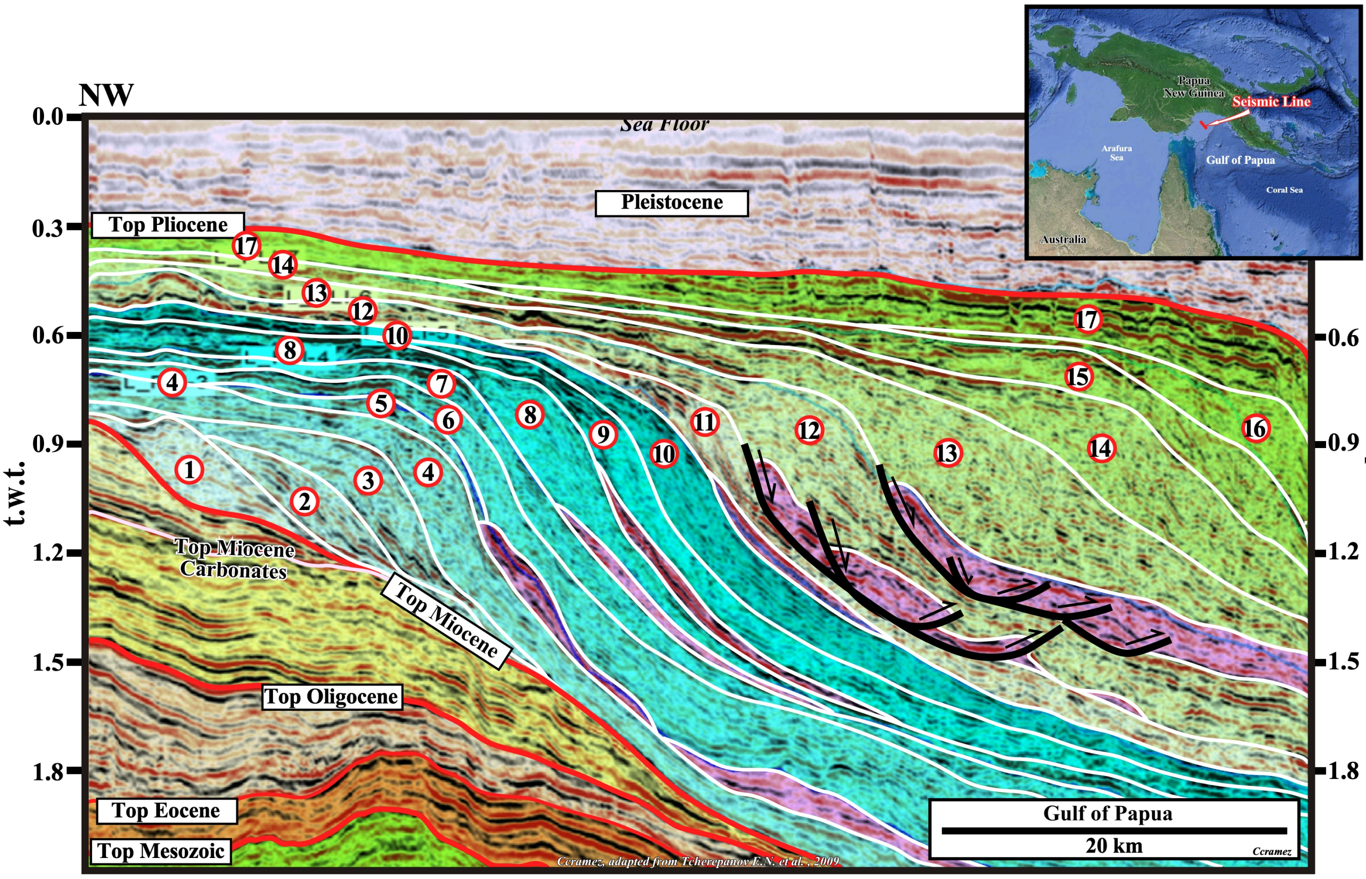
# Glaciation - Deglaciation Cycles & Carbonates




*Ccramez, 2022*

## Abstract

***According a lot of geoscientists a good understanding of sea-level changes during the deposition time of reservoir zones is essential in petroleum exploration. The eustatic sea level (absolute sea level) is not only a parameter of the climate system, but of the sedimentation as well. The Earth's climate has been cooling since, at least, the beginning of the Neogene. The cooling trend is punctuated by three steps, in which the cooling rate is higher: (i) Late Eocene–Early Oligocene (± 36 Ma), (ii) Middle Miocene (± 15.5 Ma) and (iii) Late Pliocene (± 3.0 Ma). The first is related with the onset of Antarctica glaciation. The Middle Miocene step is linked with a poor understood climatic transition. The Pliocene step is related with the expansion of Northern Hemisphere ice sheets. The glacial and interglacial periods associated with such a cooling steps have induced the building-up of prograding carbonate during the eustatic sea level rises caused by the deglaciations during the warm interglacial periods. The reservoir-rocks of certain hydrocarbon fields linked in Antarctica glaciation. They developed in Oligocene carbonate «undaforms» bounded by erosional surfaces (unconformities) created by absolute sea level falls induced by the maximum glacial periods. Such erosional surfaces often enhanced the petrophysical characteristics of the potential reservoir-rocks developed in «unda» depositional environments. However, the importance and the mechanisms of such a weathering enhancing are poor understood and must must be carefully studied.***

## Contents:



## 1) Long & Short Term Eustatic Curves

**The long and short term eustatic curves proposed by Jan Hardenbol et al., in 1998, which are supposed to depict absolute sea level[1] changes, show several time-periods (thousands to millions of years) of sea level lowstands during which the eustatic sea level is below the basin edges, induced by glacial weather conditions. Such sea level lowstand conditions favor a strong outbuilding of the geological formations (outward spreading) and mass transport deposits in deep water environment.**

**[1] Three main sea level types can be considered function of the reference surfaces taking into account and the points on which we desire to measure the sea level : (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 is the distance between such a point and the Earth's centre. The relative sea level, in a given point of the sea floor, is the distance between such a point and the sea level surface. The sea surface height, in a given point of the sea surface, is the distance between such a point of the ellipsoid of reference. The absolute sea level is dependent of four main factors : A) Tectono-Eustasy, B) Glacio-Eustasy, C) Geoidal-**

Eustasy and D) Steric-Eustasy or Thermal Expansion of Oceans. The relative sea level is the result of the combined action of the absolute (eustatic) sea level and the tectonics (subsidence or uplift of the sea floor). On seismic lines, a relative sea level can be 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.

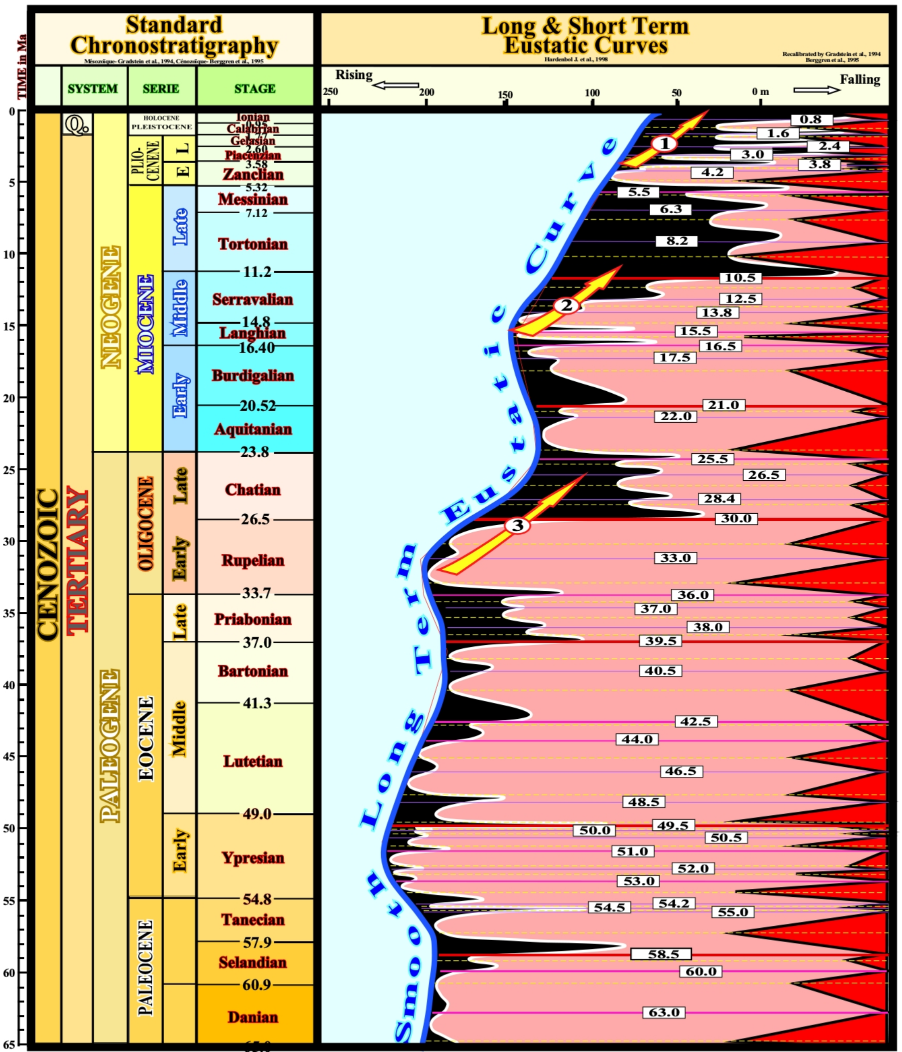
These time-periods are, easily, recognized on the sea level chart (Fig. 1) by rightward increasing (colored black areas), which emphasize an overall falling, in steps, of an absolute sea level. Within these time-periods, we find between the full glacial conditions (ice ages or glaciations[2]) and the subsequent warm interglacial conditions characterized by a global warming and sea level rise  created by changes in continental ice volume during the deglaciation periods.

[2] An ice age or glaciation is a long period of low in the temperature of Earth's surface and atmosphere resulting in the formation or expansion of ice sheets and sea-ices. There are two type of glaciations: continental and alpine. The first affects part of the continental land mass (e.g., the Antarctic inlandsis). The second is, generally, restricted to deep valley in high mountains with formation of glaciers (e.g., Aletsch Glacier – Valais, Southern Switzerland). Sea-ices arise as seawater freezes and floats on the ocean's surfaces. Contrariwise to glaciations, the formation or melting of sea-ices does not affect too much the sea level.

As illustrated on Fig. 1, during the Cenozoic, three glacial lowstand geological time-periods associated with significant climate changes are well known: (1) Plio-Pleistocene ; (2) Middle Miocene and (3) Oligocene.

These time-intervals, which can be considered as ice ages, are characterized by an overall falling, in steps, of the absolute sea level. However, from time to time, the temperature increases creating interglacial periods (duration of thousand years), which induce significant absolute sea

Absolute Sea Level Curves



**level rises (deglaciations) and subsequent deposition of depositional systems with a progradational geometry (outbuilding largely preponderant on upbuilding).**

***Figure 1- On the left is illustrated the standardc hronostratigraphy and on the right the long and short term eustatic curves (absolute sea level changes, i.e., Eustasy). Time-periods of glacial lowstand geological conditions are emphasized on the eustatic curves by significant absolute sea level falls, easily, recognized by the increasing black areas (red arrows). In fact, on the sea level chart, from top to bottom, three main lowstand geological periods can be considered : (1) Plio-Pleistocene, (2) Middle Miocene (Langhian, Serravalian) and (3) Oligocene, which are separated by time-periods during which the absolute sea level rises. They correspond to global climatic signals, underlined by a positive $\delta_{18}O$ shifts recorded in bulk carbonate records. Such $\delta_{18}O$ positive shifts seem to be associated with sea level fallings caused by glaciations. Stratigraphically, these time-intervals correspond, often, to progradational limestones unities deposited during the stability periods of the absolute sea level following the absolute sea level rises (deglaciations), which take place after the fallings of the sea level created by the glaciations.***

**The oxygen isotopic stratigraphy[3], based on $\delta_{18}O$ or $^{18}O/^{16}O$ (ratio of the numbers of oxygen-18 and oxygen-16 atoms in a sample) present in sea water, is function of time. It allows geoscientists to approach climate and sea level changes of the past geological times.**

**[3] The ratio (relative amount) of these two types of oxygen ($^{18}O$ and $^{16}O$) in the water varies with the climate. The proportion of heavy $^{18}O$ and light $^{16}O$ oxygen in marine sediments, ice cores or fossils, which is, generally, different from the accepted standard, indicates past climate changes. The scientific standard used for comparison is based on the proportion of oxygen isotopes in sea-water at a depth of 200/500 meters which, on a global scale, indicates warmer temperatures and melting and, on a local scale, indicates heavier rains. Evaporation and condensation are the two processes that most influence the ratio of oxygen isotopes in the oceans. Water molecules containing light oxygen evaporate a little faster than water molecules containing a heavy oxygen atom. Water vapor molecules containing the heavy oxygen ($^{18}O$) condense more easily.**

**On this notes, firstly, I'll concentrate in the Plio-Pleistocene glacial lowstand period, taking as example the Coral Sea (Gulf of Papua). Then, we will review the Eocene-Oligocene boundary and the Oligocene glacial lowstand period using Iraqi Kurdistan seismic lines (Fig.2).**

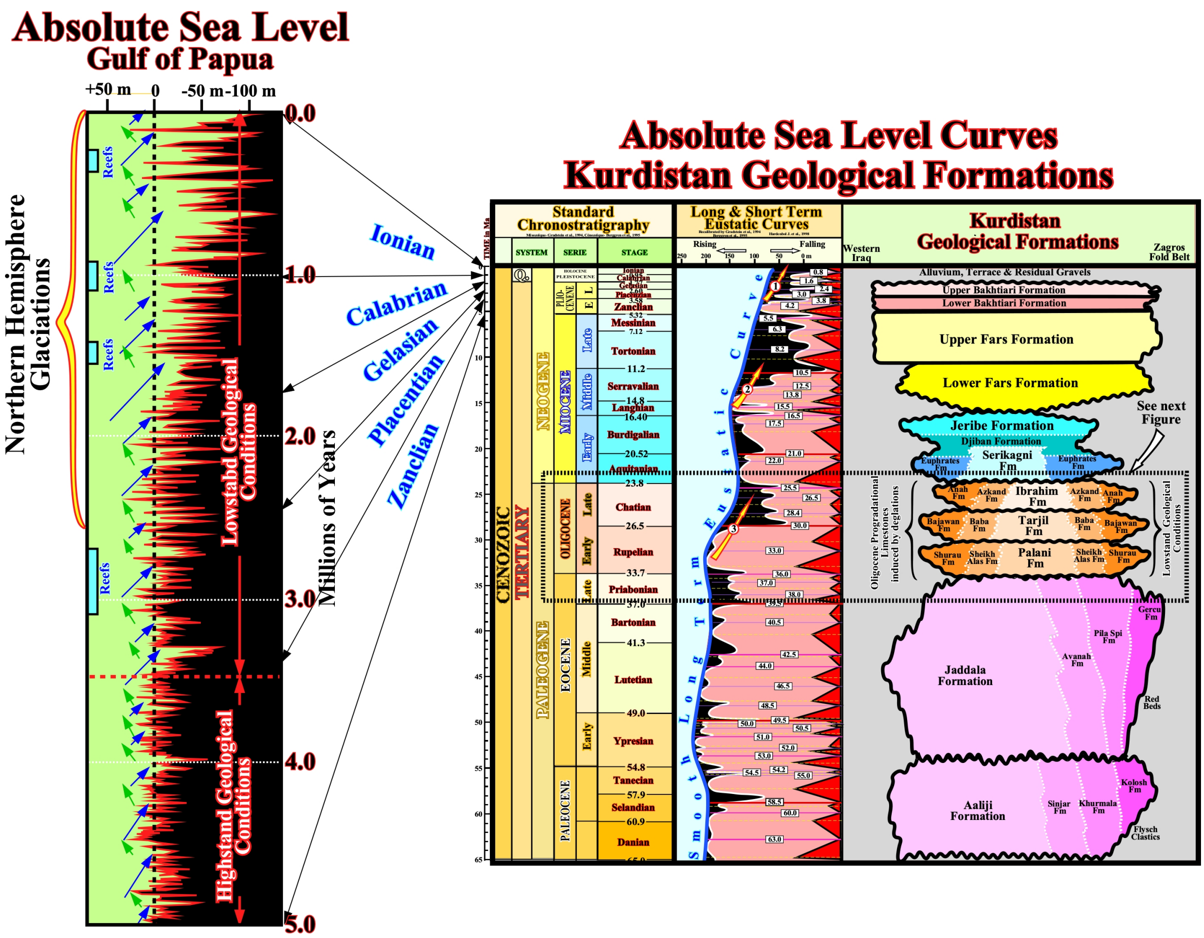



***Figure 2- On the left, the oxygen isotopic stratigraphy ($\delta_{18}O$ curve) illustrates the glacial Plio-Pleistocene period in Coral sea (Gulf of Papua), which is represented by the arrow (1) on the eustatic curves. The glacial Oligocene period, represented on the eustatic curves by the arrow (3), corresponds to Palani, Tarjil and Ibrahim Kurdistan deep-water geological formations and their associated Sheikh-Shurau, Baba-Bajawan, and Azkand-Anah shallow-water formations. These glacial sea level lowstands are***

*highlighted by $\delta_{18}O$ shifts induced by significant Earth's temperature coolings. On the $\delta_{18}O$ curve, the amount of $^{18}O$ increases, by steps, leftward emphasizing a set of increasing important sea level falls alternating with smaller and smaller sea level rises. These glacial sea level lowstands are highlighted by $\delta_{18}O$ shifts induced by significant Earth's temperature coolings.*

**However, previously, it is important to see how the oxygen isotopic stratigraphy works, just to show that geoscientists, contrariwise to environmentalists[4], explain their hypotheses, which are just falsifiable conjectures that can be corroborated or refuted by new data. A fact cannot verify a scientific hypothesis, it can only falsify it.**

[4] Politicians who use ecology as a punitive political weapon, that French geoscientists call «écologiste», since a scientific who studies ecology, in french, is an « écologue».

## 2) Oxygen Isotopic Stratigraphy

**In spite of the fact that the relative proportions of the isotopes[5] are, often, masked by the diagenetic alteration of sediments and the differentiation between primary and secondary isotopic proportions is difficult and controversial, the basic principle is that the proportions of some isotopes embedded in biogenic minerals such as calcite, aragonite, phosphate and others change with time in response to paleoenvironmental and geological changes.**

[5] An isotope is one of two or more varieties of a chemical element whose atoms have the same number of protons and electrons (even atomic number), but which have a different number of neutrons in the nucleus (different atomic weight).

**The isotopic oxygen stratigraphy is based on the oxygen isotope curve in which the relative proportions of $^{18}O$ and $^{16}O$ isotopes are projected (Fig. 3). Oxygen may exist in various forms, but only $^{16}O$ and $^{18}O$ are important in the analysis of the oxygen isotopes. Oxygen-16 or $^{16}O$ is a stable isotope of oxygen, which has 8 neutrons and 8 protons at its core. It is the most abundant isotope of oxygen (99% of the natural abundance of oxygen). It is not only the main product of stellar evolution but also a primordial isotope made by nucleosynthesis in stars that were originally made exclusively of hydrogen.**

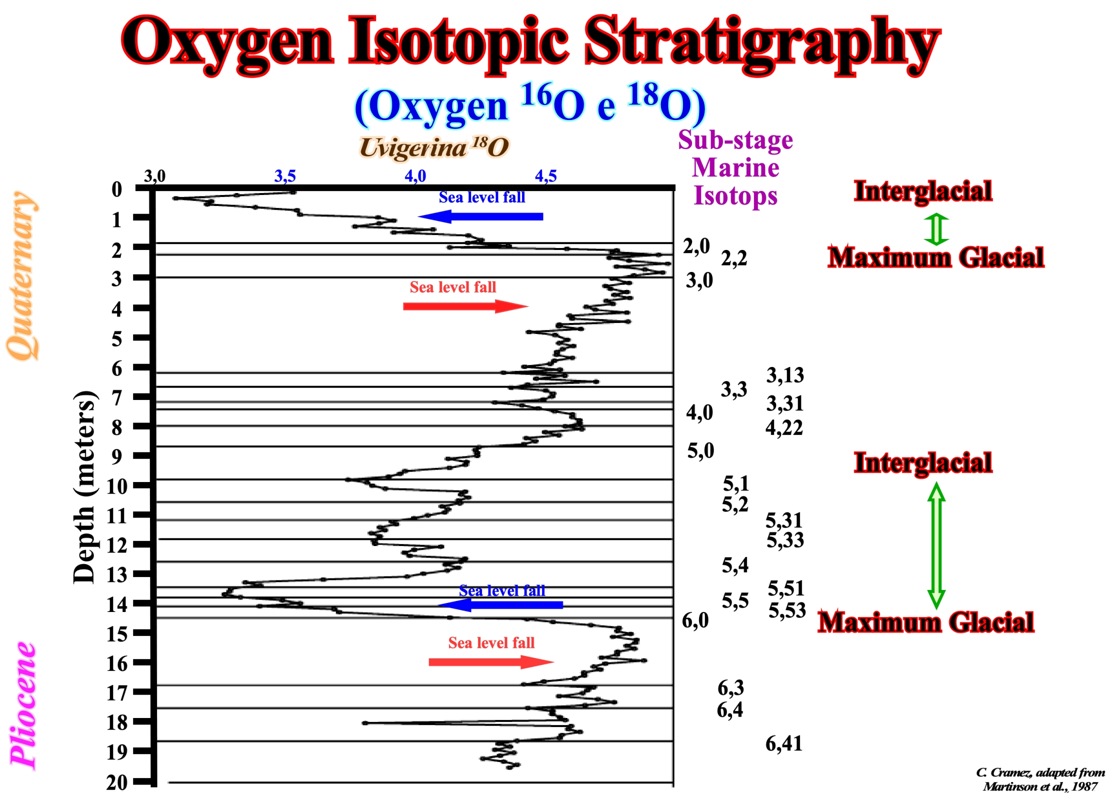



*Figure 3- Isotopic oxygen ($^{18}O/^{16}O$) stratigraphy, in depth, determined from the shells of the benthic foraminifera Uvigerina (ODP, Site 1014, Tanner geographic basin, California). The oxygen isotope data (horizontal lines) are numbered at sub-stages of the marine isotopes and correlated with the reference section (depth) of deep sea oxygen isotopes. The maximum glacials are much better marked than the associated interglacial. They corroborated the cyclicity of the absolute sea level changes.*

**The rate of abundance of these two isotopes gives various types of information about geological Past, such as the origin of water and the most probable temperature of the oceans. As at present time, the average rate of $^{18}O$ over $^{16}O$ is, more or less, 1 to 500, all measures are taken against this value, which is taken as a reference.**

**Geoscientists consider that the rate between $^{18}O$ and $^{16}O$ varied in the oceans is cyclic. It is a function of the alternation of the glacial and interglacial periods. The rate between $^{18}O$ and $^{16}O$ depends on the water temperature. The $^{18}O$ increases as the temperature decreases.**

**The oxygen incorporated in the calcium carbonate of the shells of marine organisms reflects the rate between $^{18}O$ and $^{16}O$. The acidification of the fossil shells releases oxygen, which allows to determine the temperature of the oceans in which the fossilized animals have lived.**

**During the peak of the last glaciation (Fig. 2), the deep-water was enriched by $^{18}O$ from about 1.6 parts per thousand (1.6 ppm), that is equivalent to an absolute (eustatic) sea level fall of about 165 meters in relation to the present sea level. Thus, it can be said oxygen isotopes can emphasize changes in ocean temperature and ice volume.**

**The oxygen isotopic stratigraphy made in the Cenozoic sediments and, particularly, the Quaternary sediment samples, using microfossils, suggested changes in ocean temperatures and ice caps thickness (Fig. 3). The separate effects of these parameters are distinguished comparing the isotope ratios in planktonic and benthic microfossils, mainly foraminifera.**

**As these parameters were, probably, induced by the Milankovitch cycles, it is possible to identify and correlate the isotope stages of oxygen globally. The$^{18}O$ curves provide a time scale (± 20 ka resolution) from the Quaternary to the Neogene. In pre-Cenozoic sediments, the use of oxygen isotopes is more limited because much of the carbonate is recrystallized and reflects, rarely, changes in isotopic proportions of oxygen.**

**Now that we known how the oxygen isotopic stratigraphy works, we can return for Fig. 1 and analyze the changes of the absolute sea level during the Neogene using the stratigraphic signature (Fig. 4) proposed by P. Vail and his students (1992).**

## 3) Neogene Stratigraphy Signature

**Let's start for place the Neogene eustatic changes in the Phanerozoic context. As illustrated on Fig. 4, two 1st order eustatic cycles lasting over 50 My (usually, around 240 My) and associated with the break-up and aggregation of supercontinents are evident in the Phanerozoic.**

**The first cycle induced what geoscientists call Paleozoic, i.e., the geological era between about 542 and 245 Ma, which follows the Neoproterozoic of the Proterozoic Era and precedes the Mesozoic Era. The second cycle induced the rock's deposits, commonly, called Mesozoic-Cenozoic.**

**These eustatic cycles are associated with changes of volume of the ocean basins during the aggregation and dispersion of the continents as Rodinia[6] and Pangea[7] supercontinents.**

[6] Rodinia supercontinent (from Russian "rodit"= growth) was formed around 1.1 Ga as a result of the Grenville orogeny. The Rodinia central part, on the equator, was occupied by Laurentia (North America and Greenland), surrounding Amazonia flanked by West Africa, Baltica, Siberia and the Indian craton associated with four Australian cratons and the Chinese craton. After the breakup of Rodinia, between 600 and 560 Ma was reconstituted the Pannotia supercontinent which, later, burst (around 540) to form Laurentia and Siberia, then Baltica at the very end of the Proterozoic opening the Iapetus Sea.

[7] Word from ancient Greek designating the world as it was 250 Ma, before the separation of the continents. Pangea designates the supercontinent that existed during the Late Paleozoic and Early Mesozoic eras. It assembled from the earlier continental units of Gondwana, Euramerica and Siberia during the Carboniferous ( ± 335 Ma), and began to break apart (± 200 Ma,) at the end of Triassic and beginning of Jurassic.

**In fact, assuming the volume of water, in all its forms, has been constant since the Earth formation (± 4.5 Ga), when a supercontinent break-up, the subsequent sea floor spreading (oceanic expansion) develops high submarine mountains (oceanic ridges) diminishing the volume of the ocean basins. Such a decreasing obliges the absolute (eustatic) sea level (supposed global and referenced to Earth's center) to rise flooding the distal parts of the continents.**
**On the contrary, since the rate of disappearance of the old oceanic crust along the subduction zones is not compensated by the formation rate of new oceanic crust, the volume of the ocean basins increases, causing a significant fall of the absolute (eustatic) sea level. Such a fall of the absolute sea level displaces seaward and downward the shoreline depositional systems, exhuming the continental platform (if the basin had a shelf) and the upper part of the continental slope.**

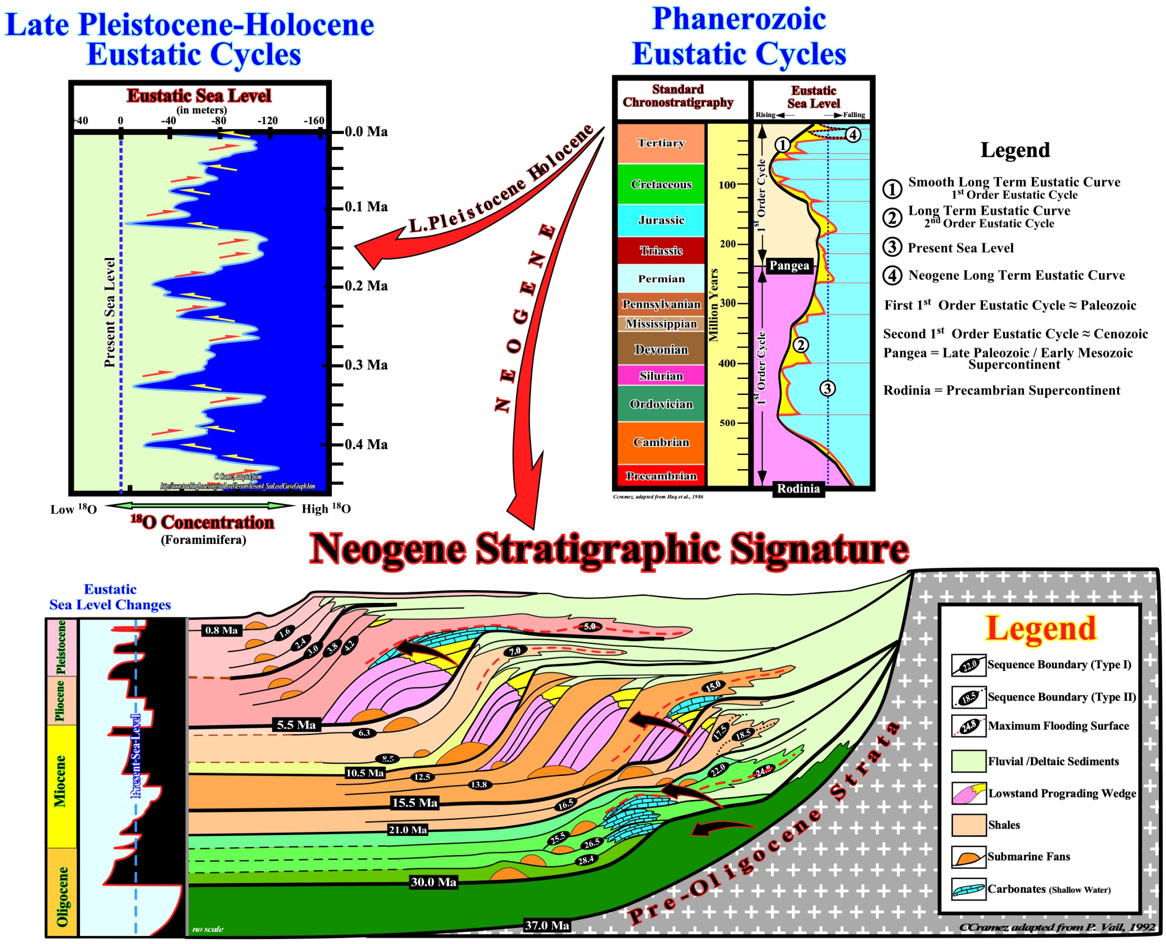



**Figure 4- On the upper part of this figure are illustrated the two 1st order eustatic cycles forming the Phanerozoic, which correspond, roughy, to Paleozoic and Meso-Cenozoic eras. The Paleozoic eustatic high, induced by the dispersion of the continents derived from the break-up of the Rodinia supercontinent, was 200-250 meters higher than at present-time sea level. It occurred at about 500 Ma, when the dispersion of the Paleozoic continents was maximal. About 91.5 Ma, the Mesozoic-Cenozoic eustatic high emphasizes the maximum dispersion of the continents derived from the break-up of the Pangea supercontinent. These absolute sea level changes were induced by changes in the volume of ocean basins created by the volume's variations of oceanic mountains induced by the oceanic ridges associated with the sea floor spreading (oceanic expansion). The amount of water in all its forms (solid, liquid and gaseous) is assumed to be constant since Earth's formation (± 4.5 Ga). Such a conjecture was not refuted until today. So, if the volume of the ocean basins increases, due to subduction of the oceanic crust and oceanic ridges. along the Benioff subduction zones, the absolute or eustatic sea level falls. If the volume of the oceanic basins decreases (formation of new oceanic crust and oceanic ridges), the absolute sea level, globally, rises causing a marine ingression. This is very important, because throughout the geological history, the volume of the ocean basins changed more or less in continuity. The 2nd order eustatic cycles with have a time-duration between 3-5 and 50 My and are probably, induced by changes in tectonic subsidence (lengthening, cooling and sedimentary charging) in association with the adjustment of the lithosphere, in response to loading and unloading created by addition and removal of the ice from the ice caps (glacio-eustasy). Actually, global variations in sea level can be a consequence of the variation of the volume of the ice on the continents and oceans. A glacial period causes a marine regression and an interglacial period produces a marine ingression. On the upper left part of this figure is illustrated the Late Pleistocene-Holocene absolute se level curve based on $^{18}O$ concentration. All values are positive, what means that the sea level was lower than the present-time sea level indicated by the vertical dotted blue line. On the $\delta_{18}O$ curve, the glacial periods are emphasized by high values (to the right), which highlight sea level falls. Roughly, the red arrows highlight time-periods of the preponderant sea level falling (glaciations) with minor intercalated sea level rises (deglaciations) while the yellow arrows highlight time periods of predominant sea level rise. The cyclicity of this curves emphasize the alternation between the**

**Quaternary glacial and interglacial periods. The Neogene long term eustatic curve (4) was interpreted in stratigraphic terms by P. Vail and his students who proposed a Neogene stratigraphic signature that is illustrated on the lower part of this figure and commented in the text.**

**Within 1st order eustatic cycles, characterized by a time-duration of more than 50 My, 2nd order eustatic cycles can be recognized. They have a much shorter time-duration ranging between 3-5 to 50 Ma. They are explained by changes in tectonic subsidence and changes in volume of the ice on the continents and oceans.**

**The Neogene long term eustatic curve (2nd order eustatic cycles), in which four major sedimentary intervals bounded by the unconformities (erosional surfaces) SB. 37.0 Ma, SB. 30.0 Ma, SB. 15,5 Ma and SB. 5.5 Ma, can be, easily, individualized.**

**Their progradational geometry (outbuilding largely preponderant over the upbuilding) was studied by P. Vail and his students of Rice University, who proposed the a stratigraphic signature illustrated without scale on Fig. 4.**

**The following geological events (Fig. 4) are quite likely:**

**(i) A significant sea level fall caused the unconformity SB. 37.0 Ma creating lowstand geological conditions (near limit Eocene-Oligocene) ;**

**(ii) During the Early Oligocene, a continentward thickening of the sediments was induced by absolute sea level rise (SB. 37.0 Ma - SB. 30.0 Ma) ;**

**(iii) A shifting of coastal onlaps toward the deep parts of the basins created by a sea level fall induced by glacio-eustasy (SB. 30.0 Ma - SB. 25.5 Ma) ;**

**(iv) A maximum flooding surface, MFS 24.8 Ma emphasize the top of a transgressive episode (upbuilding) ;**

**(v) A predominant outbuilding during the Early Miocene and deposition of large lowstand prograding wedges (MFS. 24.8 Ma - SB. 22.0)**

**(vi) A predominant aggradation and deposition of lowstand prograding wedges, by the end of Early Miocene (SB. 22.0- 21.0 Ma) ;**

**(vii) A flooding (upbuilding) during the Middle Miocene (16.0 Ma -15.5 Ma), i.e., a rising of the the absolute sea level ;**

**(viii) An absolute sea level fall created by a climate change (glaciation) with progradation (outbuilding) during Middle Miocene (Serravalian, 15.0 Ma / 10.5 Ma) with seaward and downward displacement of lowstand prograding wedges (10.5 Ma);**

**(ix) An aggradation (upbuilding) and deposition of lowstand prograding wedges (10.5 Ma / 5.0 Ma), at the end of Late Miocene, i.e., the absolute sea level rise with flooding during the Early Pliocene (5.0 Ma) ;**

**(x) An absolute sea level fall induced by the Plio-Pleistocene glaciations ;**

**(xi) An aggradation during the Early Pliocene and Pleistocene with many lowstand deposits (5.0 Ma / 1.6 Ma) and finally**

**(xii) Deposition of glacial high frequency stratigraphic cycles during Late Pleistocene.**

**Taking into account that:**

**1) a seaward displacement of the sediments, often, associated with an absolute sea level fall, corresponds to a set of increasingly important sedimentary regressions thickening seaward and**

**2) a continentward displacement, associated with a absolute sea level rise, corresponds to a retrogradational set of smaller and smaller sedimentary regressions induced by increasingly important marine ingressions, i.e., by transgressions (not by a transgression),**

**in the above Neogene stratigraphic signature (Fig. 4), three major transgressive episodes are recognized. They are topped by carbonate rocks and limited by downlap surfaces associated with a condensed stratigraphic sections, often, rich in organic matter. The downlap surfaces correspond to the following maximum flooding surfaces: MFS 24.8 Ma, MFS 15.0 and MFS SB 5.0 Ma.**
**In terms of displacement of the depositional coastal break[8] and sedimentary thickening, that is to say, in transgressions-regressions cycles or landward-seaward thickening or upbuilding versus outbuilding, the Neogene stratigraphic signature can be summarized as follows:**

- **(i) Seaward (regressive episode, outbuilding), between 30.0 Ma and 25,5 Ma ;**
- **(ii) Continentward (transgressive episode, upbuilding), between 25.5 Ma and 24.8 Ma ;**
- **(iii) Seaward (regressive episode, outbuilding), between 24.8 Ma and 15.5 Ma ;**
- **(iv) Continentward (transgressive episode, upbuilding), between 15.5 Ma and 15.0 Ma ;**
- **(v) Seaward (regressive episode, outbuilding), between 15.0 Ma and 10.5 Ma ;**
- **(vi) Continentward (transgressive episode, upbuilding), between 10.5 Ma and 5.0 Ma ;**
- **(vii) Seaward (episode regressive, outbuilding), between 5.0 Ma and 0.8 Ma.**

**[8] The point, upstream of which the depositional surface is at or near the marine base level. Seaward of the depositional coastal break, the depositional surface is low. The position of this point coincides, roughly, with the distal part of the delta bars or with the reef / forereef deposits. It corresponds to the lowest erosion level of wave action when the sea is calm (fair weather wave base), i.e., more or less, 10/20 meters below sea level.**

**Outbuilding (seaward thickening) and upbuilding (continentward thickening) are characterized, respectively, by an aggradational (retrogradational) and progradational (foresteeping) geometries. They are, obviously, separated by a downlap surface, since outbuilding highlights a shallowing (decreasing of the water depth), while upbuilding highlights a deepening (increasing of the water depth). Outbuilding and upbuilding are genetically related. Outbuilding requires always an upbuilding substratum. In Latin «aggradatio ut progradamus» means « aggradation to advance ».**

**In fact, during a significant sea level fall (due to a glaciation, for instance), that puts the sea level under the shelf edge, the already deposited platform sediments are exhumed. An erosional surface is formed (unconformity) and the basin becomes a no-shelf-basin.**

**The sedimentary particles transported along the continental slope by turbidite currents can be deposited in the deep parts of the basin forming coeval turbidite depositional systems, which upbuild the deep water paraconformity (sequence boundary) that correlates with the updip unconformity.**

**As soon as the absolute sea level starts to rise (in association with a deglaciation, for instance), lowstand depositional systems will be deposited. They fossilize the unconformity and the turbidite depositional systems, mainly, by a predominant aggradation (upbuilding) but not only, in order to reduce the angle of the continental slope.**

**The continuation of the sea level rise, in acceleration, can flood the pre-existent coastal plain and create a new shelf as aggradational transgressive sediments are deposited. The maximum of the sea level rise is materialized by maximum flooding surface (MFS), which will be fossilized by outbuilding sediments deposited as soon as the rising of the sea level becomes in deceleration. The outbuilding of the sediments ends since the sea level falls again due to a new glacial episode.**

**This simplified depositional history can explain the genetical relationships between unconformity (sea level fall), upbuilding (marine ingression followed by a sedimentary transgression) and outbuilding (sedimentary regression), i.e., the genetical relationships between a glaciation (unconformity) and a deglaciation (aggradation - downlap surface - outbuilding), which highlights the importance of the glacio-eustasy in areas were tectonic subsidence is deficient or lacking.**

## 4) Glacio-Eustasy

**The absolute sea level changes (Eustasy or Eustatism), induced by a change in the amount of ocean water or a change in the shape and capacity of the ocean basins, are dependent of several parameters:**

**a) Glacio-Eustasy that is controlled by the volume of water in the oceans as a function of the amount of ice (assuming that the amount of water in all its forms is constant since the formation of the Earth, about 4.5 Ga) ;**

**b) Tectono-Eustasy that is controlled by the volume variation of the ocean basins in association with oceanic expansion following the break-up of the supercontinents ;**

**c) Geoidal-Eustasy which is controlled by the distribution of ocean water caused by variations in the Earth's gravity field (where gravity is stronger than normal, sea level is thrown to the Earth's center) and**

**d) Steric Rise of the Sea Level or thermal expansion of the oceans, which is controlled by the temperature increase of the oceans (if the temperature of the oceans increases, the density of the water decreases and, for a constant mass, the volume increases).**

**As of these geological parameters controlling the eustatic changes of the sea level, only the glacial changes (glacio-eustasy) are both significant, i.e., greater than 10 meters and rapid (duration less than 1 million years), it is important to remember few things of the glacio-eustasy:**

**1) The glacio-eustasy is the eustatism (sea level changes) induced by climatic changes, i.e., created by the glaciation / deglaciation cycles or, in other words, created by the variations of the cryosphere (part of the Earth's surface that is permanently frozen).**

**2) In glacio-eustasy, the adjustment of the lithosphere, in response to the loading and unloading induced by the addition and removal of the ice from the ice caps, is taken into account. During a glaciation, the weight of the ice cap (3-4 km thick) sinks the lithosphere.**

**3) During a glaciation, the absolute sea level falls. During a deglaciation (de-icing epoch), the absolute sea level rises.**

**4) Glaciation - Deglaciation cycles happened several times in the geological history, as during the Pliocene/Pleistocene : (i) the absolute sea level began to fall about 120 meters, creating lowstand geological conditions and then (ii) it rose, more or less, the same creating highstand geological conditions.**

**5) Much more time is needed to deposit ice on the continent than to melt it. The heat exchange between the ice caps, ice seas (generally, less than 3 m thick), ice shelves[9] and the ocean cools the water surface. The water becoming colder and denser sinks being replaced by warmer water from the bottom, i.e., the formation of ice shelves requires cooling of the whole water column, which is not the case during a deglaciation which spread in surface a layer of water little salted.**

9 An ice shelf, which thickness can ranges from 100 to 1000 meters, is a large floating platform of ice that forms where a glacier or ice sheet flows down to a shoreline.

**6) During the melting ice caps, in response to the load of water added to the ocean basins, the sea level will be depressed, and in response to the removed charge (where the ice caps have melted), the continent will be lifted. Redistribution of material within the Earth is affected by overload. It will further constrain the ocean surface variations (induced by gravity anomalies) and so further water redistributions will be required to attempt to equalize gravitational potential. This continuous retroactive gravitational process between the ice**

caps, oceans and the mainland is the process that, in the end, determines the signature of the absolute sea level, which is observed everywhere the continent and the ocean meet.

7) Since the pressure caused by the ice disappears a position of equilibrium is, slowly, restored (the asthenosphere is very viscous). It takes about 15,000 years for the Earth's surface to regain its original attitude and re-establish the conditions necessary for another glaciation.

8) The isostatic rebalancing associated with glacio-eustasy should be taken into account to understand sea level changes. In areas where the uplift (crustal rebound) was important, the sediments were tilted (by lengthening) in a significant way. In the North Sea (Norway offshore), for instance, the crustal uplift (crustal rebound) is around 1,500 meters, which has important implications in the petroleum systems exploration.

Summarizing:

Glacio-eustasy tries to explain the global variations in sea level, especially, during the different Earth's glacial periods, as a consequence of the variation of the volume of the ice on the continents and oceans. It suggests that (i) a glacial period corresponds a marine regression, i.e., to a geological process during which of submerged seafloor sediments are exposed, and (ii) an interglacial period correspond to a marine ingression, i.e., a process during which pre-exposed sediments are flooded. Glacio-eustasy is, often, the preponderant factor sedimentary cyclicity and shelfal accommodation (space available for the sediments), particularly, when the tectonic subsidence[10] is unimportant, i.e., when the undaforms and fondoforms of sigmoidal sedimentary unities (progradational unities) are sub-horizontal.

[9] The tectonic subsidence or controlled subsidence, is different from the sinking created by the isostatic effects associated with sediment and water column loading. Tectonic subsidence corresponds to total subsidence decreased of the effect of isostatic compensation and increased by the compaction effect. It is controlled by tectonic stresses that affect the way the lithosphere floats over the asthenosphere.

The Glacio-Eustasy was the predominant parameter in the developement of the (1) Plio-Pleistocene, (2) Middle Miocene (Langhian, Serravalian) and (3) Oligocene lowstand geological periods as corroborated by the positive $\delta_{18}O$ shifts recorded in bulk carbonate records. In other words, the absolute sea level falls, which created the erosional surfaces (unconformities), were induced by glaciations and the marine ingressions, which create the space available for the sediments, were induced by deglaciations.

## 5) Plio-Pleistocene Prograding Carbonates

The lowstand sea level conditions during the Pliocene and Pleistocene illustrated by the long and short term eustatic curves (Fig. 1) and by the the oxygen isotopic stratigraphy, i.e., by $\delta_{18}O$ curve (Fig. 1 & Fig. 2) and by the Late Pleistocene-Holocene absolute se level curve based on $^{18}O$ concentration (Fig. 4), were developed by a significant cooling of the Earth's temperature.

In fact, during the Pliocene (between ± 5.3 Ma and ± 2.6 Ma), the Earth's climate became cooler and drier marking a transition between the relatively warm Miocene to the cold Quaternary.

Following different geoscientists, it is possible to say:

1) The global average temperature in the mid-Pliocene (3.3 Ma–3 Ma) was 2–3°C higher than today and the global sea level 25 meters higher ;

2) The ice sheet of the northern hemisphere was ephemeral before the onset of extensive glaciation that occurred in the Late Pliocene around 3 Ma ;

**3) During the Pliocene, the Earth climate system response shifted from a period of high frequency-low amplitude oscillation, dominated by the 41 ky period of Earth's obliquity, to one of low-frequency, high-amplitude oscillation dominated by the 100,000-year period of the orbital eccentricity characteristic of the Pleistocene glacial-interglacial cycles.**

**4) During the Late Pliocene and Early Pleistocene, i.e., between 3.6 to 2.2 Ma, the Arctic was much warmer than it is at the present day (± 8°C warmer than today).**

**5) The extent of the West Antarctic Ice sheet oscillated at the 40 ky period of Earth's obliquity.**

**6) Ice sheet collapse occurred when the global average temperature was 3°C warmer than today and $CO_2$ concentration was at 400 ppm.**

**7) Global sea-level fluctuation associated with ice-sheet collapse was probably up to 7 meters for the west Antarctic and 3 m for the east Antarctic.**

**8) Several mechanisms have been proposed to explain global cooling after 3 Ma and the onset of extensive northern hemisphere glaciation : a) Panama seaway closure ; b) Collapse of permanent El Niño ; c) Uplift of the Rocky mountains and Greenland's west coast ; d) Amount of $CO_2$ in atmosphere.**

**Such a climate changes and, particularly, the glacial-interglacial cycles are the main responsible of the progradational geometry and facies of Plio-Pleistocene depositional systems, as illustrated on the following seismic lines (Fig. 5 and 6 of Gulf of Papua, Fig. 7 of Mozambique offshore ).**

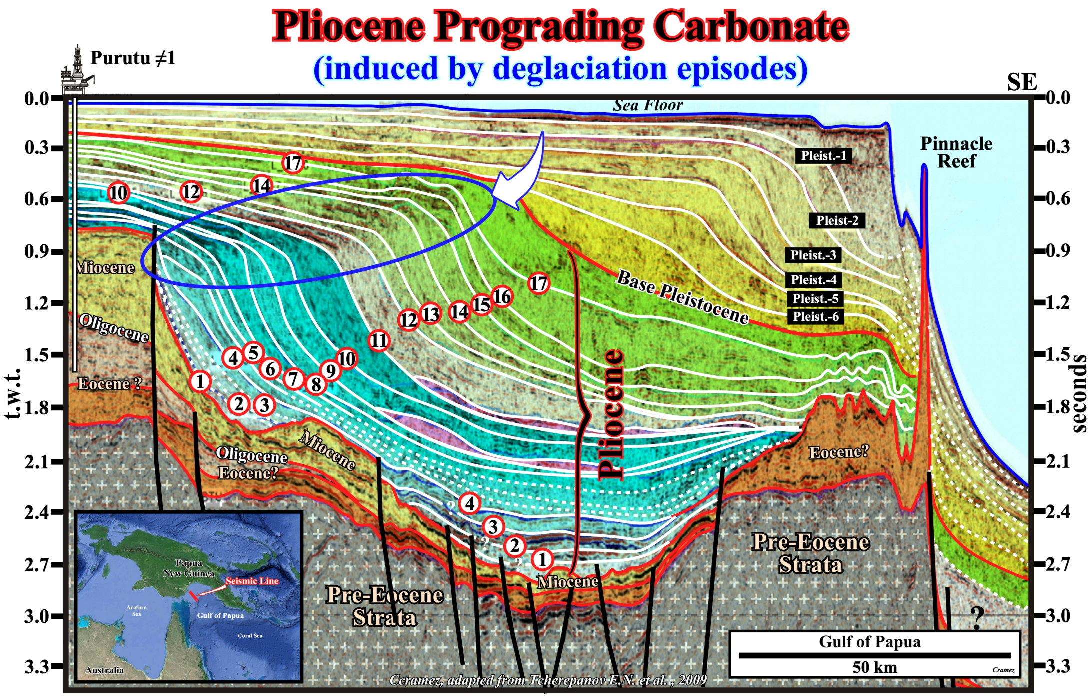



*Figure 5- On this seismic line (vertical exaggeration ± 50 x), coming from the Gulf of Papua, above the Mesozoic rift-type basin sediments, is illustrated the Cenozoic continental divergent margin developed after the breakup unconformity, i.e., during the sea floor spreading associated with the dispersion or drifting of the continents (large-scale horizontal movements relative to one another. Stratigraphic speaking, the divergent margin corresponds to the post-Pangea continental encroachment stratigraphic cycle, in which two phases can be considered. The lower transgressive phase, between the breakup unconformity and top Eocene (?), which has, mainly, an aggradational geometry. The upper progradational regressive phase seems to start in the Oligocene. It shows a reinforcement of the outbuilding during the Pliocene and Pleistocene, that several geoscientists associate the eustatic sea level falls induced by a significant cooling of the Earth's temperature that produced set of glacial-interglacial cycles. The cold glacial periods (eustatic sea level falls) produced, mainly, the unconformities bounding the different Plio-Pleistocene high frequency sequence-cycles. The warm interglacial periods (eustatic sea level rises) seem to have created the geological conditions for development of carbonate factories (water column, favorable climate and stability period of the sea level) responsible for the Pliocene prograding carbonates quite well recognized on the distal section of the undaform (depositional setting for shallow water overlying the shelf) of each high frequency sequence-cycle. The tectonic subsidence is meaningless in the creation of the shelfal accommodation. The seaward tilting of the undaform is just the sinking created by the isostatic effects associated with sediments and water column loading, that is to say, glacio-eustasy is paramount.*

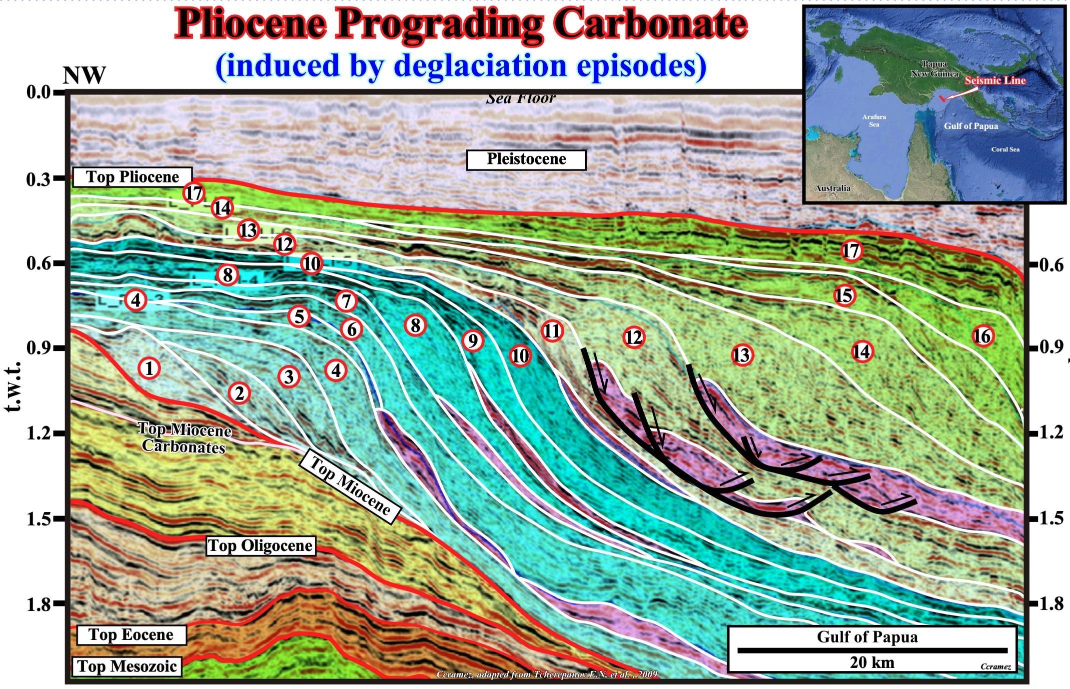



*Figure 6- On this seismic line, shot not far from the one illustrated on Fig. 5, depicts, in detail, the Pliocene prograding carbonates in the southern offshore of Papua New Guinea (northern Coral Sea), developed in association with the absolute sea level rises induced by the interglacial periods (deglaciation). Taking into account the vertical exaggeration of this line (± 20 x times), you realize that at the natural scale 1:1, the facies lines, defined by the carbonate deposition on the distal "unda" depositional environment, are practical sub-horizontal, what strongly suggest the main parameter of the shelfal accommodation is the eustasy. The Pliocene is formed by, at least, by seventeen (17) high frequency sequence-cycles build-up during the deglaciations (interglacial periods) and bounded by unconformities, i.e., by erosional surfaces induced by significant eustatic or absolute sea level falls caused by the glaciations (glacial periods). During this geological time-period (Pliocene), the outbuilding highlighted by the progradations (seaward and upward displacement of the shoreline or of the basin edge) of the successive shelf breaks, is largely higher that the upbuilding, that certain times is negative (negative aggradation), as between the sequence-cycles (1) and (2), (4) and (5) or (10) and (11). It is interest to point out the presence, along certain unconformities, the presence of slope deposits associated with turbidite currents and faulting (listric faults).*

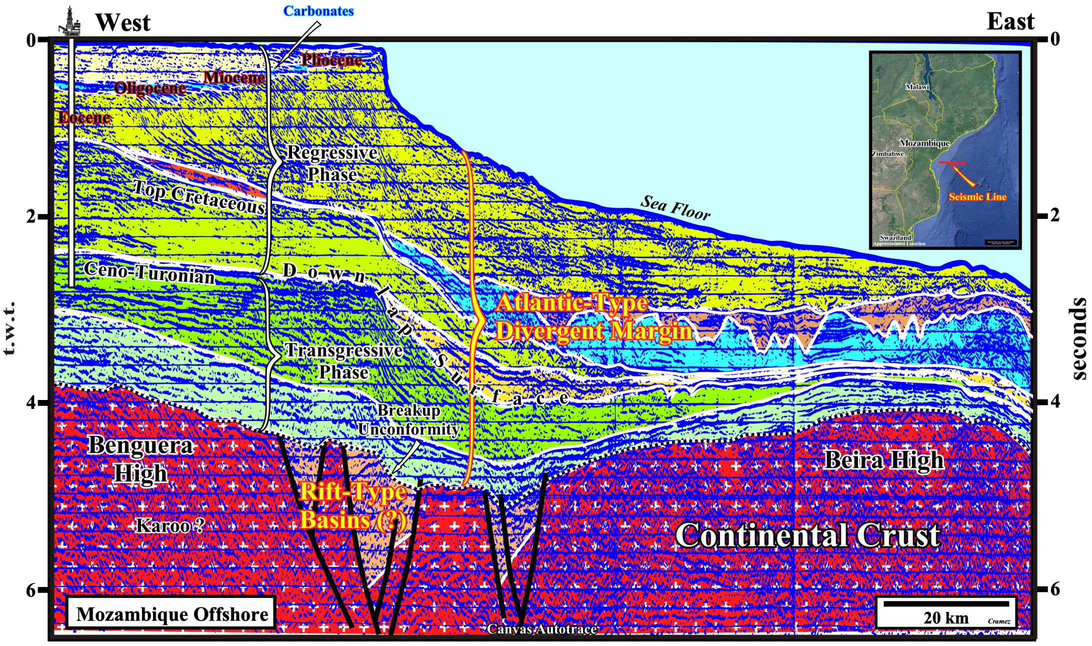



*Figure 7- The Atlantic-type divergent margin developed above the an extended substratum (rift-type basins and basement). The transgressive phase, with a retrogradation geometry, and the regressive phase, with a progradational geometry, are separated by the Cenomanian-Turonian downlap surface In the regressive phase and particularly in the Tertiary package, the seaward movement of the successive shelf break can be, easily, followed. The three steps of tNeogene cooling (Pliocene, Middle Miocene and Eocene-Oligocene) are highlighted by the deposition of prograding carbonate deposits during the interglacial episodes.*

## 6) Middle Miocene Prograding Carbonates

**Prograding carbonate are associate with the Middle Miocene cooling step of the Neogene Earth's climate, that certain geoscientists call MMCT (Middle Miocene Climatic Transition) are**

**well know in different part of the world (Gulf of Suez, Maldives, Australia, etc.), however origin of such a climatic change is not quite well understood.**

**Taking into account that the marine isotopic studies suggest significant volume expansion in Antartica and coeval cooling of the Southern Ocean (Lewis, A. R. et al., 2008), it is possible that the carbonate deposits (Fig. 8) are associated with warm interglacial episodes during which the rising of the absolute sea level creates the geological conditions to the developement of carbonate factories.**

**The Miocene climatic optimum that occur between ± 17 Ma and 15 Ma, that, temporally interrupted. The Neogene cooling trend, contrast with the subsequent Middle Miocene climate transition that was marked by cooling of high and low latitudes, stabilization of Antarctic ice sheets, major sea level fall and marine biota overturn (Methner K., et al., 2020).**

**The sea level fall created lowstand geological conditions that are, clearly, recognized on seismic data by the development of progradational depositional systems, in which the outbuilding is, largely, preponderant on the upbuilding. In additional as illustrated on the following seismic lines the upbuilding is mainly by glacio-eustasy rather by subsidence.**

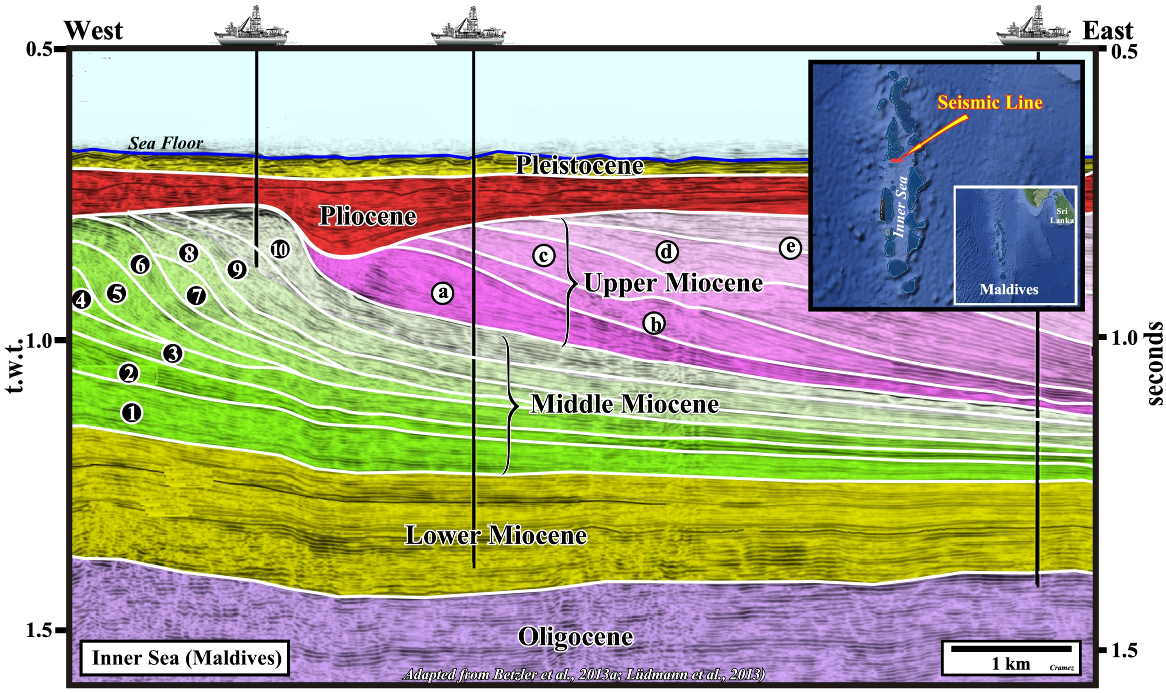



*Figure 8- At the end of the Middle Miocene the Maldives represent a rimmed platform with the Inner Sea forming an empty bucket. Middle Miocene prograding carbonates are, easily, recognized. Lowstand geological conditions are predominant. The periods of highstand are almost no existent. However, in the Inner sea, contrariwise to the Middle Miocene carbonates (colored green), the Upper Miocene prograding carbonates, are associated with bottom currents, i.e., the carbonate particles are not in situ. They have been transported by bottom currents from a near carbonate factory. Their deposition is independent of the sea level changes. These current-controlled carbonate deposits (drift deposits) are deposited at the edges of the atolls adjacent to the passages, where the velocity of the current entering the Inner Sea is higher. The atolls are separated from each other by inter-atoll channels, which deepen towards the Indian Ocean.*

**On this subject, it is important do not forget that in lowstand or highstand geological conditions to have deposition it is always necessary to increase or create space available for sediments (accommodation).**

**That seems to be true not only in clastic depositional systems but in carbonate depositional systems as well.**

**In fact:**

**(i) The carbonate particles are, generally, created by a carbonate factory that requires an appropriated water column. Production of carbonate is function of the water-depth ;**

**(ii) The penetration of sunlight into any aquatic environment decreases exponentially when the water column increases ;**

**(iii) The organic matter production curve, in a carbonated basin, can be correlated with the intensity of sunlight by a hyperbolic function ;**

**(iv) The carbonate production curve has a peak in the zone of light saturation, near sea level, where light is not a limiting factor of production ;**

**(v) The peak production is followed, in depth, by a rapid decrease in production.**

**Finally, geoscientists must take always in mind the three basic rules, proposed by Schlager W. (1991, that must always considered in the deposition of carbonates:**

**(i) Carbonates are mainly of organic origin ;**

**(ii) Carbonates build structures that resist waves and**

**(iii) Carbonates undergo major diagenetic changes because the original minerals are metastable.**

**Let's see one more example of Middle Miocene prograding carbonates (Fig- 9)**

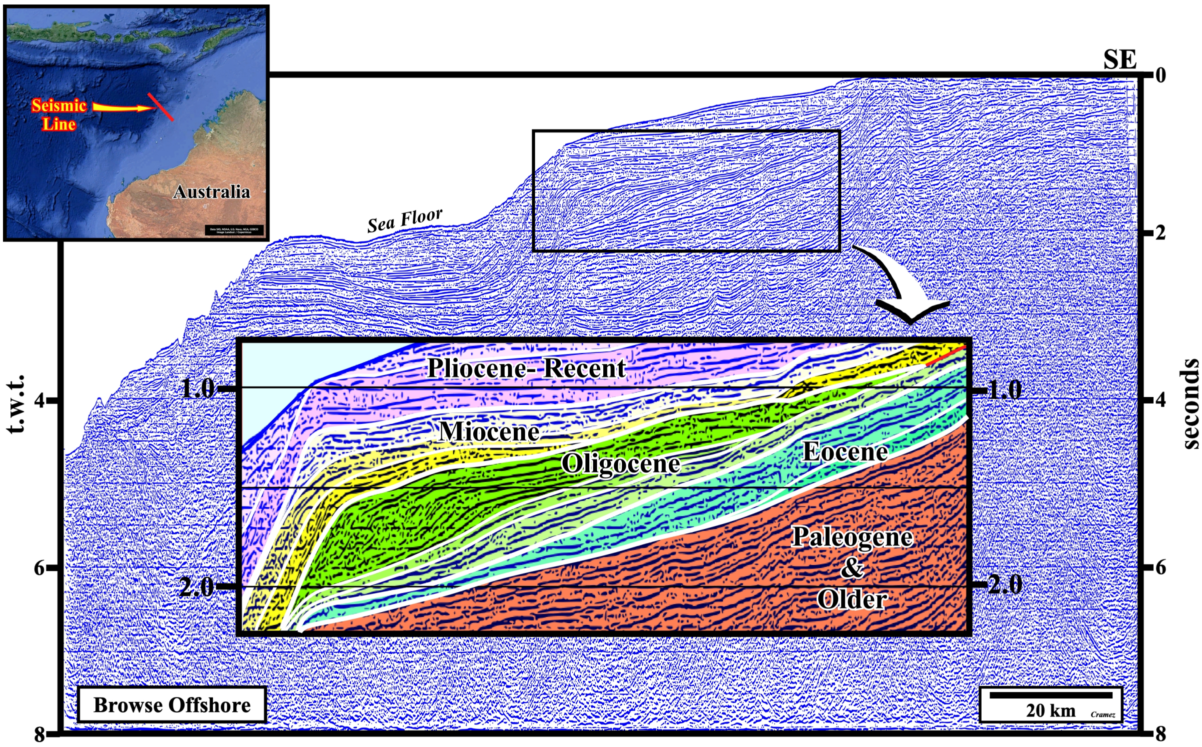



*Figure 9- This auto-trace of seismic line of the Browse offshore (Australia), illustrates the outbuilding of the Neogene carbonates, which emphasizes the falling by steps of the eustatic sea level by steps (long term eustatic curve, Fig. 1 & Fig. 3), the sea level changes are the result not only of the Tectono-Eustasy, but the Glacio-Eustasy as well. The tectono-eustasy is controlled by the volume variation of the ocean basins in association with oceanic expansion (sea floor spreading) following the breakup of the supercontinents. The glacio-eustasy is controlled by the water volume of water in the oceans as a function of the amount of ice (assuming that the amount of water in all its forms is constant since the formation of the Earth ± 4.5 Ga). In fact, since the Neogene, the Earth's climate cools with the three periods of higher cooling rate : Late Pliocene (± 3.0 Ma) ; (ii) Middle Miocene (± 15.5 Ma) and Late Eocene–Early Oligocene (± 36 Ma). During these periods, the volume of continental ice sheets have changes, which affects, significantly, the eustatic sea level and so the geological conditions. On this seismic line, the Middle Miocene prograding carbonates are associated with the Middle Miocene Climatic Transition as discussed previously. The Oligocene prograding carbonates, which are quite evident on this line (green intervals) are associated with the older cooling step that is related with the onset of Antarctica glaciation as we will see next.*

## 7) Eocene-Oligocene Prograding Carbonates

**The Eocene-Oligocene transition (ranging between 36.0 Ma and 33.0 Ma) seems to be most important oceanographic and climatic change of the past 50 My with an $\delta^{18}O$ increasing of 1-1.5% (Fig. 10). It seems to mark the onset of an ice-house Earth. Consequently, the absolute or eustatic sea level was strongly affect, as illustrated by the sea level curves on the Fig. 10.**

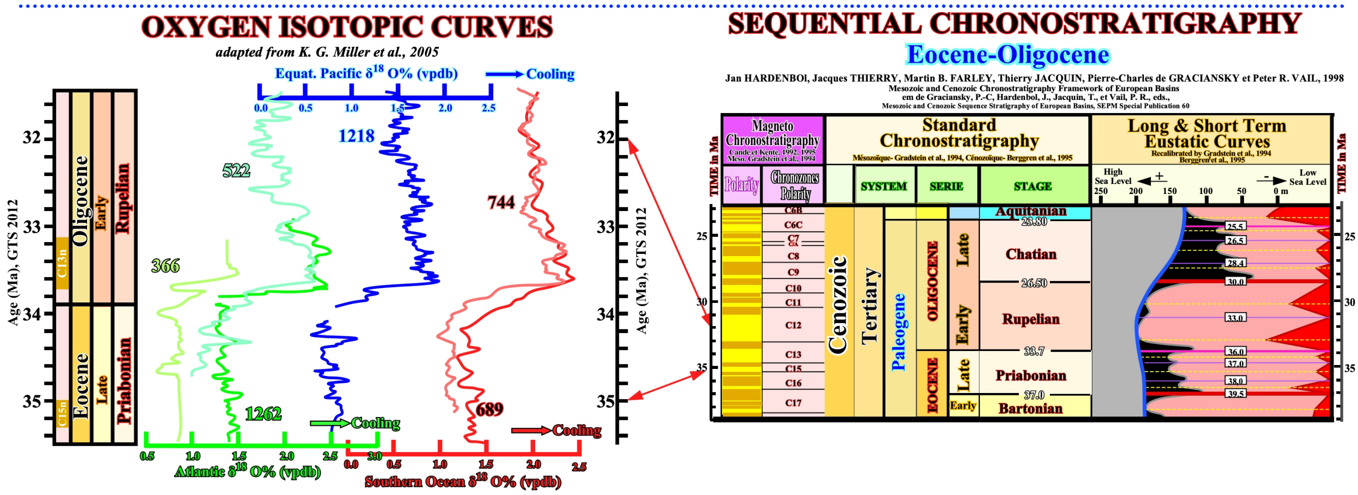



*Figure 10- A simple time correlation of the standard chronostratigraphy of each plate (Oxygen Isotopic Curves & Sequential Chronostratigraphy) strongly suggests the sea level fall observed on the long and short term eustatic curves matches with the oxygen the isotopic stratigraphic curves (Atlantic, Equatorial Pacific and Southern Ocean), in which a sharp global cooling is suggested by the δ18O increasing shift.*

**In Kurdistan embayment where prograding carbonates developed (Fig. 11), glacio-eustasy seems to be the main factor of the Oligocene lowstand geological conditions, as well as, of the shelfal accommodation**

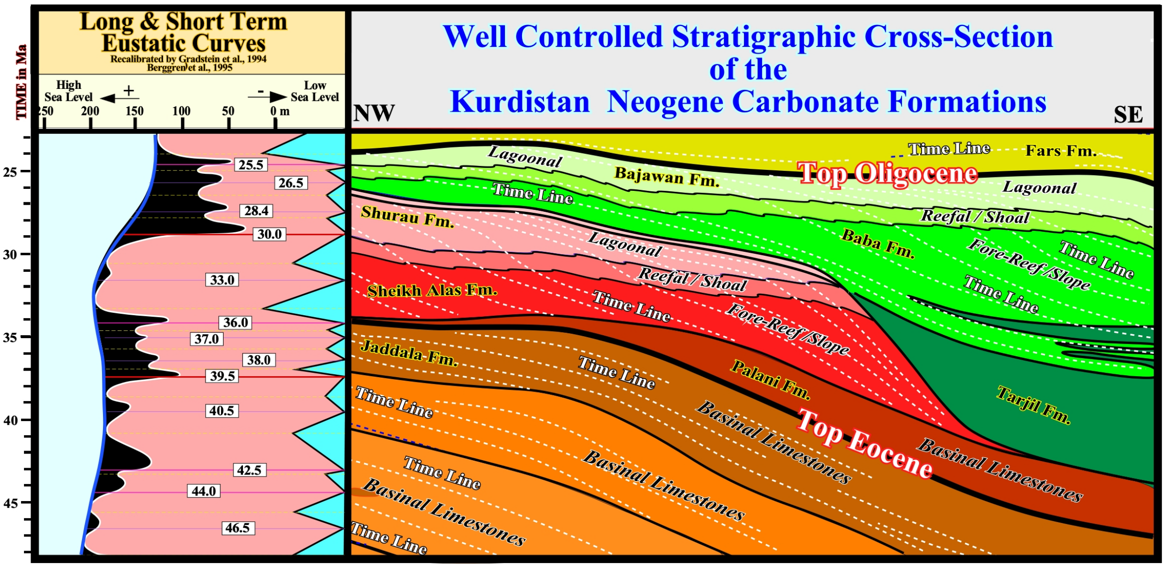


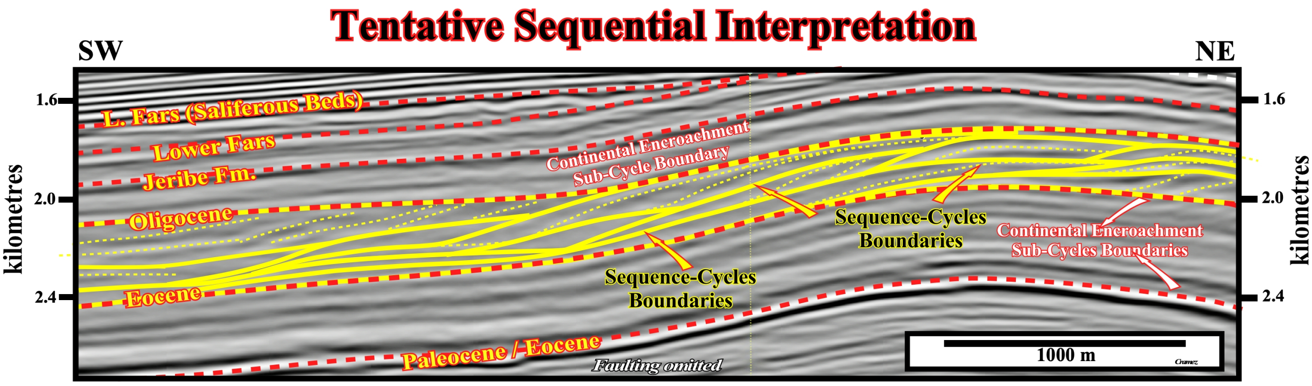

*Figure 11- The Oligocene step of the general Neogene eustatic sea level falling created by climate changes (oxygen isotopic curves, Fig. 10), illustrated on the left part of this figure, induced, during the Oligocene, the lowstand geological conditions in Kurdistan embayment and the deposition of carbonate prograding geological formations of the area. As illustrated on the right part of the figure, three continental encroachment stratigraphic sub-cycles form the Oligocene strata. They correspond to prograding sedimentary prisms bounded by significant relative sea level falls (unconformities = erosional surfaces) created by glacial conditions that displaced seaward and downward the coastal deposits form during the subsequent relative sea level rises (deglaciations).*

**In spite of the fact that the above cross-section has no horizontal scale, the outbuilding (hundreds of kilometers) is largely predominant over the upbuilding, which do not exceeds more than 300 meters.**

**Such a geometry implies chronostratigraphic lines oblique to facies lines. The chronostratigraphic or time lines correspond to depositional surfaces along which the sedimentary particles are deposited, in a synchronous manner function of the sedimentary environment.**

**Along a chronostratigraphic line, several slope's breaks of the depositional surface are evident. They emphasize the limits between different lithologies, i.e., different facies, which from continent seaward are unda beds, clino bed and fondo beds. The limits between the different beds, deposited in different environments, highlights the facies lines as illustrated on next figures .**

**In stratigraphic terms, the Oligocene interval in Iraqi Kurdaistan (Fig. 12) corresponds to set of two continental encroachment sub-cycles (Rupelian and Chatian), induced by 2nd order eustatic cycles, in which different high frequency sequence cycle can be recognized. Second order eustatic cycles have a time-duration between 3-5 and 50.0 My (millions of years), which are, probably, induced by a combination of glacio-eustasy and tectonic subsidence.**



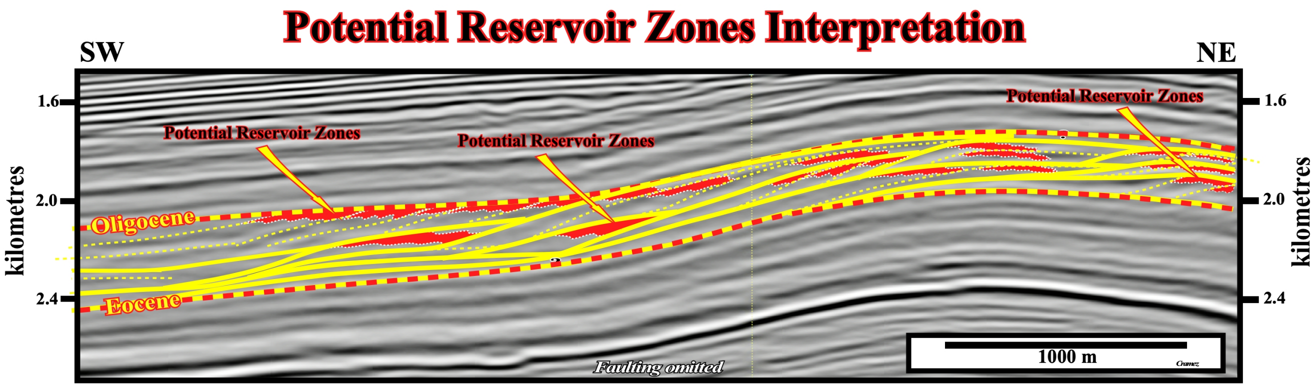




*Figure 12- On this depth seismic line, the Oligocene progradational carbonate interval is obvious, in spite of the fact that the Eocene interval is also a progradational interval, but the size and geometry of the chronostratigraphic lines is quite different. Both sedimentary interval, but particularly the Oligocene, were deposited in lowstand geological conditions associated with sharp climate cooling as said previously.*

**However, when the tectonic subsidence, which can be, easily, calculated from the sediment thickness plus water-depth (total subsidence), decreased from the effect of isostatic compensation (due to sedimentary overload) and increased by the compaction effect, is small, i.e., when geometries of the undaforms and fondoforms are sub-horizontal, the glacio-eustasy is the principal geological parameter of the shelfal accommodation, which is an important responsible of the deposition of the sequence-cycles.**

**This is the case of the Oligocene sequence-cycles, in which different reservoir zones containing several reservoir-rocks can be identified. However, their geometry is oblique to the unconformities bounding the sequence cycles (time lines) as illustrated on Fig. 13.**

**In fact, the more likely reservoirs zones, in which several reservoir-rocks, connected or not between them, can exist, are located in prograding stacking of undaform rocks with an overall geometry oblique to the chronostratigraphic lines, particularly, to the top Oligocene unconformity.**

**The time seismic linesthrough the anticline structure (Fig. 14) do not falsify the previous advanced geological conjectures. On the contrary, they corroborate them. They strongly suggest lowstand geological conditions are paramount during the prograding Oligocene interval.**

**Such seismic interval can be, easily, subdivided in several seismic sequence-cycles bounded by unconformities, which were induced by eustatic sea level rises created by the warm interglacial periods, while the unconformity's boundaries of the sequence-cycles were, most likely, induced by absolute sea level falls associated with maximum glacial time-periods.**

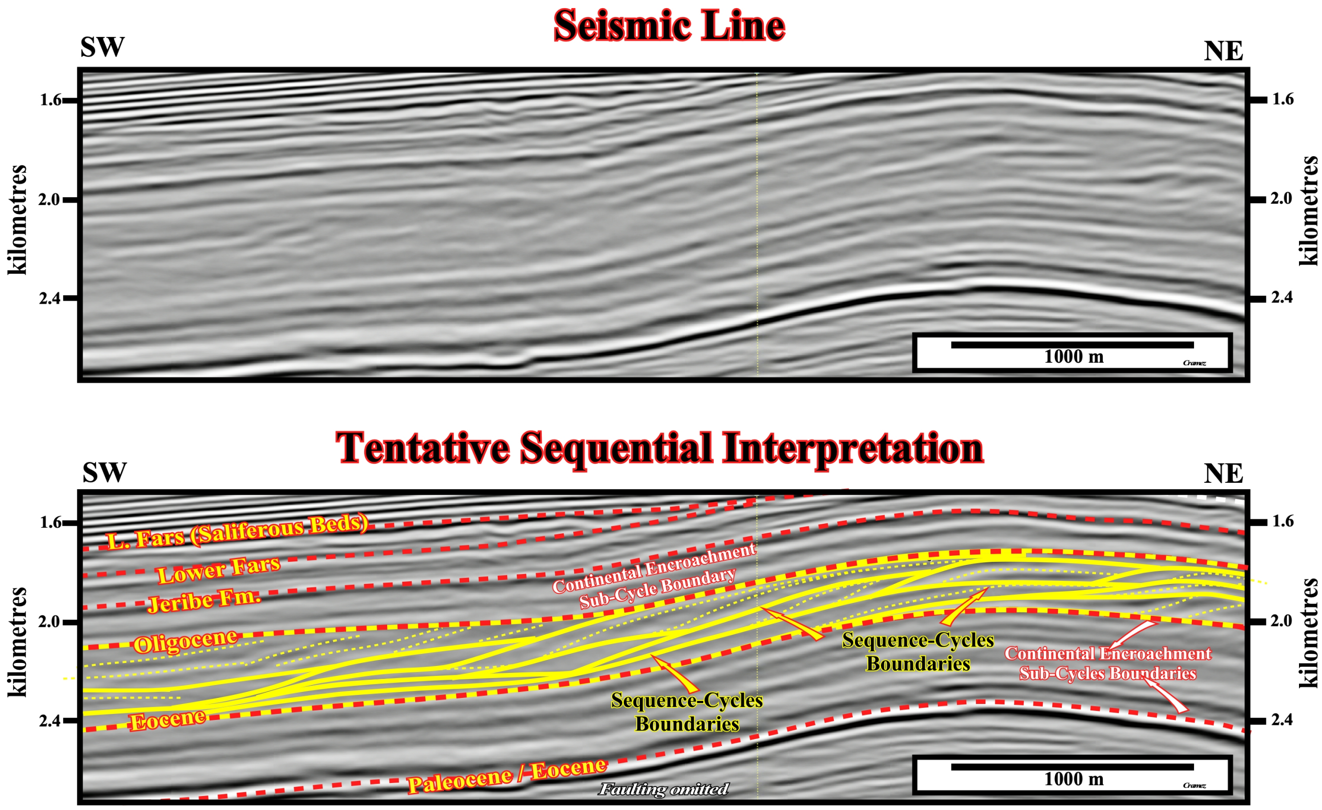



*Figure 13- The potential reservoir zones, in which potential reservoir-rocks are likely, are illustrated on this tentative interpretation by the colored red zones. They highlight the unda rocks deposited in the upper segment of the chronostratigraphic lines, where the environmental conditions are the most favorable to the development of carbonate factories.*

**It is important to point out that during the Oligocene, the subsidence has played a meaningless role in the creation of space available for the sediments (accommodation).**

**The angle of the clinoforms of the Oligocene chronostratigraphic lines advocates for a carbonate facies rather than a sand-shale facies. Such a carbonate facies was stimulated by the eustatic sea level cycles created in association warm interglacial periods.**

**In these eustatic cycles, limited between two consecutive falls, the sea level starts to rise in acceleration and then in deceleration, before the beginning of the falling.**

**Consequently, two sedimentary phases with quite different geometries are induced:**

**(i) A transgressive phase and**

**(ii) A regressive phase**

**These stratigraphic phases are separated by a downlap surface, characterized by an significnt hiatus.**

**The first stratigarphic phase is associated with a rise of the sea level in acceleration and it is characterized by a retrogradational geometry (upbuilding predominant). The second phase is associated with a rise of the sea level in deceleration and it ids characterized by a progradational geometry (outbuilding predominant). In stratigraphic term, that means that within a complete sequence-cycle of the Oligocene interval, from land seaward :**

**a) The transgressive phase is a set of increasingly important marine ingressions and increasingly smaller sedimentary regressions, which create, globally, a retrogradational geometry, while**

**b) The regressive phase is a set of increasingly important sedimentary regressions and increasingly smaller marine ingressions that globally create a progradation geometry.**

**These phases, easily recognized on the seismic lines of Iraqi Kurdistan (Fig. 14), are corroborate by the sequential stratigraphy the electrical logs of the wells drilled in the area.**

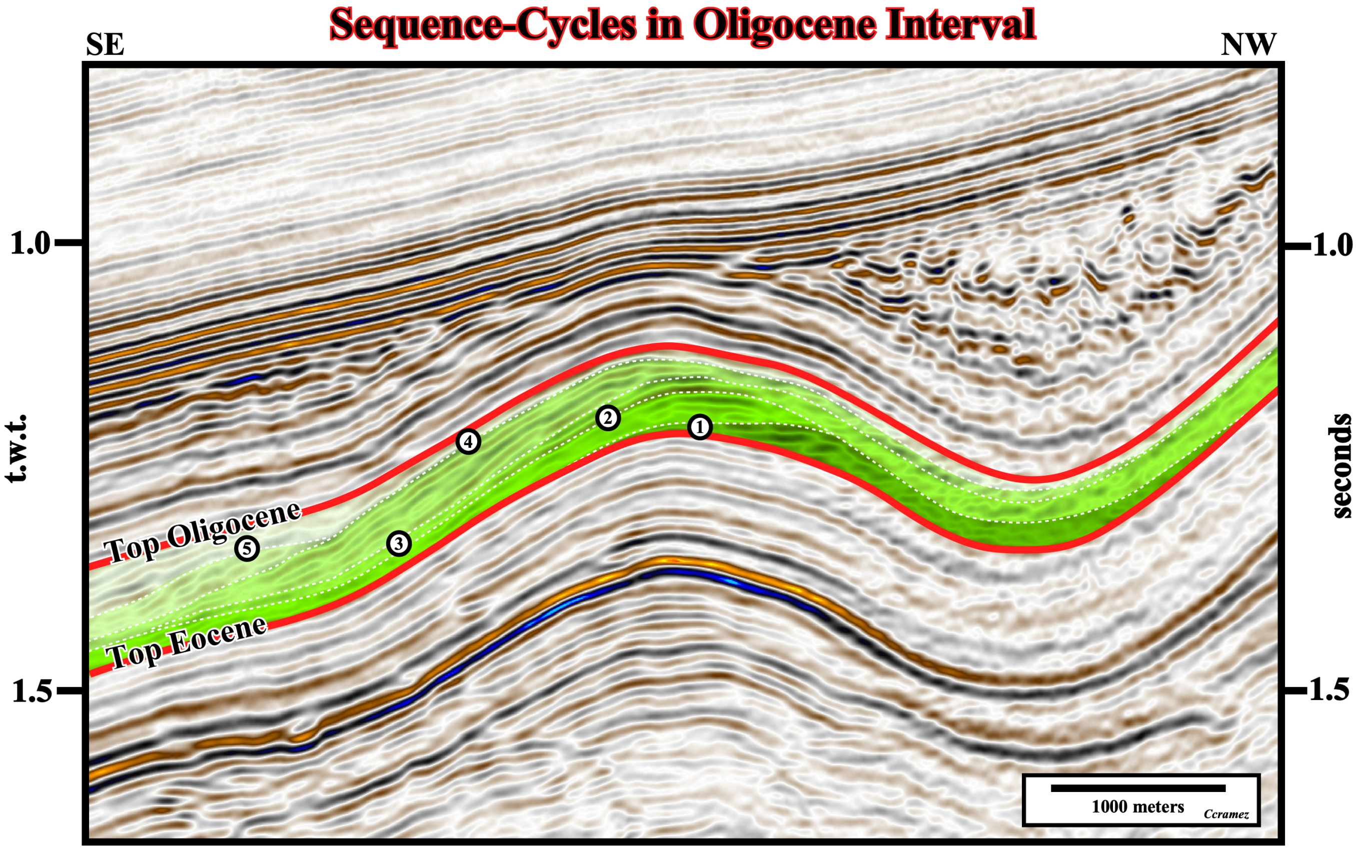



**Fig.14- As illustrated on this seismic line, within each Oligocene sequence-cycle, the chronostratigraphic lines have, mainly, a sigmoid geometry (inverted S-shape), in which, generally, undaform, clinoform and fondoform can be recognized. Take into account seismic resolution, the more likely reservoir zones, in which several reservoir-rocks connected or not between them, are developed, mainly, in the exhumed unda geological environments, in which the petrophysical characteristic of the reservoir-rocks are enhanced, which to be corroborated by the study by different seismic attributes.**