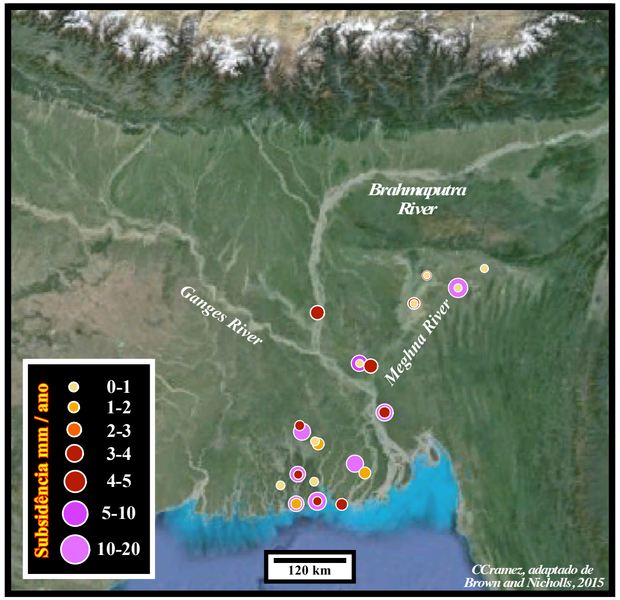
The clay in which the city sits nedds to retain moisture, otherwise it dries out becoming more susceptible of subsidencee. Groundwater is needed to allow the clay to retain concreted urban sprawl prevent it from seeping through to the rigth areas

Subsidence / Year



Weight of Buildings Jakarta

Subsidence / Year



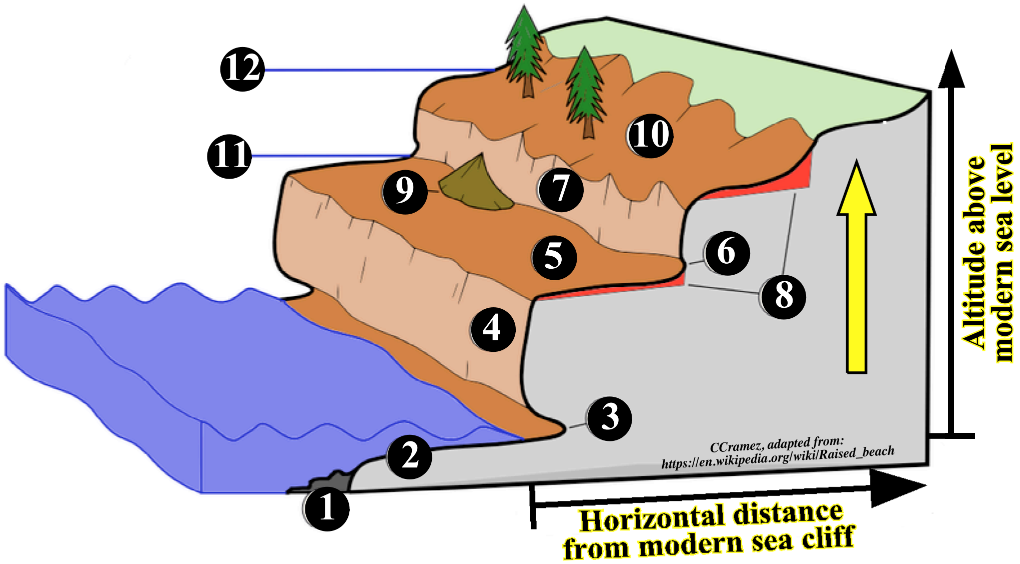
Weight of Sediments Bengladesh

In certain places, tectonics (subsidence or uplift of the sea floor) can be more important than Eustasy. A significant relative rise of the sea level can occur just due to: (i) An anthropogenic subsidence of the sea floor, as it is the case in many coastline near the large agglomerations, such as the city of Jakarta, in Indonesia, illustrated above or (ii) A natural subsidence (weight of the sediments), as it is the case of the Ganges delta building, particularly, in Bangladesh. The case of Bangkok is particularly interesting, since in addition to the weight of the recent modern buildings an additional subsidence, induced by an exaggerated water extraction of the substratum, is added. In generally, it can be said all littoral cities built on a recent sedimentary substrate, will subside if the number of buildings is exaggerated. Such a sinking of the sea floor induces a local marine ingression, i.e., a continentward displacement of the shoreline, which should not be interpreted as a sea level rise (as claimed by certain media and politians), but as a relative rise in sea level, i.e., it is the sea floor that go down and not the sea surface that rises.

(i.b) Uplift

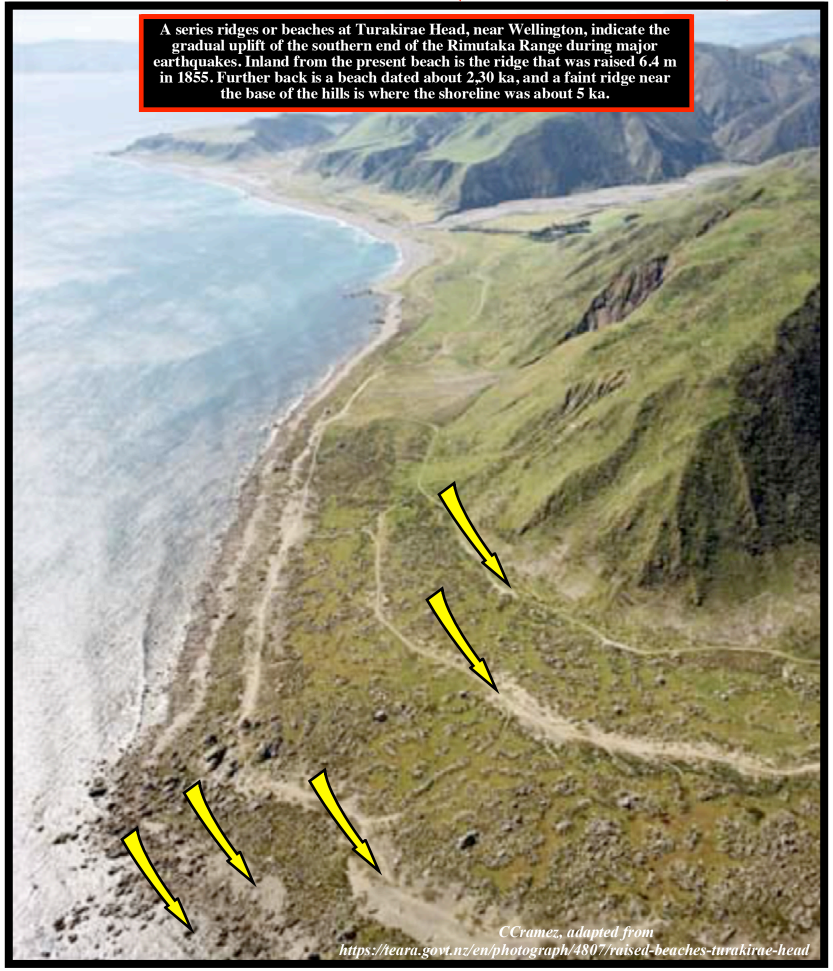
(Sea level falls relatively)

Uplift decreases the space available for sediments inducing erosion and a seaward displacement of the coastal deposits



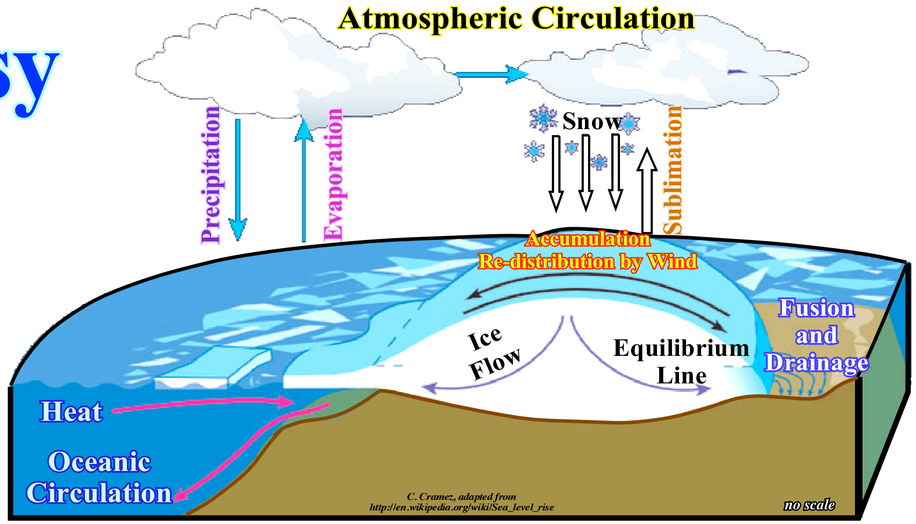
1- Low tide cliff /ramp ; 2- Wace-cut /abrasion platform ; 3- Notch /inner edge ; 4- Modern cliff , 5- Old wave -cut / abrasion platform ; 6- Olde notch /inner edge ; 7- Paleosea cliff ; 8- Terrace deposits ; 9- Alluvial fan ; 10- Old wave-cut / abrasion platform ; 11- Paleosea level II , 12- Paleosea level I.

Raised Beaches
Turakirae Head (New Zealand)

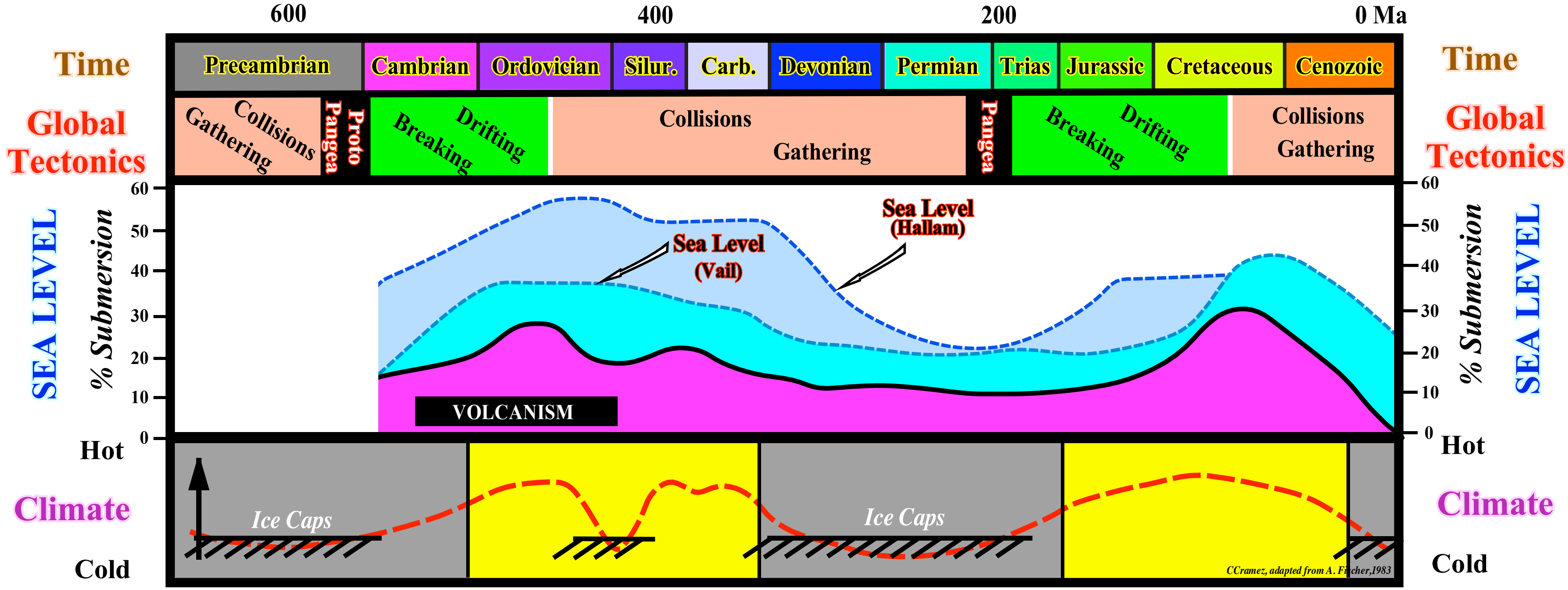


Raised shore platforms and raised beaches reflect the changes in relative sea level (see later) induced with the gross and decay of ice sheets during the Quaternary Ice Age. The uplift is due to the isostatic rebound, i.e., to the elevation of the continent in response to the discharge induced by the removal (melting) of the ice from the ice caps. During the last glacial period, most of northern Europe, Asia, North America, Greenland and Antarctica were covered with ice sheets, ice caps and ice seas. The thickness of the ice reached about 3,000 meters at the Last Glacial Maximum, about 21 ka. The enormous weight of this layer of ice forced the crust to deform in an inverted bell shape, obliging the material of the terrestrial mantle to flow away from the overloaded area. Since the temperature increased and the ice began to melt, the removal of the overload from the sunken region caused an uplift of the area and a return of the material from the Earth’s mantle to its original position. Taking into account, the viscosity of the mantle material, it will, probably, take several thousand years for the Earth’s surface to reach an isostatic equilibrium. For an ice thickness of about 2,000 m, the terrain sank about 700 meters (the ice density is about 1/3 of the density of the mantle).

(ii) Glacio-Eustasy



Glacio-Eustasy is controlled by variations in ocean water volume



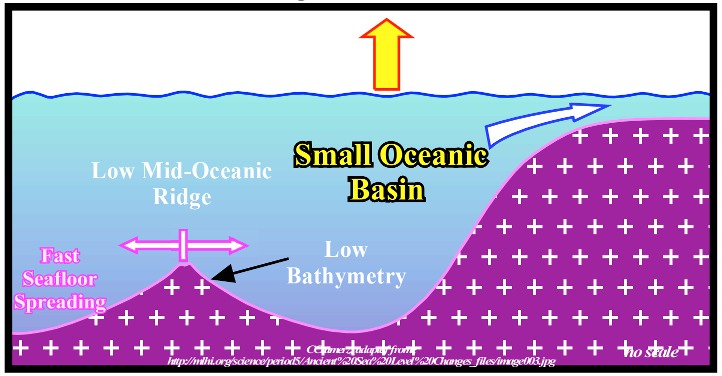
During glaciations, the eustatic sea level falls. On the contrary, during the thaw (deglaciations) the eustatic sea level rises. The eustatic level rose about 120 meters during the millennia that followed the end of the last glacial age (more or less, 21 ka) and it has stabilized between 3 and 2 ka. A particular attention has to be given to ice caps or ice sheets (ice masses covering respectively less than or greater than 50,000 km² of a continent) and ice shelves or ice seas (thick, but floating, ice that has been discharged, as illustrated in this figure, or formed, directly, on the surface of the sea). The melting of the former implies a rise in sea level, while the melting of the latter does not. The sea level falls. The ice is less dense than the water. The maximum extent of the ice caps and ice-seas (Northern and Southern hemispheres) during the last ice age was reached, approximately, at about the same time and more or less at are 19 k years ago. Glacio-Eustasy is, sometimes, considered globally and uniform. However, they can neither be global nor uniform, since any cause of sea level also affects the terrestrial geoid. There is no eustatic curve valid globally.

(iii) Tectono-Eustasy

Tectono-Eustasy is controlled by volume variations of the oceanic basins

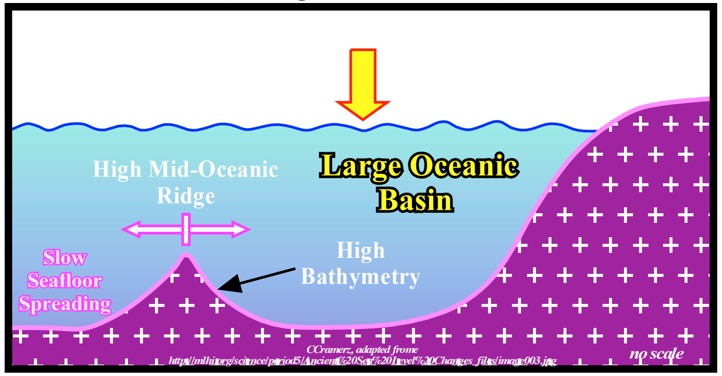
Highstand Conditions

(Rising of the Sea Level)



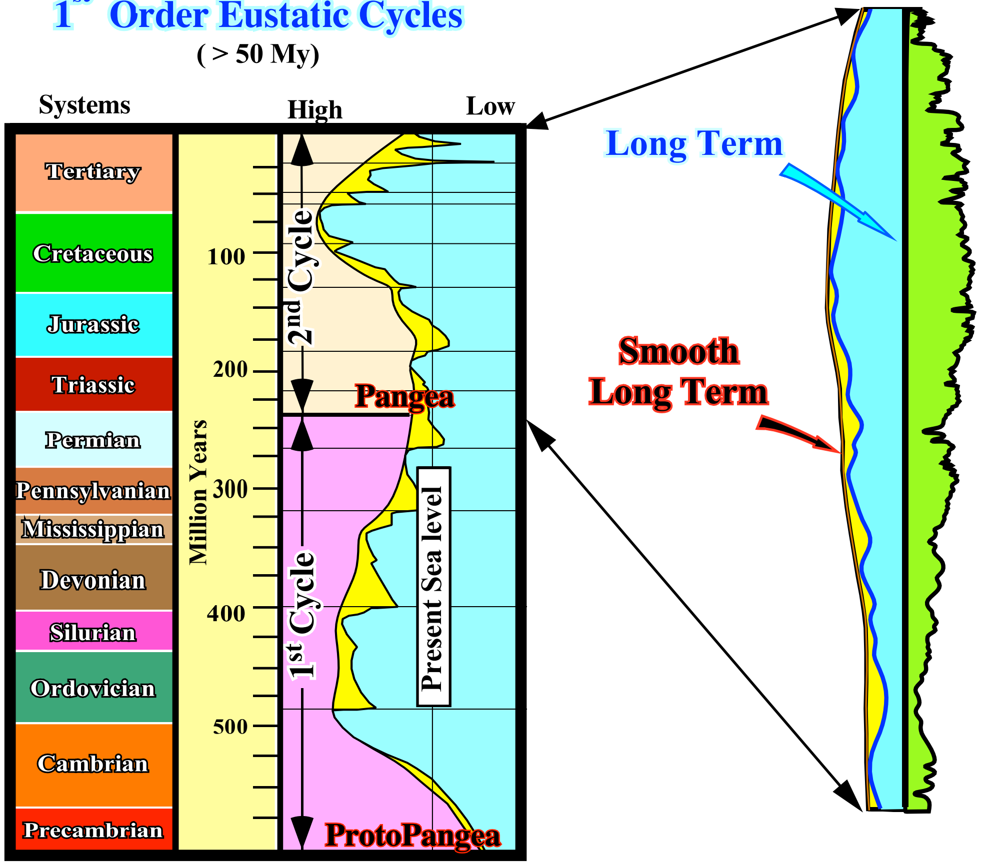
Lowstand Conditions

(Falling of the Sea Level)



1st Order Eustatic Cycles

(> 50 My)

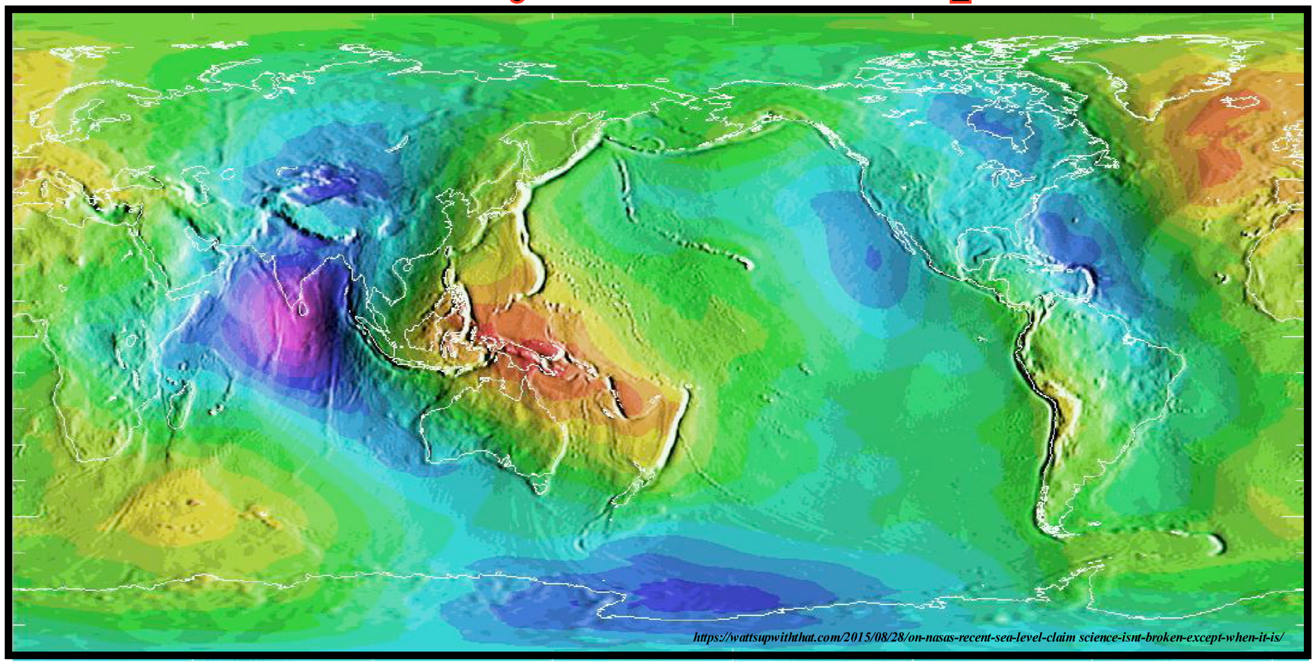


The Paleozoic eustatic maximum, with the sea level 200-250 meters higher than at present-time, occurred at about 500 Ma. The dispersion of Paleozoic continents was maximum. The Mesozoic / Cenozoic eustatic maximum, with sea level 150/200 meters higher than today, occurred about 91.5 Ma when the dispersion of the post-Pangea continents was maximum. As the continents began to approach each other to finally form a new supercontinent, the level of the absolute (eustatic) sea fell. It reached to a minimum height at the formation time of the of the new supercontinent. Assuming the amount of water (in all its forms) is constant since the Earth formation (± 4.5 Ga), it is evident that at time of supercontinents, the volume of the ocean basins is large (less oceanic ridges) and the absolute sea level low. On the contrary, when the volume of the ocean basins is small (abundance of ocean ridges), i.e., when the continents, created by the break-up of a supercontinent, are far apart, the absolute sea level is high. Tectono-Eustasy and Glacio-Eustsay are eustatic changes, which are, sometimes, erroneously, considered global and uniform.

(iv) Geoidal-Eustasy

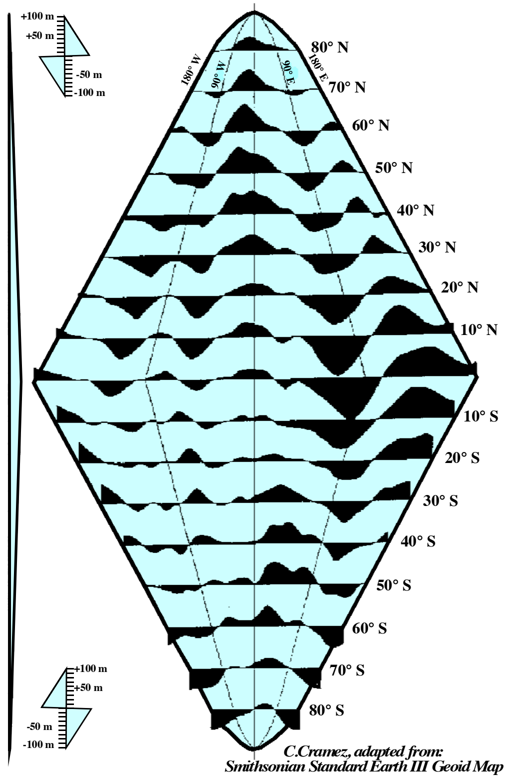
Geoidal-Eustasy is controlled by the distribution of water caused by the Earth's gravity field changes

Gravity Anomalies Map



Above average Gravity ← → Below average Gravity

Sea Level Profiles



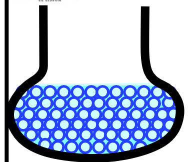
C.Cramez, adapted from: Smithsonian Standard Earth III Geoid Map

As illustrated on these profiles (Smithsonian Standard Earth Geoid Map III) and on the map of gravity anomalies, sea level shows important irregularities with very high and low values. That means the sea level, contrary to a very accepted idea, is not flat. The amplitude of the undulations is exaggerated by a factor of 100,000 with respect to the radius of the Earth. The high values (where sea level is higher) correspond to areas of the Earth where the force of gravity is below normal. In the same way, when the values of the force of attraction are high, the sea level is low. This results from the fact that the Earth's material is not distributed, neither uniformly nor in layers, perfectly, concentric. If this were so, the geoid (the equipotential surface that would give the average surface of the oceans, if they were in equilibrium, without movement and continue under the continents) it would coincide with the Earth's surface. Between the areas where sea level is high, such as near New Guinea and the areas where it is lower than normal, such as in the Seychelles, there is a difference of about 180 meters.

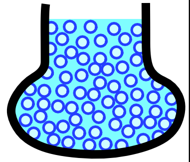
(v) Ocean Thermal Expansion

Thermosteric Sea Level Rise

If ocean temperature rise, water density decreases and for the a constant mass, the water volume increases.



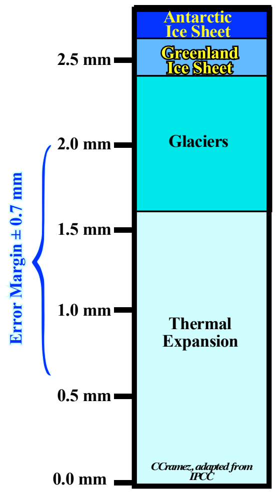
15° C
Cold Water

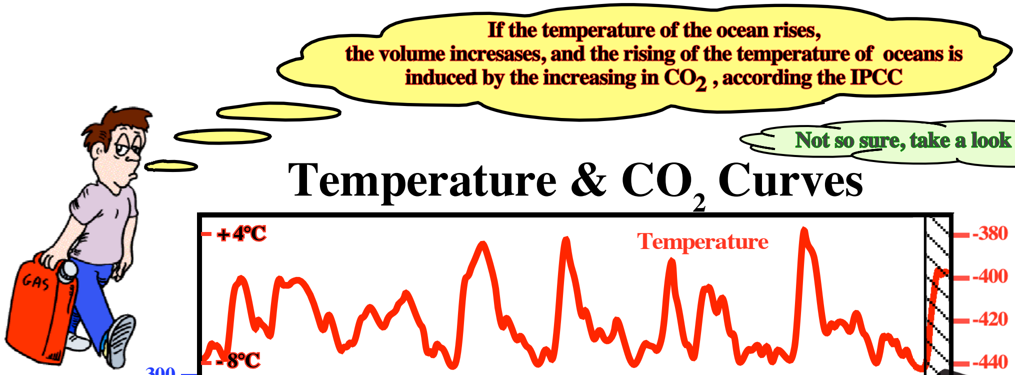


55° C
Hot Water

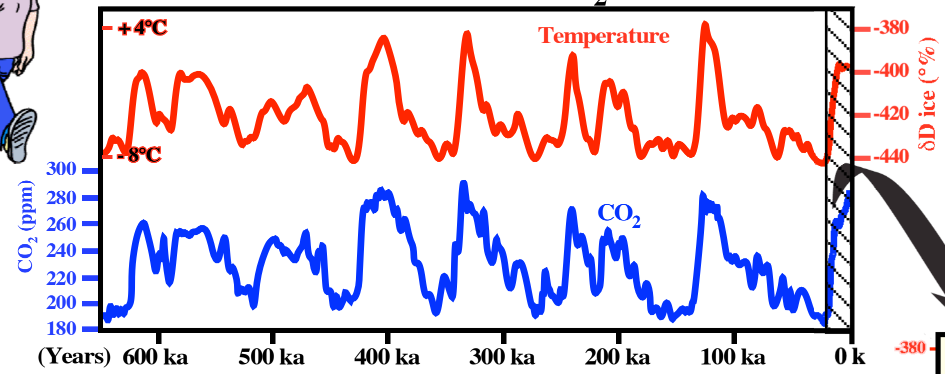
An ocean temperature increasing of 1° would rise the sea level around 30 cm.

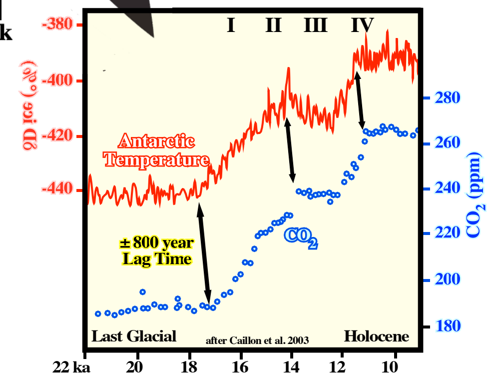
Annual sea-level rise (mm) 1993-2003 according IPCC





Temperature & CO_2 Curves

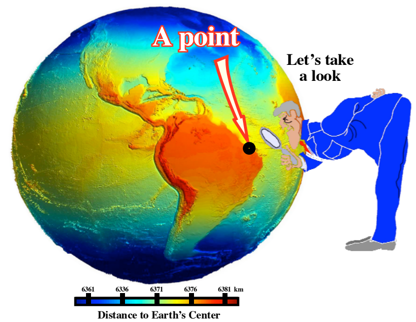




Al Gore used these curves, set up with the result of ice-cores taken from different parts of the world including Vostok (Antarctic), to show the increase of CO_2 in atmosphere (in blue) causes the increasing temperature of the Earth (in red). All scientists know that correlation is not causation, and so, the advanced Al Gore conjecture must be able to resist valid testing, particularly when a lot of observations suggest the temperature variations precede the CO_2 atmospheric variations with a lag-time ranging between 500 and 1000 years. Just take a look at a close-up of these curves between 22 ky and today: it is evident the temperature variations occur systematically ± 800 years before the CO_2 variation.

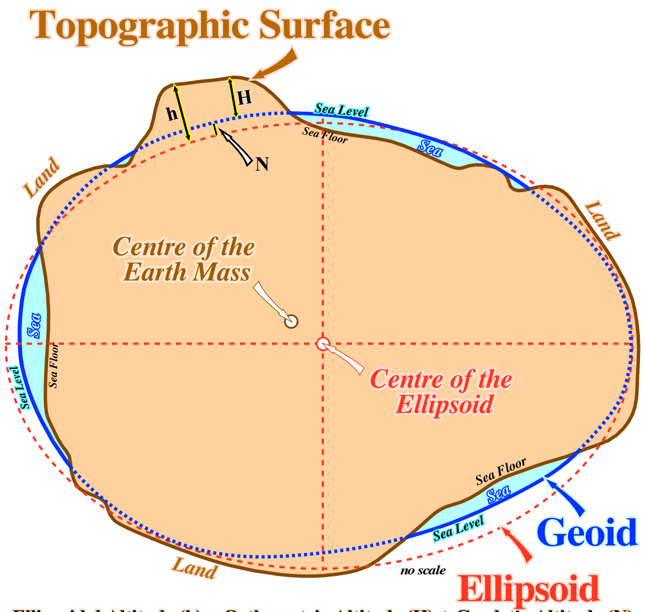
If the temperature of the oceans increases, the density of water decreases and, for a constant mass, the volume increases, is what geoscientists call thermal expansion of the oceans or steric sea rise (function of the spacial arrangement of atoms). The whole problem is to know whether it is the increase of CO_2 in the atmosphere that increases the temperature of the oceans or if it is the increase in the temperature of the oceans that releases CO_2 into the atmosphere. The ability of water to maintain a certain amount of dissolved CO_2 is a function of its temperature. The lower the water temperature the more dissolved CO_2 it supports. At high latitudes, the surface water is icy and allows the dissolution of high concentrations of atmospheric CO_2. When the surface of the sea freezes, the salt is kept out of the freezing process and dissolves in the water, immediately, under the sea of ice. Ice-cold and salty, with much dissolved atmospheric CO_2, the water becomes more dense, sinks and flows along the continental slope of the polar platforms, invading the deeper regions of the ocean basins.

Reference Surfaces



Any measure of the sea level is always changing due to geography, gravity, temperature, ocean currents tides, tectonics, etc. A mesure is always done in relation to a surface of reference:

(i) Topographic Surface ; (ii) Geoid ; (iii) Ellipsoid.



Ellipsoidal Altitude (h) = Orthometric Altitude (H) + Geodetic Altitude (N)

The topographic surface is the visible Earth's surface. The geoid is the equipotential surface of the Earth's gravitational field that would coincide, exactly, with the "mean sea level" of the Earth's oceans, if they were in equilibrium, at rest and extending across the continents. The geoid is the zero surface as defined by the Earth's gravity. The geoid is irregular and too complicated to serve as the computational surface.

Earth is, more or less, an ellipsoid of revolution with a flattening (f= {a-b) /b}) around 0,00335 (a and b are the semi-major and minor axis). An Earth representation on a computer screen would be sized, for instance, as 300 px by 299 px. The Earth's ellipsoid flattening is big enough to require calculations to plotting accurate maps at a scale larger than 1:100,000.

Different ellipsoids have been used as approximations. The semi-axis of the WGS-84 ellipsoid are: a = 6378137.0 m and b = 6356752.3142 m. A data set describing the global average of the Earth's surface curvature is called the mean Earth Ellipsoid. The Reference Ellipsoid is close to the "mean sea level".

An Ideal Earth ellipsoid has the same volume as the geoid. In addition, Earth is not an exact ellipsoid and no single smooth ellipsoid will provide a perfect reference surface for the entire Earth.

The orthometric altitude (H) is the vertical distance from an Earth's surface point to the reference geoid. The ellipsoidal altitude (h) is vertical distance from an Earth's surface point, to the reference ellipsoid. The geodetic altitude (N) is the difference between the orthometric and ellipsoidal altitude (difference between the ellipsoid and the geoid).

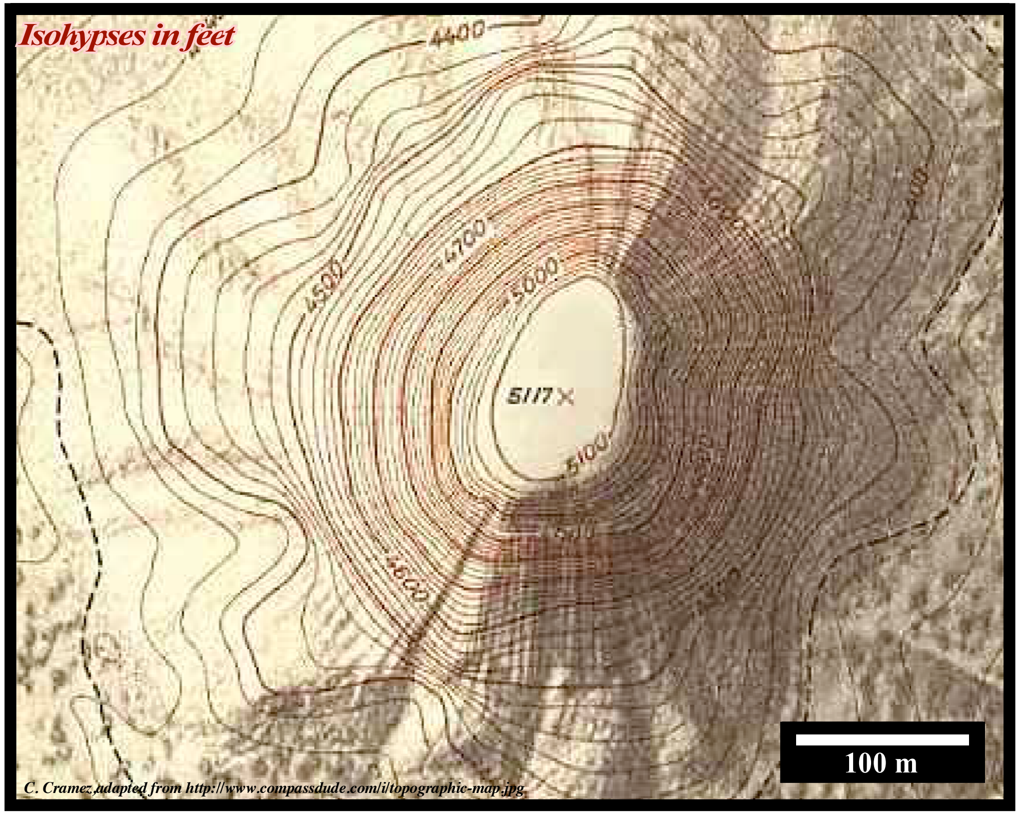
Due to currents, variations in air pressure, temperature, etc., the mean sea level (MSL) does not coincide with the geoid, not even as a long-term average. Function of location, (persistent over time), the separation, between the MSL and geoid, is referred as the geodetic topography. It varies, globally, on a scale of ± 2 m. It is this stationary sea surface that is called geodetic sea level (it corresponds to a set of digital values of the highest geoid points in relation to a reference ellipsoid). Nevertheless, the geoid is the best representation the MSL. The sea level is wavy and mimics the topography of the sea floor. Its ondulations are very small and can just be measured by altimetric radars from satellites. The GOCE mission measured the gravity gradients and proposed a global model of the Earth's gravity field and the geoid. Everything depends on the knowledge of the Earth's gravity field, which defines the horizontal. It is a function of several factors (mountain ranges, oceanic trenches, etc), which make Earth's surface very uneven. In addition, as Earth's materials have different densities and are not uniformly distributed, the force of gravity varies from one place to the other at the Earth's surface.

Topographic Earth' Surface

Visible Earth's Surface

Contour Map

(Devil's Tower, Wyoming)



Devil's Tower

(Wyoming, USA)

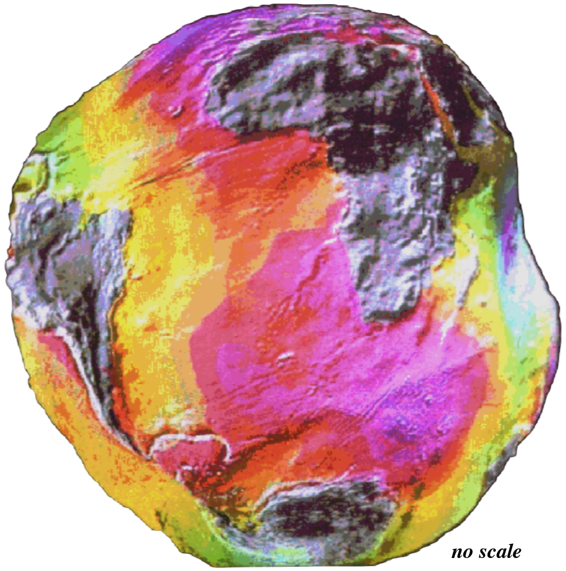
Around 60 million years ago, Devil's Tower itself either protruded through or a volcano grew from the earth. With time, the flanks were eroded to give the present appearance.

A map in isohypses (contours map), like the map illustrated in this figure, is nothing more than a topographic map, i.e., a type of map characterized by large-scale details and a quantitative representation of the relief. As it is easy to see in this figure, when more important is the relief plus the contour lines are close to each other. On a cliff with a slope close to the vertical, like the flanks of the volcano illustrated here, the isohypses are very close to each other and overlap if the escarpment is vertical. On the contrary, the greater the distance between the contour lines more flattened is the topography, which means that a horizontal area is limited upstream and downstream by the same isohypse. Conventional topographic maps not only show contours, but also any type of water-courses or other water-bodies, forest cover, built-up areas or individual buildings (function of the scale), and other features and points of interest. While isohypses maps show the topography, the distribution of the roads or rivers or the county boundaries, a geological map shows the distribution of the geological resources, including the different types of rocks and faults.

Geoid

Geoid

(Vertically exaggerated)

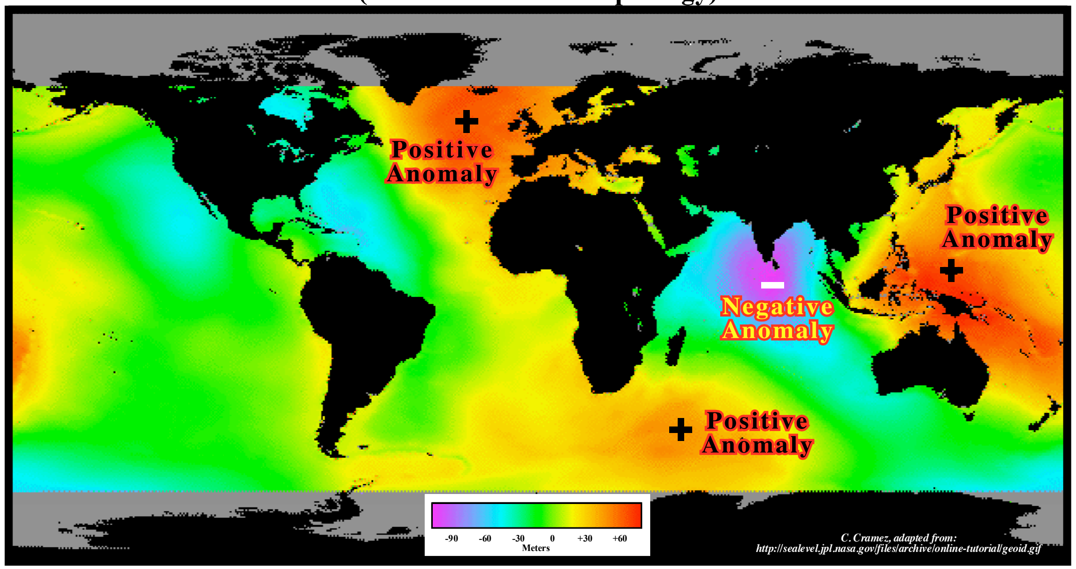


no scale

CCramez, adapted from https://www.esa.int/spaceinimages/Images/2001/08/Amplified_view_of_the_Earth_s_geoid

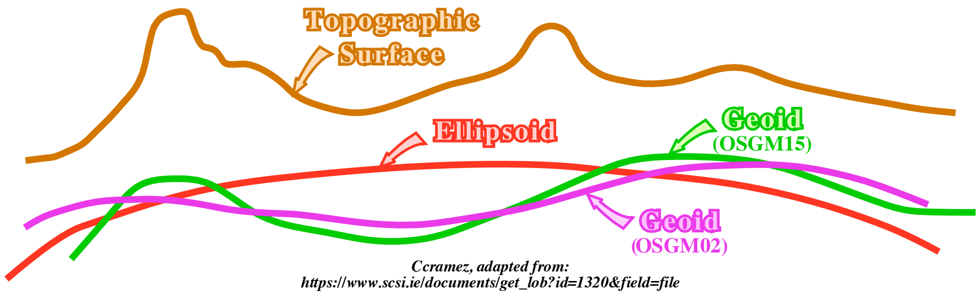
Geodetic Sea Level

(Mean Sea Level Morphology)



Positive & Negative Heights

between geoid models

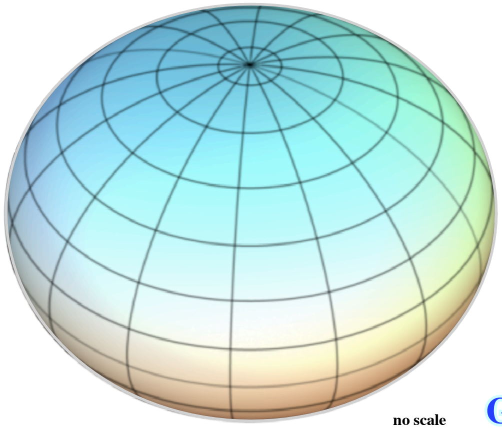


Ccramez, adapted from: https://www.scsi.ie/documents/get_lob?id=1320&field=file

The morphology of the Earth's topographic surface (based on GPS, i.e., Global Positioning System) ranges from +8,848 meters (Mount Everest) to –11,034 meters (Marianas Trench), while the geoid's deviation from an ellipsoid ranges from +85 m (Iceland) to –106 m (southern India). So, all representation of the geoid (more or less the mean sea level) as the one illustrated above (GOCE, i.e., Gravity Field and Steady-State Ocean Circulation Mission) are, highly, vertical exaggerated (> 1000 sacale factor). The differences between OSGM02 and OSGM15 can be, largely, attributed to improvements of the gravity data (additional gravity data from GRACE – Gravity Recovery And Climate Experiment – satellite mission) and fitting of the OSGM geoid model. In addition, much of the available orthometric height data in the extreme west of Ireland is of a lower standard, having been derived from a transformation datum rather than levelling. These effects combine to produce significant deviations between current and previous models.

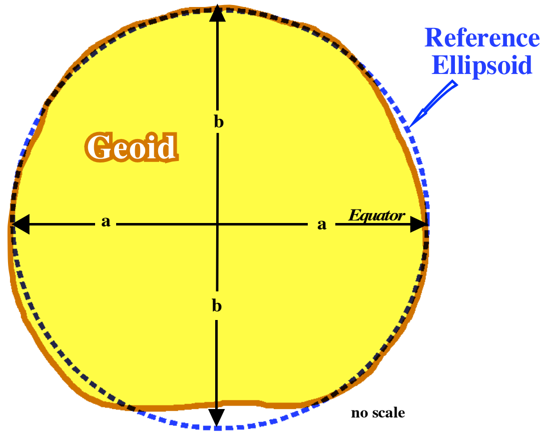
Earth Ellipsoid

Our Oblate Spheroid Planet Earth



CCramez, adapted from: https://gisgeography.com/ellipsoid-oblate-spheroid-earth/

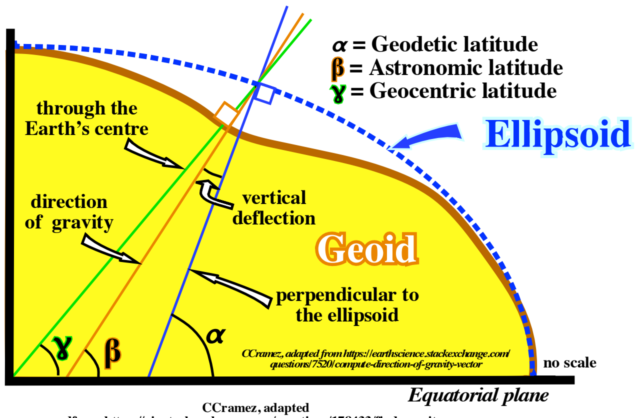
Earth Ellipsoids are approximations of the Geoid



CCramez, adapted from: https://www.e-education.psu.edu/natureofgeoinfo/c2_p15.html

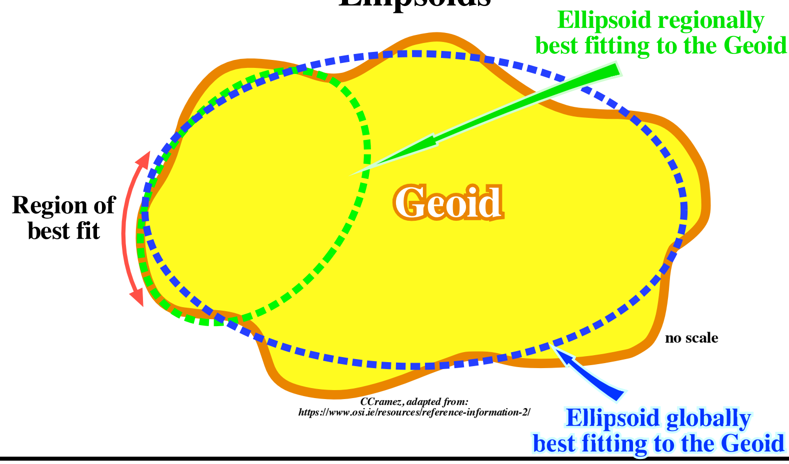
Many ellipsoids have been defined in the world. Local ellipsoids are established to fit the Geoid (mean sea level) well over an area of local interest. A global ellipsoid approximates the Geoid as a mean Earth Ellipsoid.

Geodetic and Geocentric Latitudes



CCramez, adapted dfrom:https://gis.stackexchange.com/questions/178433/find-gravity-normal-by-ecef-or-gps-coordinate-of-point

Local and Global Ellipsoids



CCramez, adapted from: https://www.osi.ie/resources/reference-information-2/

An ellipsoid is a three-dimensional geometric figure that resembles a sphere, but whose equatorial axis (a) is, slightly, longer than its polar axis (b). The equatorial axis of the World Geodetic System of 1984, for instance, is, approximately, 22 km longer than the polar axis, a proportion that closely resembles the oblate spheroid that is planet Earth. Geoscientists have adopted an ellipsoid model to determine latitude and longitude coordinates. Ellipsoids are, commonly, used as alternate for geoids so as to simplify the mathematics involved in relating a coordinate system grid with a model of the Earth's shape. Ellipsoids are good, but not perfect, approximations of geoids. The best fitting of a global ellipsoid is not, necessarily, the most for a detailled area. The map in previous plate shows differences in elevation between a geoid model called GEOID96 and the WGS84 ellipsoid. The surface of GEOID96 rises up to 75 meters above the WGS84 ellipsoid over New Guinea. In the Indian Ocean , the surface of GEOID96 falls about 104 meters below the ellipsoid surface.

Measuring Sea Level

Carlos Cramez
(born in 1939)

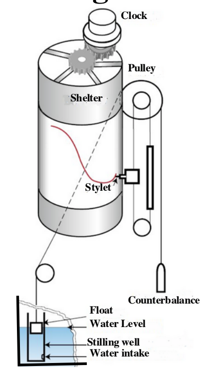
There are, basically, two way to measure the changes of sea level:
(i) Maregraphs and (ii) Radar altimetry

(i) Maregraphs

Maregraphs or tide gauges are instruments that measure sea level, relatively, to a vertical datum.

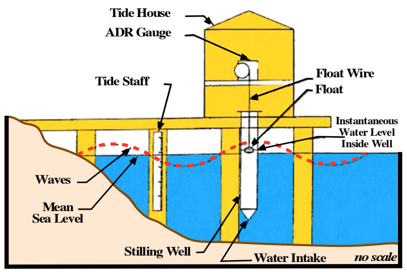
Marseille Maregraph
(France)

Tide Gauge Sketch

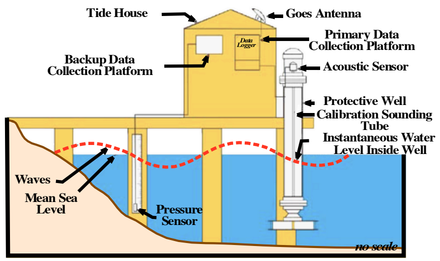


Ccramez, adapted dfro http://refmar.shom.fr/en/ documentation/ instrumentation/maregraphe-a-flotteur

Old Tide Gauge



Modern Tide Gauge



Ccramez adapted from https://oceanservice.noaa.gov/facts/tide-gauge.html

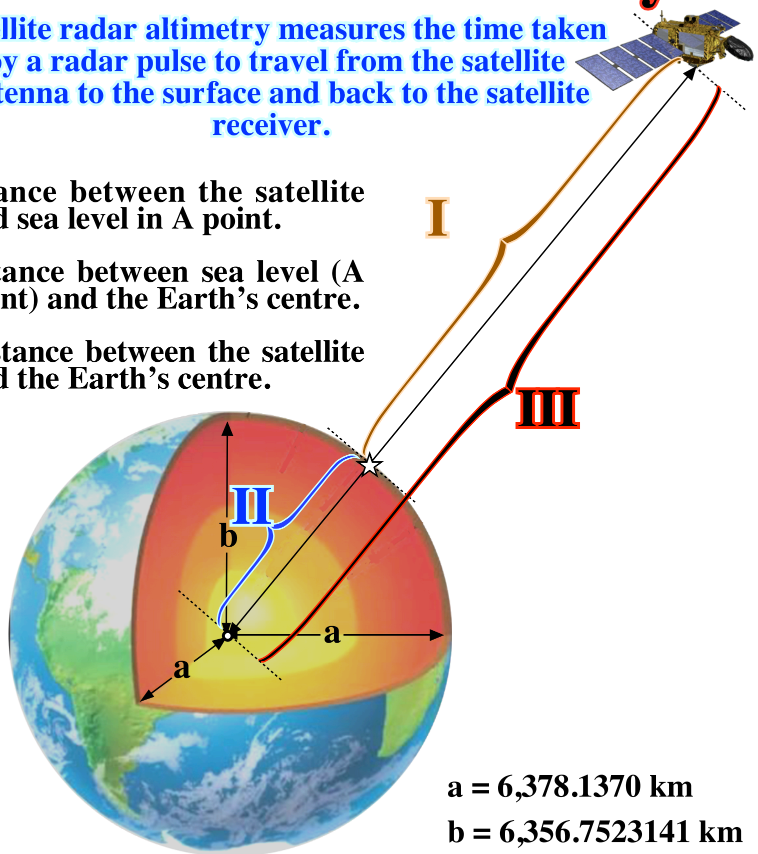
(ii) Satellite Radar Altimetry

Satellite radar altimetry measures the time taken by a radar pulse to travel from the satellite antenna to the surface and back to the satellite receiver.

I- Distance between the satellite and sea level in A point.

II- Distance between sea level (A point) and the Earth's centre.

III- Distance between the satellite and the Earth's centre.



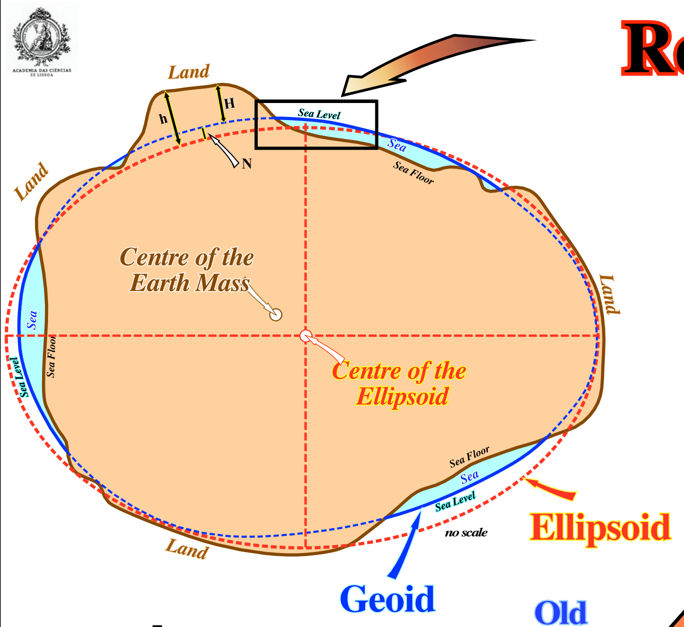
a = 6,378.1370 km

b = 6,356.7523141 km

Float gauges were the first self-recording tide gauges and even today are still in widespread use despite technological developments. The float is located in a stilling well, usually, topped with a shelter containing the chart recorder, to protect against the weather. These instruments are, generally, reliable and relatively unsophisticated. If high accuracy is not required, highly skilled personnel are not needed to maintain and use them. Satellites, as for instance Jason-3, can measure the distance from themselves to the sea level within an error of about three centimeters (I). In addition, they have instruments allowing to measure the distance from them to the Earth's center (III). By subtracting the first distance (between the satellite and sea level) from the second distance (between the satellite and Earth's center), geoscientists can calculate the distance from the sea level to Earth's center (II). In about 10 days, they measures the sea level height over the entire Earth, allowing to find the mean sea level for the whole planet. After several years of measuring, it is possible to determine how much and how quickly sea level changed.

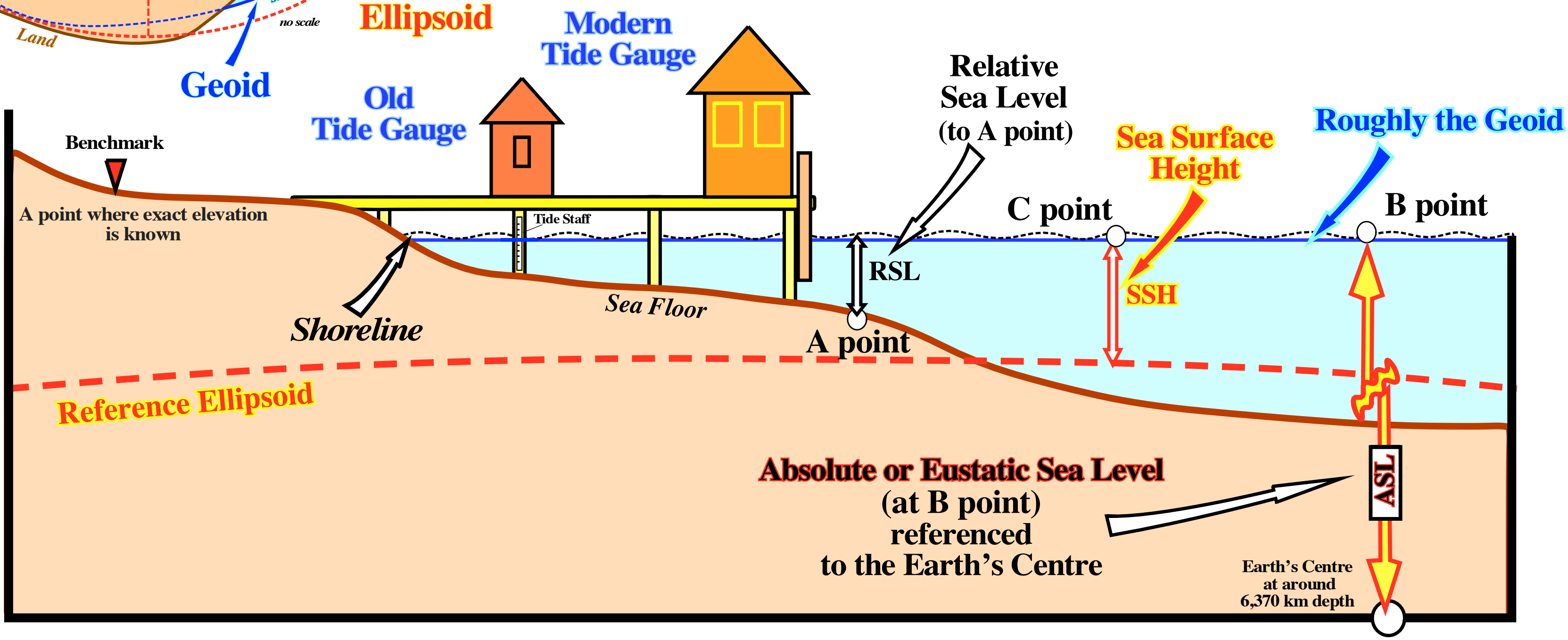
As we are going to see, function of the reference surfaces taking into account and the points on which we desire to mesure the sdea level, three main sea level types can be considered: (i) Absolute or Eustatic Sea Level ; (ii) Relative Sea Level ; (iii) Sea Surface Height. In a certain point of the sea level surface, the absolute or eustatic sea level, which is the distance between such a point and the Earth's centre, is a funtion of Tectono-Eustasy, Glacio-Eustasy, Geoidal-Eustasy and Thermal Expansion of Oceans, The relative sea level, in a given point of the sea floor, is the distance between such a point and the sea level surface. On seismic lines, a relative sea levels can be, also, determined by the vertical distance between a given point on the sea level surface and the base of the sediments (top of the continental crust) taken as reference surface. One can say, the relative sea level is the result of the combined action of the absolute (eustatic) sea level and the tectonics (subsidence ou uplift of the sea floor). The sea surface height, in a given point of the sea surface, is the distance between such a point of the ellipsoid odf reference.

Relative Sea Level, Absolute Sea Level & Sea Surface Height



Depending upon the reference surfaces or points, sea level measurements have different names:

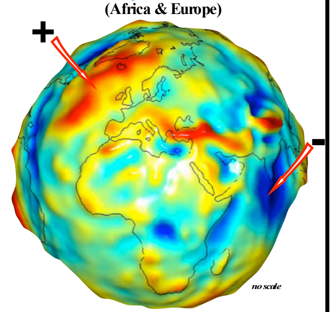
(i) Relative Sea Level (Sea Floor)
(ii) Absolute Sea Level (Earth's Centre)
(iii) Sea Surface Height (Ellipsoid)

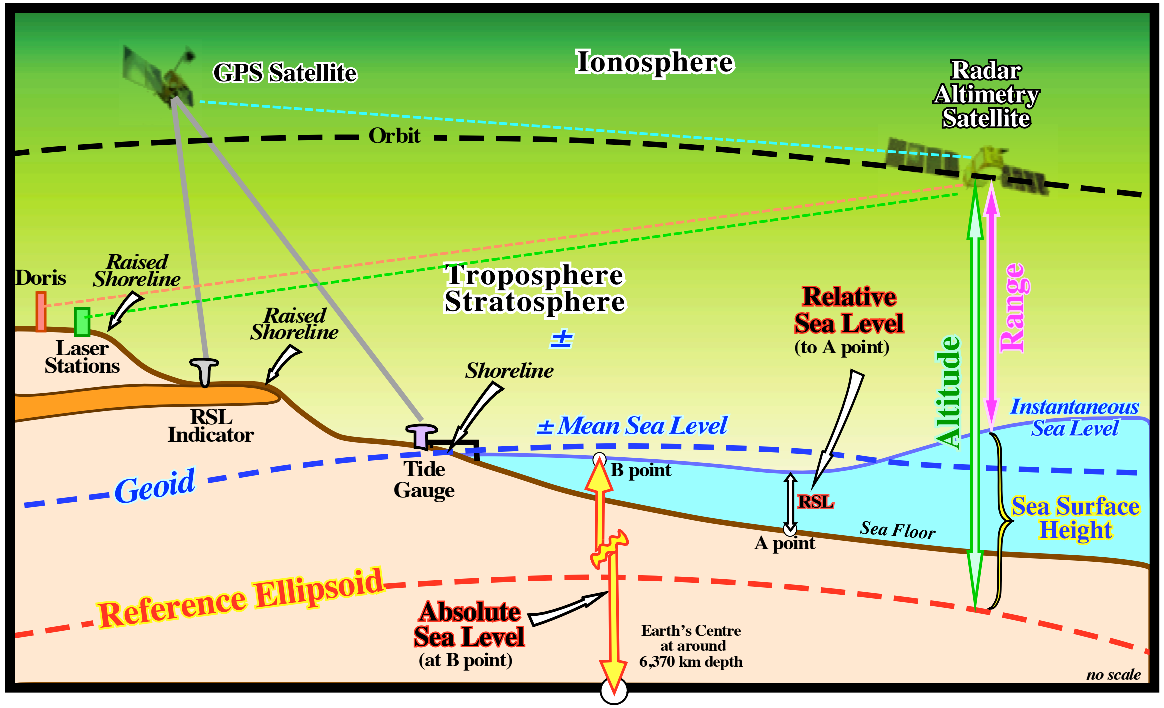


The relative sea level (RSL) is the measure of the sea surface with respect to a given point in sea floor or at the top of the continental crust. RSL changes are quite important for coastal planings. Geoscientists measure RSL changes using tide gauges (mareograph, marigraph), which are device for measuring the change in relative sea level to a vertical datum. In modern tide gauges the water enters through a bottom pipe and the water level is measured using electronic sensors, usually, GPS (Global Positioning System is a set of ± 30 well-spaced satellites that orbit the Earth and make it possible for people with ground receivers to pinpoint their geographic location). Adjustment of relative sea level measures are required to try to take away the influence of the land uplift (glacial isostatic rebound, sedimentary shortening) and sea floor subsidence. The use of satellite observations allows, partially, solve major problem. Sea surface height (SSH) is the measure of sea surface with respect to a reference ellipsoide. When the reference is the Earth's centre, geoscientists measure the absolute or eustatic sea level, which often is, erroneously, supposed global.

Relative Sea Level
Absolute Sea Level
Sea Surface Heigh
Mean Sea Level

Gravity Anomalies
(Africa & Europe)

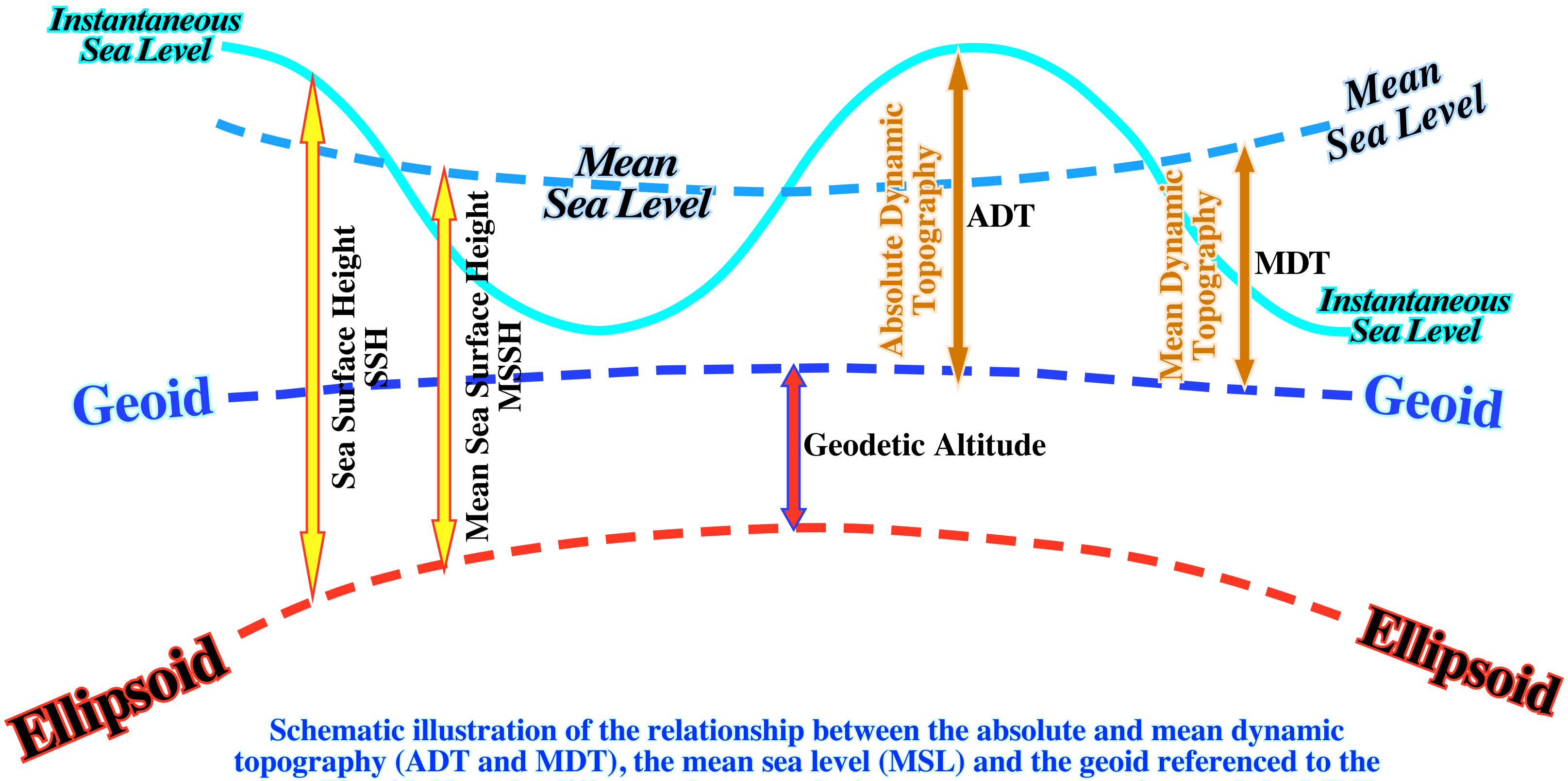




GPS receivers use the reference ellipsoid to calculate elevation. The elevation reading from the GPS receiver is not the vertical distance from true sea level, but rather the distance from the reference ellipsoid. A GPS receiver gives latitude, longitude and elevation. To calculate the elevation, the following informations are required (i) The location of at least four satellites in space ; (ii) The current time ; (iii) The reference ellipsoidal shape of the sea level for the entire Earth. There are many different reference ellipsoids, but all GPS receivers use the same one, and it is called the WGS-84 Reference Ellipsoid.

The mean sea level (MSL) is used to describe the average height of the oceans around the world, determined by measurements of less active water avoiding possible increases due to waves, wind, etc. MSL is the Earth's equipotential surface as described by the lastest revision (2004) of the World Geodetic System (1984) suposed to be valid up to about 2010. It comprises a standard coordinate frame for the Earth and the gravitational equipotential surface (the geoid). The sea level measurements are changing, constantly, due a certain number of factors (surface waves, seiches, tides, etc.). Certain changes are the result of short-term factors (tides, storms, etc.), but others, result from long-term factors such as those induced by plate tectonics, melting of glaciers, thermal expansion of oceans,, volume of oceanic basins, etc. The altitude of the satellite is stablished with respect to an ellipsoid. The difference between the altitude and the range (distance between the satellite and the instantaneous sea level) is defined as the sea surface heght (SSH). Subtracting the measured SSH to a reference mean sea surface (e.g.,the geoid), one can obtains de SSH anomaly.

Absolute & Mean Dynamic Topography



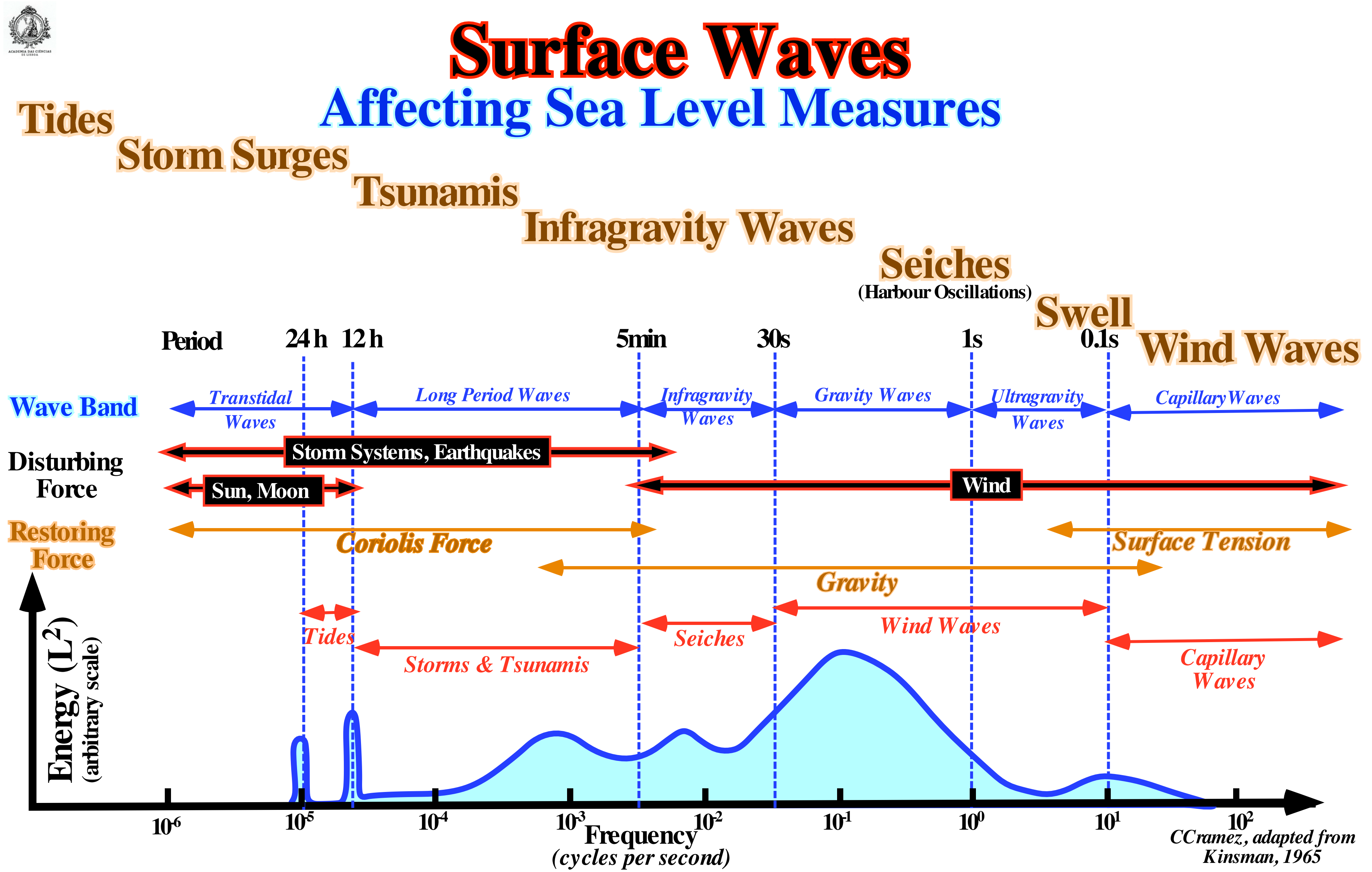
Schematic illustration of the relationship between the absolute and mean dynamic topography (ADT and MDT), the mean sea level (MSL) and the geoid referenced to the same ellipsoid. Note the difference between the instantaneous sea surface and the MDT.

Ccramez, adapted from: https://link.springer.com/article/10.1007/s10712-013-9270-y

Convection of the mantle interior produces dynamic deflection of the Earth's surface with amplitudes of up to ± 1.5 km. This "dynamic topography" occurring within the ocean basins changes the ocean basin volume inducing sea level changes. These dynamic sea level changes vary with time if either: (1) Dynamic topography changes with time ; (2) Continents move over the dynamic topography. The rate of sea level change due to these processes can be estimated using a time-dependent model of present-day mantle flow. Presently, dynamic topography, positively, offsets sea level by 92 ± 20 m. Upwelling mantle flow is, currently, amplifying the sea level change at a rate of up to 1 m/My (depending on mantle viscosity). The downwelling contribution to sea level change is, poorly, constrained. Continental motion over the present-day dynamic topography produces ± 0.3 m/My of sea level change, depending on mantle reference frame. During a complete supercontinent cycle (breakup of a supercontinent and formation of another, i.e., a Wilson's cycle) sea level should fall during supercontinent stability and rise during periods of dispersal.

Bannenjar'ga Porsangerford, Finnmark Norway

For a geoscientist asking for proofs of sea level change is, simply, an affront. Actually, when he looks to an outcrop of sedimentary rocks, all bedding planes correspond to relative sea level changes, i.e., to the combined action of the absolute sea level and tectonics (subsidence of sea floor, when the predominant tectonic regime is extensional or uplift when the predominant tectonic regine is compressional). In fact, to have marine sedimentation landward of the basin edge, i.e., marine turbidite deposits excluded, the space available to the sediments (accommodation) must increase, that is to say, a marine ingression must take place displacing landward the shoreline. During the stability period of the relative sea level, which follows the marine ingression, the shoreline, progressively, is displaced seaward as the sediments deposit, generally, by progradations, till a new marine ingression (new relative sea level rise) take place. Significant relative sea level falls displace seaward and downward the shoreline, creating erosional surfaces (unconformities), which later, since the sea level rise, are fossilized by sediments.



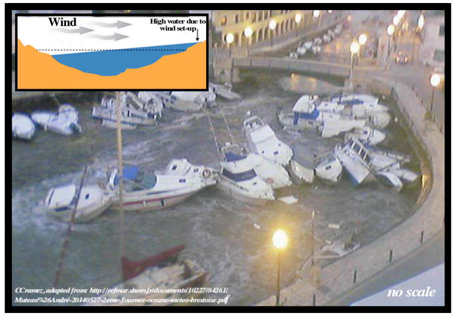
The very obvious evidence of sea levels changes is given by the surface waves, which period ranges from 0.1 sec (capillary waves) to more than 24 hours (transtidal waves). However, in the subject of this conference, their importance is rather associated with the problems they pose at the sea level measures. One way to classify waves is by wave period T or by the reciprocal wave frequency. The Kinsman's classification (1965) shows the relative amount of energy contained in ocean waves having a particular frequency. Gravity waves have periods from 1 to 30 seconds. In these waves, the gravity is principal restoring force (force due to gravity attempts to return the fluid to its equilibrium position). A large amount of the total wave energy is associated with gravity waves, which can be separated into two states: (a) Seas, when the waves are under the influence of wind in a generating area, and (b) Swell, when the waves move out of the generating area and are no longer subjected to significant wind action. Seas are, usually, made up of steeper waves with shorter periods and lengths, and the surface appears much more disturbed than for swell.

Waves Affecting Sea Level Measures

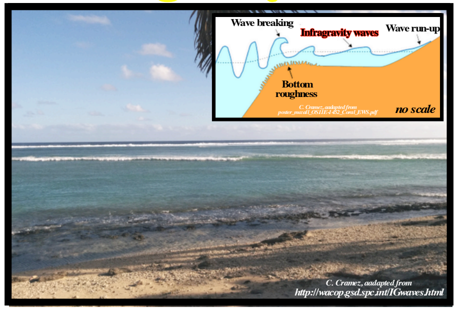
Wind Wave

Swell

Seiches



Infragravity Waves



Tsunamis

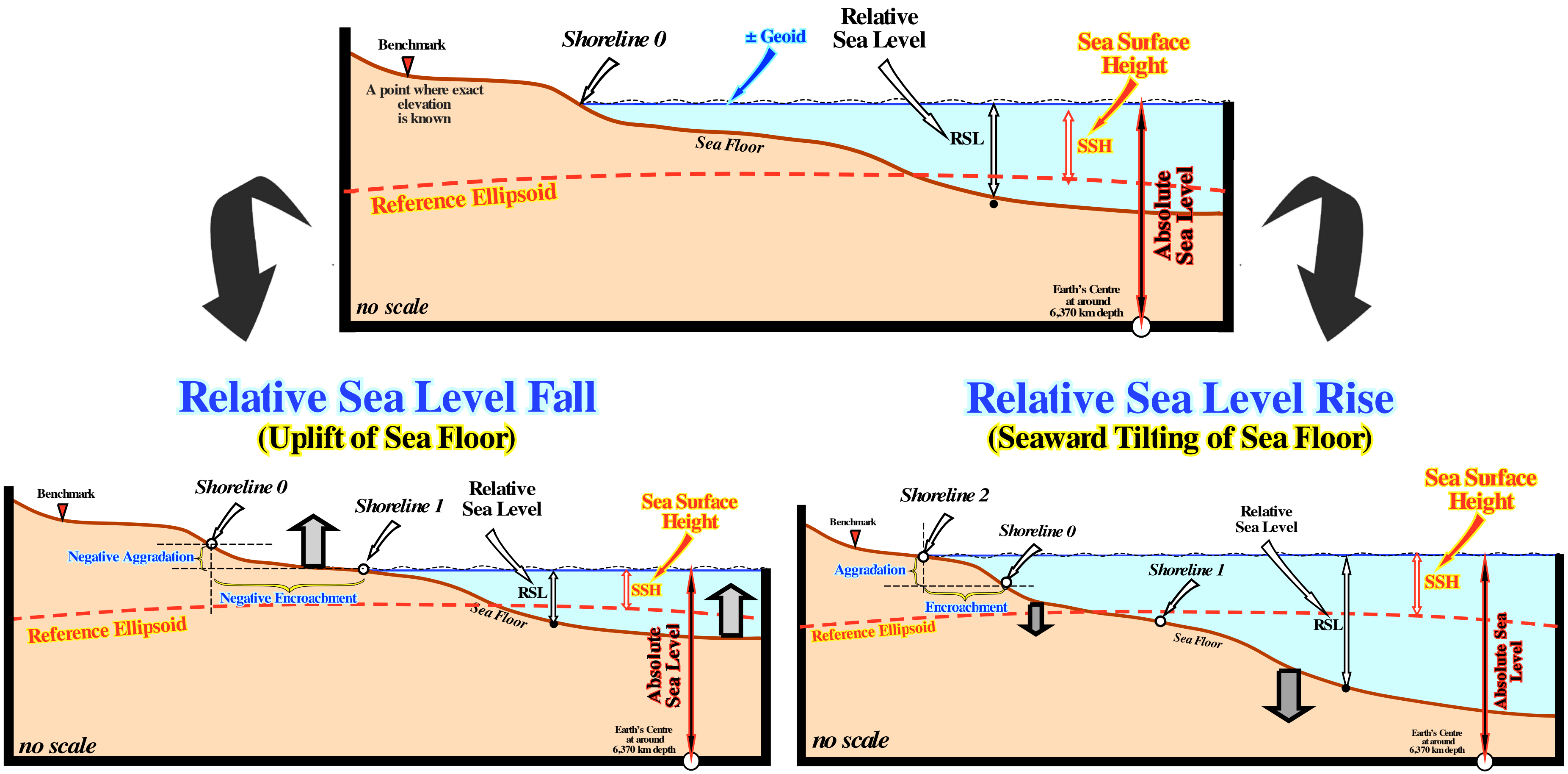
Storm Surges

Low Tide

High Tide

Wind waves occurring on the free surfaces of waterbodies, when the wind blows over an area. They range from small ripples to waves over 30 m high. Swell occurs when waves move out of the wind generating area. Seiches are a standing waves in more or less enclosed waterbodies. Seiches can be observed on lakes, swimming pools, bays, harbours and seas. Infragravity waves are surface gravity waves with frequencies lower than the wind waves and amplitudes relevant in shallow water. Tunamis are waves of very great period propagating through waterbodies, resulting from the sudden movement of a large volume of water, generally, caused by earthquakes, submarine landslide or volcanic explosions, which can transform themselves, reaching the coast, into a very height breaking destructive waves. Storm surges are, generally, associated with low pressure weather systems. Their severity is dependent of the shallowness and orientation of the waterbody, relatively, to storm path. Tides are sea level rises and falls caused by the combined effects of the gravitational forces exerted by the Moon and the Sun and the Earth's rotation.

Relative Sea Level Fall & Relative Sea Level Rise

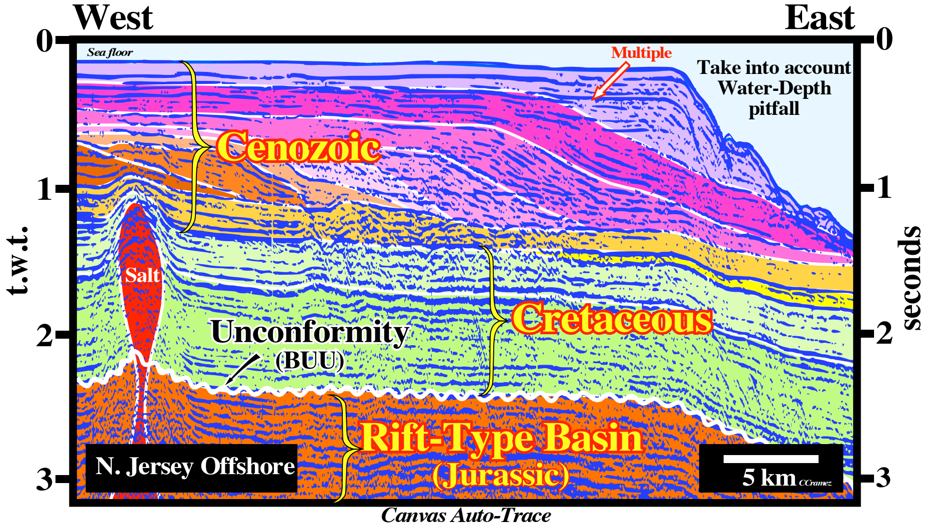


Besides the surface waves, relatively short-term movements of the sea floor, strongly, affect the relative sea level measures without affecting the absolute sea level. Sea floor rises, during compressional tectonic regimes (sedimentary shortening) or during glacial isostatic rebound. Sea floor sinks (subsidence) during extensional tectonic regimes (sedimentary lengthening) or during the ice ages due to the loading of the ice. As the amount of water (under its all forms, i.e., liquid, solid and gaseous) seems to be constant (geological hypothesis not yet refuted) since the Earth's formation (± 4.5 Ga), in the first cases there are relative sea level falls (erosional surfaces), while in the second cases there are relative sea level rises (marine ingressions). In a compressional tectonic regimes, geoscientists said: σ_1 horizontal ⇒ Shortening ⇒ Uplift ⇒ Relative Sea Level Fall ⇒ Erosion ⇒ Unconformity and, in an extensional tectonic regime: σ_1 vertical ⇒ Lengthening ⇒ Subsidence ⇒ Relative Sea Level Rise ⇒ Increasing Accommodation ⇒ Deposition. A relative sea level rise or fall can be just due to a subsidence or an uplift of the sea floor, with constant absolute sea level.

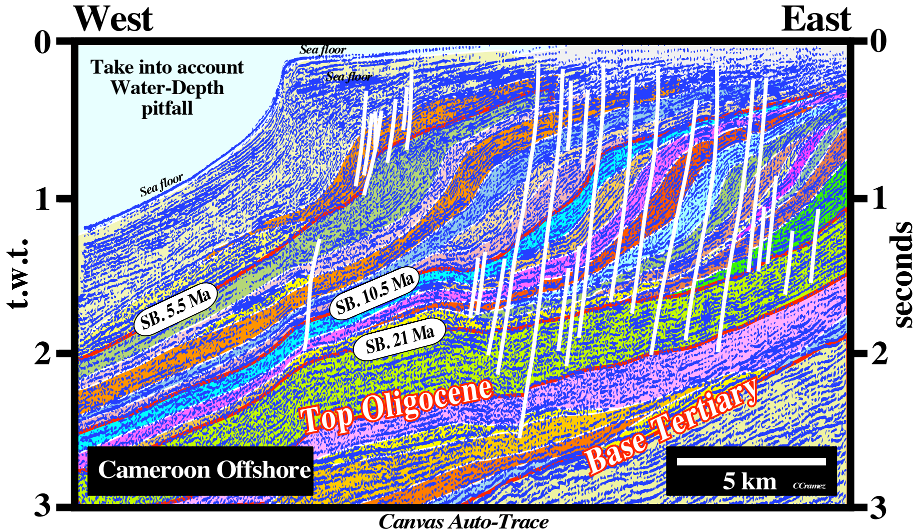
Shelfal Accommodation

Relative Sea Level Rise

Accommodation induced, mainly, by Absolute Sea Level Changes (Eustasy), particularly during the Cenozoic. Time lines are subhorizontal.



Accommodation induced, mainly, by Relative Sea Level Changes (Eustasy + Tectonics, i.e., sea floor Subsidence). Time lines are tilted seaward.



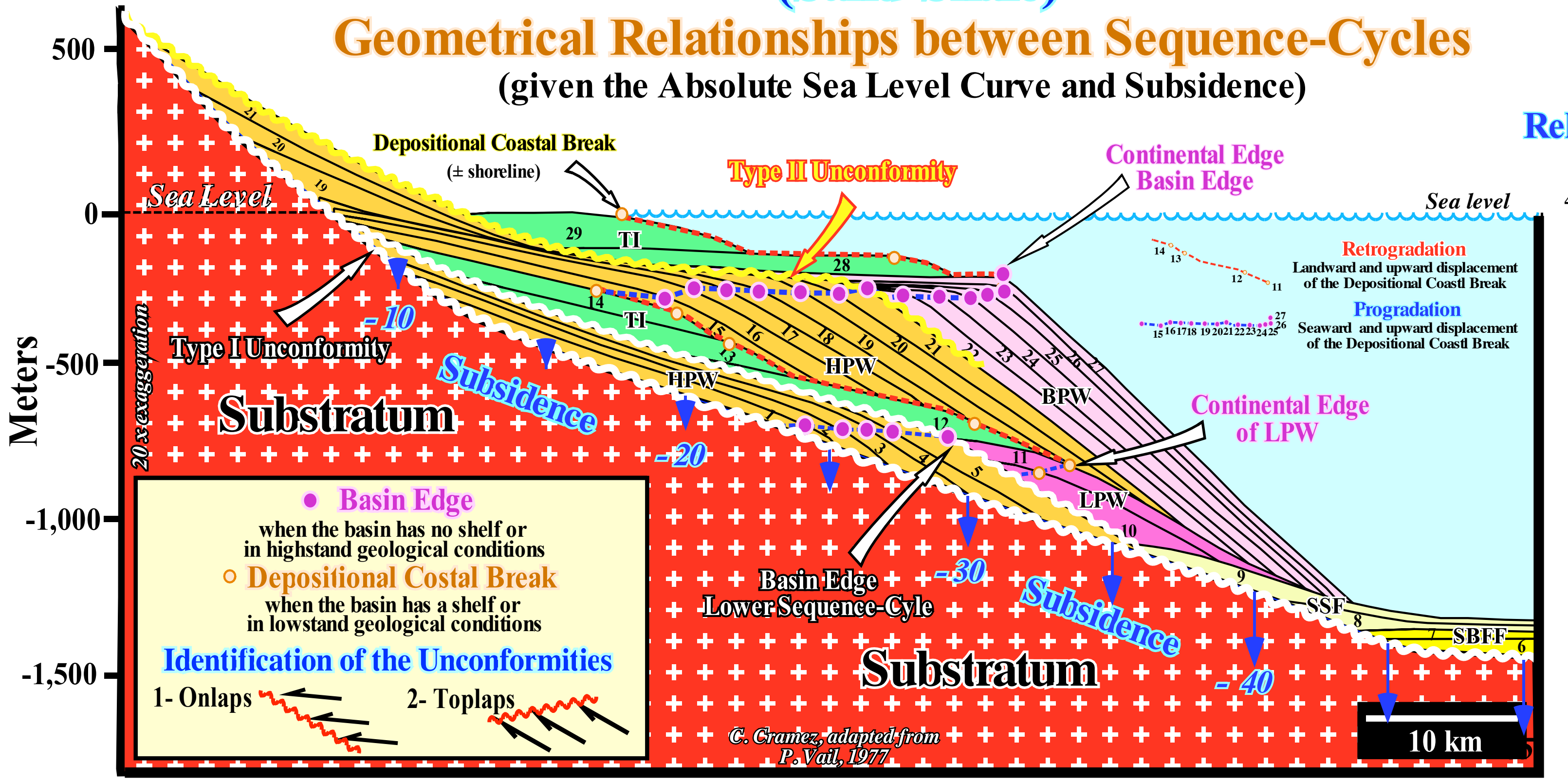
Accommodation is the space available for the sedimentary particles to deposit, i.e, to have sedimentation the space available must increase or, in others terms, the relative sea level (combined action of the absolute sea level and tectonics) must increase. Depositional surfaces are chronostratigraphic lines, that have a sigmoid geometry, in which three sectors can be individualized: (i) Upper subhorizontal ; (ii) Middle seaward dipping and (iii) Lower subhorizontal. When on seismic lines, the lower subhorizontal sector has a, more or less, horizontal behaviour (as on the auto-trace of the New Jersey seismic line), obviously, eustasy (absolute sea level changes) is the preponderant factor of shelfal accommodation. When the lower subhorizontal sector of the depositional surface dips seaward, as it is the case in Cameroon offshore, tectonics, i.e., the increasing seaward tilting of the sea floor (subsidence) is the main responsible for the creation of accommodation. Generally, the cyclicity observed in sedimentary series, is due to the absolute sea level changes. Tectonics is, mainly, chargeable for the amount of the accommodation created.

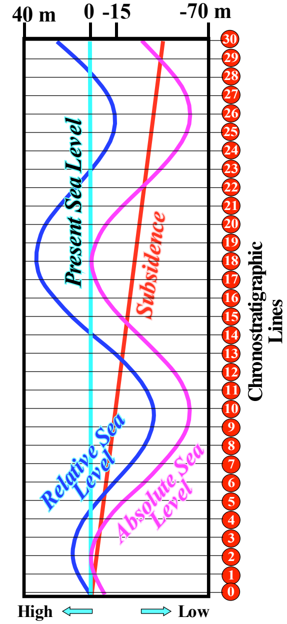
Geological Depositional Model

(Sand-Shale)

Geometrical Relationships between Sequence-Cycles

(given the Absolute Sea Level Curve and Subsidence)





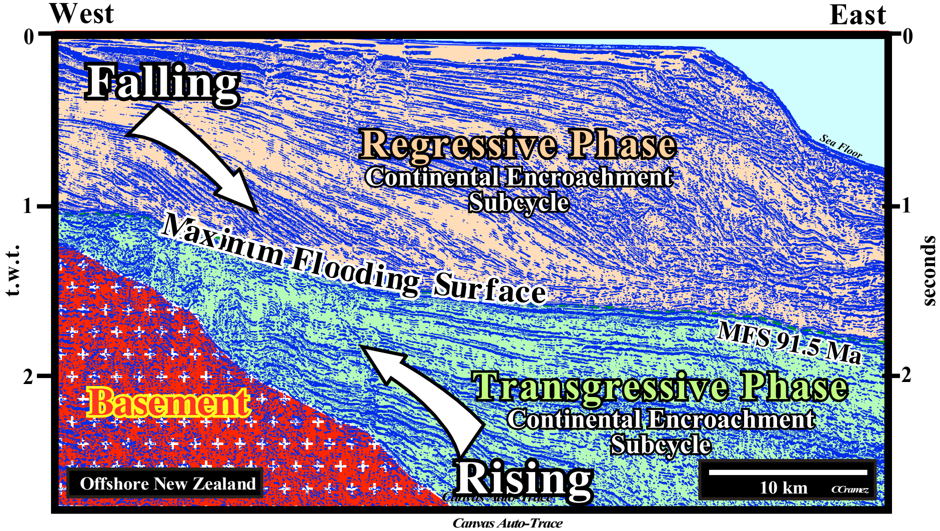
Assumptions:

- A climate and a terrigeneous influx avoiding carbonate deposition ;
- A constant (time and space) terrigeneous influx ;
- A gradual and linear basinward increasing of subsidence ;
- A 100 k years time interval between each chronostratigraphic line ;
- An aleatoric location of erosion features (incised valleys, canyons, etc.) during the major relative sea level falls.

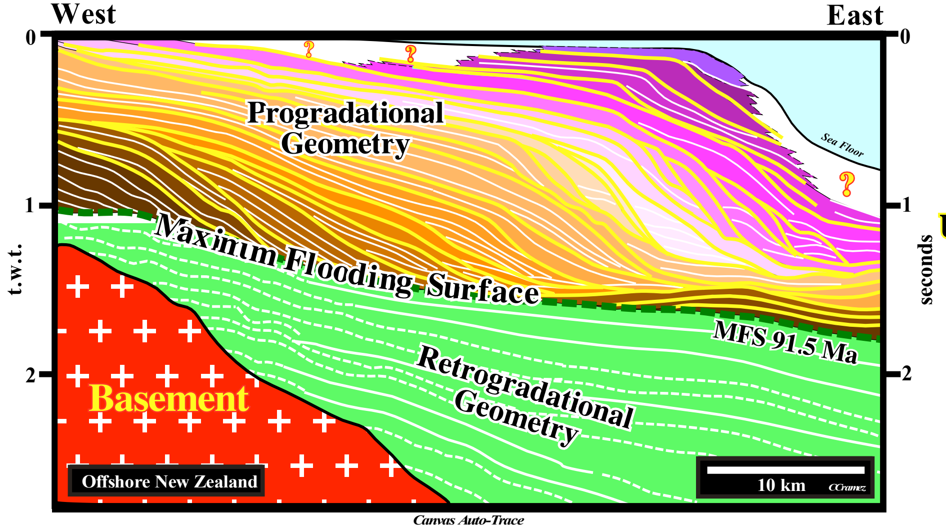
In geology to have marine deposition (turbidites excluded), the space available for sediments must increase, i.e., a marine ingression (relative sea level rise) is required. A marine ingression displaces landward the shoreline (± the depositional coastal break) increasing the water depth over the shelf. During the stability period of the relative sea level occurring after the marine ingression, the shoreline is displaced seaward as sediments are deposited (in progradation) till a new marine ingression or a relative sea level fall occurs. At the level of a sequence-cycle (time-duration between 0.5 and 3-5 My), the back and forth shifts of depositional coastal breaks, emphasize sedimentary transgressions (retrogradational geometry) and sedimentary regressions (progradational geometry) induced, respectively, by relative sea level rises in acceleration and in deceleration. At higher hierarchies (continental encroachment cycles and subcycles with time-duration higher than 5 My), the sedimentary transgressions and regressions have similar retrogradational and progradational geometries, but are, globally, caused by absolute sea level rises and falls respectively.

Shelfal Accommodation

Absolute & Relative Sea Level



During the Postpangea Transgressive Phase of the Continental Encroachment Cycle, theAbsolute Sea Level rises, while during the Regressive Phase, the Absolute Sea Level falls.

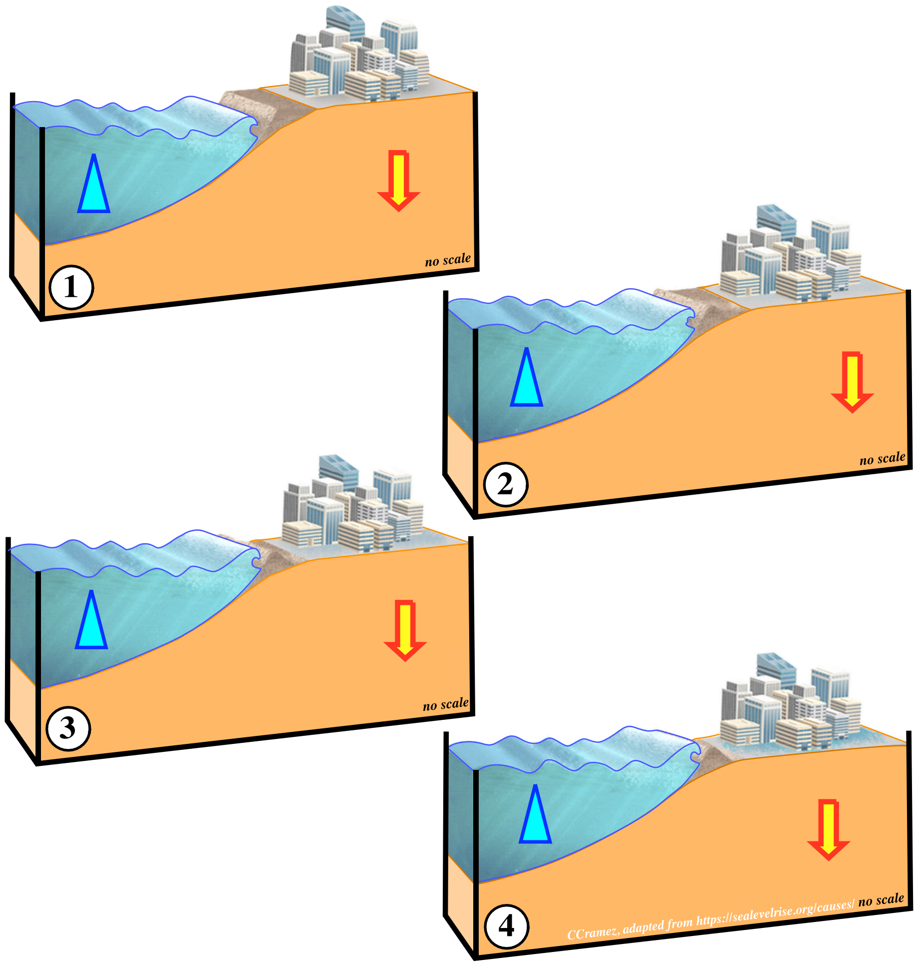


In the Postpangea Regressive Phase of the Continental Encroachment Cycle, at each unconformity (erosional surface in yellow), the Relative Sea level falls. Between them, the Relative Sea Level rises.

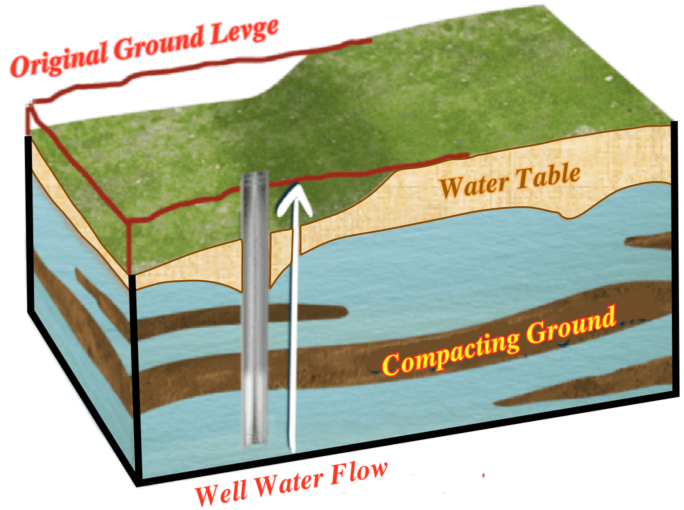
In the highest hierarchical stratigraphic cycles, i.e., in both Phanerozoic continental encroachment cycles the associated eustatic cycles (1st order eustatic cycles with a time-duration higher than 50 My) are induced by the changes of sea level created by volume variations the oceanic basin caused by the Wilson's cycles (supercontinent's breakup ⇨ formation and dispersion of continents ⇨ gathering of continents and formation of a new supercontinent). As illustrated, a continental encroachment cycle is formed, at the bottom, by the transgressive phase (retrogradational geometry), which is overlain by the regressive phase characterized by a progradational geometry. The transgressive phase is associated to a rise of the absolute sea level, while the regressive phase is associated with the fall of the sea level of the 1st order eustatic cycle. Using these tentative geological interpretation of a Canvas auto-trace of a regional seismic line of New Zealand, it can be said, that, globally, the absolute sea level rose since the breakup of the Pangea till the top of the transgressive phase (MFS 91.5 Ma) and then it fall till the Present-Time.

Relative Sea Level Rise Land Shinkrage

Weight of Buildings & People



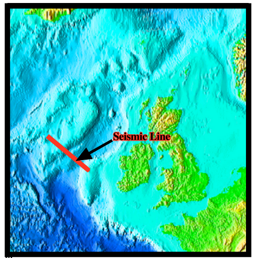
Extraction of Ground Water

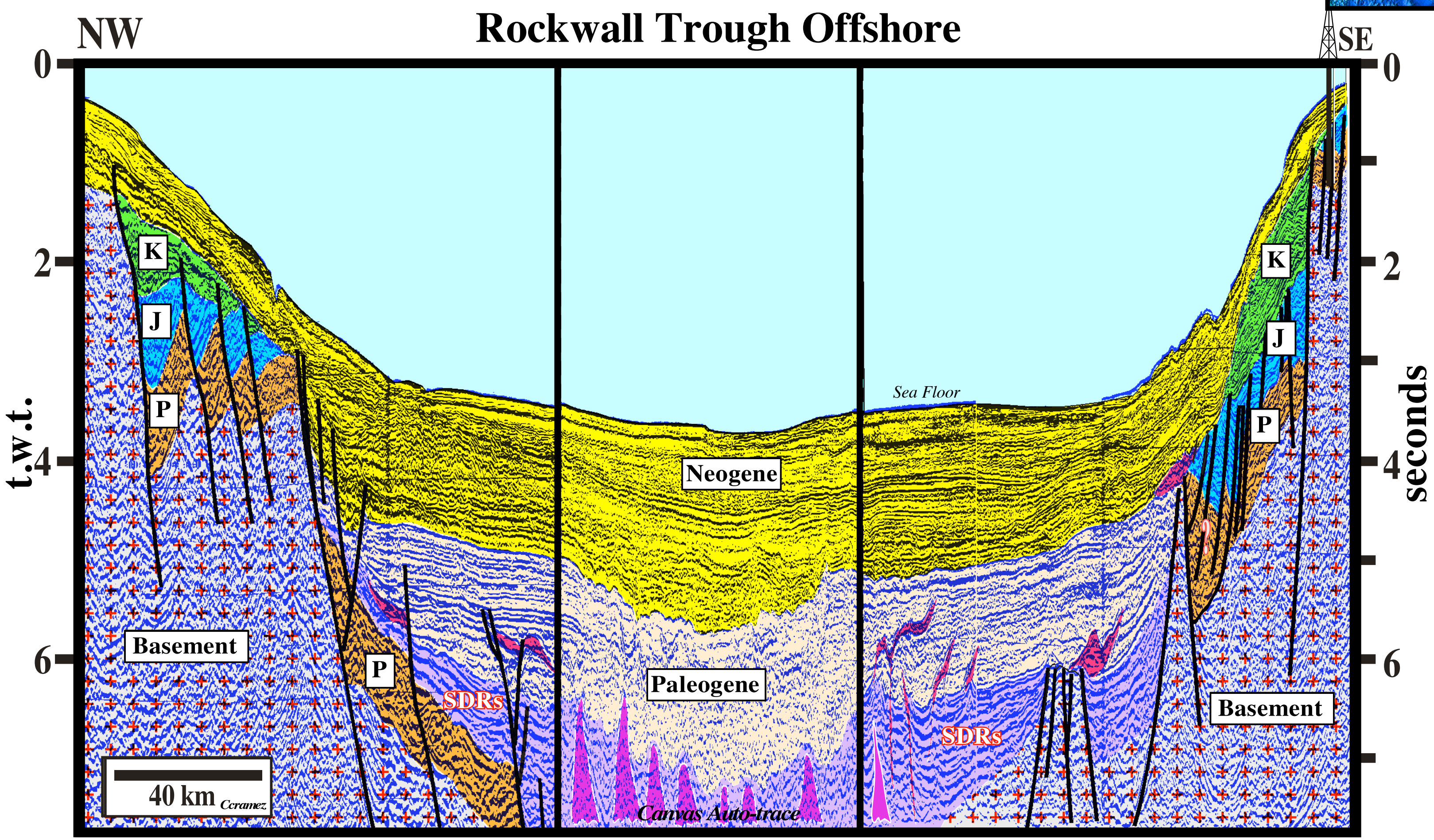


Land sinkage is, generally, a small contributor to relative sea level rise, but in some places it's responsible for more than half of the sea level rise. Sea levels are measured relative to land (a given point on sea floor or the bottom of the sediments, i.e., top of the continental crust), which means that when the ground sinks, relative sea levels reach higher. Sea level rise is faster in towns like Norfolk, Virginia, because the land beneath these towns is, actually, sinking. This sinking moves the ground below the town downward and closer to the sea level, speeding up a relative sea level rise. In California, the land is rising due to shifts in the tectonic plates. Relative sea level is not rising as fast as it is in other places. As people pump water out of the ground, gaps form where the water used to be, causing the land to sink in order to fill the empty space. This leads to ± 80% of the land sinkage in the USA. Relative sea level rise is fastest along the East Coast and Gulf Coast, where the land is sinking by ± 2.5 cm every 5-10 years. The land in Alaska is rising over 2.5 cm every 3 years. Most coastal towns fall somewhere in between, with slight land sinkage.

Subsidence

Induces a Relative Sea Level Rise



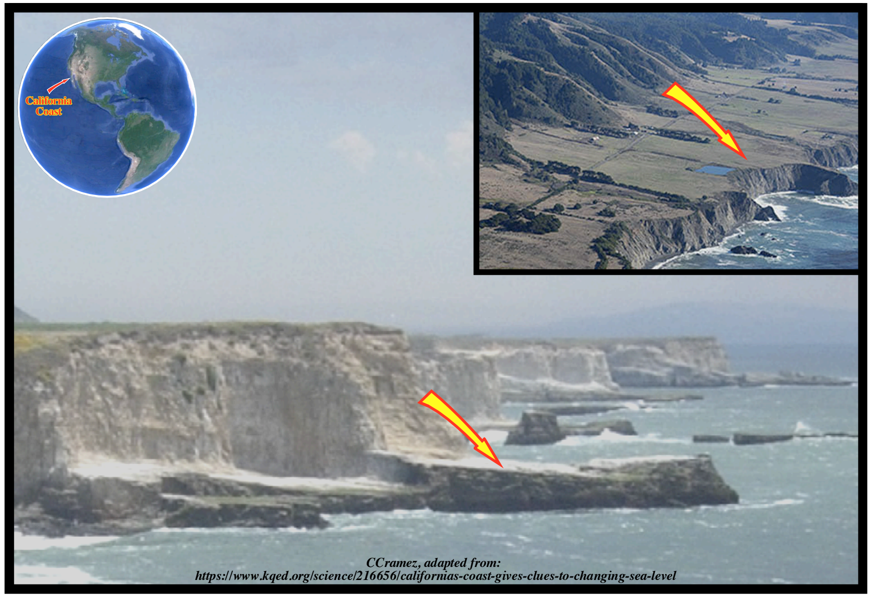


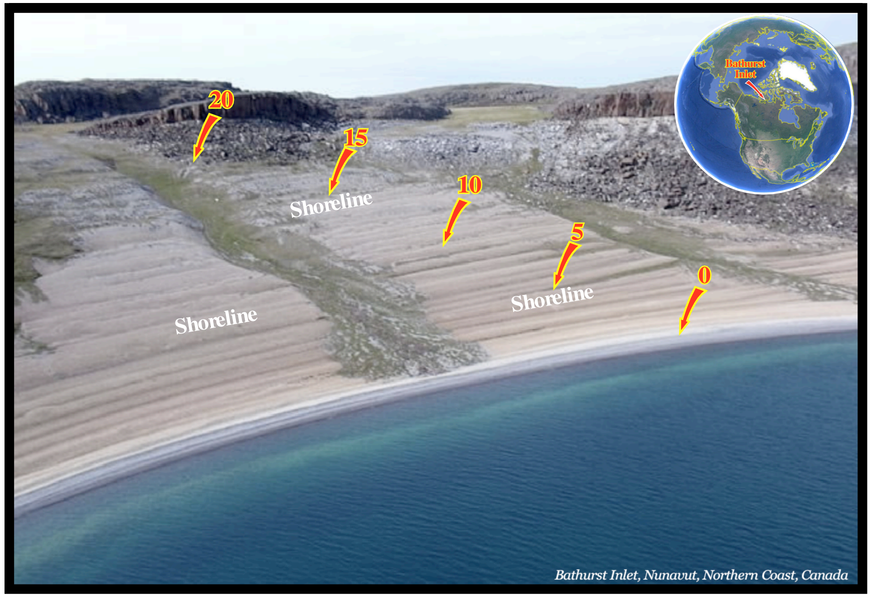
This tentative geological interpretation of a Canvas auto-trace of a composite regional seismic line of the Rockwall trough, strongly, suggests the subsidence of the Cenozoic (Basement + Paleozoic sediments) was the main responsible for the huge thickness of Cenozoic sediments (SDRs, i.e., tilted lava flows, Paleogene and Neogene clastic sediments). On this subject, the conjugate normal faulting systems developed during the lengthening of the Pangea supercontinent, is highly significant. It is during this rifting phase that the Mesozoic rift-type basin were formed. Later, particularly, during the Paleogene and Early Neogene the rate of subsidence of the central area was so high, in relation to the rate of terrigeneous influx, that a huge depression was formed under a high water column (enormous relative sea level rise). Under a so high water column and far from the terrigeneous influx, the sea level changes have any influence on sedimentation that is, mainly, made by decantation. The deepwater depression was, progressively, filled by onlapping of deepwater sediments forming a large Cenozoic depocentre that geoscientists call Rockwall Trough.

Raised Shorelines Terraces

(Relative Sea Level Fall)

Uplift (Relative Sea Level Fall) induced, mainly, by Tectonics (uplifts, earthquake)



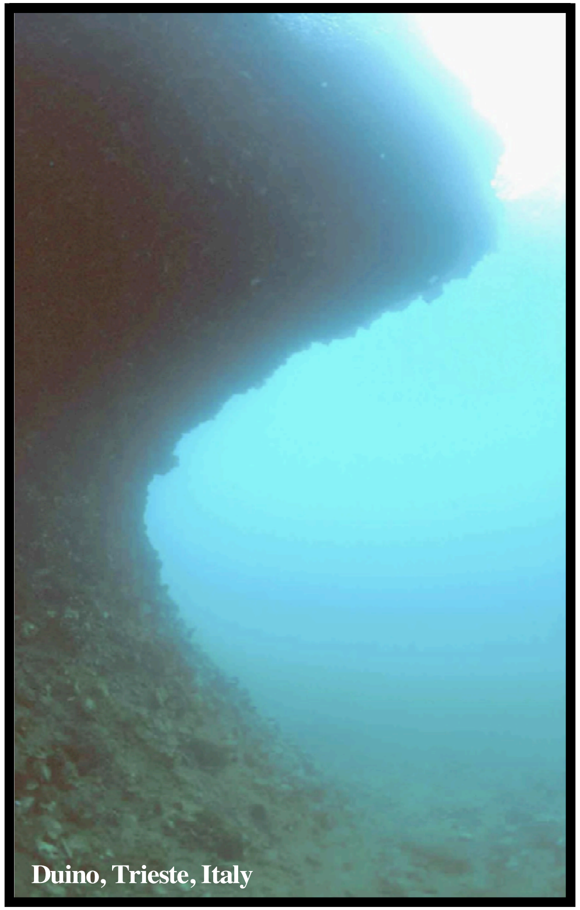


Uplift (Relative Sea Level Fall) induced, mainly, by Post-Glacial rebound after the last Ice Age

Raised beaches, characterized by being above the range of action of the present marine agents, mark the old sea levels and, particularly, the spring high tides (occur twice each lunar month all year long, without regard to the season, when this happens, the bulge of the ocean caused by the sun, partially, cancels out the bulge of the ocean caused by the moon) underline, more or less, old shorefaces. Marine regressions are, mainly, induced by rising continents (isostatic equilibrium due to melting of glaciers and ice caps). They are formed during the highstand of interglacial times. Similar displacements are well known in Norway's onshore, where relative sea level falls were induced the isostatic rebound following Quaternary glaciation. Marine terraces are bench-like features found in many actively uplifting coastal settings and are an indicator of sea level in a distant past. Paleosea level is approximated by the inner-shoreline elevation were a terrace abrasion platform meets a paleosea cliff. Stability periods of sea leve provide the requisite length of time for wave action to cut terraces leaving behind depositional remnants of the paleoshoreline.

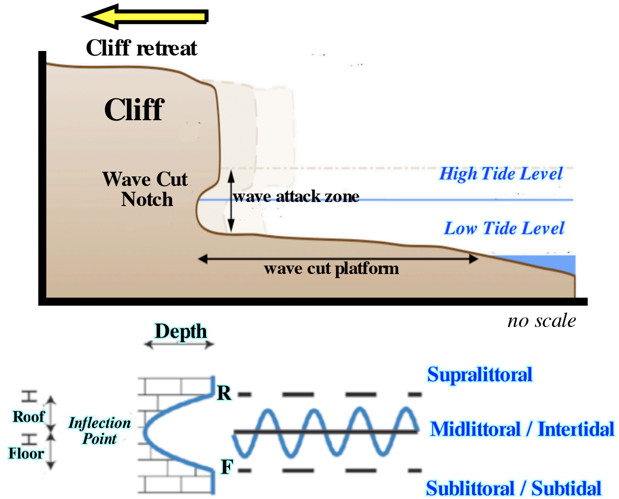
Absolute Sea Level Rise

Submerge Tidal Notches



CCramez, adapted from
http://people.rses.anu.edu.au/lambeck_k/pdf/265.pdf

Formation of a Tidal Notch & Wave cut Platform



Ccramez, adapted from
https://www.internetgeography.net/topics/cliffs-wave-cut-platforms/

The past sea levels relies, largely, on the interpretation of sea level indicators, as paleotidal notches, which are considered one of the most precise sea level indicators, since their formation is closely tied to the local tidal range. The photo on the left, illustrates the submerged tidal notch at 2.2 meters below sea level in Duino (Trieste, Italy). The photo on the right illustrates the tidal notch (0.8 meters sea level) found at Rovinj in Croatia. Both are excellent proofs of a recente relative sea level rises, in which the eustatic factor was, largely, preponderant over the tectonic factor. As depicted in the sketch at the right of the photos, in the formation of a wave cut platform (narrow flat area often found at the base of a sea cliff created by erosion, obvious at low tide) the sea weares a wave cut notch through hydraulic action and abrasion, particularly, on the wave attack zone associated mainly with the high-tide. The backwash transport material from the base of the cliff forming a wave cut platform. The weight of the an unsupported cliff causes it to collapse. Weathering (chemical, biological and freeze-thaw) weakes, also, the top of the cliff.

As the major processes controlling sea level changes are: (i) Epeiro-Eustasy, subsidence/uplift of the sea floor, as glacial isostatic rebound ; (ii) Tectono-Eustasy, volume variations of the oceanic basins ; (iii) Glacio-Eustasy, oceanic net mass change related to an increase/decrease of ice sheets and glaciers ; (iv) Geoidal-Eustasy, water distribution caused by changes of the Earth's gravity field induced or the opposite ; (iv) Steric-Eustasy (thermosteric, i.e., changes of ocean water temperature or halosteric, i.e., changes of the ocean water salinity, the volume increases by a small factor, but the mass increases by a bigger factor) and (v) Ocean-Eustasy associated with variations of wind-driven or buoyancy-driven ocean circulation. Global changes seem determined by tectono-eustasy, glacio-eustasy and steric-eustasy, while local changes seemrelated to geoidal-eustasy and ocean-eustasy. Neither of these processes change the mean sea level. They just redistribute the water mass, within the ocean. Sea level rises in one area while falling in another, leading to an uneven change of local sea level (https://www.nature.com/articles/s41467-018-03474-8)

Sea Level Change Factors

Assuming the amount of water, under all its forms, is constant (excluding the water's varitions associated with the orbital perturbations), since the Earth's birth, the main factors of sea level changes are:

A) Volume of Oceanic Basins

- Mid-Oceanic Ridges Volume ;
- Oceanic Trenches ;
- Sedimentation ;

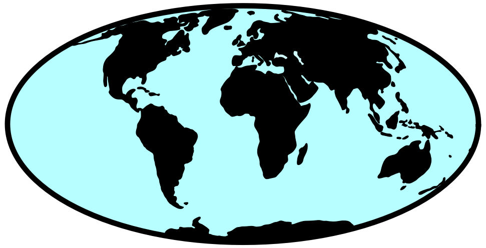
B) Total Volume of Ocean Waters

- Glaciations ;
- Hydrosphere Volume ;
- Bassin Dessication ;
- Average Temperature of Oceans ;
- Atmosphere Water Steam ;

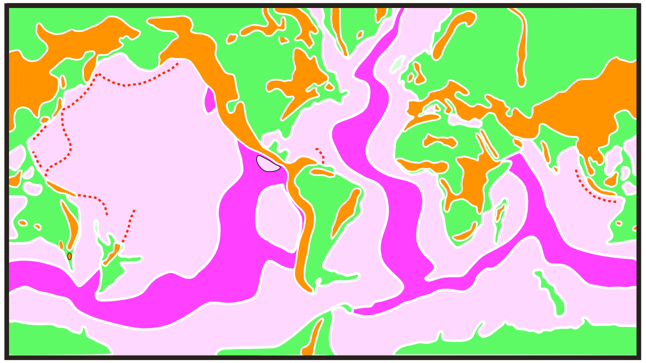
Some os these factors, particularly, those affecting the volume change of oceanic basin are long-term factors, i.e., they require require a lot of time for its realization. This is the case, for instance, for changes in volume of the mid-oceanic ridges, which control the volume of the oceanic basins during a Wilson's cycle. In fact, about 400 My (million years) are need to destroy and aggregate a new supercontinent. In a Wilson's cycle: (i) ± 120 My seems to be needed to accumulate heat heat under a supercontinent to breakup it into several continents ; (ii) The continent move away from each other with formation of oceanic ridges in deep sea floor ; (iii) ± 200 My later, the continents reach the maximum of dispersion and finally, (iv) the continents collide to, eventually, form a new supercontinent. Other parameters as bassin dessication or the changes of average temperature of the ocean and the glaciations can be considered short term and, often, local, while others as the changes in atmospheric water steam and the hydrosphere volume are considered as instantaneous (in geological terms), often associated with climate pulsations.

A.1) Mid-Oceanic Ridges Volume

Present Time (0 Ma)

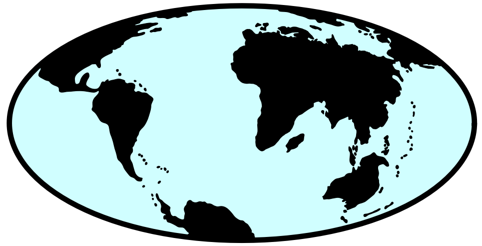


Present Morphology of the Earth

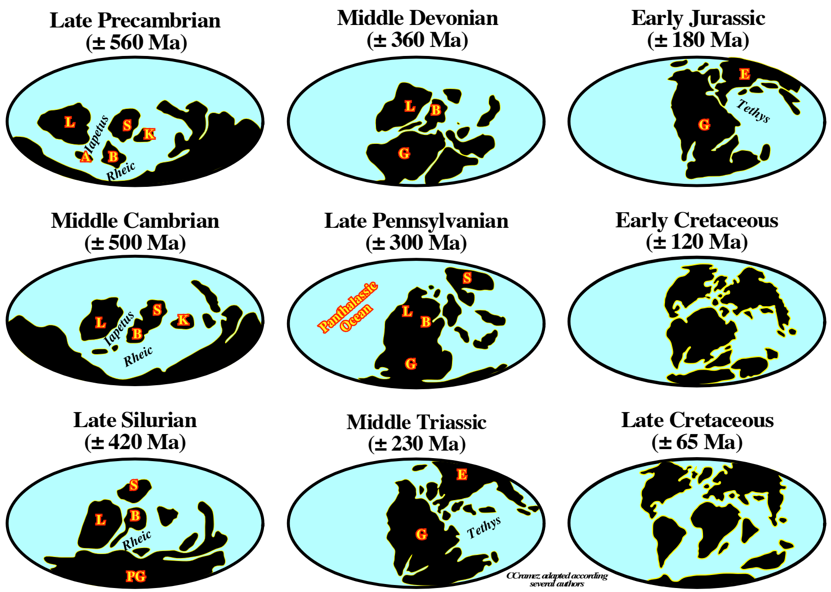


Platform / Slope (30%) Oceanic Mountains (23%) Oceanic Floors (35%) Fold Belts (12%)

In ± 50 million years



At Late Proterozoic, Precambrian supercontinent (Rodhinia) brokeup. At Late Pre-cambrian (± 560 Ma), Laurentia & Baltica detached from the supercontinent: 1) Baltica began to separate from Laurentia; 2- Iapetus & Rheic seas opened. At Middle Cambrian (± 500 Ma), the drifting of Laurentia & Baltica was at its maximum. At Middle Ordovician, Laurentia collided with South America (Taconian Orogeny). At the end the Ordovician, Laurentia became, again, individualized. Formation of Proto-Gondwana. At Middle Silurian, Baltica collided with Laurentia. Formation of old red sandstones continent. At the beginning of Permian, there was a collision between the Laurentian / Baltica continent and Gondwana. Pangea was surrounded by a universal ocean - Panthalassa, which may be considered as the ancestor of the Pacific, while Tethys Sea, between Gondwana and Eurasia, is the ancestor of a part of Mediterranean Sea.

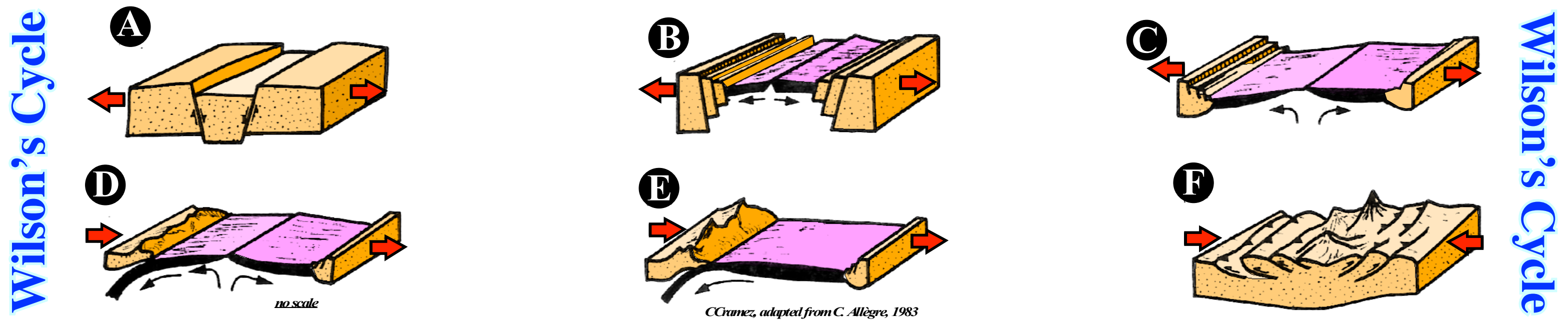


Laurentia- L Baltica- B Siberia- S Kazakstania- k Proto-Gondwana- PG Gondwana- G Avalonia- A Eurasia- E

The breakup of Pangea was announced by the formation of rift-type basins and volcanic flows. At the beginning of the Jurassic (± 180 Ma), Atlantic Ocean opened, partially. Tethys Sea began its closure. Laurasia separated from Gondwana creating a new ocean. India began its long journey to the North. At end Jurassic (±, 140 Ma): (i) Birth of South Atlantic Ocean; (ii) North Atlantic and the Indian Ocean expanded; (iii) Tethys Sea continued to close; (iv) India continued to migrate north. At end Cretaceous (± 65 Ma): (a) South Atlantic Ocean was largely developed ; (b) Madagascar separated from Africa ; (c) Tethys Sea closed creating an internal sea, the Medterranean ; (d) At this time, the current configuration of the continents was perceptible. Since the end Cretaceous: India collided with Asia, Australia separated from Antarctica and Africa moved closer to Europe which led to the Alpine Orogeny.

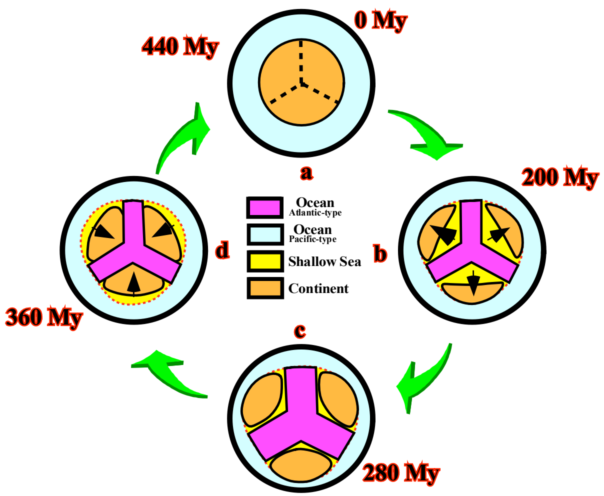
The present morphology of the Earth strongly suggest the surface of the oceanic floors (35%) and oceanic mountains (23%) in relation to the total surafce of the Earth. Knowing the amplitude of the oceanic mountains can be over 7,000 meters, it is evidence that the volume of the oceanic mountains is a primary parameter of the absolute sea level. The schematical dance of the continents since the break-up of the Rodhinia till Present time, with openings and closures of oceans in response to drifting and continent collisions try to show the volume of the oceanic mountains (oceanic ridges) strongly change during the Earth's history and so the absolute sea level. The volume was minimum at the time of the supercontinents (Rodhinia or proto-Pangea and Pangea) and maximum when the continents were further away from each other. Consequently, for a constant aumont of water (under its all forms) is possible to predict that at the time of the supercontinents (small number of lithospheric plates) the absolute sea level was very low and very high when the number of lithospheric plates was maximal (maximum sea floor spreading).

A.1.1) Wilson's Cycle & Supercontinents



Evolution of a Supercontinent

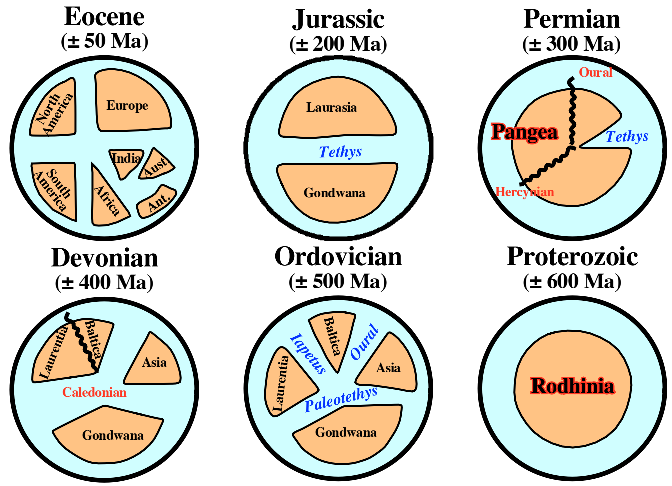
Ccramez adapted from D. Nance et al., 1988



About 400 My (million years) of years would be needed to destroy and collect a supercontinent: a) At least 120 My seems to be needed for accumulate heat under a supercontinent to fracture it into several continents ; b) The continents are moving away from each other ; c) About 200 My later, the continents reach the maximum of dispersion ; d) The continents are approaching to eventually form a new supercontinent.

Phanerozoic Supercontinents

Ccramez adapted from P. de Wever & F. Duranthon, 2015

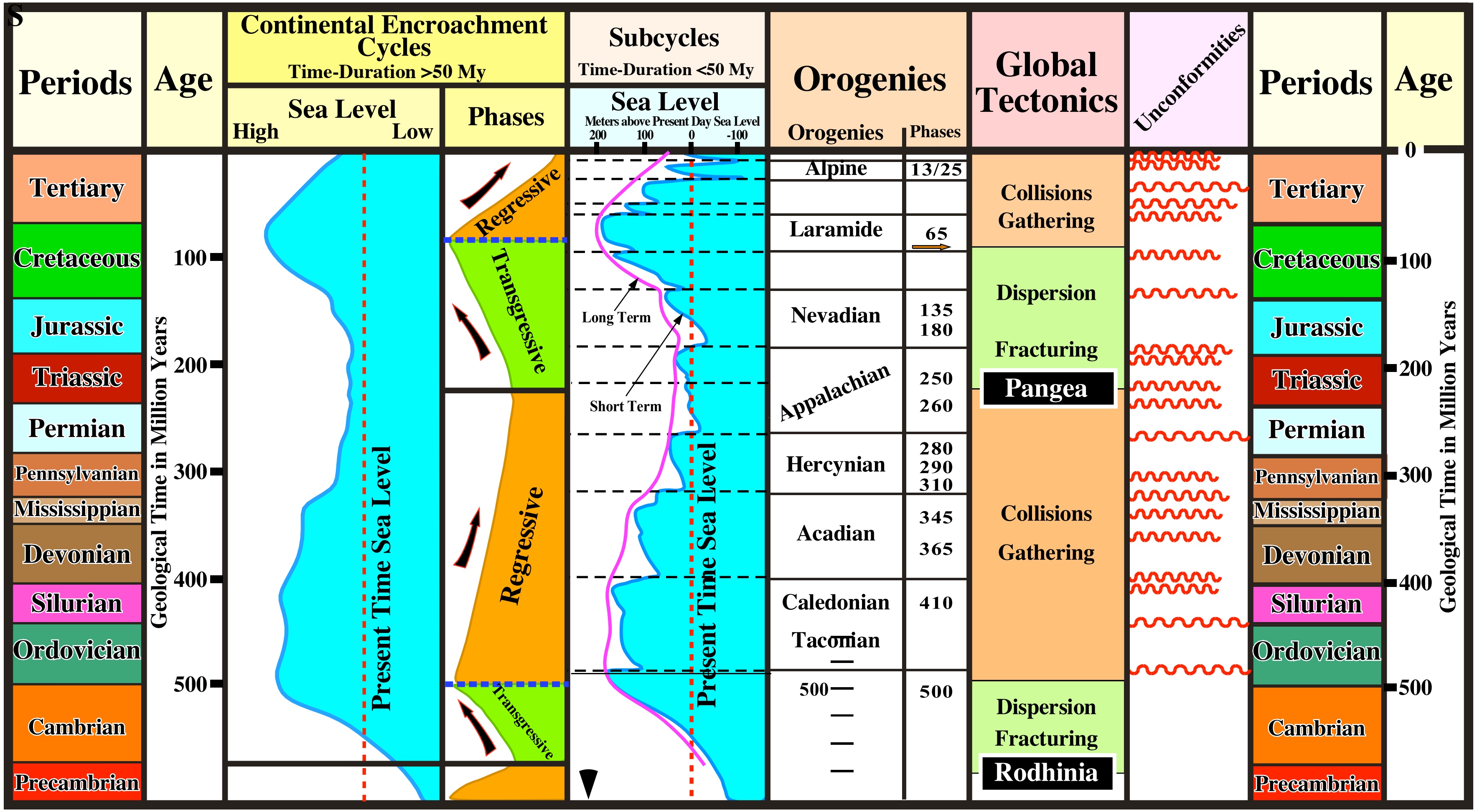


The Rodhinia break-up individualized the Gondwana, Laurentia, Baltica and Asia isolated by three oceans: Paleotethys, Iapetus and Oural. Laurentia and Baltica collide (Caledonian orogeny). In Permian, Pangea formed, by gathering of Gondwana, Laurentia and Asia with formation of Hercynian and Oural Mountains. The break-up of the Pangea individualize Gondwana and Laurasia separated by the Tethys Ocean.

The consequences of a Wilson's cycle can be summarized as follows: (i) The breakup of a supercontinent and the dispersion of its fragments (continents), due to the oceanic expansion, produces changes in the volume of the ocean ridges, which induces long term sea level chnages ; (ii) The dispersion of the continents, individualized by the breakup of the supercontinent, decreases the volume of the ocean basins which, for a constant amount of water, forcing the sea level to rise ; (iii) The decrease in the volume of ocean basins is the consequence of the setting up of oceanic ridges associated with the oceanic expansion (iv) As soon as the continents begin to come together to assemble a new supercontinent, the volume of ocean basins increases ; (v) The increase in the volume of ocean basins induces the fall of the sea level (eustatic fall) ; (vi) The decrease in the volume of the ocean basins is due to the subduction of the crust along subduction zones (B and A subduction-types). The Roddhinia breakup individualized the Gondwana, Laurentia, Baltica and Asia isolated by three oceans: Paleotethys, Iapetus and Oural.

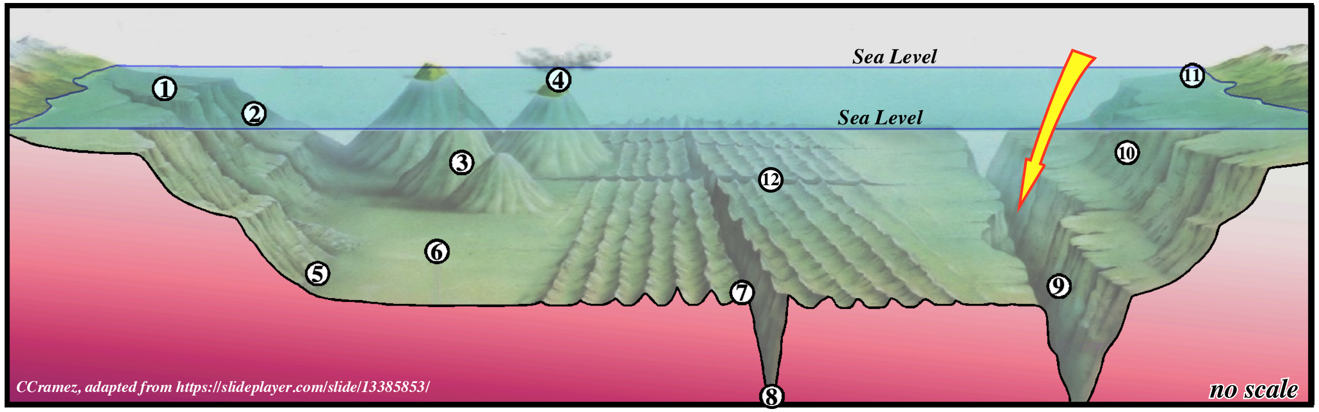
A.1.2) Eustasy & Orogenies

Potential Correlation between Supercontinents, 1st & 2nd order Eustatic Cycles and Global Tectonic Movements (Orogenies)

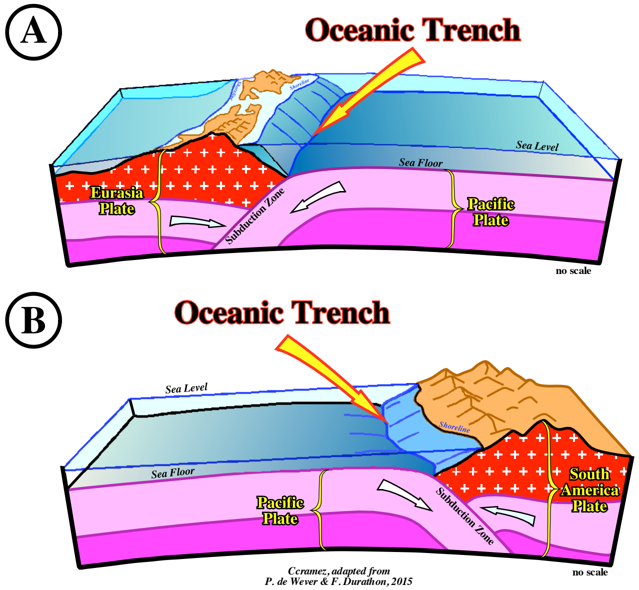


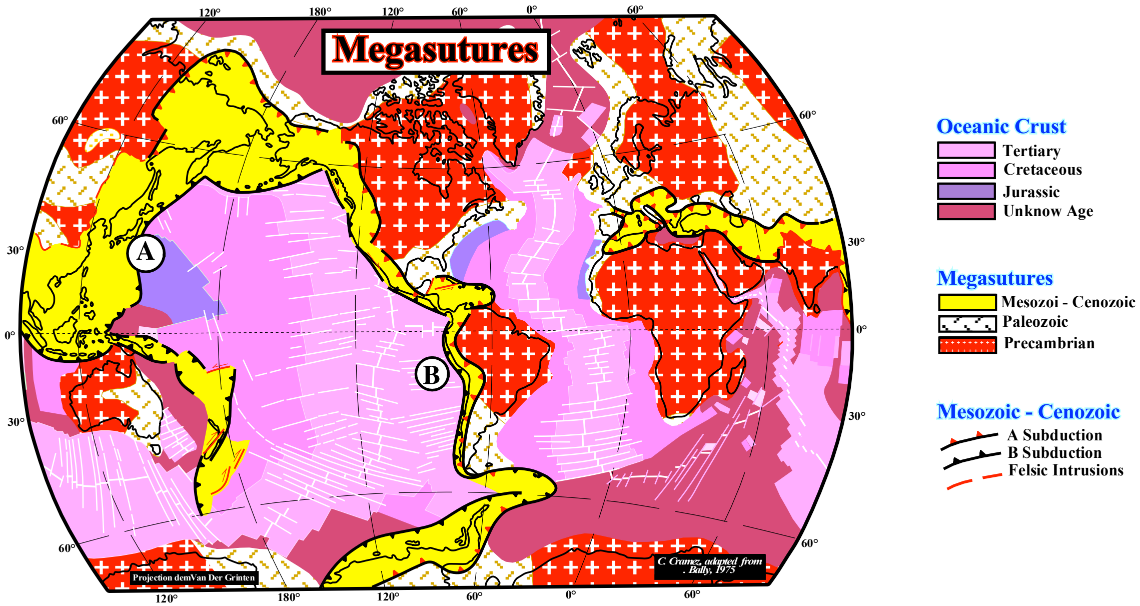
The rise of the sea level during the Triassic / Late Cretaceous and the eustatic fall since the Late Cretaceous (second Phanerozoic 1st order continental encroachment eustatic cycle), can easily be explained, as a consequence of the dispersion and collision of the Meso-Cenozoic continents (resulting from the break-up of the supercontinent Pangea), since the volume of the ocanic basin decreases (increasing of oceanic ridges), more or less, until the Cenomanian / Turonian and then, globally increases (predominance of lithospheric collision) to the Present. The same can be said to lower 1st order Phanerozoic continental encroachment cycle (rising till the Ordovician followed by a more or less continuous fall up to the formation of the Pangea supercontinent. It seems there is a correlation between Wilson's cycles (formation of the supercontinents) and the eustatic cyles with a time-duration higher 50 Ma (1st order). A similar correlation can be advanced between the global tectonic movements (Orogenies) and the continental encroachment eustatic subcycles (time-duration between 3 and 50 million years).

A.2) Oceanic Trenches



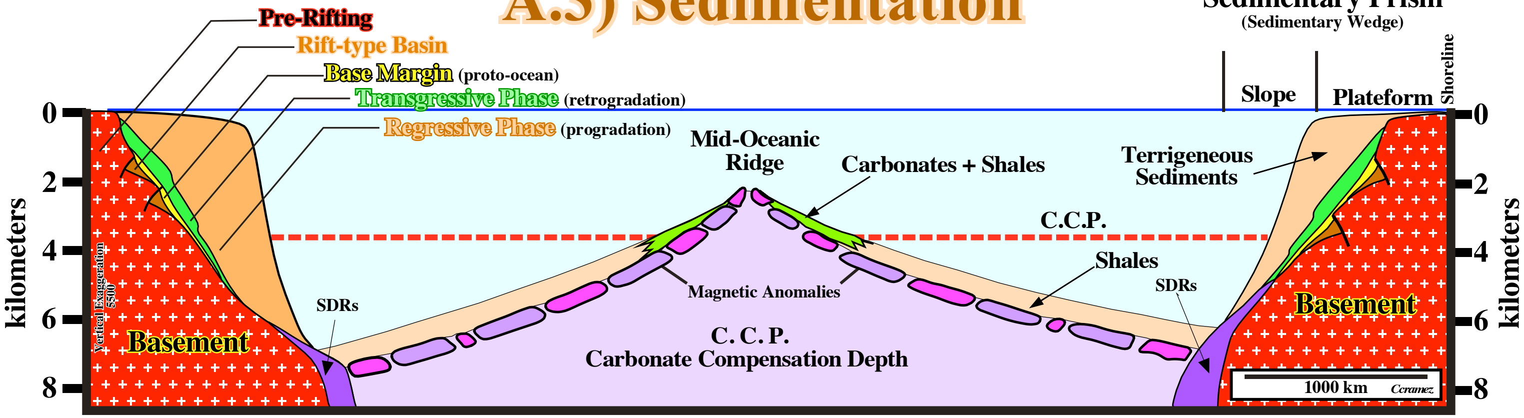
1- Continental Shelf ; 2- Continental Slope : 3- Seamount : 4- Volcanic Island ; 5- Continental Rise ; 6- Abyssal Plain ; 7- Mid-Oceanic Ridge ; 8- Valley Rift ; 9- Oceanic Trench ; 10-Continental Slope ; 11- Continental Shelf ; 12- Transform Fault





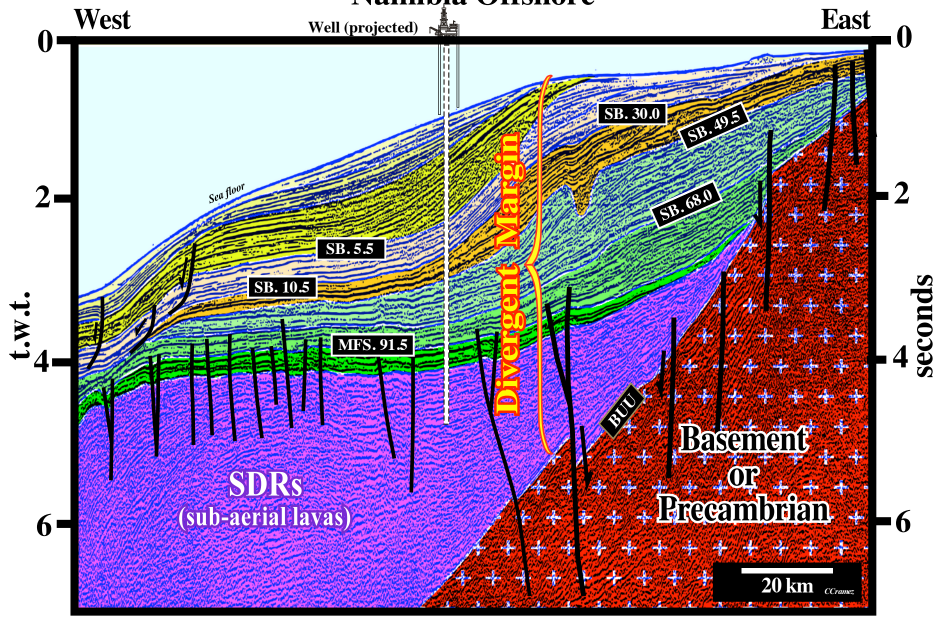
As illustrated above and in previous plate, assuming that ocean water is removed, the present morphology of the Earth's surface consists of five morphological sets: (i) Folded chains (12%) ; (ii) Oceanic mountains (23%) ; (iii) Ocean floors (35%) ; (iv) Platforms / Slopes (23%) ; Ocean trenches (< 1%). Folded chains are associated with subduction mechanisms. There are two different subduction types. B-Type subduction (Benioff), when the plunging lithospheric plate is oceanic and A-type subduction (Ampferer) when it is continental. Oceanic mountains, which are linked to the ocean ridges, are the result of sea floor spreading mechanism. The height of these mountains decreases away from the mid-oceanic ridge. The faster the sea floor spreading, the more marked the bathymetry. Ocean floors are directly related to oceanization and thermal subsidence induced by cooling of the new oceanic crust. The platforms / slopes are associated with the sedimentary accretion of the continents. Ocean trenches induced by the subduction of the diving plates, may reach depths higher than 10,000 m, as it is the case of Mariana trench (11,034 meters).

A.3) Sedimentation



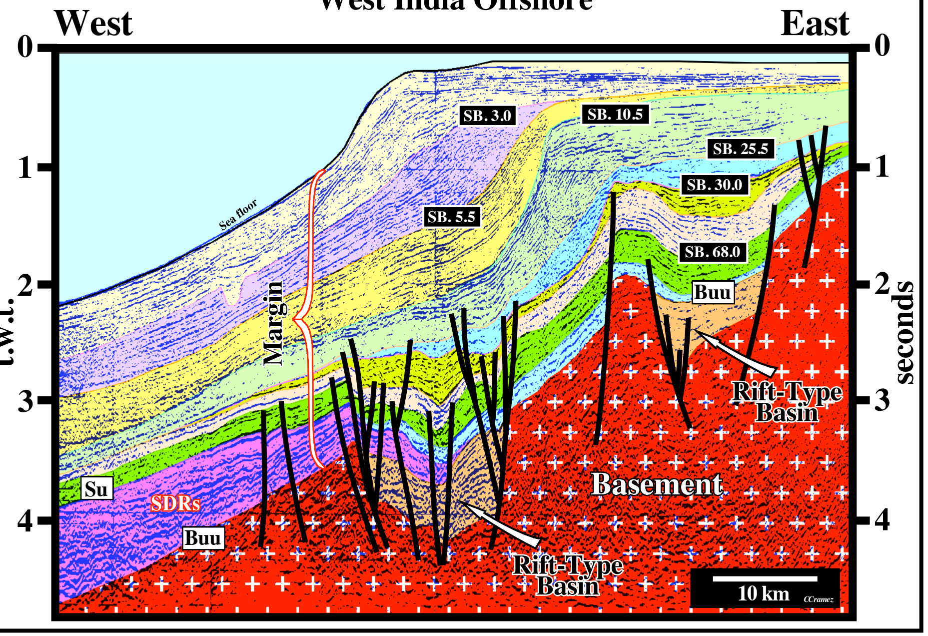
Sedimentary Wedge

Namibia Offshore



Sedimentary Wedge

West India Offshore

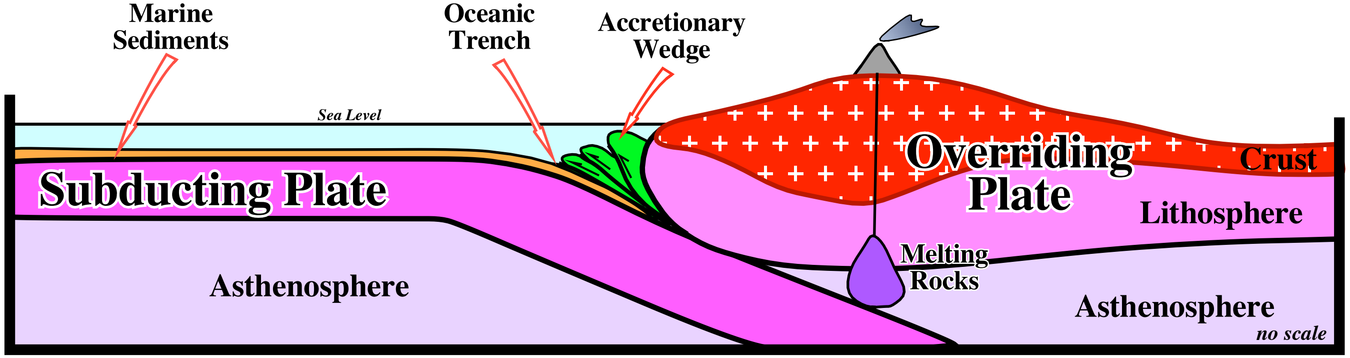


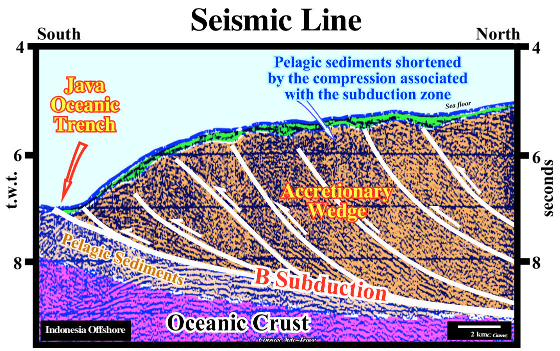
Since the break-up of a supercontinent, the individualized continents are separated by sea floor spreading, associated with a mid-oceanic ridge, at same time that the seaward margin is accreted by subaerial lava flows (SDRs) and a sedimentary wedge. This is particularly true on continental margin divergentes as illustrated, on the sketch above, on whch the mid-oceanic ridge is above the carbonate compensation depth (C.C.P.). The volume of the subaerial lava flows, which can have huge thickness, as on Namibia and West India offshores, as well as the volume of the sedimentary wedge contributes, largely, to the reduction of the volume of the oceanic basins, which has an obvious implication in the position of the absolute sea level. In the sedimentary wedges, during a marine ingression (relative sea level rise), the space available for the sediments increases, particularly, landward of the basin edge (shelfal acommodation). Later the space available can be total or partially filled. In the first case the water column above the sediments stays constant, while in the second (low terrigeneous influx) the height of the water column increases.

A.3.1) Accretionary Wedge

Geological Model

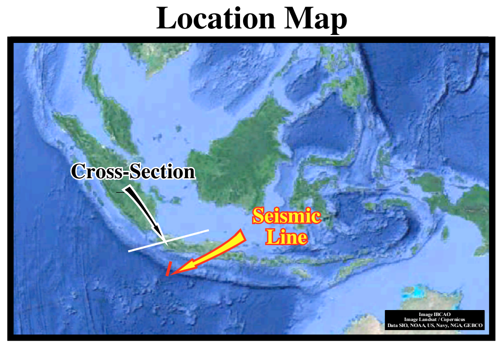
Accretionary Wedge
Oceanic Trench

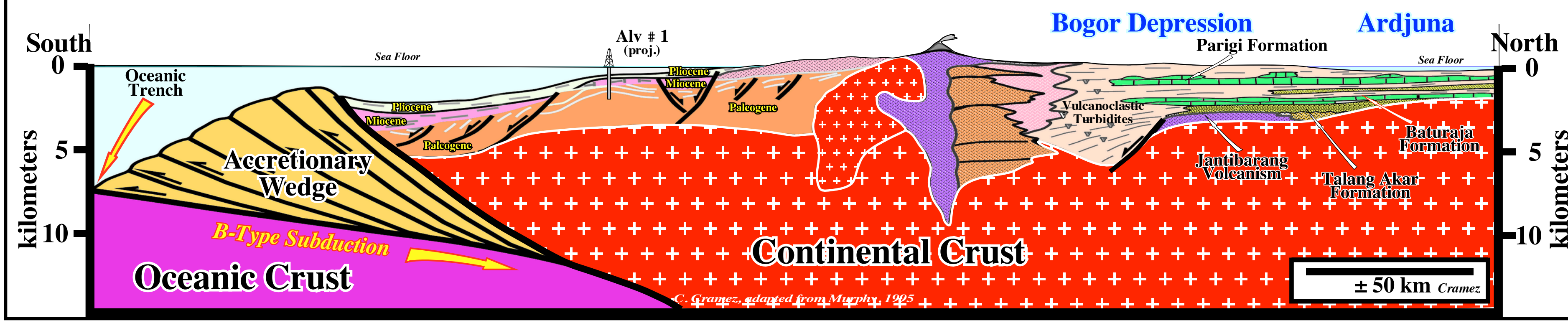




West Java Region Geological Cross-Section

(Indonesia)



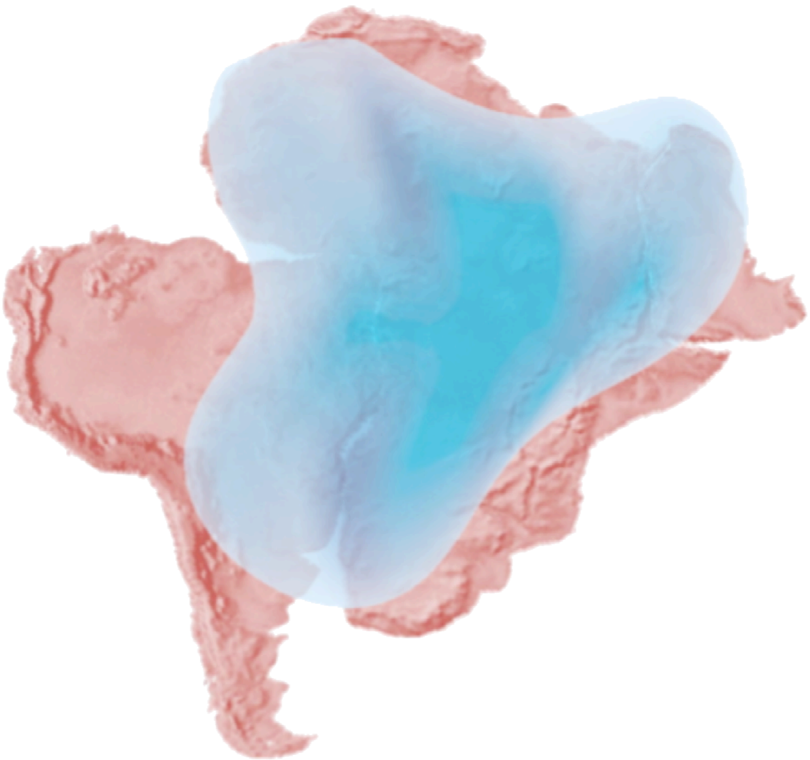


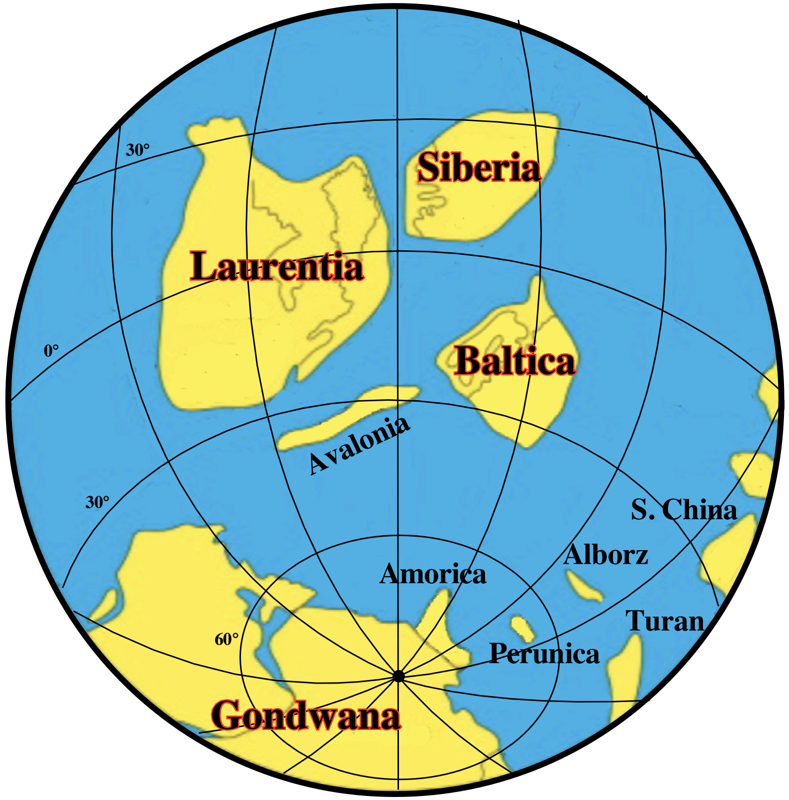
B subduction zones the basaltic slice and the sedimentary cover plunge into the mantle and warm up. When reaching the fusion temperature of the mixture (basalt + water + sediment) giving rise to volcanic magma, which being less dense than the mantle, it will tend to rise give birth to volcanoes at certain distance from the oceanic trench (function of the angle of subduction). When the speed of convergence between two plates and the absolute velocity of the overriding plate, towards the oceanic trench, are important, the sediments are shortened by folds and reverse faults: (i) in the forearc area, they are parallel to the plane of subduction, (ii) in the backarc area, their vergence is antithetical.The accretionary wedge develops in the area of the ocean trench and forearc. The sediment input is, normally, low. The accretionary wedge thickness is insignificant, but sufficient enough to allow the development of nested tectonic structures. When, exceptionally, the thickness of the accretionary wedge reaches 10-12 km, as illustratee above, the shortening mechanism can be accompanied by sedimentary creep with formation of clay diapirs.

B.1) Glaciations

Cold Paleoclimatic Phase with Ice Covered Continents

Late Ashgilian Glacial Cap





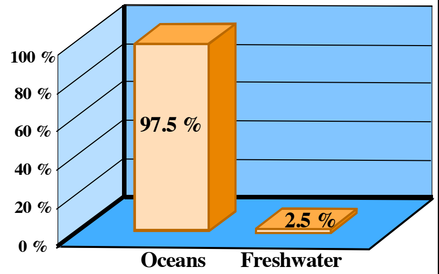
CCramez, adapted from
https://www.sciencedirect.com/science/article/abs/pii/S0031018213002745

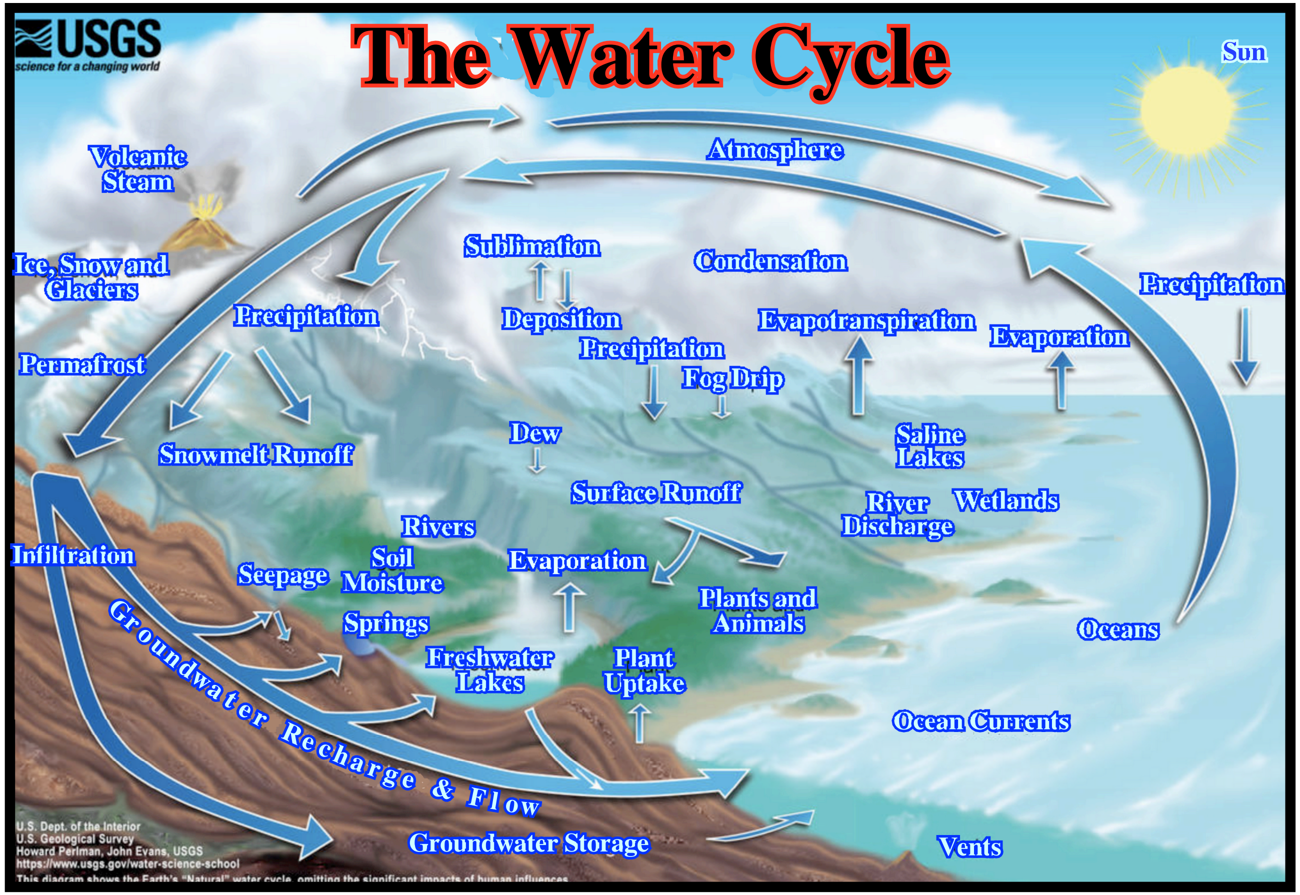
Probably, the displacement of the small supercontinent Gondwana towards the South Pole was one of the causes of this glaciation. The glaciation period seems to have ranged between 1 to 35 million years, which is, more or less, equivalent to the time of the tectonic displacement.

The geometry and extent of the ice cap during Late Ashgilian allows a prediction of the most likely position of the South Pole at that time. From the Protorezoicc, six major ice ages were recognized : (i) Proterozoic (± 2.7 Ga) ; (ii) Proterozoic (± 2.2 Ga) ; (iii) Precambrian (700-600 Ma); (iv) Ordovician (500-400 Ma); (v) Late Carboniferous (290 Ma) and (vi) Pliocene - Pleistocene (3-2 Ma). After the Pliocene-Pleistocene glaciation, the absolute sea level rose ± 130 meters. Glacio-eustasy, considered, sometimes, global and uniform cannot, in fact, be either global or uniform. Any significant variation in absolute sea level affects, also, the terrestrial geoid. During the thaw, in response to the load of water added to the oceanic basins, the absolute sea level will be depressed, and in response to the load removed, the continent will be lifted. Redistribution of material within the Earth is affected by overload and will further force variations of the surface of the ocean (induced by gravity anomalies), and thus further redistributions of water will be required to attempt to equalize gravitational potential.

B.2) Hydrosphere Volume

There are currently 1,385,990,800 km³ of water in the hydrosphere





The presence of water is a distinctive element of the Earth. The water of the oceans cover around 71% of the Earth's surface. The remaining 29% are land, in which water can be found in lakes, rivers, soil cover, underground and bound up in the composition of the Earth's crust and core. The biosphere and atmosphere also contains water without which life is impossible. Water exists in three states: liquid, solid and gas. When water freezes its molecules form a crystalline structure maintained by hydrogen bounding, whose orientation causes the molecules to push farther appart lowering the density. Due to the energy of the electromagnetic radiation coming from the sun, the water is in permanent transformation from one state to another and in constant motion between oceans, land, atmosphere and biosphere. The estimated amount of water contained in the hydrosphere (average over a long period of time) is 1,386 M km³ (97,5 % salt water and 2.5% freshwater). Freshwater encompasses: (i) 1.74 % ice and snow ; 0.75 % groundwater ; 0.0066 % lakes ; 0.0002 % rivers ; 0.0009% atmosphere ; 0.0001% biosphere.

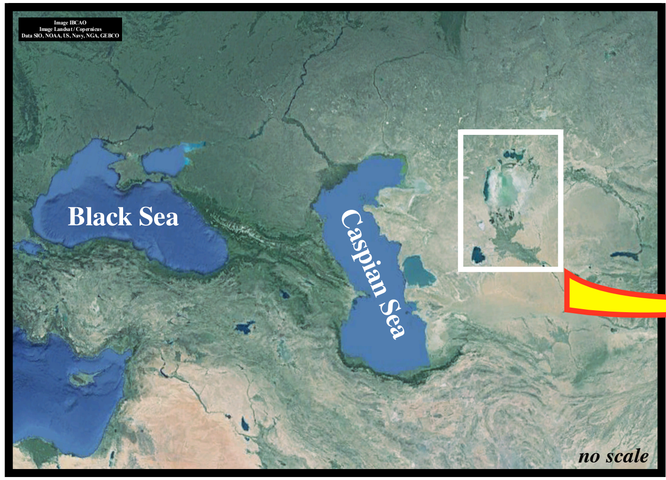
B.3) Bassin Dessication

Messinian Salinity Crisis

Mediterranean Sea Today

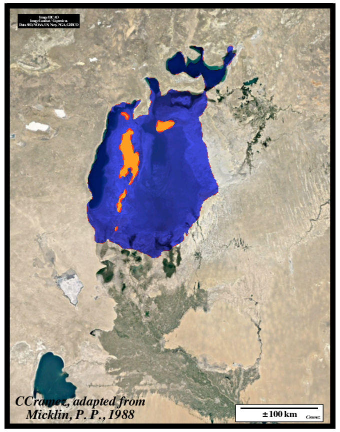
Mediterranean Sea between ± 5.9 / 5.3 Ma

Location Map

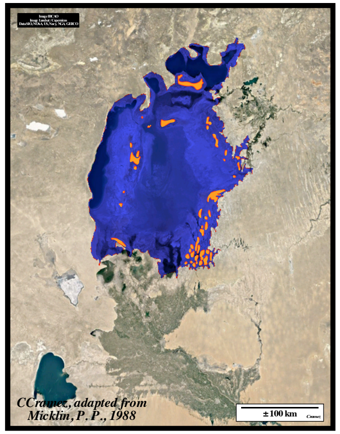


Aral Sea Anthropic Dessication

2018



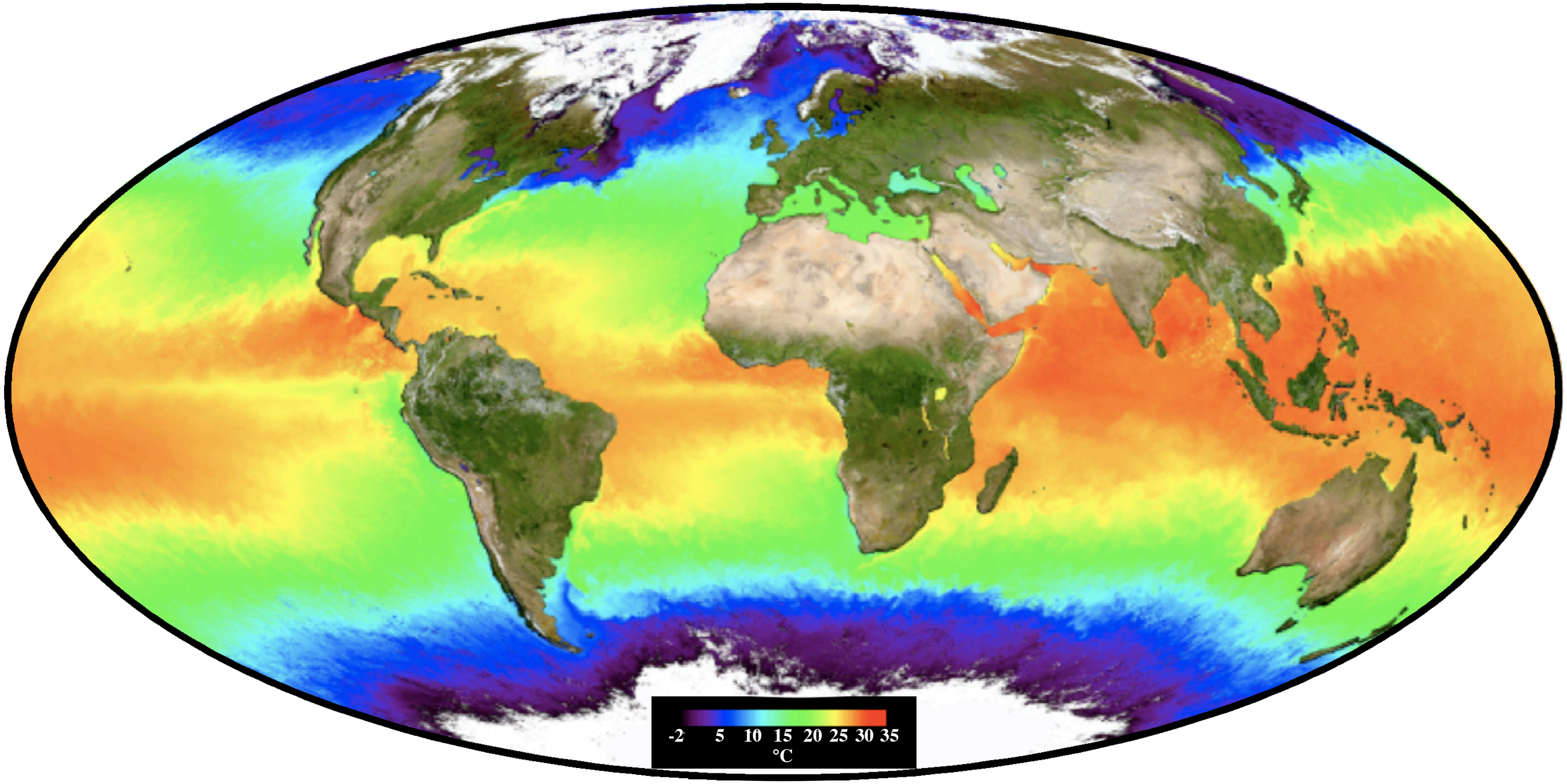
1968



1960

The Messinian drying of the Mediterranean sea seemsrather of tectonic origin than a consequence of the Plio-Pleistocene glaciation. It was, probably, due to the gradual closure of the Strait of Gibraltar as a result of the northward movement of the lithospheric African plate. This closure prevented eustatic rebalancing with the Atlantic Ocean and led, locally, to to a drop in sea level of about 1,500 to 2,500 meters. At the rate of 3,300 km³/year of net evaporative loss, the Mediterranean basin (3.7 Mkm³) dried up roughly in 1,000 years, leaving a salt layer with some tens meters thick (decreasing the average salinity of the the world ocean and rising its freezing point) and rising the absolute sea level around 12 meters (the evaporated water reached the oceans when it fell as rain or snow). **The Aral Sea, formerly the world's fourth largest lake in area, is disappearing. According to Micklin, P. P., (1988), between 1960 and 1987, its leve.l dropped nearly 13 meters, and its area decreased by 40 percent. Recession has resulted from reduced inflow caused primarily by withdrawals of water for irrigation.**

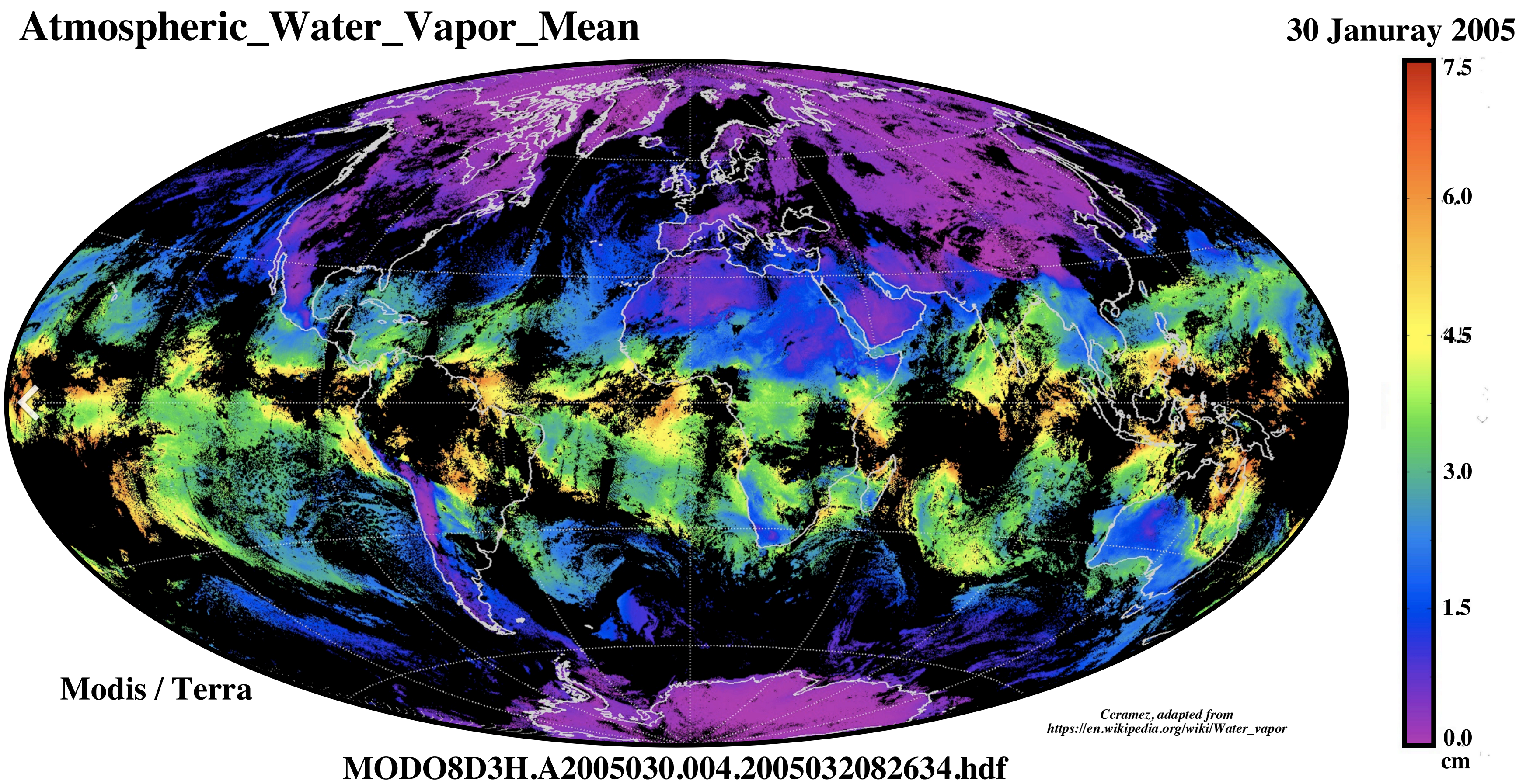
B.4) Average Temperature of Oceans



The steric (arrangement of atoms in space) sea level rise or thermal expansion of the oceans is an important component of the absolute sea level changes. In fact, if the temperature of the oceans increases, the density of the water decreases and, for a constant mass, the volume increases.

Steric sea level changes are caused when variations in the density of the water column imply an expansion or contraction of the column. It is produced, essentially, through surface heating/cooling. The Earth temperature rise seems, mainly due to accumulation of heat-trapping induced by greenhouse gases (> 90 % of the trapped heat is absorbed by the oceans). The water volume rises with temperature due to the tendency of matter to change in shape, area and volume in response to a change in temperature, through heat transfer (thermosteric effect). Rhein et al., 2013, estimated the rate of thermosteric sea level rise, from 1971 to 2010. It ranged between 0.4 - 0.8 m/y. This corresponds to a warming rate of 0.015° C per decade, in the upper 700 m of the global ocean. Temperature measurements of the sea surface (ships, satellites, drifting sensors), along with subsurface measurements and observations of global sea-level rise, suggest that this warming is, virtually, certain. A contribution to sea level rise of ± 0.1 mm per year by warming of ocean waters at depth, 700 to 2,000 meters, is considered likely, with about another 0.1 millimeter.

B.5) Atmosphere Water Steam



Atmospheric water vapour in atm-cm
(centimeters of water in an atmospheric column if it condensed)

The amount of water vapour in the atmosphere (± 99.13 % is contained in the troposphere) varies from place to place and from time to time, since the humidity capacity of air is determined by temperature. At 30 °C, a volume of air can contain up to 4 %. At -40 °C, however, it can hold no more than 0.2 %. The water vapour is, the most important and effective greenhouse gas owing to the presence of the hydroxyl bond (oxygen bonded to hydrogen, OH^-) which strongly absorbs in the infrared sector of the light spectrum). The energy of electromagnetic radiation received from the Sun heats the Earth's surface, which transfers it, under the form of heat, to the lower atmosphere, where it is absorbed by the water vapour molecules. Without atmosphere the temperature of the Earth's surface will be around -18°C (temperature of the Earth seen from space, out of atmosphere). Its condensation to the liquid or ice phase is responsible for clouds, rain, snow and other precepitation. The amount of energy released to the atmosphere during condensation is one of the most important factor in the atmospheric energy budget.