Volume III

Sequential Stratigraphy

Sequential Stratigraphy

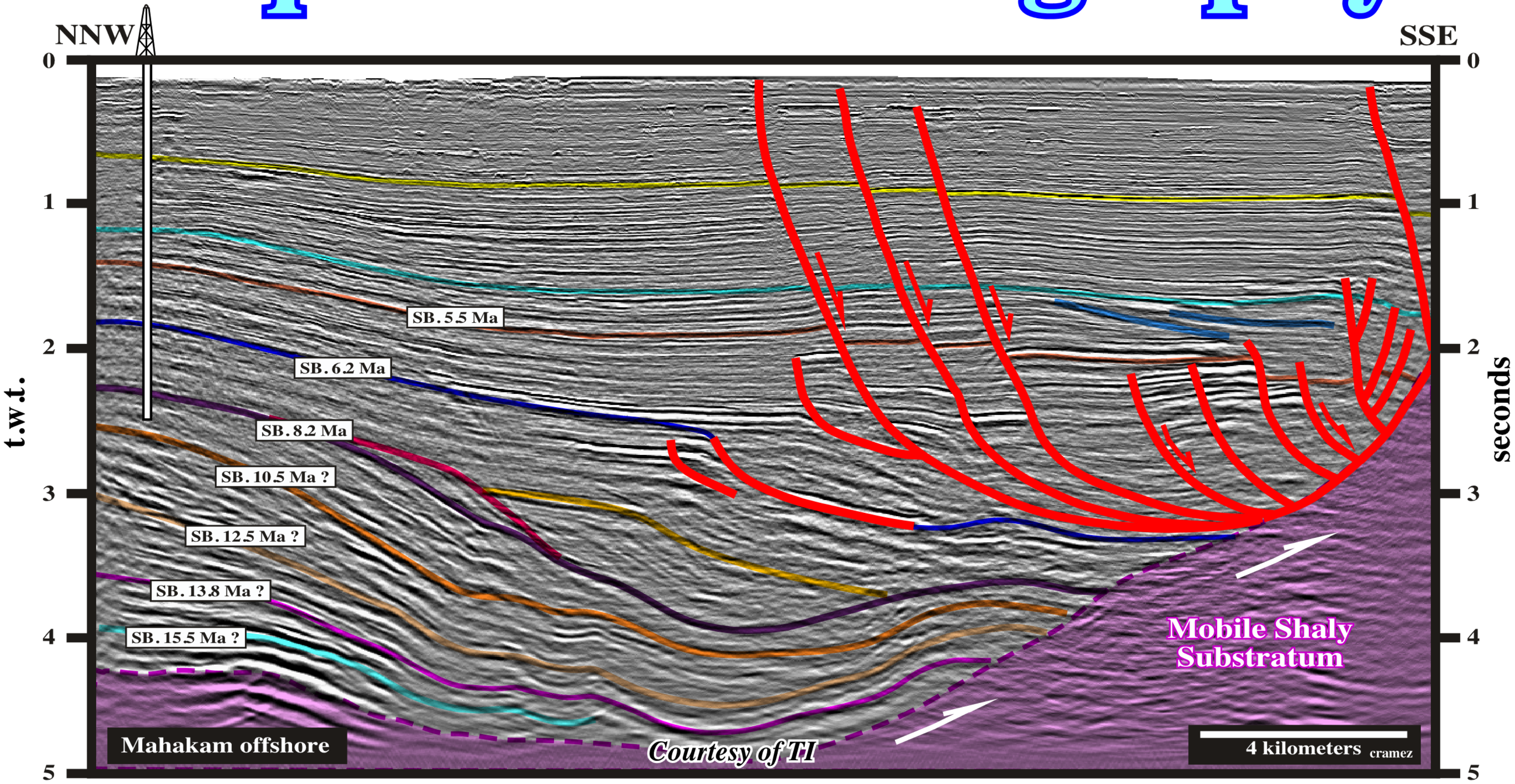


Fig. 1- In seismic interpretation and particularly in sequential stratigraphy, geologists must take into account that without an underlying theory, without a model, observations or experiments picking seismic markers will not have any significance. The theory gives meaning to the observed, but, on the contrary, a theory without observations, for corroboration and testing, has no grip on reality. In other words, the better a geologist knows the global and regional geological setting of an area; the easier the geological interpretation of the seismic lines of the area will be. Summing up, on a seismic line, a geologist recognizes only what he knows; he has very little chance to find something that he is not looking for.

Sequential Stratigraphy

Sequential Stratigraphy is the study of rock relationships within a chronostratigraphic framework of repetitive genetically related strata bounded by surfaces of erosion or their correlative conformities.

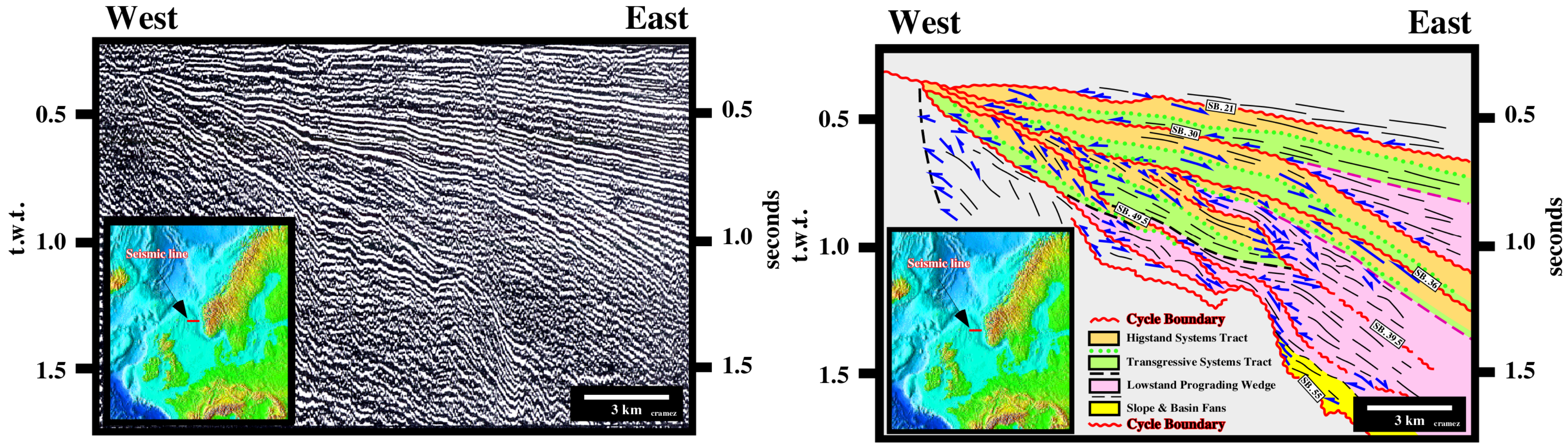


Fig. 2- The fundamental unit of sequential stratigraphy is the sequence stratigraphic cycle. It is induced by a 1st order eustatic cycle (see glossary) and bounded by unconformities (erosional surfaces) or their correlative conformities. The age difference between the upper and lower unconformities should not be greater than 3-5 My. A sequence stratigraphic cycle can be subdivided into systems tracts, which are defined by their positions within the sequence, and by the stacking patterns of parasequence sets and parasequence stratigraphic cycles (see later) bounded by marine-flooding surfaces. Subsequently, the geological interpretation of the North Sea line proposed above is far from being correct. The age difference between the unconformities bounding the seismic intervals is much higher than 5 My. The seismic packages do not correspond to sequence cycles, but to cycles with a higher hierarchy (see later). So, they cannot be subdivided into single systems tracts systems tracts and so lithological predictions are hazardous. At such cycle hierarchy, geologists can speak in transgressive and regressive episodes but not in transgressive and highstand systems tracts.

Seimic Line

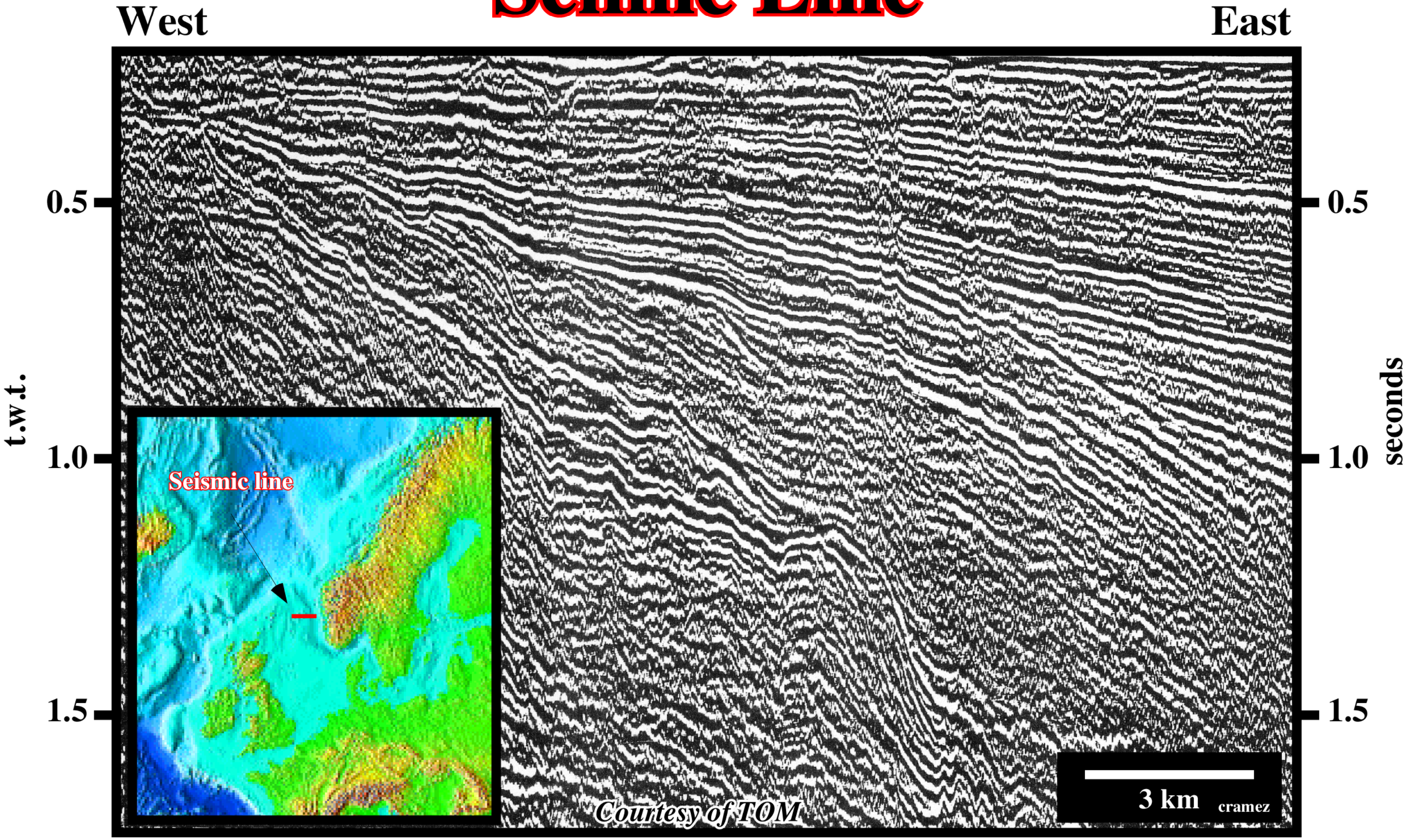


Fig. 3- A lot of reflection terminations, and subsequent seismic surfaces, can be recognized on this semi-regional line from the North Sea. So, a sequential interpretation seems quite easy. However, before starting the interpretation, the seismic interpreter (geophysicist or geologist) must not only know the global and regional geological settings of the area, but also decide at what hierarchical level the interpretation is possible. Indeed, as you will see later, different stratigraphic cycles can be considered, depending on the order of the generative eustatic cycles. A glimpse at the seismic line strongly suggests at least six well defined seismic packages bounded by onlap and truncation surfaces as illustrated on the next figure.

Sequential Interpretation

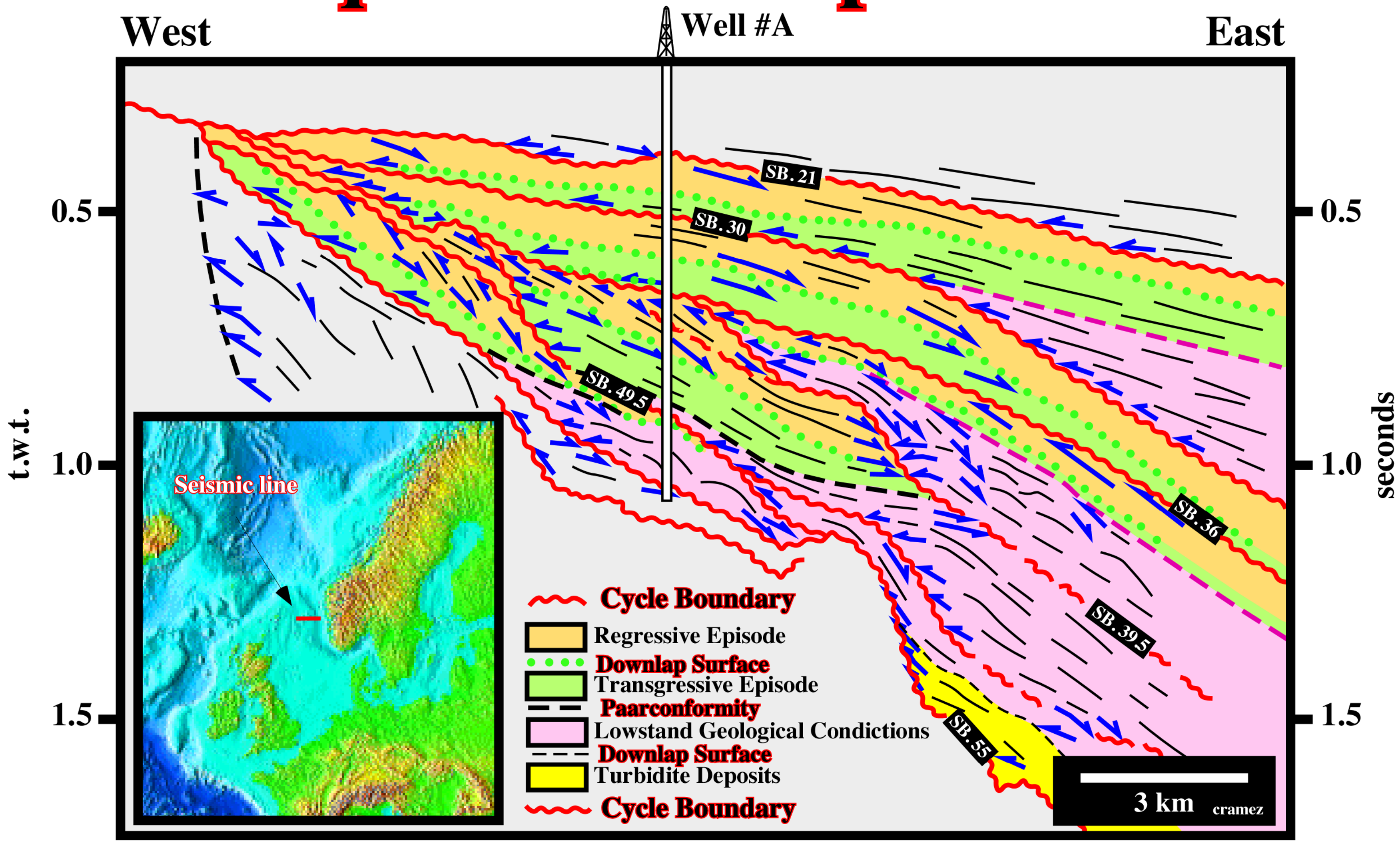


Fig. 4- In this interpretation of the previous North Sea line, the stratigraphic and paleontologic results of well #A indicate the more likely age of the unconformities, individualizing the different seismic packages as 21, 30 36, 39.5 (?), 49.5 and 55 millions years ago. Subsequently, the erosional surfaces associated with them were induced by eustatic cycles with time durations higher than 3-5 My. In other words, the seismic packages do not correspond to sequence stratigraphic cycles (see fig. 2). Within them, transgressive and regressive depositional episodes can be considered, but not systems tracts. The purple intervals represent seismic packages deposited during lowstand geological conditions, that is to say, periods of time during which the sea level was below the shelf break.

Sequential Stratigraphy Procedure

A) Recognition of the **Unconformities** using onlap and truncation reflection terminations.

B) Identification of **Stratigraphic Cycles** (see glossary). For sequence cycles, identify type I and II unconformities.

C) Location of **Shelf Breaks** for each sequence cycle using sedimentary dip changes.

D) Construction of **Coastal Onlap** and **Relative Sea Level Curves**.

E) Recognition of **Systems Tracts** inside of each sequence cycle.

F) **Facies** (lithology) prediction for each depositional system composing the different systems tracts.

G) **Calibration** of sequence cycles and systems tracts using exploration wells.

H) **HC Potential** of each sequence cycle using coastal onlap and sea level curves.

Seismic Stratigraphy Analysis

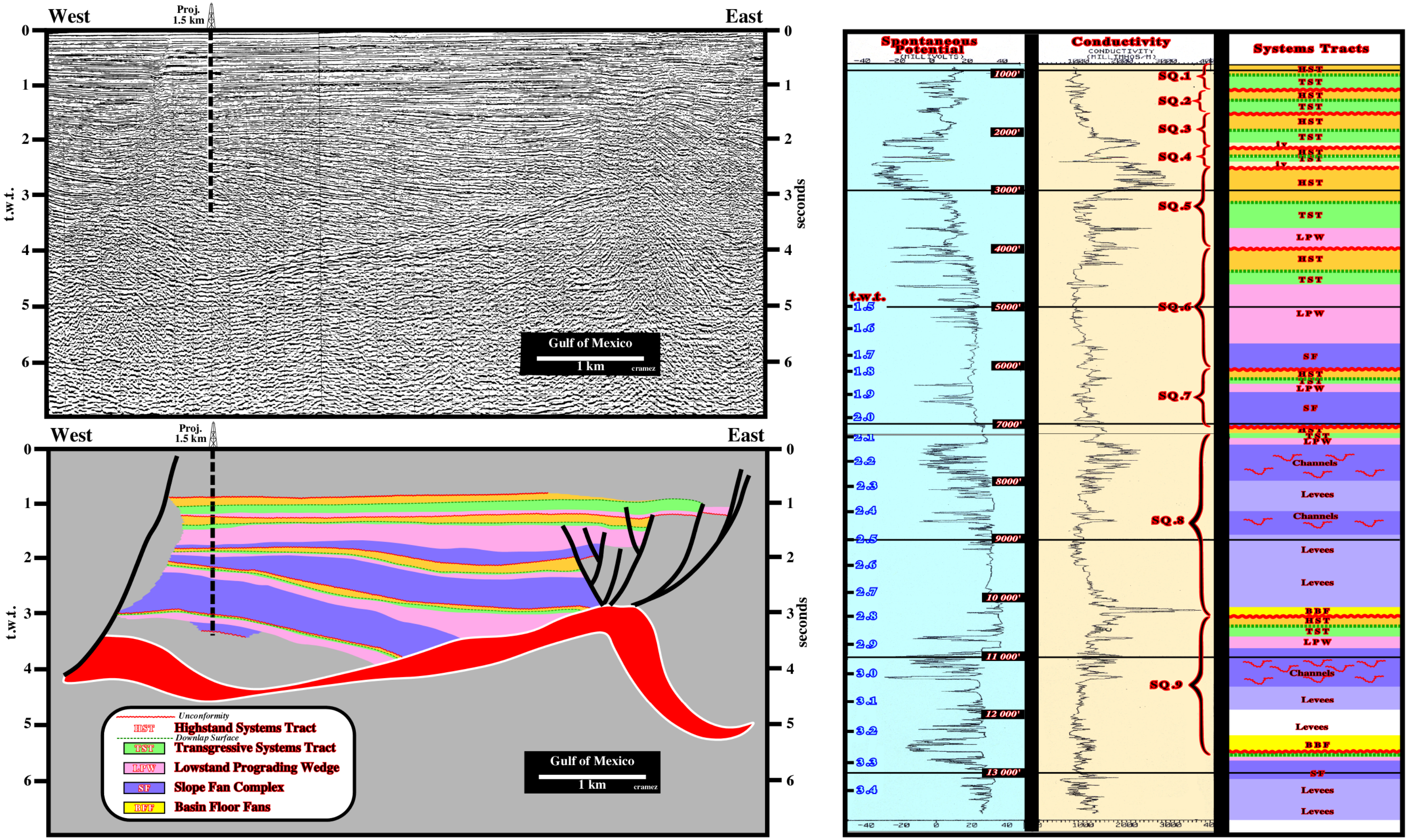
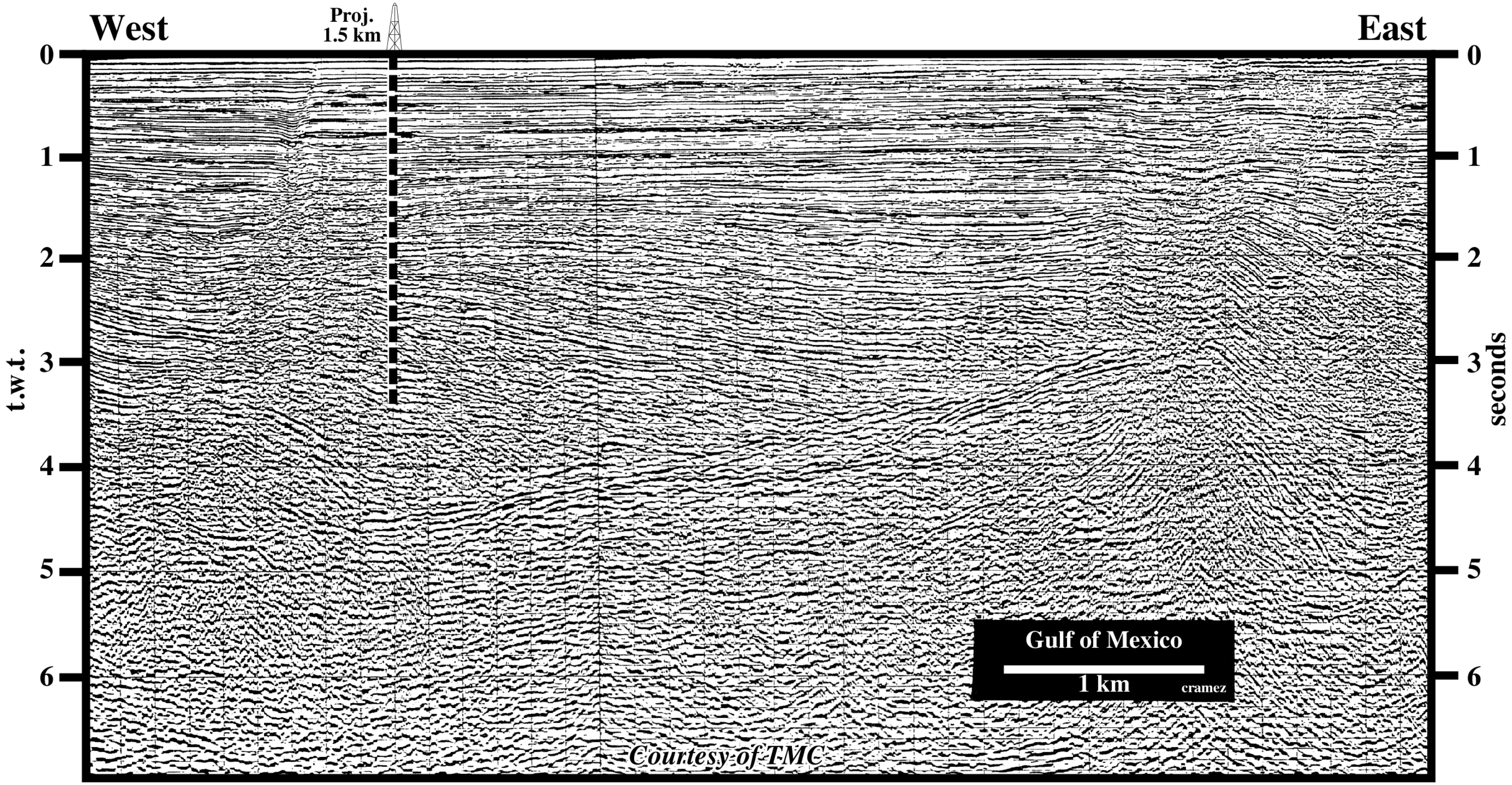


Fig. 5- A sequential interpretation at the level of sequence stratigraphic cycles, which, as said previously, are induced by eustatic cycles with a time duration between 0.5 - 3 My, or 0.5 and 5 My (according certain geologists), is generally possible on the ground and electric logs, but seldom on seismic lines. On seismic lines, it depends on the depositional rate and seismic resolution, as shown on the next figure.

Seismic Stratigraphy Analysis



Courtesy of TMC

Fig. 6- On this line from the Gulf of Mexico, it is easy to understand the depositional systems are mainly induced by a compensatory subsidence created by salt flowage. A tectonic disharmony, associated with the salt flowage, was developed at the top of the salt layer (probably autochthonous). It is recognized by tilted onlap reflection terminations, which are responsible for the thickening of the seismic packages toward the disharmony. The geometry of the seismic reflectors and the stratigraphic results of the projected well, suggest a rate of deposition large enough for the thickness of the sequence stratigraphic cycles to be above the seismic resolution, as indicated on the interpretation depicted on the next figure.

Seismic Stratigraphy Analysis

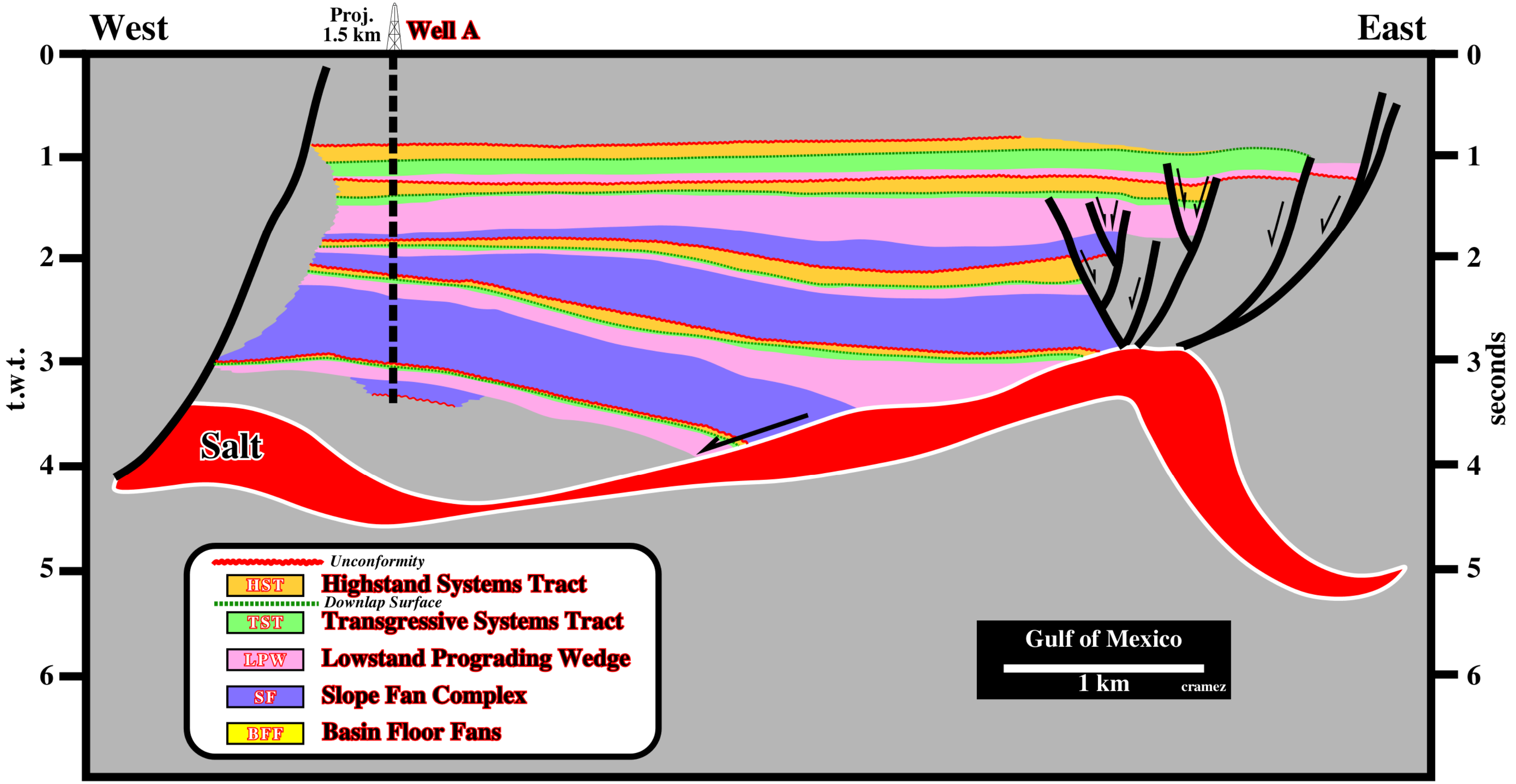


Fig. 7- On this interpretation of the previous line, the interpreter performed a sequential interpretation at the level of sequence cycles. Indeed, the stratigraphic results of the exploration well, drilled not to far off the profile, corroborated (see fig. 8) that the unconformities (in red) bound sequence cycles. As illustrated, the upper seismic intervals are composed of systems tracts, that is to say, coeval and genetically related depositional systems, deposited in highstand geologic conditions (sea level above shelf break). In the lower intervals, systems tracts deposited in lowstand geologic conditions (sea level below shelf break, or when the basin does not platform) were also deposited. When these intervals were deposited the shelf break was located eastward of the line.

Seismic Stratigraphy Analysis

Well A

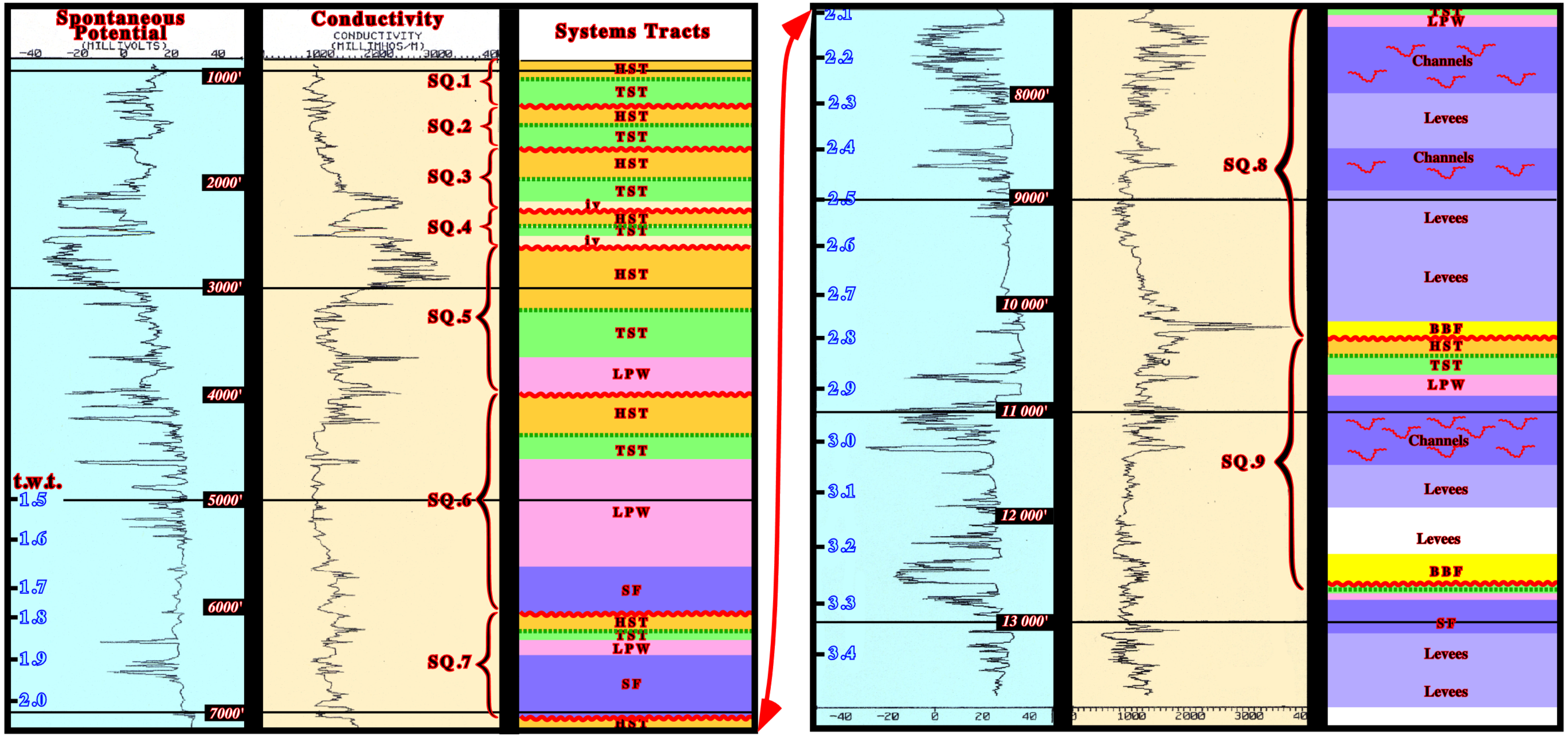


Fig. 8- As we will see later, each systems tract has a typical signature on electric logs. In addition, their stacking patterns, as well those of parasequence sets and parasequences (low level stratigraphic cycles) bounded by marine-flooding surfaces, allow accurate sequential interpretation. As illustrated, the upper sequence is composed by highstand and transgressive systems tracts, while in the lower sequences all systems tracts, that is to say, Higstand (HST), Transgressive (TST), Lowstand prograding wedge (LPW), Slope Fans (SF) and Basin Floor Fans (BFF) are present. Don't be afraid with all these names. Actually, very soon, we are going to study all stratigraphic cycles and particular the sequence cycles, in which, systems tracts can be individualized.

Sequential vs Genetic Stratigraphy

Sequential and **Genetic stratigraphy** are complementary. Both are holistic and global. Their complementarities are particularly true in hydrocarbon exploration, where the predictions of the more likely potential source-rocks (generating petroleum subsystem) and reservoirs-rocks (entrapment petroleum subsystem) are of paramount importance.

On regional seismic lines, genetic interpretations, performed in terms of **transgression / regression cycles** are easier than sequential interpretations performed at lower hierarchical levels, that is to say, (i) **Sequence cycles** and (ii) **Continental encroachment sub-cycles**. Sequential stratigraphy is based on the identification of unconformities (fig. 9), while genetic stratigraphy is mainly based on the recognition through time of: (a) major displacements of depositional coastal break (roughly the shoreline), (b) shelf break and (c) downlap surfaces (fig. 10).

During a transgression, the shelf break and the depositional coastal break are individualized. The distance between them (platform or shelf environment) increases since the shoreline is progressively displaced landward. During a regression, the area of the shelf decreases progressively, and it happens, very often, the depositional coastal break and the shelf break become coincident. When that takes place, the sedimentary basin has no platform.

The interpretation of the seismic line illustrated in fig. 9 is quite easy whether in stratigraphic cycles, bounded by unconformities (sequential stratigraphy) or in transgression / regression cycles (genetic stratigraphy). Onlap and toplap seismic surfaces are easily recognized. The identification and mapping of the unconformities bounding the different stratigraphic cycles can be made without difficulty. However, in normal seismic data (vertical exaggeration 2-5 times), sequential and genetic interpretations interpretations can only be correctly performed at high hierarchical levels (see later).

In normal conditions, at the beginning of interpretation of seismic data, explorationists must know at what hierarchical level of interpretation can be performed. In order to achieve such a task, Duval (1993) proposed a hierarchy of the stratigraphic cycles based on unconformities (sequential stratigraphy). Such a hierarchy, based exclusively on the picking and dating of unconformities, will be proposed later.

Sequential Interpretation

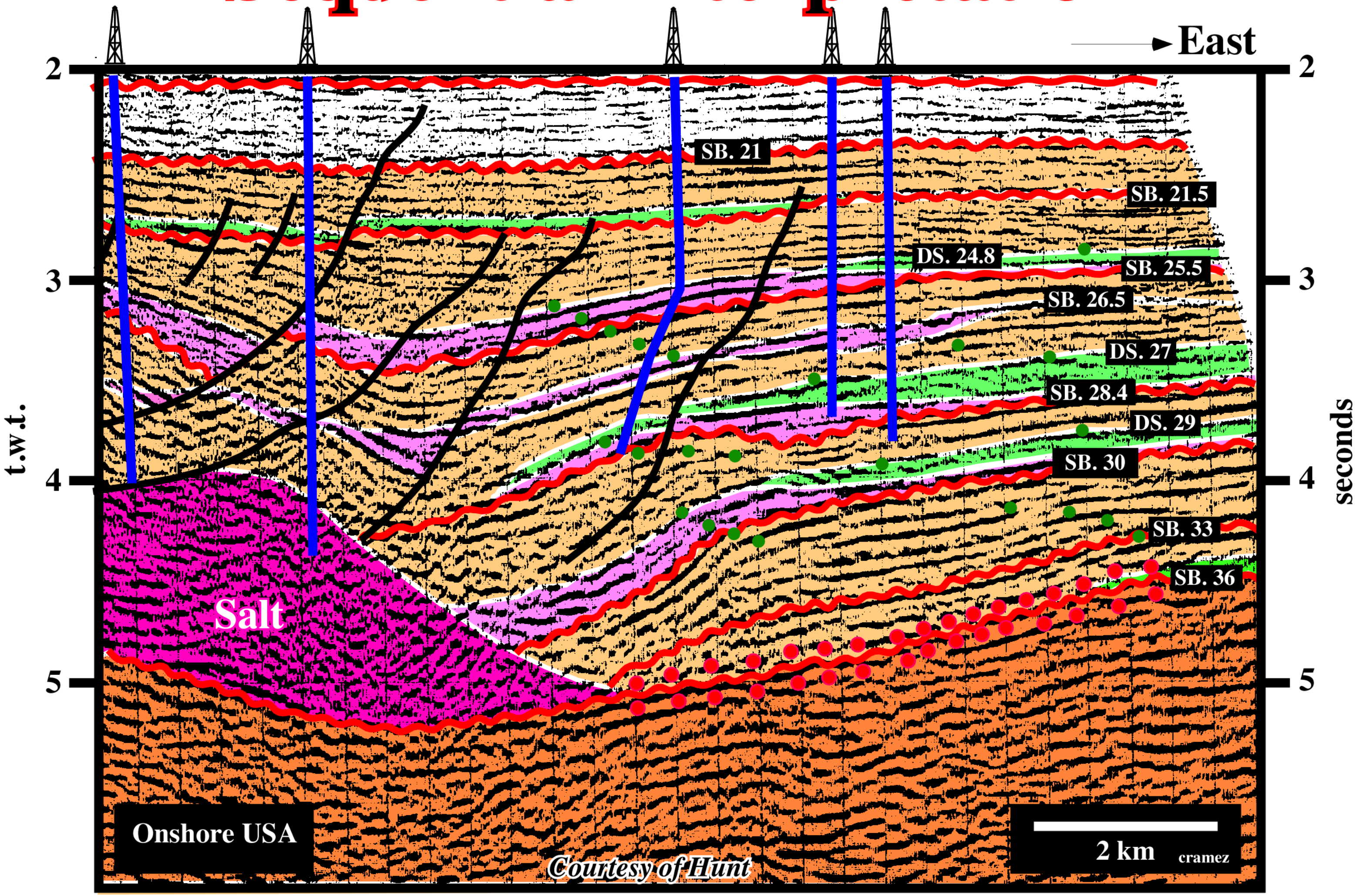


Fig. 9- On this line, each unconformity (relative sea level fall) bounding sequence stratigraphic intervals is calibrated by well results. Their age is proposed in million years ago (Ma and not My, which means just million years). The large red dots underline a salt weld, while the green dots mark the successive positions of the shelf break. The stratigraphic intervals in purple correspond to an interval deposited during lowstand geological conditions.

Genetical Interpretation

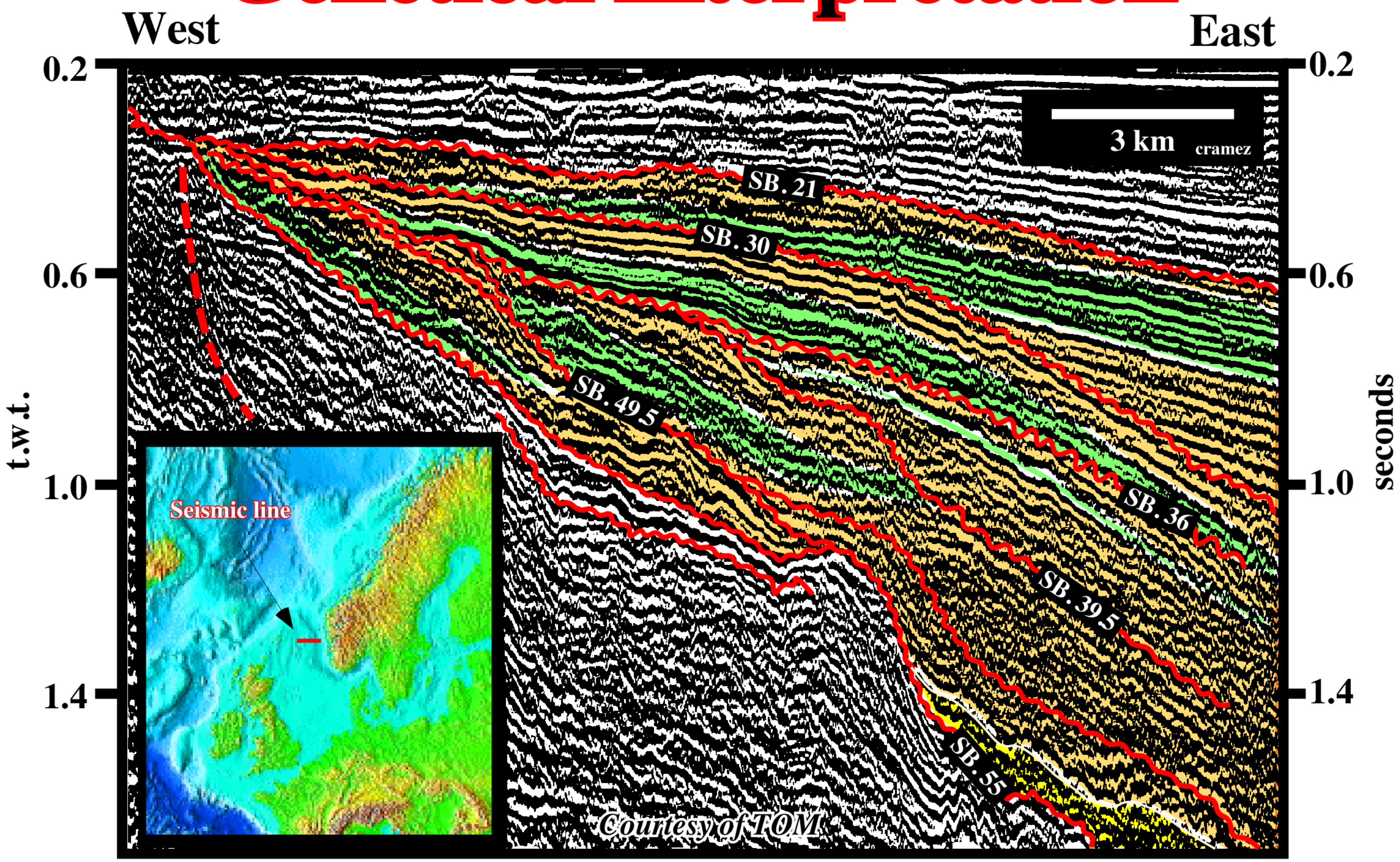


Fig. 10- This seismic line, from the North Sea, illustrates a genetic interpretation. Major transgressions (in green) and regressions (in orange) are recognized and picked. The limits between transgressive and regressive intervals correspond to downlap seismic surfaces. The limits between regressive and transgressive intervals do not necessarily correspond always with an unconformity, that is to say, with erosional surfaces. Indeed, sometimes they can correspond to conformities (e.g. the limit between the a lowstand prograding wedge systems tract (regression episode) and a transgressive systems tract).

Sequential vs Genetic Stratigraphy

Genetic interpretations are easy when performed in vertical exaggerated mathematical models, cross-sections, electric logs, or seismic lines shot through thick sedimentary depocenters (high rate of sedimentation). Offlap breaks (coastal or, and, shelfal) and major downlap surfaces (interfaces between backstepping and forestepping geometries) bounding the different genetic cycles are easily recognized:

1- **A backstepping or a retrogradational geometry** underlines a transgression, i.e. a landward displacement of the coastal deposits.

2- **A forestepping or a progradational geometry** emphasizes a regression, i.e. a seaward displacement of the coastal deposits.

The to and fro movement of coastal deposits, generally, is not driven by the worldwide sea-level regime and its fluctuations induced by absolute changes in the quantity of Earth's seawater. The displacements of shorelines are, in fact, mainly related with relative sea level changes resulting from the interactions between:

A) Sea level changes

B) Subsidence (Tectonics)

C) Terrigeneous influx

Coastal deposits (roughly near the shoreline) can be associated either with the coastal break or shelf break. During transgressive episodes both breaks are individualization with a progressive landward displacement of the coastal break which creates of a platform (shelf) environment.

In petroleum exploration, **sequential interpretations** are mainly used in to **predict potential reservoir-rocks**, which onlap against the unconformities, while **genetic interpretations** are mainly used **to predict major potential marine source-rocks**, which are associated with downlap surfaces.

Hierarchical Level of Interpretation

In spite of the fact that the **Hierarchy Theory** has been embraced by a large majority of geologists, it will be useful here to describe several of its aspects advanced mainly by Huxley (1925) and Koester (1967). We will start with the parable of the **Two Watchmakers** taken from Koestler‘s book “The Ghost in the Machine”. It illustrates the main principles and advantages of the hierarchy theory.

> “There were once two Swiss watchmakers named Bios and Mekhos, who made very fine and expensive watches. Although their watches were equal in demand, Bios prospered, while Mehkos just struggled along; in the end he had to close his shop and take a job as mechanic with Bios. The people in the town argued for a long time over the reasons for this development and each had a different theory to offer, until the true explanation leaked out and proved to be both simple and surprising. The watches they made consisted of about one thousand parts each, but the two rivals had used different methods to put them together. Mekhos had assembled his watches bit by bit rather like making a mosaic floor out of small coloured stones. Thus, each time when he was disturbed in his work and had to put down a partly assembled watch, it fell to pieces and he had to start again from scratch. Bios, on the other hand, had designed a method of making watches by constructing, for a start, sub-assemblies of about ten components, each of which held together as an independent unit. Ten of these sub-assemblies could then be fitted together into a sub-system of a higher order; and then of these sub-systems constitute the whole watch. This method proved to have two immense advantages. In the first place, each time there was an interruption or a disturbances, and Bios had to put down, or even drop, the watch he was working on, it did not decompose into its elementary bits; instead of starting all over again, he merely had to reassemble that particular sub-assembly on which he was working at the time; so that at worst (if the disturbance came when he had nearly finished the sub-assembly in hand) he had to repeat nine assembling operations, then Mekhos will take four thousand times longer to assemble a watch than Bios. Instead of a single day, it will take him eleven years. And, if for mechanical bits we substitute amino acids, protein molecules, organelles, and so on, the ratio between the time-scales becomes astronomical; some calculations indicate that the whole lifetime of the earth would be insufficient for producing even an amoeba - unless he becomes converted to Bios‘ method and proceeds hierarchically, from simple sub-assemblies to more complex ones. A second advantage of Bios‘ method is of course that the finished product will be incomparably more resistant to damage, and much easier to maintain, regulate, and repair, than Mekhos‘s unstable mosaic atomic bits” The universal characteristics of hierarchies are the relativity and, indeed, the ambiguity, of the terms **part** and **whole** when applied to any of sub-assemblies”.

Hierarchical Level of Interpretation

"**A part** as we generally use the word... wrote Abraham... means something fragmentary and incomplete, which by itself would have no legitimate existence. On the other hand, **a whole** is considered as something complete in itself, which needs no further explanation. But wholes and parts, in this absolute sense, just do not exist anywhere, either in the domain of living organisms, geological structures or social organizations. What we find are intermediary structures on a series of levels in an ascending order of complexity: **sub-wholes**, which display, according to the way you look at them, some of the characteristics commonly attributed to parts"

The relativity of hierarchies, known as **Janus dualism**, it is an important feature in a sequential interpretation approach:

- Geologists progress from the general to the particular.
- They cannot study geological events in isolation.
- Geological structures, as well as biological structures, are multi-levelled.
- Each of them forms a whole with respect to its parts, while, at the same time, they are a part of a larger whole.
- Geological structures, and particularly stratigraphic intervals, have a hierarchical nature, which implies different levels of stratigraphic interpretations.

Taking into account that on the seismic line illustrated in fig.9 : (i) the ages of unconformities SB. 25.5 Ma and SB. 28.4 Ma are based on micropaleontologic results of the exploratory wells drilled in the area, (ii) the ages proposed for the unconformities older than SB. 28.4 Ma are speculative (they are not calibrated), (iii) the wells located on the left part of the seismic profile reached the allochthonous salt nappe, but they did not recognize the sediments overlying the salt weld, which, conventionally, is underlined by double red dots, one can say the proposed interpretation is cyclic and multi-levelled

Indeed, we tried to identify stratigraphic cycles bounded by unconformities (erosional surfaces associated with significant relative sea level falls). The cycles identified are sequence cycles since they are associated with eustatic cycles of time duration less than 3 My (the difference of age of two consecutive unconformities is always lower than 3 My). Similar detailed interpretations (low hierarchical level) cannot be done on lines from basins with moderate or low rates of sedimentation (see later).

Hierarchical Level of Interpretation

The North Sea regional profile, illustrated in fig. 10, allows only systemic or genetic geological interpretations at a high hierarchical level, in which major transgression / regression cycles can be readily identified. Generally, genetic interpretations are easier than sequential interpretations. Indeed, downlap seismic surfaces are sharper and more continuous than unconformities. The proposed interpretation (fig. 10) suggests:

(i) The time interval between the successive unconformities, or downlap surfaces, is always higher than 3.0 My.

(ii) The limits between transgressive and regressive episodes are downlap surfaces. They underline and emphasize non-depositional hiatus and starved geological conditions.

(iii) Downlap surfaces are associated with condensed stratigraphic sections, in which faunistic peaks are paramount; that is to say, they are better, and easier, dated than unconformities.

(iv) The limits between regressive and transgressive episodes are flooding surfaces and unconformities.

(v) In proximal parts of sedimentary basins, particularly, landward of lowstand deposits, the interface between regressive and transgressive episodes belong to different stratigraphic cycles. The interfaces are mainly unconformities.

(vi) When transgressive and regressive episodes belong to the same stratigraphic cycle, the interface between them corresponds to a flooding surface.

(vii) In distal parts of a basin, it is possible to find successive regressive intervals pertaining to different stratigraphic cycles separated by unconformities. In other words, basinward and downward shifts of coastal onlap (unconformities) do not necessarily imply a change in the geometry of the deposits; forestepping deposits remain predominant.

Controlling Parameters
of
Sequential Stratigraphy

Controlling Parameters

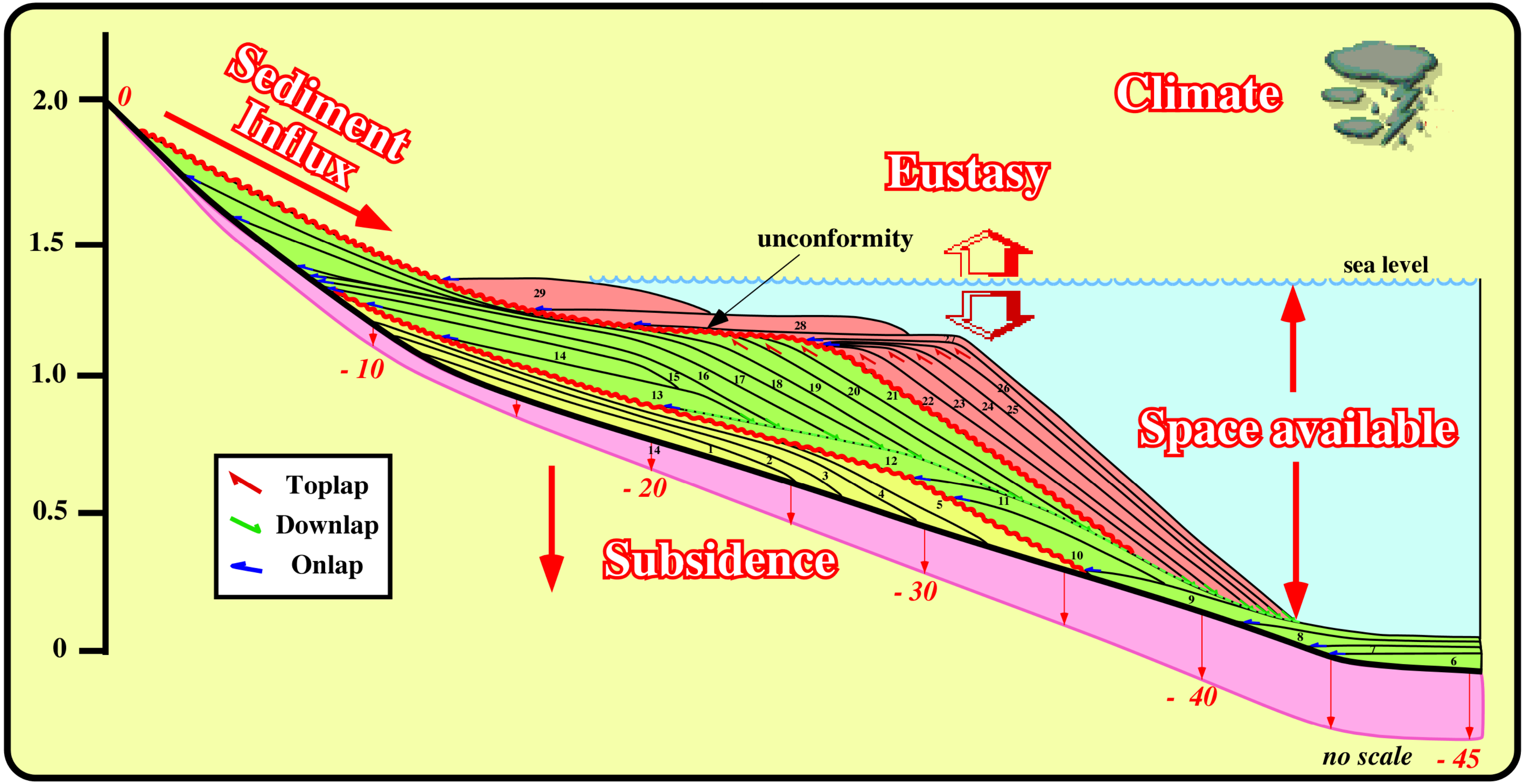


Fig. 11- The main parameters controlling depositional systems are indicated in this sketch. They are: (i) Eustasy, (ii) Subsidence, (iii) Sedimentary Influx and (iv) Climate. Landward of the shelf break (depositional coastal breaks are not depicted), the combination of eustasy and subsidence can increase, or decrease the space available for sediments. In other words, shelfal accommodation can be positive or negative. In the first case, there is sedimentation, in the second, there is erosion. Assuming that between each chronostratigraphic line (1 to 29) there is 100 ky, in this sketch three sequence stratigraphic cycles are represented. However, onlu the cycle composed by time lines 6-21 is complete. Notice the unconformities, the downlap surfaces; as well as, the time line terminations.

Controlling Parameters

Theoretically, sequential stratigraphy must solve the problems that classical stratigraphic approaches, such as **lithostratigraphy**, **biostratigraphy**, **chronostratigraphy**, **magnetostratigraphy**, etc., can not explained. It also explains what was already explained by classical approaches, particularly by **transgressive-regressive facies cycles**, which is one of the principal geological concepts resulting from classical stratigraphic studies.

Trangressive / regressive cycles represent an assembled picture of lithofacies in relationship to the shoreline location and its position throughout geological time. Suess (1888) believed that transgression-regression displacements of the shorelines were caused by **sea level changes**. He used the term **eustasy** to coin sea level changes, which he believed were global. However, with time, the eustatic concept became unpopular as studies on different continents showed that transgression / regression facies cycles did not correlate globally and were mainly due to local uplift and subsidence.

Concerning sea level changes recorded by geologists there is always the question of what actually changed, that is to say, is it the elevation of the continent or the absolute level of the sea?

After all, wrote MacDougal (1966),

> “Sediments only record relative changes, and we know that the continents undergo vertical movements. Rocks high in the Alps and the Rockies contain fossils deposited in the ocean, for example, and we know that oceans were never that deep”

Geologists have mapped the occurrence of various sediment types almost everywhere on earth in considerable detail. Through synthesis of such data there is now a fairly good understanding of the magnitude and timing of global sea level changes.

If the rock record indicates there have been large changes in sea level, the obvious question is:

Why?

Controlling Parameters

As far as we know there are really only two possibilities:

A) There must have been changes in either the volume of water in the oceans itself.

B) In the volume of other things that displace the water, such as continents, islands or ocean ridges.

We know that glacial periods are characterized by sea level lowering. Large amounts of the earth‘s surface water are tied up in ice sheets on the continents. It is estimated that at the height of the last glacial advance, roughly 20000 years ago, **sea level was well over 100 meters lower that it is today**. Although much of that ice is gone, there is still a considerable amount of water frozen in the ice caps. **If all of it were to melt, sea level would rise by about another 65 meters**. That may not sound like much, but a large fraction of the earth’s population lives close to sea level, Mexico City would be spared, but much of Los Angeles, New York, Tokyo, and Berlin (to cite just a few examples) would be inundated. Glacial episodes have a major effect on sea level. Most fluctuations that are recorded in Phanerozoic rocks don‘t occur at times in which there is independent evidence for global ice ages. Most likely they were caused by variations in the volume of the oceanic ridges.

In order to achieve global or regional correlations, sequential stratigraphy uses physical criteria to define chronostratigraphic intervals and biostratigraphy to determine their age. These intervals are considered genetic, in the sense that the rocks inside them are related by facies and bounded by physical surfaces that are, in part, discontinuities. In addition, they are believed to be regional. Some of them can even be global. They can be generally mapped within a basin, and sometimes in any basin around the world with a marine base level.

Complex interactions between (i) **Eustasy**, (ii) **Tectonic**, (iii) **Sediment supply** and (iv) **Climate**, which control the sequential stratigraphic patterns, are recognized in the rock record. Tectonic and eustatic effects cause relative changes of sea level, which control the space available for sediments (accommodation). Sediment supply controls how much of the accommodation space, created by relative changes of the sea level, is filled. Tectonics and climate control the amount and type of sediments. Each of these parameters has a stratigraphic signature and a certain rate of change, which can be recognized in rock records.

Controlling Parameters

P. Vail (1977) assumed that:

"Eustatic changes have a higher rate of change than the other parameters and control the stratal patterns"

A large majority of geologists agree that long-term eustatic changes are driven by changes in ocean-basin volume and that these changes are induced by mechanisms of basement movement that act over time periods of tens to hundreds of millions of years and are continental in scope. However, the causes of short-term sea level changes are still very controversial.

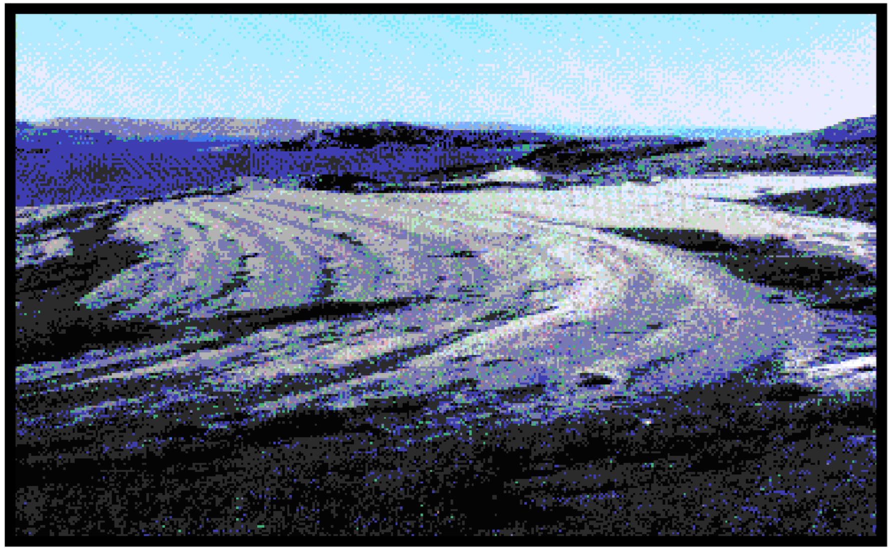


Fig. 12- The landward topographic changes, recognized onshore Norway, underline successive seaward displacements of the shoreline. Such displacements were induced by relative sea level falls. In this particular example, the relative sea level falls seem to be mainly created by the uplift of Scandinavia, in order to reach isostatic equilibrium, rather than by glacio-eustasy.

Controlling Parameters

Three major factors determine eustatic ocean level changes:

(i) Climate changing the ocean water volume.

(ii) Earth movements changing the ocean basin volume.

(iii) Gravitational changes of the ocean level distribution.

Ocean basin volume changes, controlled by earth movements and ocean water volume changes mainly induced by glacio-eustasy (climate), determine the ocean level:

A) The ocean level is not equally distributed but rough and uneven, due to gravity. It forms the equipotential surface of the geoid or the geodetic sea level.

B) The vertical ocean level changes may be caused both by real ocean changes, i.e. true eustasy and by geodetic sea level changes (geoidal eustasy).

Sea Level Change Factors

A) Volume of oceanic basins

- Mid-oceanic ridges volume
- Oceanic trenches
- Sedimentation

B) Total volume of ocean waters

- Glaciations
- Hydrosphere volume
- Basin desiccation
- Average temperatures of oceans
- Atmosphere water steam

Controlling Parameters

The three ocean variables are:

- The ocean basin volume, which is a **function of vertical and horizontal earth movements** (silting up plays a minor role).
- The ocean water volume, mainly determined by **climate and the glacial volume**. Juvenile water, water in sediments, water in clouds and lake volumes play a minor role.
- The ocean level, that is to say, the geological eustatic level, assumed to be parallel to the Earth‘s ellipsoid, **changed to rough and uneven geodetic sea level**, or equipotential surface of the geoid, **due to gravity irregularities**.

A) Eustasy or Eustatism

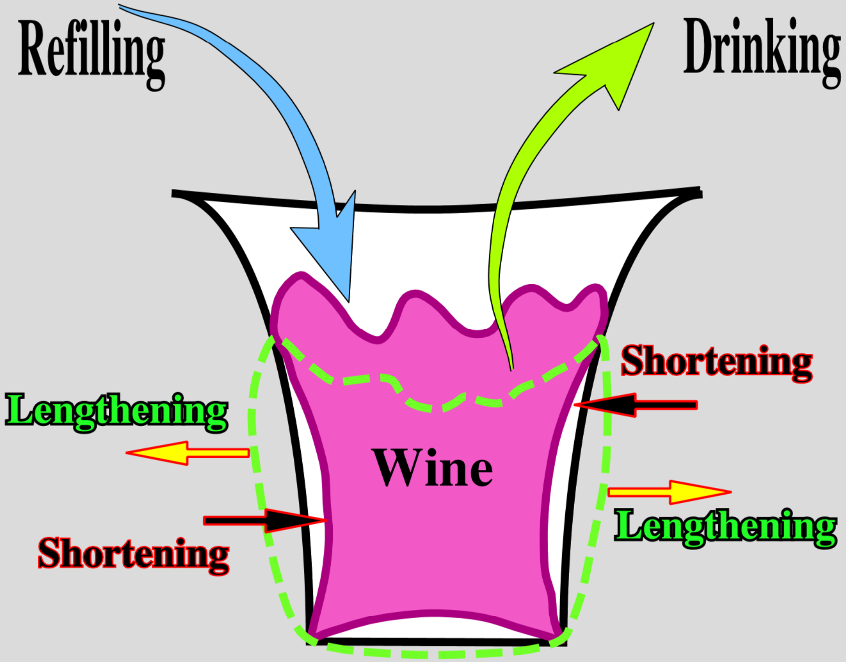
A.1- Eustasy metaphor

Eustasy can be illustrated by the variations of the level of wine in a cup. The size of the cup simulates the ocean basin volume (fig.13), which can be changed by compressing and expanding the cup (earth movements simulation) causing the rise and fall. The rise and fall of the wine‘s surface simulates tectono-eustasy. The wine volume in the cup can be changed by drinking and refilling (climate); giving rise to corresponding rises and falls in the wine level (glacial-eustasy).

Dilatation depending on temperature (which is sometimes advocated) plays no significant role. Earth‘s movements and climate determine the level of the water in the oceans, that is to say, the eustatic sea level. In the cup, the wine table is not flat but a rough and uneven one (geodetic sea level), in other words, any change in the gravity gives rise to redistribution in irregularities in the water surface. This metaphor will be better understood after reviewing the concepts of geoid and eustasy.

Controlling Parameters

Eustasy Metaphor



The size of the cup = Ocean basin volume
The wine volume = Water volume
Surface of wine = Geodetic sea level

Fig. 13- The ocean basin can be considered as a rubber cup of wine: (i) when you refill it, the wine-level rises, (ii) when you drink it, the wine-level falls, (iii) when you stretch the cup (shortening), the wine-level rises, (iv) if you extend the cup (lengthening), the wine-level falls. In addition, if you take a close look at the surface of the wine, you will see that it is not flat, but undulated with highs and lows.

Controlling Parameters

A.2- Geoid

The geoid is **the equipotential surface of the Earth's gravity field**, which is determined by attraction and rotation potentials. The ocean geoid is often termed geodetic sea level. The sea level profiles of the Smithsonian Standard Earth III geoid map are illustrated in fig. 14.

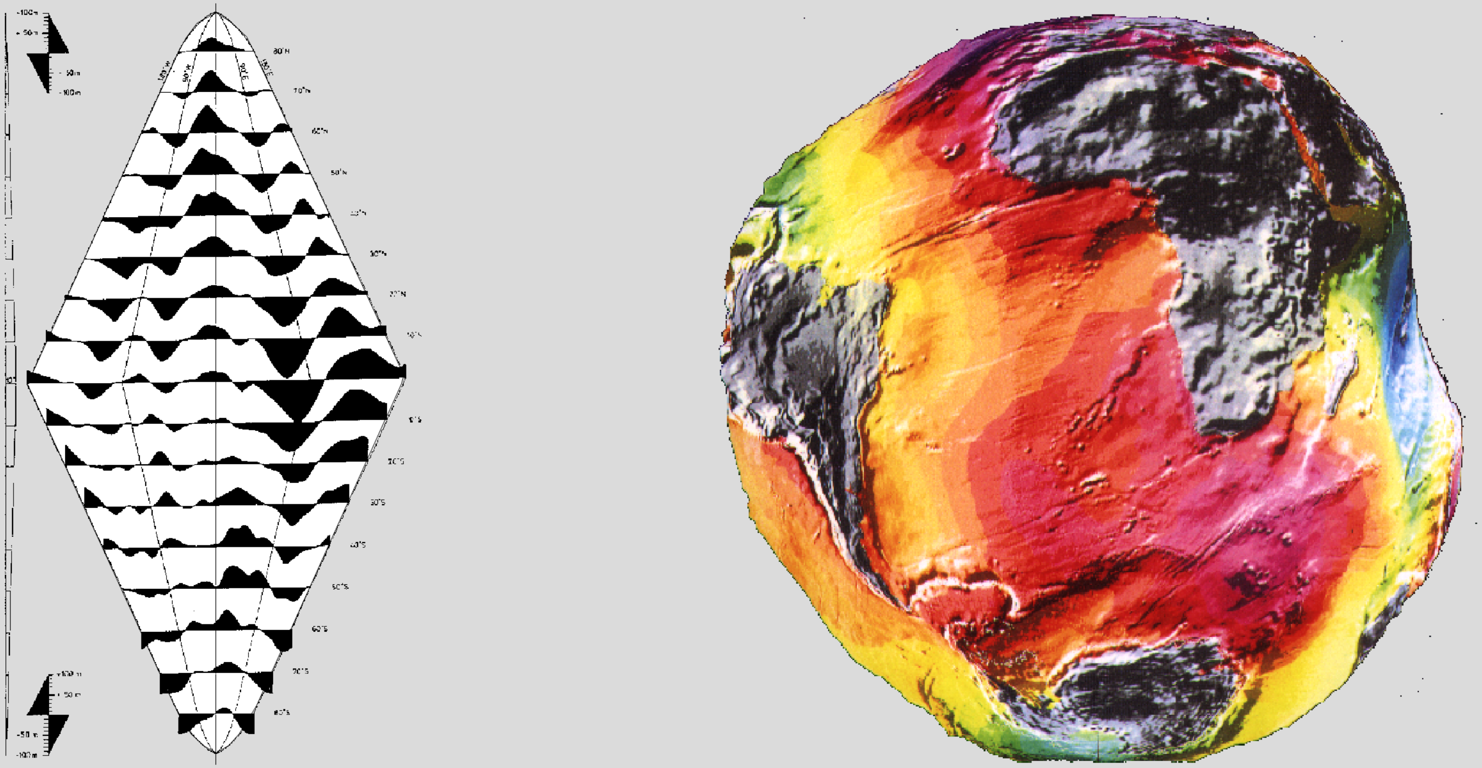
With respect to the Earth's center, one can note that there is a 180 meter sea level difference between the geoid hump at New Guinea and the geoid depression at Maldives Islands. In addition, the present geoid configuration is, of course, not stable. It must have changed with changes in gravity and the factors controlling it. In other words, through geological time, the location of humps and depressions of sea level have changed continuously. This feature must be taken into account when proposing global stratigraphic correlations. In fact, the geoid map clearly emphasizes that two areas, not too far apart, can have, at same time, different geological conditions (highstand and lowstand).

A.3- Geoid Changes

As said previously, the best definition of eustasy is simply **ocean level changes** instead of crustal tectonic and isostatic movements. However, eustasy was also defined as **"worldwide simultaneous changes in sea level"**, as distinguished from local sea level changes. According to Mörner (1976) the geoid changes must be included under the general term **eustasy** for the following reasons:

1) They have a direct effect on ocean level changes and most sea level records are faced with the problem of separating the ocean eustatic factor from the crustal factor.
2) They affect the ocean level globally (though by different signs) and distinguish from local effects.
3) It will be very hard, almost impossible, to distinguish them from glacial-eustatic and tectonic eustatic changes and will therefore, at any rate, and in the majority of papers, be included in term **eustatic changes**.

Controlling Parameters



Smithsonian Standard
Earth III Geoid Map

Gravity Field
Anomalies

Fig. 14- Sea level profiles show strong irregularities. Sea level is not flat. Large humps and depressions, related to gravity irregularities and the factors that control them, are quite evident. Between the highest area, near New Guinea, and the lowest, near Maldives, there is a difference of around 180 m. So, eustatic sea level changes must take into account local sea level variation induced by gravity anomalies. On the Earth's morphology, illustrated on the right, the amplitude of the undulations is exaggerated by a factor 100000 to the Earth 's radius.

Controlling Parameters

B) Eustatic Cycles

Five orders of eustatic cycles have been identified in the geological record (fig. 15). They have been designated as 1st to 5th order cycles. The 1st order eustatic cycle corresponds to continental flooding cycles defined on the basis of major times of encroachment (landward extension) and restriction of sediments onto the cratons (fig. 16). They are associated with the break-up of supercontinents (fig. 18). They are recognized on all continents and are believed to be global. Their time duration is greater than 50 My, which P. Vail takes as the minimum duration for a 1st order cycle.

- Since the Phanerozoic two eustatic cycles of 1st order have been recognized in the rock record (fig. 15).

- P. Vail (1977) considered that the youngest Phanerozoic 1st order eustatic cycle started at the base of the Triassic and extended to Present (more than 200 My).

- The older cycle started in the uppermost Proterozoic and extended to the end of Permian (more than 300 My).

Eustatic cycles of 2nd to 4th order are believed to be caused by smaller magnitude, but higher frequency, and more rapid rates of eustatic change. They cause high frequency variations on the relative change of sea level curve (eustasy + tectonics). In spite of the fact that time duration of these cycles has changed since the birth of sequential stratigraphy, the majority of geologists assume the following time durations:

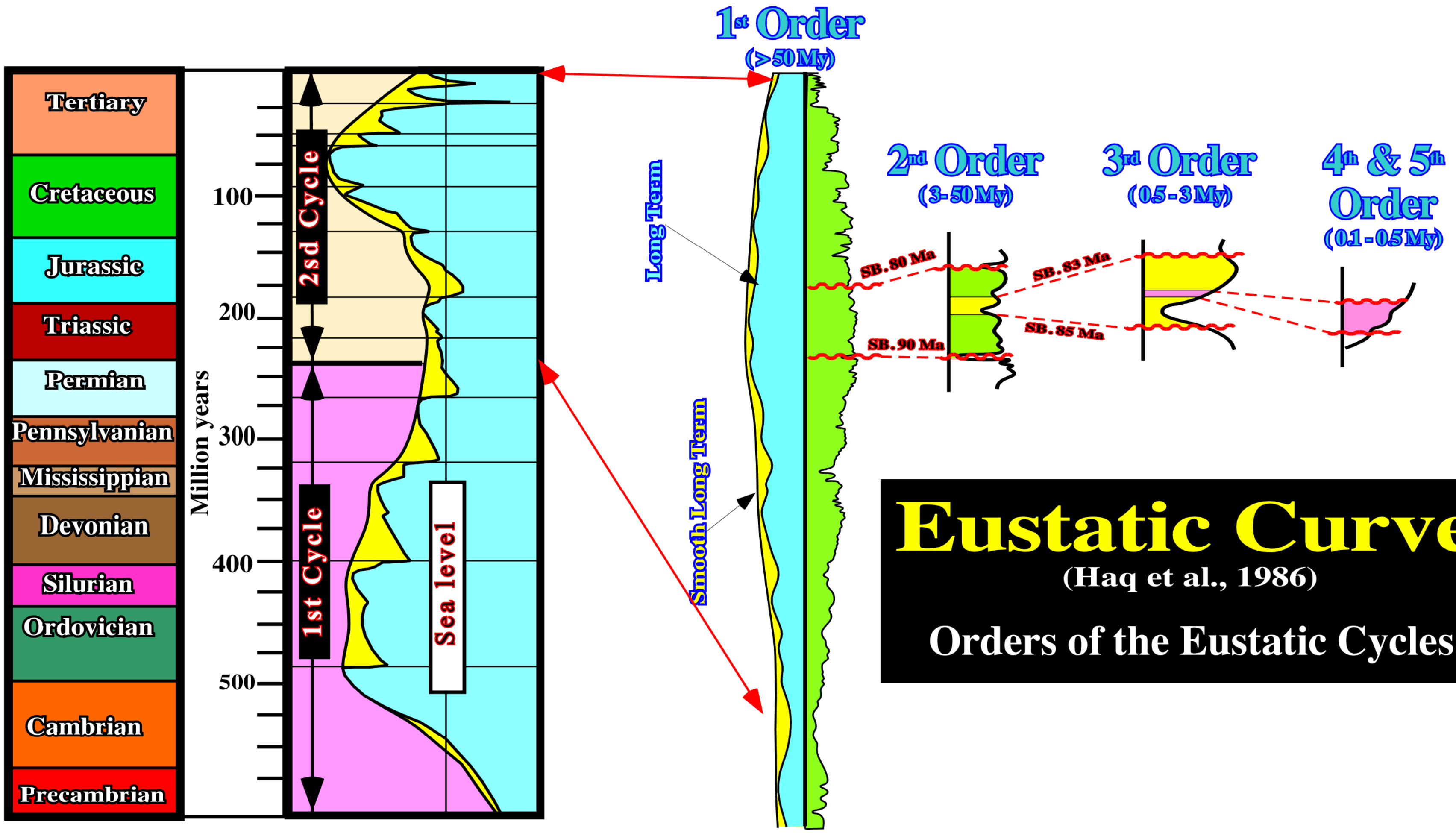
1) > 50 My for 1st order eustatic cycles,

2) 3-5 to 50 My for 2nd order eustatic cycles,

3) 0.5 to 3-5 My for 3rd order eustatic cycles

4) 0.1 to 0.5 My for 4th and 5th order eustatic cycles.

Controlling Parameters



Eustatic Curve

(Haq et al., 1986)

Orders of the Eustatic Cycles

Fig. 15- Five orders of eustatic cycles can be recognized on Exxon's eustatic curve. Since the Phanerozoic, there are two 1st order eustatic cycles. The first one defines the Palaeozoic and the second one the Caino-Mesozoic. The time duration of these cycles is as follows: 1st order > 50 My, 2nd order between 3-5 and 50 My, 3rd order, between 0.5 and 3-5 My, 4th and 5th order between 0.1 and 0.5 My.

Controlling Parameters

The classification of eustatic cycles in five orders clearly illustrated that P. Vail and co-authors considered Eustasy as a multi-levelled complex geological structure, in which each eustatic cycle forms a whole with respect to its parts, while, at same time, it is a part of a larger whole.

Systems thinking paradigm recognizes the existence of levels of complexity in eustasy with different kinds of laws operating at each level. At each level of complexity, that is to say at each eustatic cycle, the associated observed phenomena exhibit properties that do not exist at the lower levels. In other words, the stratigraphic cycle deposited in association with each eustatic cycle has specific properties. Thus, during 3rd order eustatic cycles, stratigraphic cycles dubbed **sequence cycles** are deposited. They are often considered as the fundamental **building blocks** of the stratigraphy. The term building blocks suggests a Cartesian approach, which I do not think, was the Exxon's approach. Indeed, stratigraphy, as a whole, is more than the mere sum of its parts or building blocks.

The 1st order eustatic curve, illustrated on fig. 15, is bimodal:

- It shows high sea level during two geological intervals:

    (i) Cambro - Ordovician

    (ii) Late Cretaceous.

- These periods have long been recognized as **thallassocratic** (craton of an oceanic block).

- They contrast with the widespread **epeirocratic** (craton of a continental block) emergences in the latest Precambrian, Permo - Triassic, and Oligocene - Neogene times.

- Each order of eustatic cycles seems to have a particular cause. The most likely cause of 1st order eustatic cycles is the **tectono-eustasy**, that is to say, change in ocean basin volume (believed to be related with the length of spreading ridges). Indeed, oceanic ridges are thermal bulges that displace seawater.

Controlling Parameters

The landward migration of a ridge increases the volume of the ocean basin and so induces a drop in sea level. This argument is readily expanded. The number of lithospheric plates varies in time, and the total length of the ridges increases with the number of plates. It seems likely that the number of plates and the length of the ridge system are maximal during **times of continental dispersal** and minimal during **times of aggregation**. As illustrated on fig. 17, rapid spreading rates cause broad and high mid-ocean ridges. Contrariwise, slow rates cause narrow and lower mid-ocean ridges. So,

During times of rapid sea floor spreading the ocean basins are relatively shallow and sea level rises onto continents (transgression). During times of slow sea floor spreading the ocean basins are deeper. The seas retreat from the continents, and are restricted to the ocean basins and areas of rapid tectonic subsidence (regression).

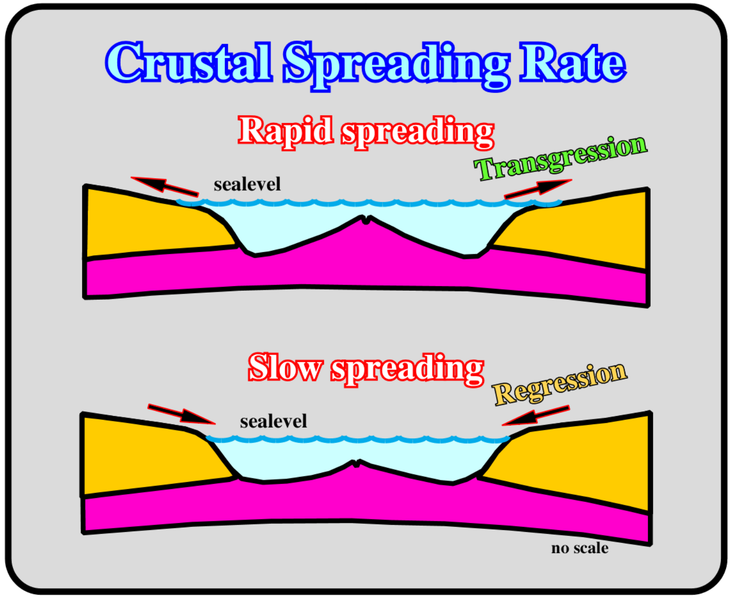


Fig. 16- Assuming, since Earth's formation, the total water volume is constant, a fast oceanic expansion induces a large volume of oceanic ridges, and so, sea level rises with the sea encroaching the continents. Contrariwise, a slow spreading induces a regression of the sea, that is to say, shorelines are displaced seaward. During the Phanerozoic, the amplitude of sea level changes seems to be roughly 300 meters and the rate of oceanic expansion around 1 cm per 1000 years, roughly speaking, the rate of nails' growth.

Controlling Parameters

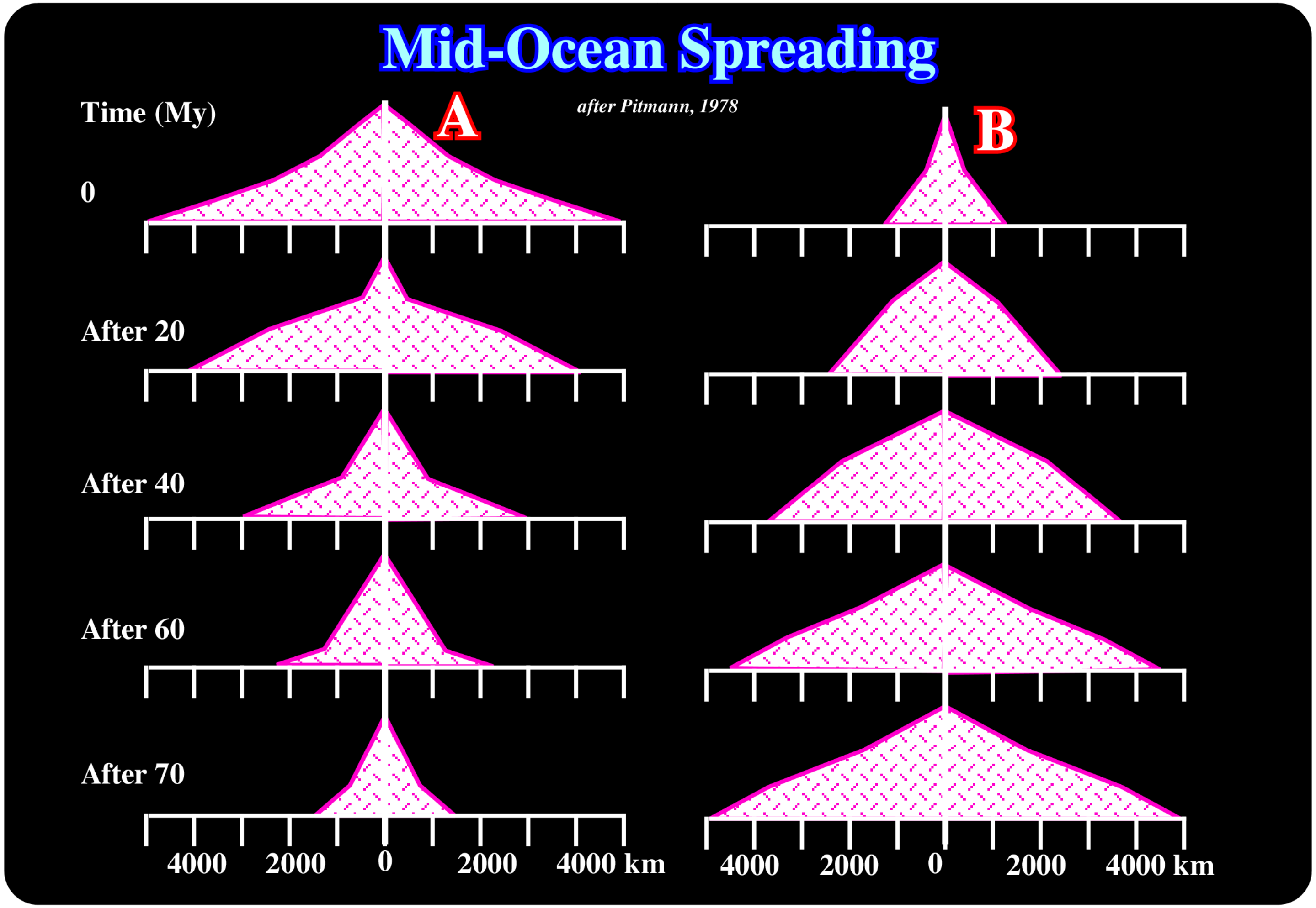


Fig. 17- This sketch illustrates the profiles of fast and slow spreading mid-ocean ridges, through 70 My of spreading. In A, a ridge that had been spreading at 6 cm/y, after 70 My, has one-third of its original volume. In B, a ridge that had been spreading at 2 cm/y and changes to 6 cm/y increases the volume of the ridge.

Controlling Parameters

Pitman (1978) calculated the profiles of a fast and a slow spreading mid-ocean ridge, through 70 My of spreading emphasizing the changes in the rate of seafloor spreading on eustasy (fig. 17):

- In A, a ridge that had been spreading at 6 cm/y, after 70 My, it has one-third of its original volume. Epeiric seas return to the ocean basins (regression).

- In B, a ridge that had been spreading at 2 cm/y changes to 6 cm/y. Such a change increases the volume of the ridge, which displaces water that causes a sea level rise (transgression).

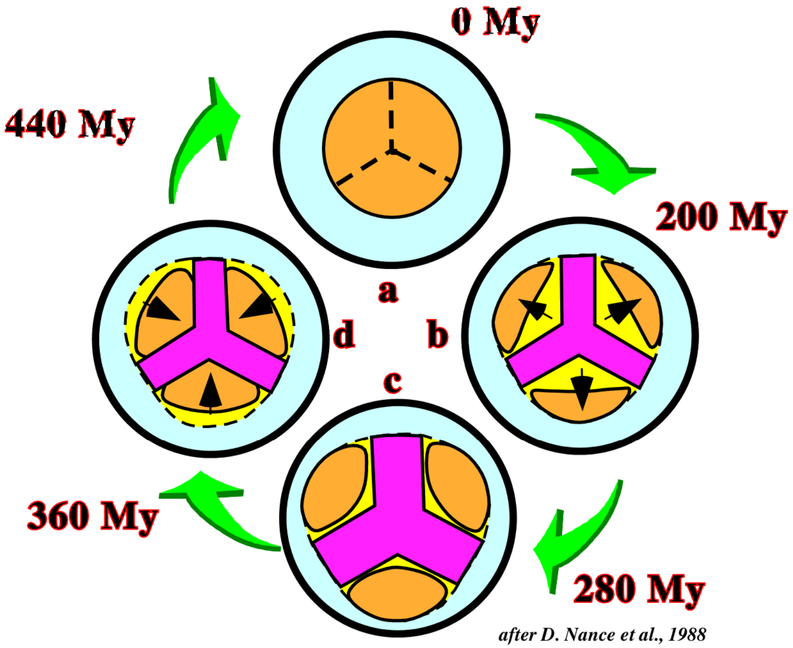
Geologists have assumed spreading rates could change sufficiently to move sea level by few hundreds of meters. Cretaceous spreading rates are still imprecisely known, and those of the earlier times are probably lost beyond recall. Relative roles might be played by changes in the ridge length versus changes in spreading rate. It seems clear that **plate activity** must have a strong influence on **long-term eustasy**.

As shown by Pitman, **volume effects are too gradual to be the principal cause of eustatic changes of 2nd or 3rd order**. **They are adequate only to explain the 1st order eustatic cycles**, particularly if the role of continental thickness changes, which can be regarded as an indirect response to plate activity, is the driving factor. Other factors contributing to changes in ocean basin volume are:

(i) Continental collisions.
(ii) Subduction trenches.
(iii) Submarine volcanism.
(iv) Sediment fill.

The combination of all these variables is estimated to cause a maximum rate of tectono-eustasy around 1.2 to 1.5 cm/ky[3]. The 2nd to 5th order eustatic cycles are believed to be caused by smaller magnitude, but higher frequency, and more rapid rates of eustatic change. Such eustatic variations would cause high frequency variations on the relative sea level curve. Second order eustatic cycles consist of sets of 3rd order cycles. According to Vail, a set of 5-7 third order cycles form a 2nd order cycle with a time duration averaging 5-10 My. As we will see later, the boundaries of 2nd order eustatic cycles are characterized by particularly large eustatic falls.

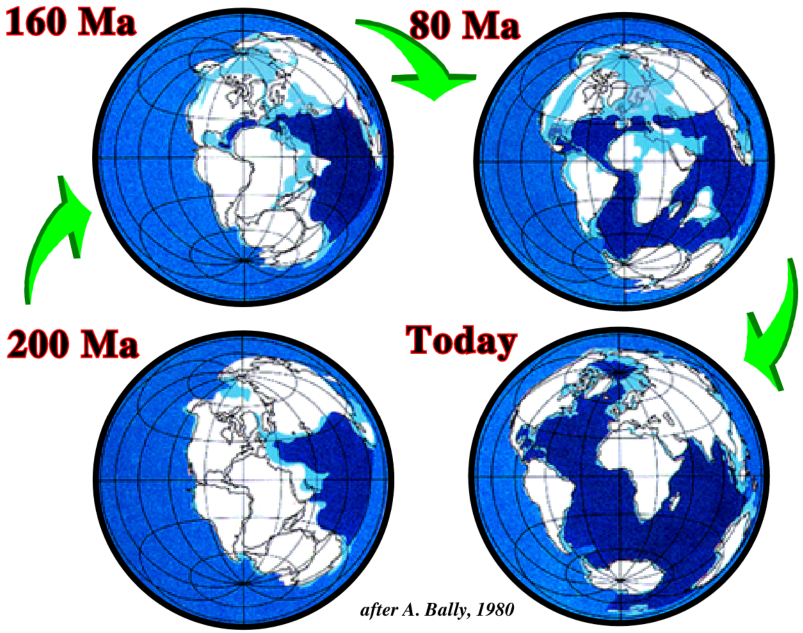
Controlling Parameters



Break-up of a Supercontinent

after D. Nance et al., 1988

🟪 Atlantic-type Ocean
🟦 Pacific-type Ocean
🟨 Shallow-Sea
🟧 Continent



Break-up of Pangaea

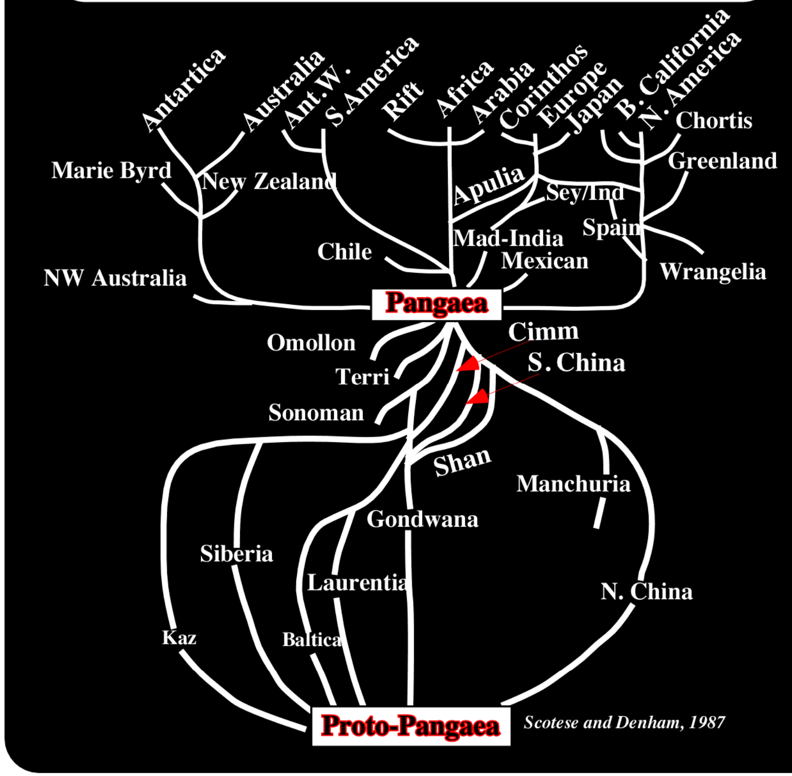
after A. Bally, 1980

🟦 Atlantic-type Ocean
🟦 Pacific-type Ocean
🟦 Shallow-Sea
⬜ Continent

Fig. 18- The majority of the margins limiting a supercontinent are Pacific-type (convergent margins). The break-up of a supercontinent induces the creation of new ocean and continental divergent margins (Atlantic-type). After the maximum dispersion of the continents, that is to say, when oceans reach their maximal size, they become, progressively, smaller and smaller to finally close. Indeed, divergent margins collide against oceanic crust (subduction B-type) or other margins (subduction A-type), closing the oceans and forming a new supercontinent. Such a tectonic evolution creates changes in the volume of the oceanic basins which controls 1st order eustatic cycles and so the highest hierarchic stratigraphic cycles, as illustrated on fig. 19 and 20.

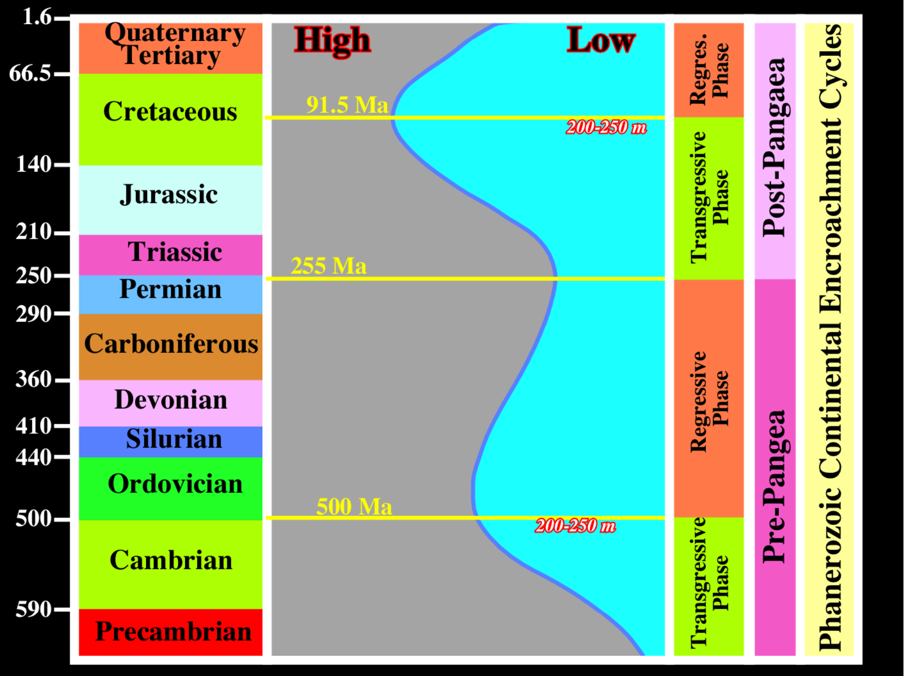
Controlling Parameters

Phanerozoic Plate Motion



Scotese and Denham, 1987

Eustasy Smooth Long Term

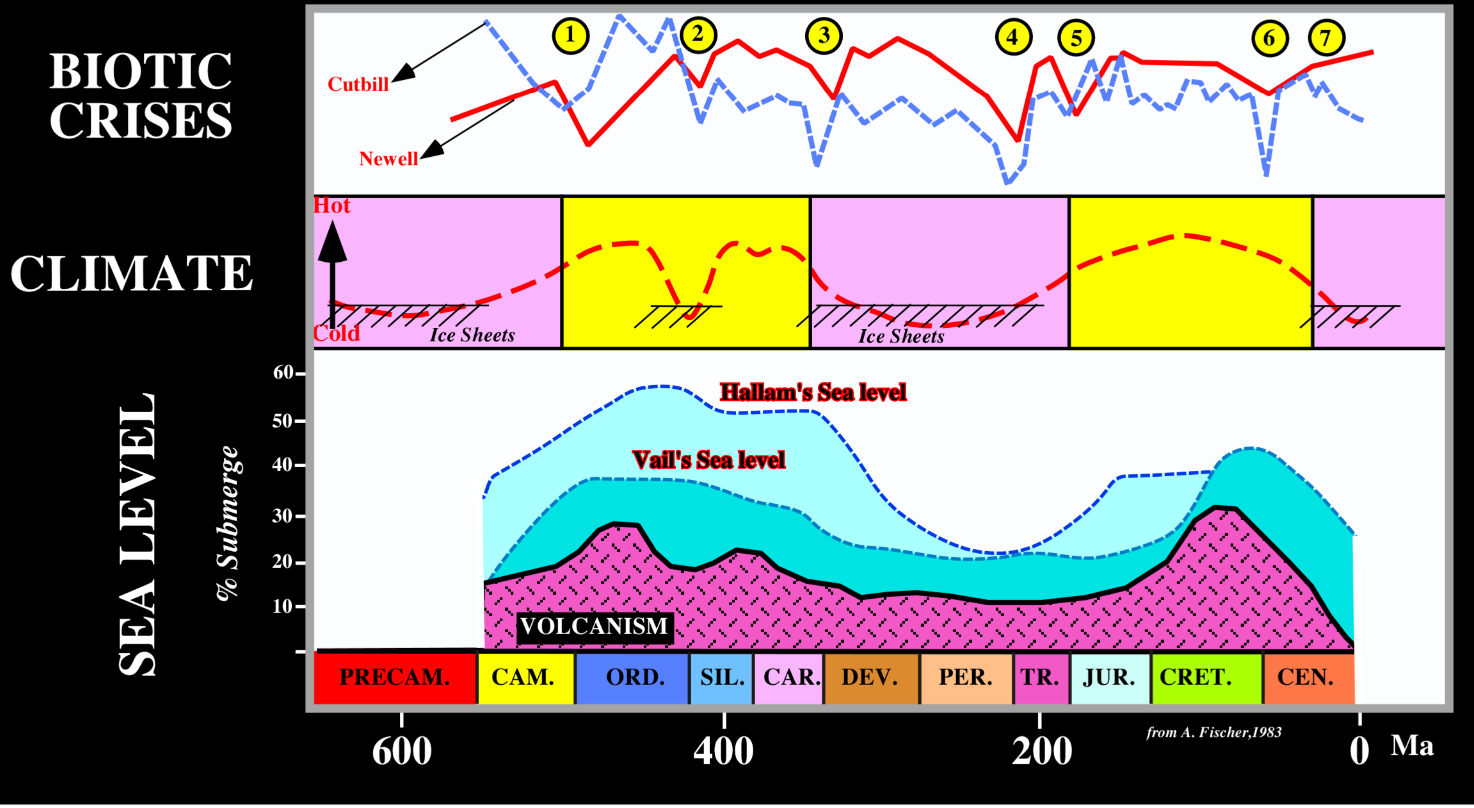


Modified from Vail et al,1991

Fig. 19- As depicted, the Phanerozoic 1st order eustatic cycles are clearly related with the plate tectonic activity. Indeed, the Palaeozoic eustatic high, with a sea level probably 200-250 meters higher than today, took place around 500 Ma, when the dispersion of Palaeozoic continents was maximal. Similarly, around 91.5 Ma, the Meso-Cainozoic eustatic high corresponds to the maximal dispersion of the post-Pangaea continents. Contrariwise, sea level was low during the Pangaea and Proto-Pangaea supercontinents. Admittedly, such sea level variations were induced by volume variations of the oceanic basins created by the volume changes of the oceanic ridges.

Controlling Parameters

Biotic Crises, Climate, Long-Term Sea Level Changes & Vulcanism



from A. Fischer,1983

Fig. 20- The relationships between long-term sea level changes, climate, volcanism and biotic crises have been quite well established by Fischer (1983), as depicted above. Again, this plate clearly illustrates that Stratigraphy is systemic, that is to say, it cannot be studied in isolation. It is interconnected and interrelated with all Earth and Cosmic events. Indeed, it is quite interesting to note that when sea level is high, climate is relatively hot and biotic crises reduces what, later are going to help us to predict the more likely marine source-rocks.

Controlling Parameters

C) Climate (Glaciations)

Variations in volume of oceanic basins are mainly due to:

(i) The break-up of supercontinents .

(ii) The changes of rates of sea floor spreading.

Sea level changes can also be induced by glaciations. Glaciations have an important effect on eustasy and, consequently, on the displacements of shoreline deposits. Glaciations occur periodically at the earth's surface. They seem to be characterized by a double periodicity:

(i) The first one is associated with the cyclicity of the geological periods characterized by predominant compressional tectonic regimes, that is to say, periods during which the earth's surface was composed just by few lithospheric plates. In other words, when the sediments were folded and uplifted forming high mountains, which are the realms of low temperatures.

(ii) The second periodicity is independent of the structural evolution of the earth's surface. It is associated with the cyclicity of the temperature variations for which several hypotheses have been proposed.

At the earth's surface the equilibrium of the heat is controlled by the amount of sun radiation received. If two amounts of heat, L_1 and L_2 are received by a surface, its centesimal temperatures, T_1 and T_2, are related by the equation:

$$(T_1+273^o) / (T_2+273^o) = (L_1 /L_2)\ 1/4$$

Controlling Parameters

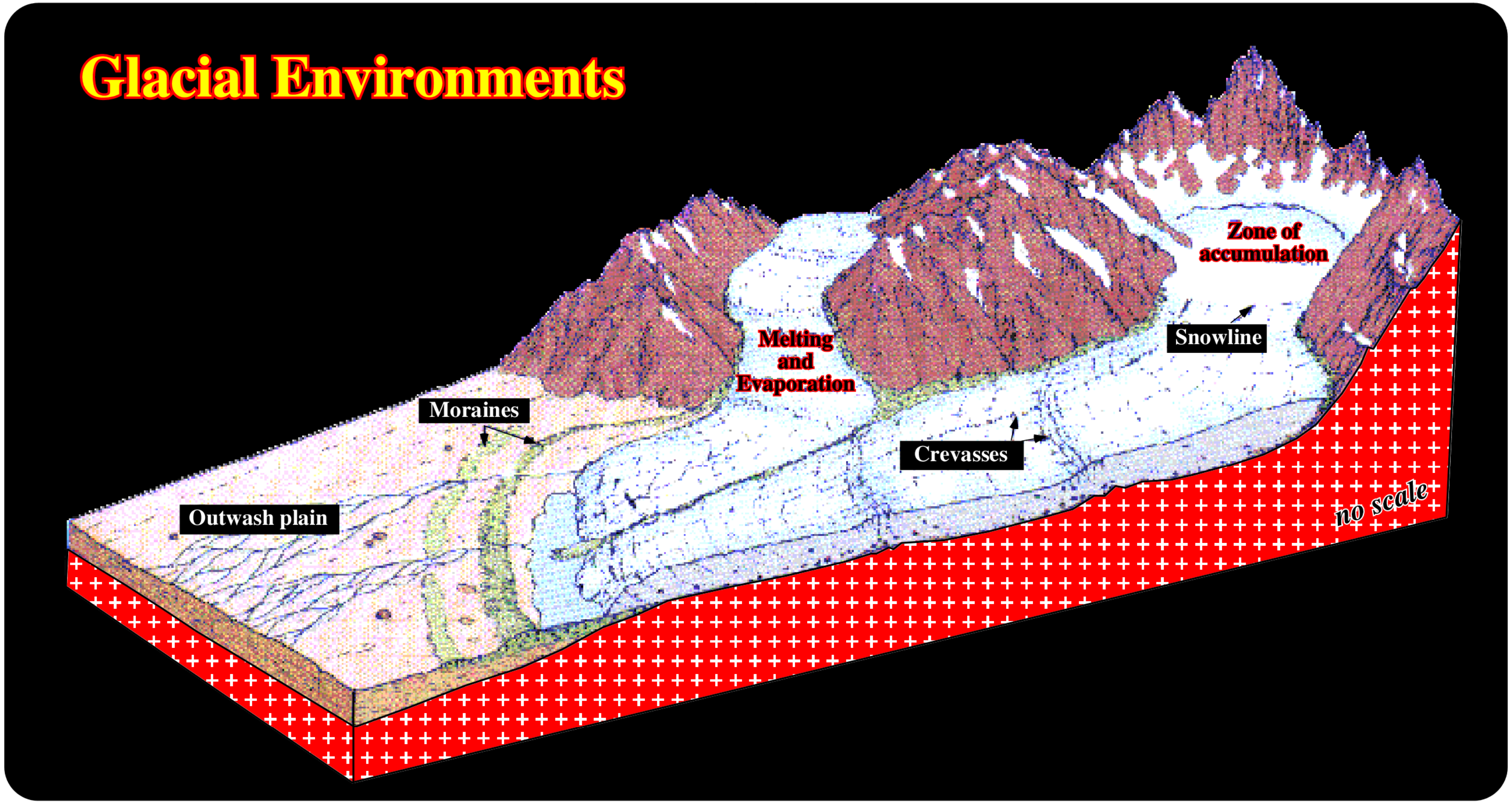


Fig. 21- As illustrated above, in a glacial environment it is important to understand the meaning of (i) accumulation zone, (ii) melting and evaporation zone, (iii) snowline, (iv) crevasses, (v) moraines and (outwash plain). Glaciers are quite important during glaciation periods, during which, the accumulation zone is extremely large and the snow line quite low, as well as the outwash plain.

Controlling Parameters

Since the Proterozoic, geologists have recognized six major ice ages within glaciations appearing and disappearing:

1) Proterozoic (roughly 2.7 Ga)
2) Proterozoic (roughly 2.2 Ga)
3) Precambrian (700-600 Ma)
4) Ordovician (500-400 Ma)
5) Upper Carboniferous (290 Ma)
6) Plio-Pleistocene (3-2 Ma)

- Proterozoic glaciations took place between 2 and 3 Ga. Mounded rocks with glacial slickensides and deposits associated with glacial environments have been found, particularly in Eastern Canada.

- The second ice age took place during late Precambrian time, around 0.6-0.7 Ga. It seems to have affected mainly Australia, South Africa, China, Europe and North America.

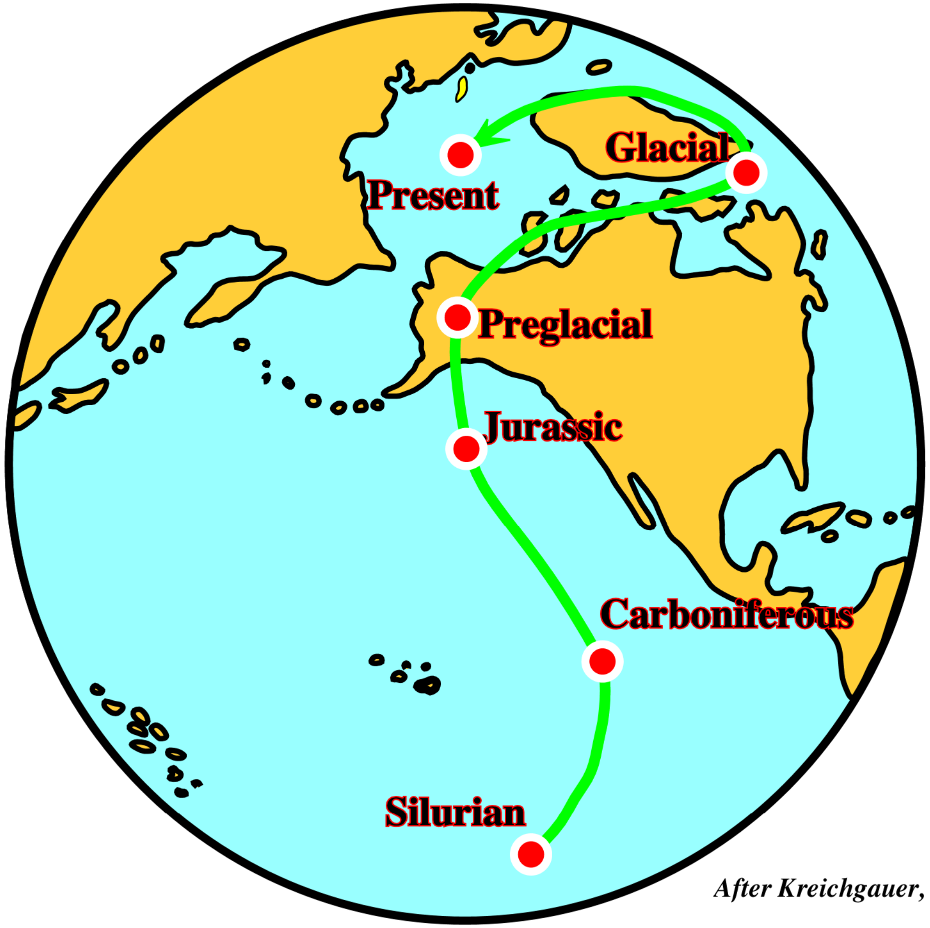
- After a long mild period (200 My) without ice sheets, a new ice age began at the end of the Ordovician. Then a new mild period (around 150 My) took place before a Late Carboniferous ice age (290 Ma).

- The Late Carboniferous ice age was very short (20-30 My). It was partially induced by the agglutination of Pangaea. Glaciations spread in Antarctica, S. America, Africa, Arabia, India and Australia.

- After a period of almost 270 My of relatively mild climate, the last ice age was Cainozoic. It took place 2-3 Ma in Plio-Pleistocene.

The temperature of the oceans and the amount of glacial ice on the continents, has a strong influence on the amount of oxygen isotopes of seawater. Both cooling temperatures and ice formation change the isotope values in the same sense. Even if the two effects cannot be untangled in detail, the timing of glacial fluctuations can be very well documented by using isotopic analysis.

Controlling Parameters



After Kreichgauer, 1950

Fig. 22- This sketch depicts the different positions of the North Pole since Lower Palaeozoic till present time. During the Lower Palaeozoic, it was localized in the lower Pacific; in the Carboniferous, it was localized near the equator, while in Jurassic time, it was localized roughly at the latitude of Vancouver. In the pre-glacial age, the North Pole was localized in Alaska, while during the glacial age it was located between south Greenland and Baffin Island.

Controlling Parameters

The temperature of the oceans and the amount of glacial ice on the continents has a strong influence on the amount of oxygen isotopes of seawater. Both cooling temperatures and ice formation, change the isotope values in the same sense. Even if the two effects cannot be untangled in detail, the timing of glacial fluctuations can be very well documented.

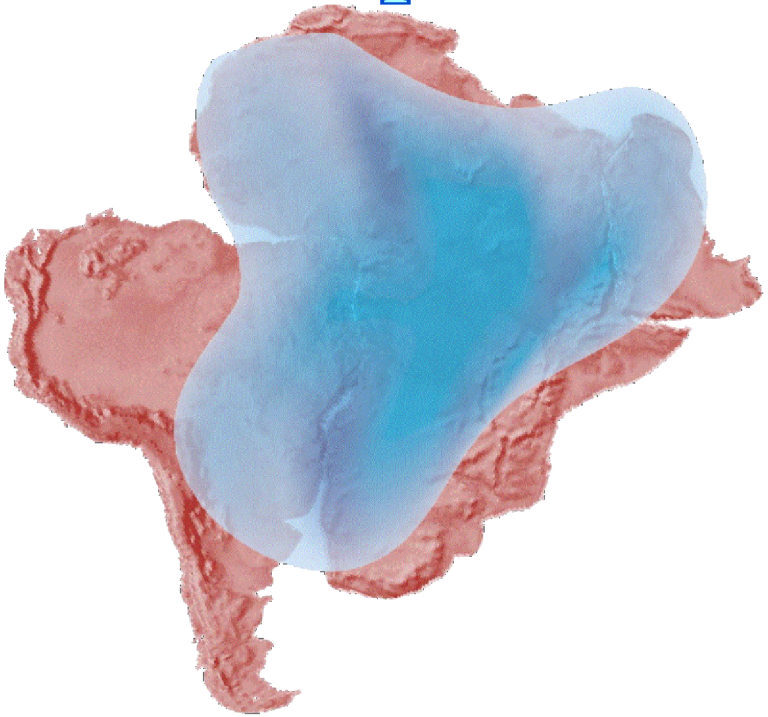
Sudden changes occurred about 35 Ma, that is to say, near the Eocene - Oligocene boundary. They have been interpreted as reflecting the onset and rapid growth of continental ice caps in the Antarctic. Before the advent of Plate Tectonics, in order to explain the change in climate suggested by stratigraphic studies, geologists thought that in the past the position of the continents and particularly the location of the poles, had changed.

To explain the glaciation during the Appalachian Orogeny, in South America, South Africa, Australia and India, several geologists suggested that these areas were once agglutinated (Gondwana Continent). They located the South Pole in the Pacific Ocean, not far from the Hawaii Islands. Kreichgauer (1950), as illustrated on fig. 22, admitted that at the beginning of Cainozoic time the North Pole travelled, firstly, toward Alaska and, then toward South Greenland. This could explain the large ice cape between North America and North Europe. The relatively mild climate nowadays was admitted to be due to the displacement of the North Pole from South Greenland to its present day position.

When these hypotheses were advanced they were very controversial. However, in the seventies, with the advent of Plate Tectonics, some of them were partially corroborated. Thus, the Ordovician glaciation (400-500 Ma), for instance, is nowadays well understood. In fact, according to the Plate Tectonics paradigm, after the break-up of the Precambrian supercontinent (Proto-Pangaea or Rodhinia), Baltica and Laurentia moved northward toward the equator and the Gondwana moved polewards. Baltica became warmer and the southern parts of Gondwana became much cooler. A few million years before the end of the Ordovician period, glaciers grew in around the south polar region of Gondwana. As the period came to a close, the glacial episode reached a climax and a coeval mass extinction in the marine realm took place. However, the relationships between the fauna extinction and the glaciations are speculative and controversial. The evidence of Ordovician glacial conditions was first found in the central Sahara Desert (fig. 23 & 24), where three or four level of glacial deposits, as well as a remarkable variety of glacial features, were discovered.

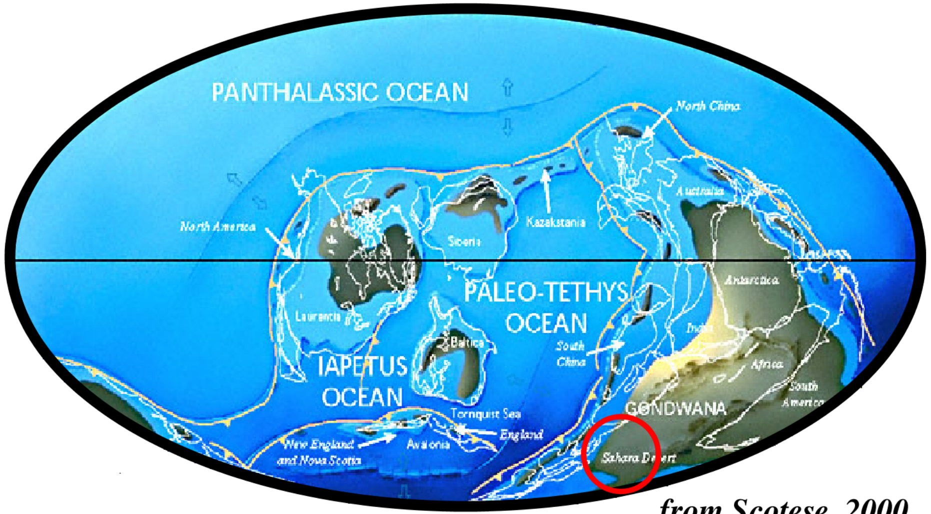
Controlling Parameters

Late Ashgillian Ice Cape



Late Ordovician

Paleogeography



from Scotese, 2000

Fig. 23- The probable extension of the Late Ordovician glaciation is illustrated on the left. The geometry of the late Ashgillian ice cap allows the prediction of the more likely location of the South Pole. The map on the right illustrates, according Scotese, the paleogeography of the late Ordovician, during which, glacial sediments were deposited, as illustrated in fig. 24.

Controlling Parameters

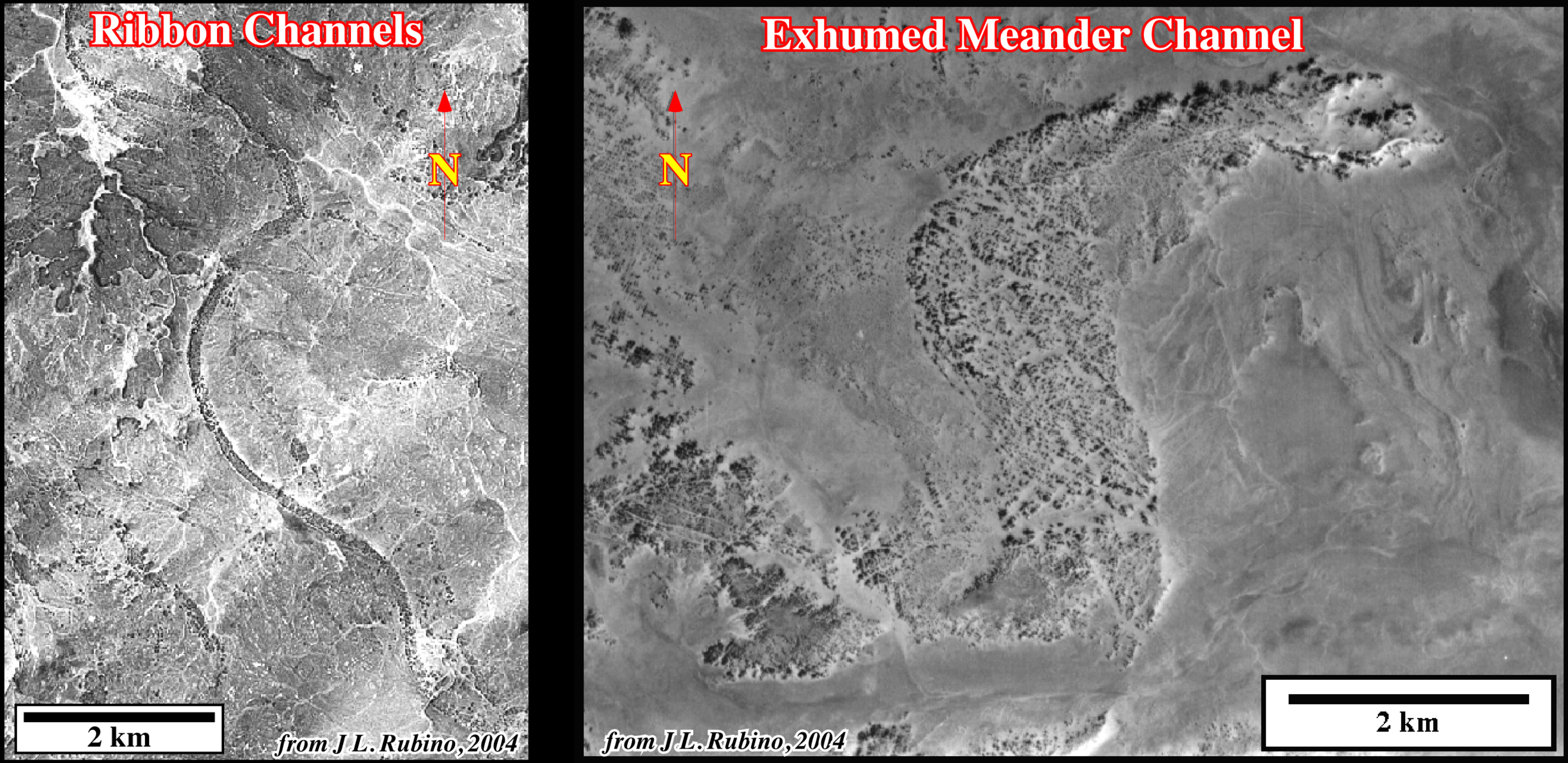
In fig. 24, for instance, is illustrated the silting up of a 50 km long and sinuous esker in South Sahara. This kind of glacial deposit, which is one of the best hydrocarbon reservoir-rocks in northern Africa, can be explained as follows (Hamblin, 1989):

> "A glacier transports debris to ice margins. Meltwater carves tunnels beneath the ice and emerges in braided streams, which deposits reworked glacial sediments on the outwash plain. In places, meltwater collects along the ice margins in temporary lakes, which develop deltas and other typical shoreline features. After the ice has receded, the hummocky hills of a terminal moraine stretch in an actuate line, conforming to the original shape of the ice margins at the farthest advance of the glacier. The retreating of glacier leaves behind unsorted debris in ground moraines, and recessional moraines mark the position of the ice margin where the glacier paused during its retreat. A subsequent advance of ice, forming drumlins, can reshape hills of ground moraine. Sinuous eskers remain where subglacial streams deposited sediments and sediments reworked by meltwater form outwash plain and lake deposits. Where ice blocks were stranded by receding glaciers and partly buried under debris, the melting of ice produced kettles. Similar glacial features and less extensive ones on other parts of the continents suggest a wide spread glaciation in Ordovician time."

Others evidence of this Palaeozoic ice age was found in North and South America. However, several geologists consider that their age may be slightly younger, probably Silurian. Confirmation of the age and the glacial origin of the associated deposits, interpreted as tillites, would indicate a continuation of the glacial episode beyond the Ordovician Period. The glacial episode peaked near the close of the Ordovician and caused sea level to drop rapidly. This sea level fall and, later, the sea level rise induced by deglaciation greatly controlled the space available for sediments and the displacement of shorelines during the lower Palaeozoic. At this point, it is important to remind here some interesting concepts proposed by Peltier (1980), which are fundamental to understanding sea level changes and their impact in sequential interpretation.

> - When ice sheets melt and their meltwater enter the oceans basins, we must be able to determine where in the oceans the water accumulates. Only then, will it be possible to describe the differential ocean loading accurately and, only then, will we know how the geoidal surface is deformed. It has been conventional in the literature of glacial isostasy to answer this question in a particular simple fashion. One assumed that the added meltwater was spread uniformly over the entire surface of the oceans and the bathymetry was the same everywhere. This assumption is clearly incorrect and, in fact, leads to errors of prediction, which may be significant in some locations. The reason for this is physically clear.

Controlling Parameters



from J L. Rubino, 2004

from J L. Rubino, 2004

Fig. 24- In the Sahara Desert, northward of the moraines of the Late - Ordovician glaciation, that is to say, in the washout plain, long and sinuous eskers outcrop. The filling sediments are potential hydrocarbon reservoir-rocks and some of them are productive.

Controlling Parameters

The equilibrium surface of the global ocean (geoid) is of necessity a surface on which the gravitational potential is constant. If for any reason, the potential on this surface is locally perturbed then the resulting unbalanced gravitational force will produce a current in the water, which will redistribute the water mass in such away that the constancy of the surface potential will be restored. If we assume, and this is an important assumption, that during the glacial maximum at approximately 20 ka BP, the ice sheets, oceans and solid Earth were in a state of gravitational (isostatic) equilibrium, then we may envision the following scenario as the ice sheets melt:

(i) Initially, the sea level is held anomalously high in the vicinity of the ice. However, everywhere on the surface of this initial ocean the gravitational potential is constant since it is in equilibrium.

(ii) When melting commences the potential on the surface is perturbed non-uniformly and the added meltwater is distributed over the oceans such as to restore the potential to a new constant value everywhere.

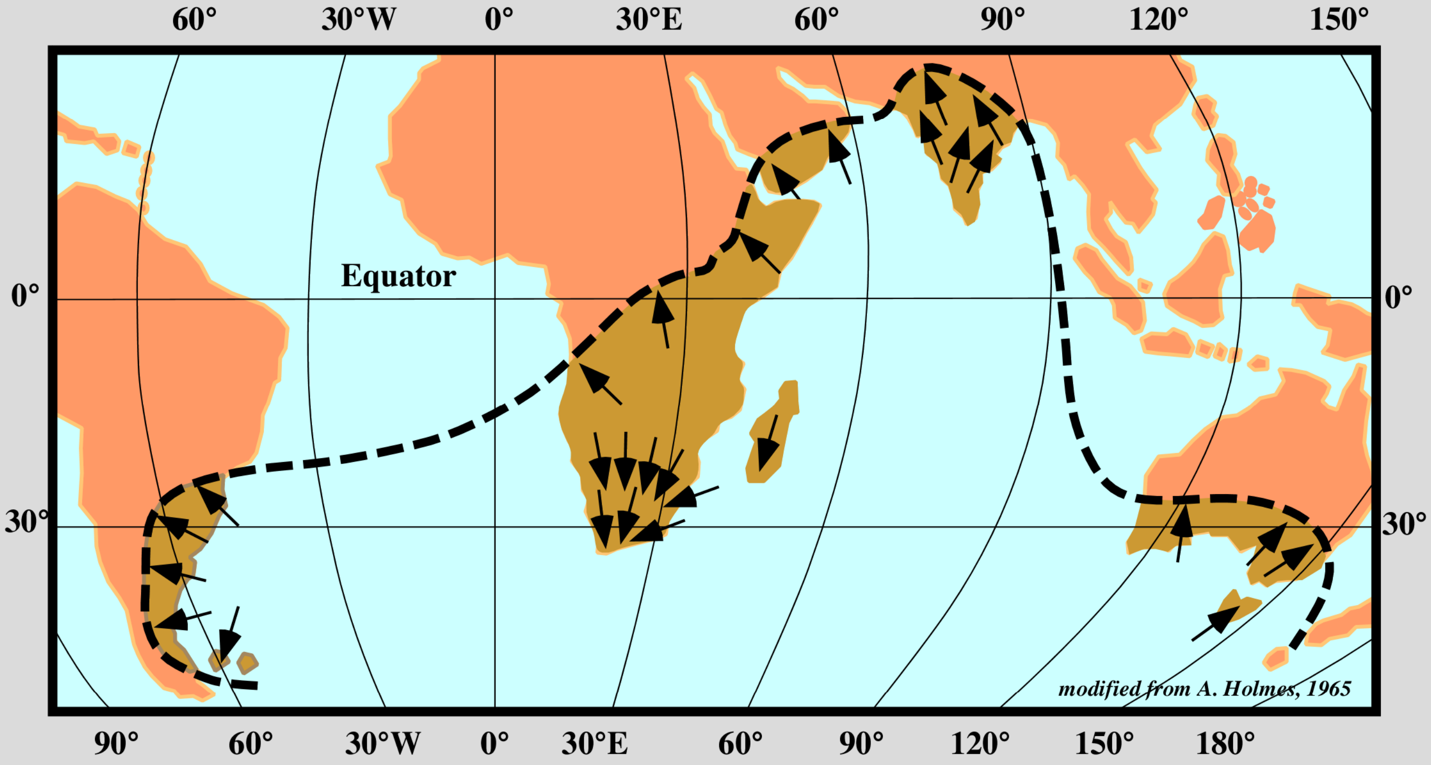
In response to the load added over every ocean basin the sea floor will be depressed and in response to the load removed where ice sheets are melting the land will be elevated. The complex redistribution of mass in the interior of the planet, which is effected by the net load variation, will force further irregular variations of potential on the ocean‘s surface and thus further redistribution of water will be required to equalize the potential. This process of continual gravitational “feedback” between the ice sheets, the oceans, and the solid earth is the process which ultimately determines the relative sea level signature, which will be observed everywhere continent and sea meet”

The Plio-Pleistocene ice age (fig. 25) and the Cainozoic glaciations, in generally, can be explained by Plate Tectonics paradigm. At that time, a thick continental ice sheet covered Europe and North America. In north of Asia, the thickness of the ice was very thin and probably only snow had been deposited there. The absence of an ice sheet is explained as due to the non-existence of mountains in North Siberia. This corroborates the hypothesis advanced by several geologists that the extension and thickness of the ice sheets are directly linked to the presence of high mountains.

The total volume of ice deposited over the Cainozoic continents, at the maximum of snowing-up, should be a large number of M km^3. The provenance of ice was, directly or indirectly, linked with the ocean’s water. The sea level should have beenlower than today. Due to the large volume of oceanic ridges, the volume of the oceanic basins was much smaller than today. In spite of the glaciation, during the Cainozoic the sea level was higher than today. The continents, larger than today, under the weight of the ice continental sheets subsided, in certain areas, at least 200 metres (Great Lakes and North Europe). Since the ice melted, these areas were flooded by rising sea level.

Controlling Parameters

Lower Paleozoic Glaciation



modified from A. Holmes, 1965

Fig. 25- The extension of Lower Palaeozoic glaciations and the mapping of associated slickensides strongly suggest (i) continental drifting and (ii) a relatively accurate position of the South Pole at that time. Indeed, a palinspastic reconstitution, not only gives a rough geometry of Pangaea but also the more likely location of the South Pole at Lower Palaeozoic time.

Controlling Parameters

Marine sediments with shells and other marine fossils have been found. They strongly suggest the present day sea level elevation is a consequence of isostatic readjustments. Detailed studies of the Plio-Pleistocene ice age deposits indicate that at least four successive glacial periods:

(i) Günz,

(ii) Mindel

(iii) Riss

(iv) Würm

were interrupted by relatively less cold periods known as interglacial stages. During these intermediate periods the retreat of the glaciers was much further than today. This suggests that nowadays we are living at the end of a glacial period, and before the next cold invasion, the climate of North America, Europe and North Asia should grow milder.

C) Climate

C.1) Origin of the Ice Ages

To explain the ice ages and sea level falls induced by glaciation, we need to find a mechanism able to reduce the amount of sun‘s energy received by the earth’s surface. There is no logical reason to believe that the sun irradiated a constant amount of energy during geological time. Modern astronomic hypothesis assume that all stars, as the sun, increase brightness with age. The calculation for the sun predicts an increase between 30 - 60 % during the last 5000 My.

Controlling Parameters

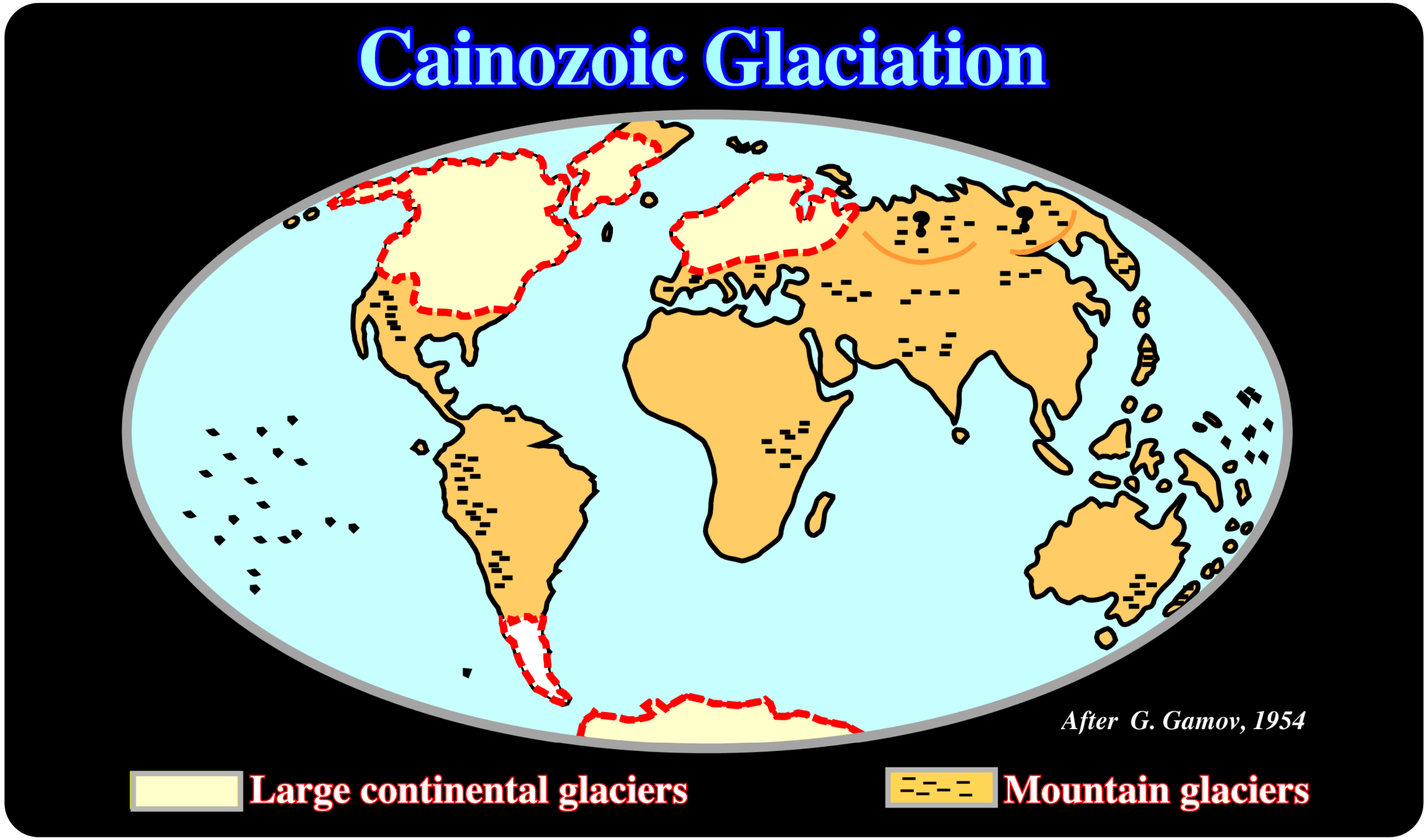


Fig. 26- On this map of the Cainozoic glaciation proposed by Gamov (1954), he individualized large continental glaciers and more restricted mountain glaciers. The continental glaciers took place not only in northern Europe and North America, but in Antarctica and southern part of South America as well. The mountain glaciers developed mainly in high areas of the Meso-Cainozoic and Palaeozoic megasutures.

Controlling Parameters

A detailed study of sun‘s surface showed the existence of important cyclic disturbances (e.g. sun’ storms):

- They appear and disappear on average every 12 years.

- They seem to have a strong short-term climate influence.

On the other hand:

- The consumption of methane and ammonia of the atmosphere and the ending of the greenhouse effect, which seems to be predominant during the Lower Proterozoic, can explain Proterozoic Ice Ages.

- The amount of different gas, volcanic particles, steam, etc., in the atmosphere, which induce important cooling due to the fact that one part of the sun’s energy is lost and does not reach the Earth‘s surface, could have contributed to the development of these ice ages.

- It is very difficult to relate volcanism and ice ages (see fig. 20). Several geologists advanced an opposite relation; the pressure of the continental ice sheets could induce volcanic activity.

To make a long history short, one can say, that so far, there is no hypothesis explaining why volcanic activity and ice ages should have the same rate. With the advent of plate tectonics, geologists associated the ice ages to periods with large amount of continental crust. They explained the Precambrian and the Late Palaeozoic ice ages due to the agglutination of Proto-Pangaea (Rodhinia) and Pangaea. However, such an explanation cannot be invoked to explain the other ice ages. On the other hand, stratigraphic studies suggest that large glacial periods seem to be, directly, or indirectly, associated with geological periods of continental shortening and uplift.

Another invoked possible explanation of the ice ages is supernovas‘ explosions. If a supernova blew up near the earth the radiation could disrupt the earth’s ozone bed and a general cooling could take place, as long and regular periods of geological time (200 My) separate the ice ages and as the solar system makes a complete galactic translation in 225 My.

Controlling Parameters

Origin of Ice Ages

The sun radiation is the main parameter of Earth's climate, so any change in radiation has a large influence over temperature.

1) Sun Storms
2) Amount of Atmospheric Gases
3) Volcanic Activity
4) Amount of Continental Crust
5) Supernova Explosions
6) Galaxy Revolutions
7) Milankovitch's Cycles

Fig. 27- According to G. Gamov (1950), the above seven causes are the most likely causes of glaciations.

Controlling Parameters

It was suggested that if the solar system crossed at a particular place a cosmic cloud, one fraction of the sun's radiation would be absorbed, or reflected, and only a minor fraction would reach the earth's surface with a subsequent cooling. This hypothesis explains very well the cyclicity of the ice ages, but there is no proof of such a cosmic cloud. The last hypothesis to explain the ice ages, or at least certain glaciation, was proposed by Milankovitch. He assumed the main parameters controlling the sun radiation received by the earth's surface are:

(i) Precession of the earth's rotation axis

(ii) Inclination of the orbit's plane

(iii) Precession of the earth's orbit

(iv) Eccentricity of the earth's orbit.

On this subject G. Gamov's ideas can be summarized as follows:

A) The earth's rotation axis moves slowly in space. It describes a cone which axis is perpendicular to the orbit's plane (fig. 28). This movement of the axis is known as "**equinoxial precession**".

- Newton explained that this was the result of attraction of the sun and the moon on the equatorial excrescence of the earth. It is an extremely slow movement. It makes a complete revolution in 26 000 years. As the phenomenon of precession reverses periodically every 13.000 years, the Earth will be at the perihelion presently to the sun, alternatively, with its hemispheres North and South.

B) In addition to ordinary precession, other perturbations of the Earth's movement, due to the influence of the planets, particular that of Jupiter, are added.

- The inclination of the earth's axis to the orbit's plane (which does not affect the ordinary precession) shows variations in period of more or less 40 ky.

Controlling Parameters

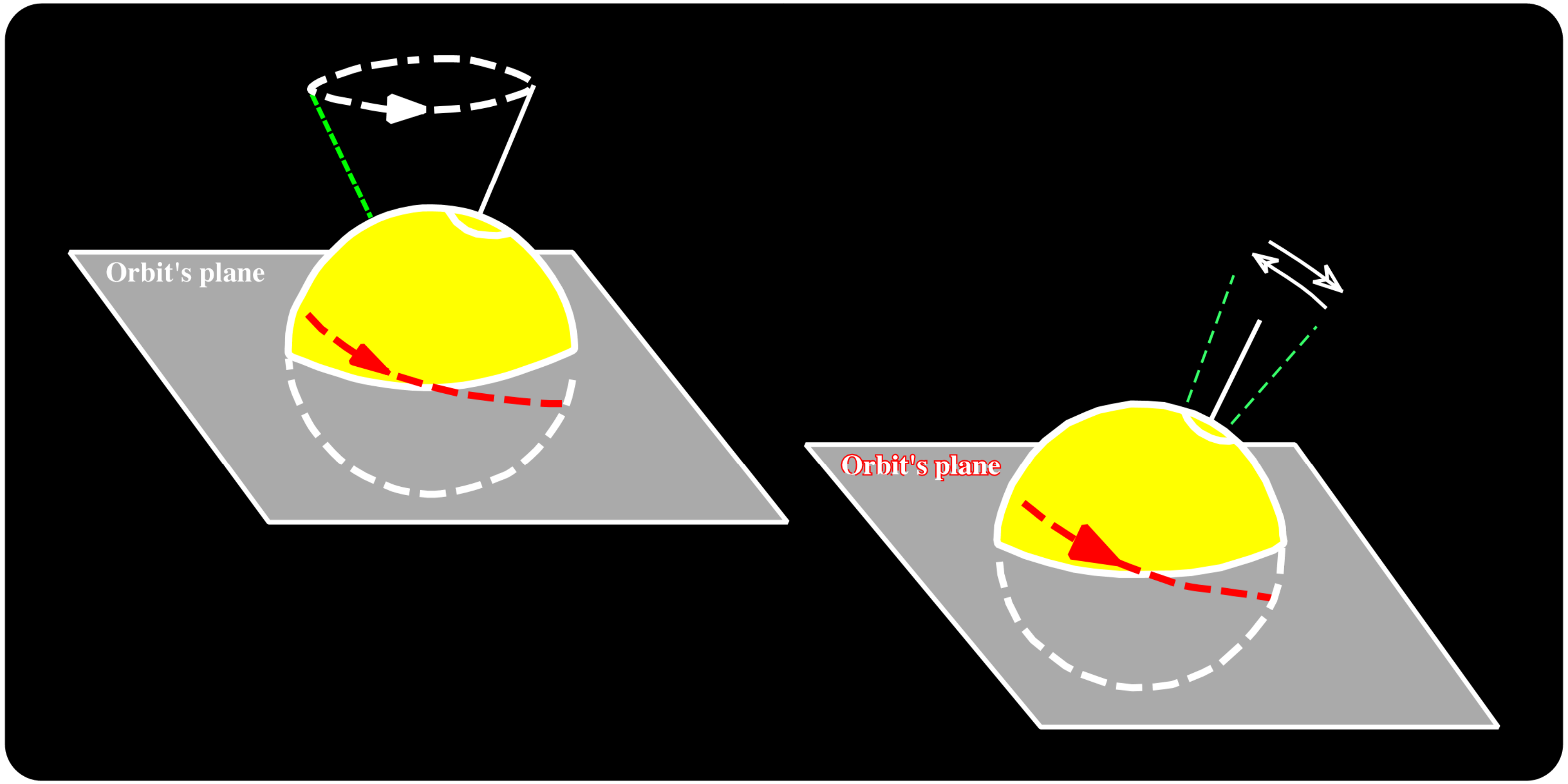


Fig. 28- The equinoxial precession, that is to say, the movement of the Earth's axis perpendicular to the orbit's plane (left) and the inclination of the orbit's plane of the earth, show periodic variations (± 40My). A precession cycle is often defined as a 19 000 to 23 000 year astronomic periodicity, in full, the precession of the equinoxes (one of the three Milankovitch parameters of the Sun's effective insolation) at the Earth's surfaces, that gives rise to important climatic and geologic cycles, notably in sedimentation rates and composition. A second cycle, the axial precession, 25 694 years rotating in the opposite direction (clockwise), also affects climate through the ecliptic angle.

Controlling Parameters

C) The earth's orbit changes. It turns slowly around the sun. Its eccentricity increases and decreases periodically.

- **The periods of these changes are 60 ky and 120 ky.**
- **The rotation of the earth's orbit has the same consequences as the precession.**
- **Their effects can be added.**
- **A super-period of the eccentricity is known. Its time lapse is around 400 ky.**

D) The periodic changes of eccentricity have a big influence on the climate conditions of earth's surfaces (fig. 29).

During periods of big elongation, the earth, at the ends of its trajectory, is particularly far away from the sun Both hemispheres receive amounts of heat abnormally lower. Calculations show that 180 ky ago the eccentricity was 2.5 times bigger than presently. This change represents a difference in temperature of 9 to 10º C between both hemispheres.

Individually, any of these causes induces substantial changes in temperature. However, if at a certain time of geological history, they are coeval, the addition of their effects can be particularly important. When the eccentricity of the orbit is significantly big, the inclination of the axis is particularly strong. The boreal summer coincides with the passage of the earth at the distal point of the orbit. The North hemisphere will be particularly cold. Contrariwise, a small eccentricity combined with an opposed inclination of the axis creates mild climatic conditions on the North hemisphere.

To sum up, astronomical events have induced an alternate of cold and mild climates during the Earth's history (fig. 30). However, it looklike the ice ages are particularly marked during the geologic intervals characterized by predominant compressional tectonic regimes. During such intervals, the shortening and uplifting of sediments creates favourable topographic conditions to a cold climate for developing larger glaciers. Asteroid impacts also originate cold climates, but the presence of mountains to seems be required.

Controlling Parameters

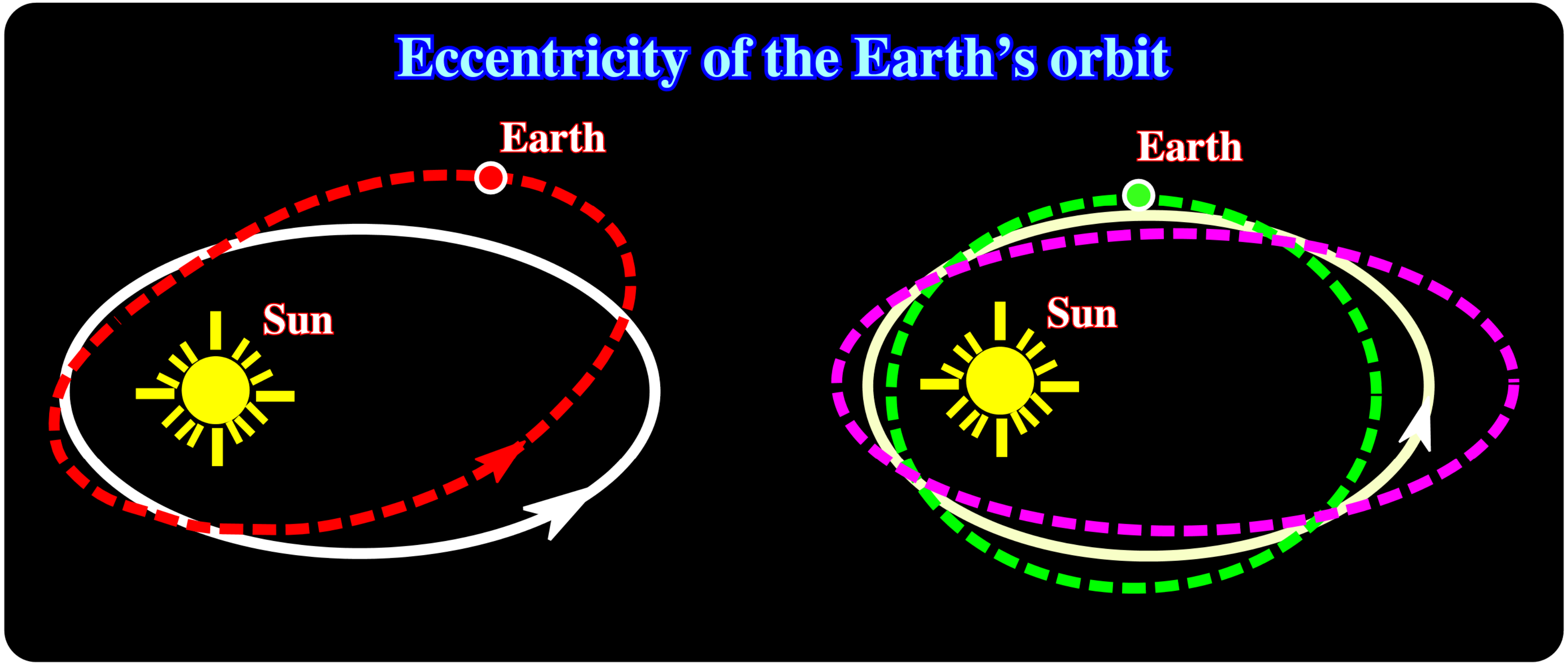


Fig. 29- The eccentricity of the earth's orbit (orbit changing) has a big influence in the radiation received from the sun, as depicted in this figure. Indeed, the rotation of the earth's orbit around the sun has the same consequences as the precession. During the periods of big elongation (as in purple trajectory) the earth, at the ends, is particularly far away from the sun, subsequently both hemispheres receive amounts of heat abnormally lower. Contrariwise, a small eccentricity, particularly when combined with an opposed inclination of the earth's axis, creates mild climatic conditions on the North hemisphere.

Controlling Parameters

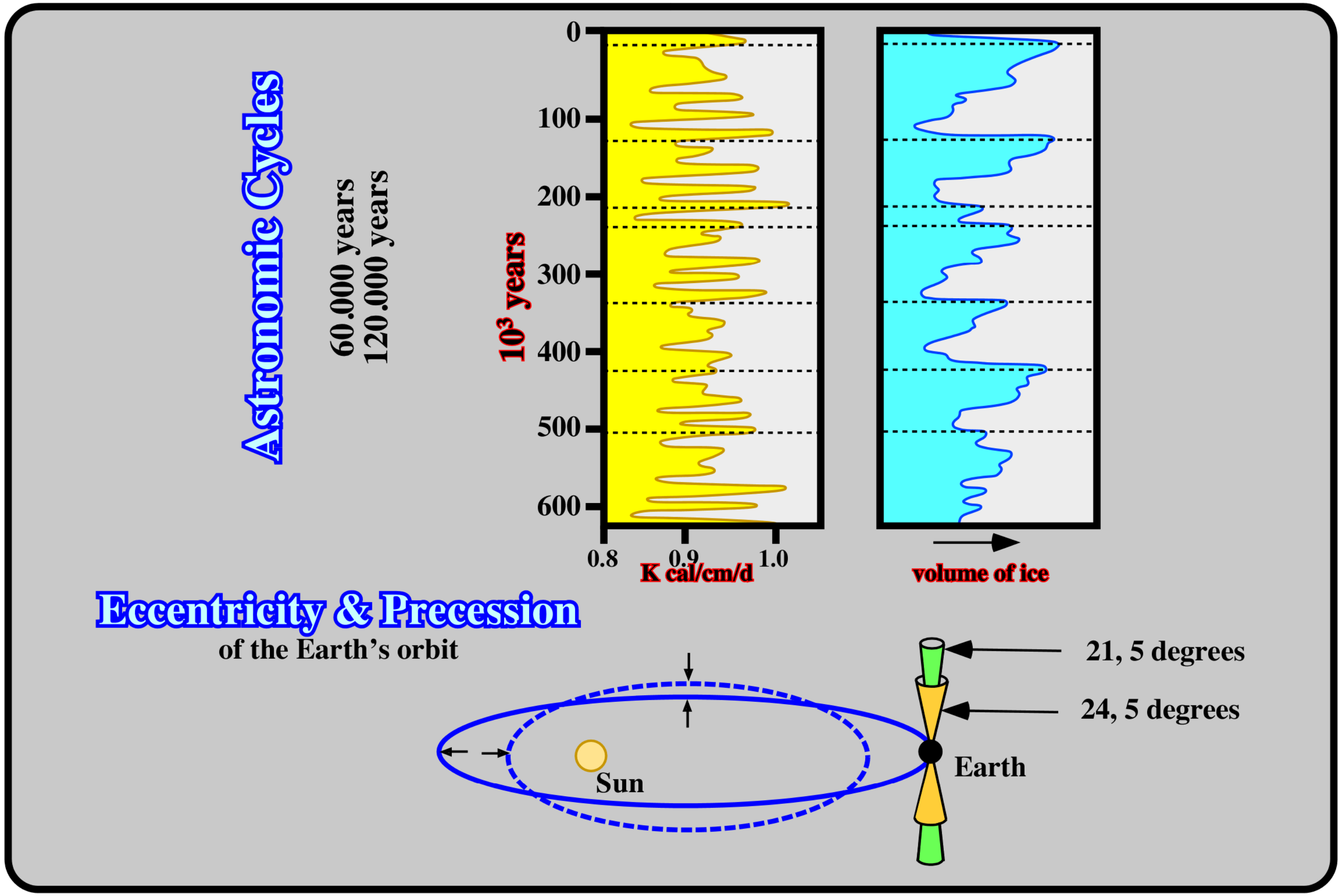


Fig. 30- It is quite evident that astronomic cycles have a great influence on the solar energy received by the earth. As illustrated above, the correlation between the volume of ice on the earth and the heat energy received from the sun is quite good. Two major cycles, around 60 ky and 120 ky, are easily be recognized. The time scale of these graphics is too small and so the well known super-cycles, with a time duration of 400 ky, cannot be recognized. When eccentricity and precession play in the same sense, the addition of their effects can be particularly important.

Controlling Parameters

D) Subsidence & Accommodation

In a certain area, at certain geological time, subsidence and uplift are directly related with the tectonic regime. Assuming a constant eustatic sea level one can say:

1) **During extensional tectonic regimes, which are characterized by a maximum vertical effective stress (σ_1), sediments are lengthened**.

   (i) This lengthening induces subsidence.

   (ii) The subsidence increases the space available (accommodation).

   (iii) The relative sea level rise induces sedimentation.

2) **During compressional tectonic regimes, which are characterized by a maximum horizontal tectonic stress (σ_1), sediments are shortened.**

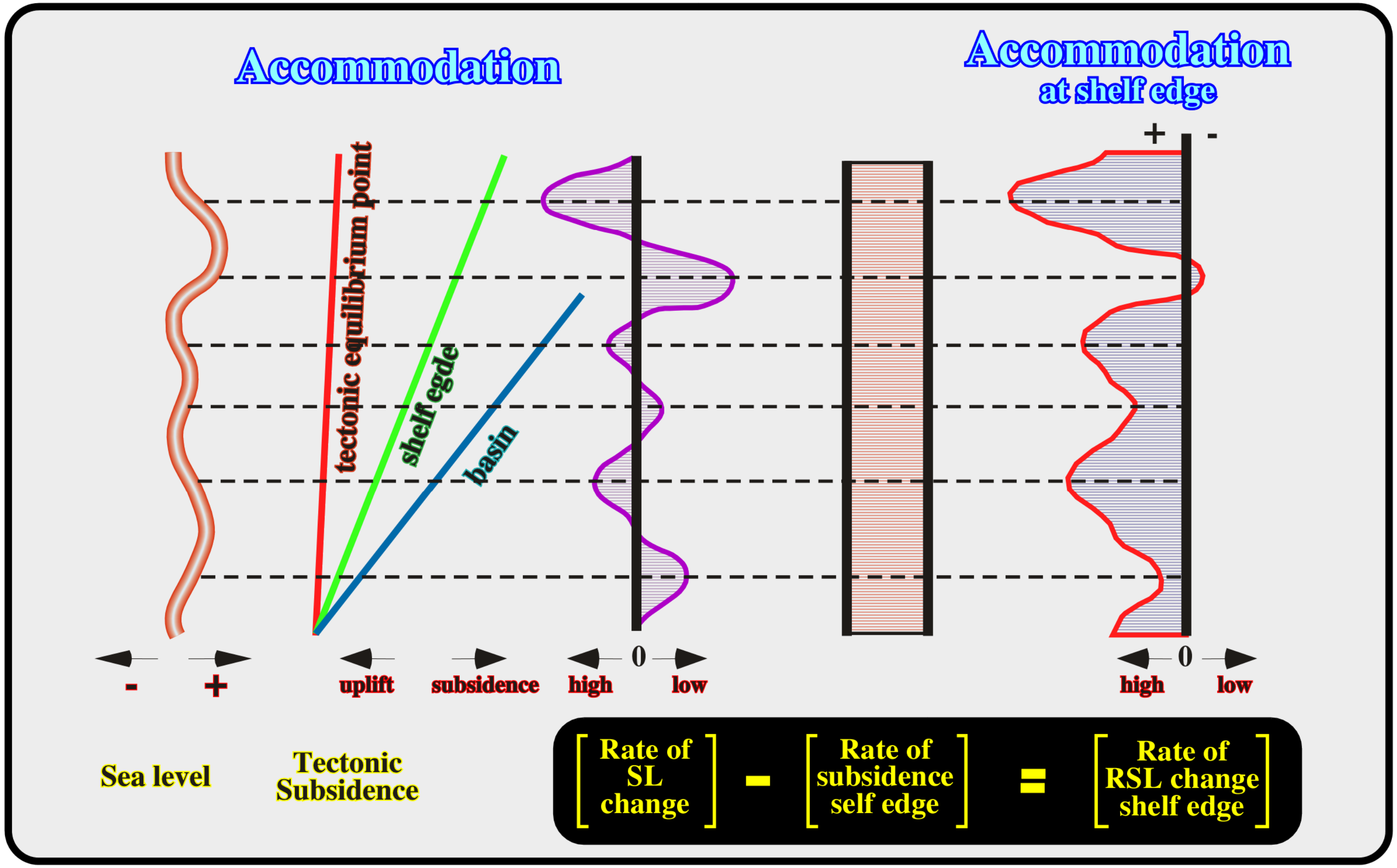
   (i) Shortening generates uplift decreasing accommodation (relative sea level fall).

   (ii) Relative sea level fall induces erosion.

When tectonics is combined with eustatic changes, the final accommodation is the sum of the space induced by tectonics and by eustasy (fig. 31):

- During eustatic sea level rise (increasing of accommodation), the amount of water depth created by subsidence is added to that created by the eustatic rise.
- During a eustatic sea level fall (decreasing accommodation), the amount of space created by subsidence must be subtracted from that created by the eustatic sea level fall (decreasing subsidence).

Controlling Parameters



[Rate of SL change] - [Rate of subsidence self edge] = [Rate of RSL change shelf edge]

Fig. 31- The combination of eustasy and subsidence drive relative sea level changes. Landward of the shelf break, a relative sea level rise increases the space available for sediments (accommodation) and favours deposition. Contrariwise, a relative sea level fall decreases the shelfal accommodation and favours erosion. Seaward of the shelf break, relative sea level changes have important sedimentary consequences particularly when a relative sea level fall is big enough to create lowstand geological conditions.

Controlling Parameters

- During a eustatic sea level fall (decreasing accommodation), the amount of space created by subsidence must be subtracted frrom that created by the eustatic sea level fall (decreasing subsidence).

- In the case of uplift, i.e. during sedimentary shortening periods, the reduction of accommodation is increased by the amount reduced by eustatic sea level fall and decreased by the space available for the sediments created by a eustatic sea level rise.

Tectonics has the greatest effect on accommodation space. Along with climate, it controls the type and amount of sediments deposited. Tectonics is a major control on stratigraphy. Tectonic events have recognizable signatures. On the basis of magnitude and duration in time, Vail distinguished three hierarchical levels of tectonic events with typical stratigraphic signatures:

A) High-level Tectonic events

B) Middle-level Tectonic events

C) Low-level Tectonic events

A) High level tectonic events

These tectonic events result from thermodynamic processes in Earth‘s crust and upper mantle. They are directly associated with Plate Tectonics’ mechanisms:

(i) Extensional rifting,
(ii) Sea floor spreading,
(iii) Tectonic sutures,
(iv) Compressional thrusting, etc.,

They are considered as belonging to long-term hierarchical tectonic events. Their stratigraphic signature is the sedimentary basin, i.e. they are the main cause of development of sedimentary basins.

Controlling Parameters

B) Middle level tectonic events

These tectonic events occur during the evolution of sedimentary basins, that is to say, within continental encroachment stratigraphic cycles (see glossary). They may be recognized by changes in the rate of subsidence. They result from reorganization of tectonic plates or from local thermodynamic anomalies. This class of events is characterized by a period of relatively high rate of subsidence followed by a relatively low rate of subsidence. The stratigraphic signatures are continental encroachment sub-cycles (see glossary) or major transgressive/regressive episodes. In other words, they are characterized by substantial downward shifts of coastal onlap and large displacements of the shoreline.

C) Low-level tectonic events

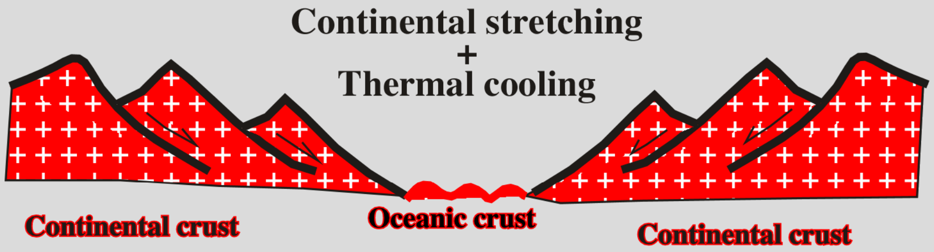
These tectonic events are folding, faulting, diapirism and magmatism activity. Their stratigraphic signatures are tilted and ruptured strata, which often can be recognize on lower hierarchical stratigraphic cycles (sequence cycle). They are commonly associated with pene-contemporanous events such as slides, slumps, megaturbidites, bentonites, datable extrusive flows and intrusive sills and dikes.

> "Tectonic hierarchical events can easily be observed"..........wrote Vail ...."on tectonic subsidence curves constructed by plotting the depth of horizon, preferably the top of the basement, at a series of ages trough time. When the total subsidence is corrected for local isostatic compensation and sedimentary compaction, the result is a tectonic subsidence curve. Such a curve shows the water-loaded hole that tectonics would create if no sediments were deposited. This is the curve to use for calculating rates and magnitudes of tectonic subsidence, assuming that isostatic compensation and compaction occur instantaneously and do not affect the subsidence of the surface deposition".

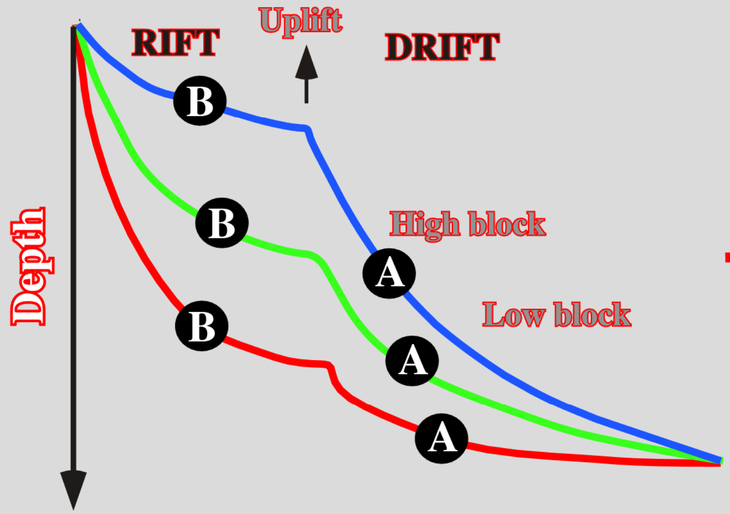
The tectonic subsidence of a basin, which evolved under extension, such as rifts and passive margins, typically shows an inflexion. The mechanism of subsidence changes from crustal extension (basin type rift) to thermal cooling (passive margin).

Controlling Parameters

Extensional Tectonic Regime

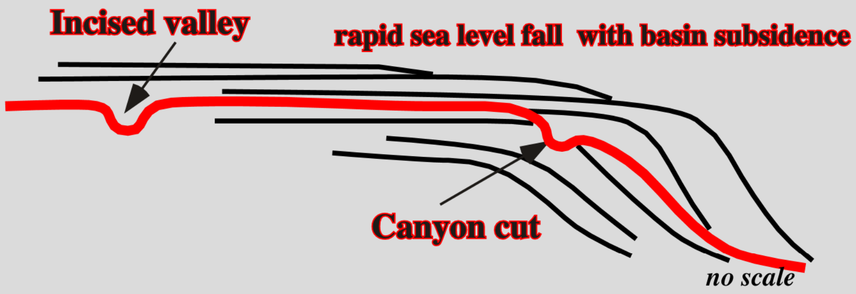


Subsidence Evolution



Associated Unconformities

(cryptic unconformity)



based on P. Vail, 1994

Fig. 32- Subsidence profiles can be used to classify sedimentary basins. Bally and Snelson (1980) have used the realm of subsidence to classify sedimentary basins. In extensional tectonic regimes, rifting is associated with differential subsidence (rift-type basin), while drifting (thermal subsidence) characterizes a continental divergent margin. Unconformities, when not tectonically enhanced, are generally cryptic landward of the shelf break and in deep water.

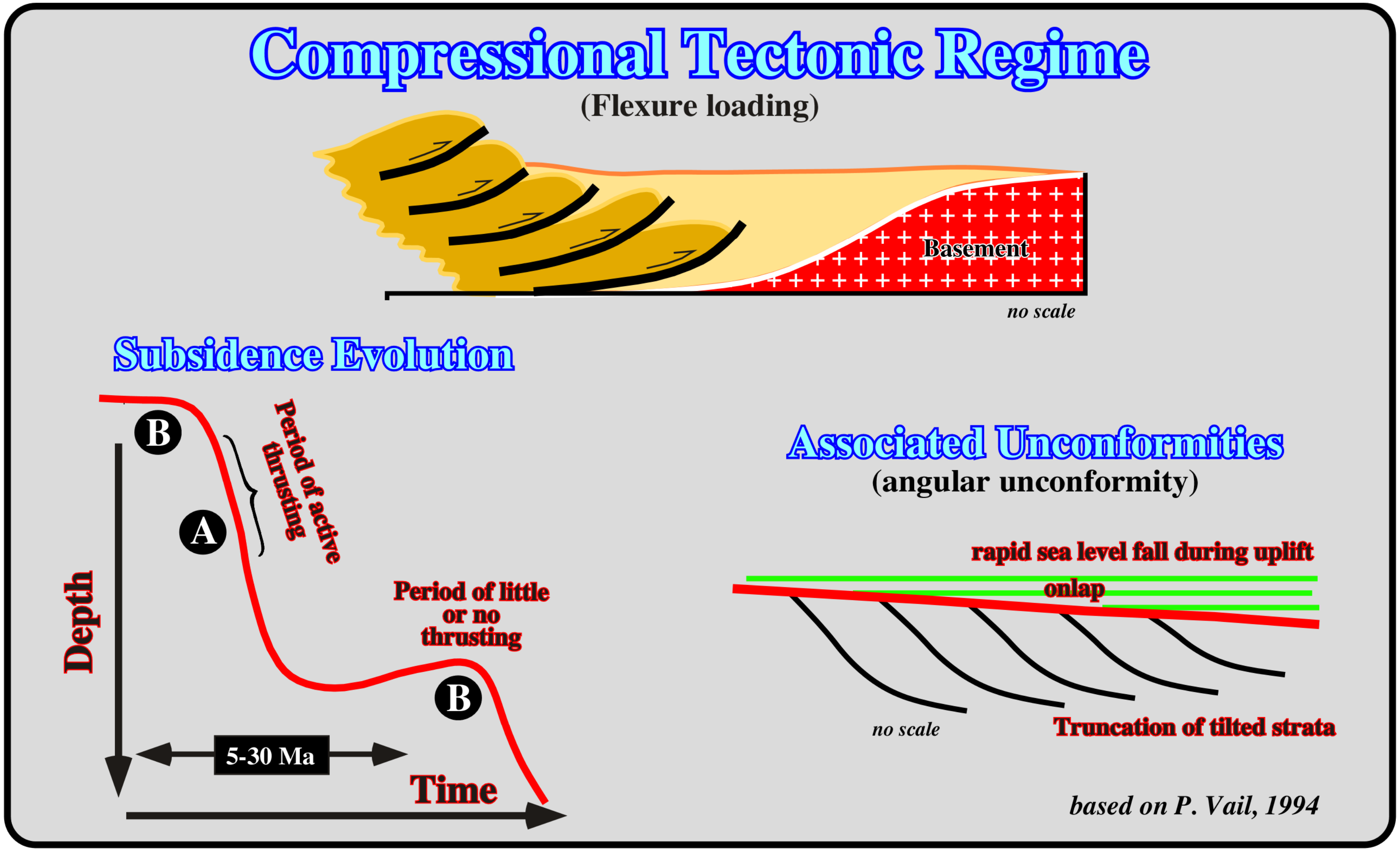
Controlling Parameters

The tectonic subsidence curves of basins evolving during extension are characterized by a concave upward pattern (fig. 32). Generally, they show at least two concave upward subsidence patterns: one, during the crustal extension phase and another, during the drift thermal cooling phase. Notice that there are additional concave upward patterns due to other crustal extension episodes, as well as thermal perturbations.

On the tectonic subsidence curve of a basin evolving under a compressional tectonic (plate 33) regime Vail wrote:

> “The curve shows a typically flexure loading convex upward pattern. The period of maximum thrusting is commonly associated with the maximum subsidence because this is the time when thrust sheets are building up their maximum load on the border of the foredeep basin. Several convex upward subsidence patterns are commonly present within compressional basins indicating changes in the rate of the thrust movements. There may be a period of stability or uplift between convex upward subsidence curves. The uplift may be due to the heating of the depressed crust. Transpressional basins show similar flexure loaded convex upward patterns indicating loading of a land area adjacent to the basin. Some basins were formed during an extensional regime, which changed through time into a compressional regime. This change will be reflected in the basin subsidence curve, which will show a concave upward pattern in the early part, a convex upward pattern in the latter. The tectonic subsidence curve of a basin will commonly show extensional or compressional pattern. Changes in basin type will generally be apparent from the curve pattern. The tectonic subsidence curve associated with each type of sedimentary basins reflects the subsidence history of each basin, and in principle it represents the stratigraphic signature of first hierarchical level tectonic events. Each concave or convex upward pattern on the tectonic subsidence curve is generally associated with transgressive-regressive facies cycles. Transgressive-regressive facies cycles are stratigraphic signatures of changes in the rate of tectonic subsidence and are considered the signature of middle level tectonic events. Folding and faulting occur during particular periods of the tectonic subsidence curve depending on the structure type. In extensional settings faulting is most active during the crustal extension phase. In compressional settings faulting is most active in the maximum subsidence phase. A tectonic subsidence curve influenced lower level tectonic events may show a deviation from the regional subsidence pattern. For example, a tectonic subsidence curve made in a basin formed under a compressional regime will show a high corresponding to the development of a structure that is causing the flexural loading. This high will be superimposed on the regional curve that will show maximum subsidence at the corresponding time”

Controlling Parameters



Compressional Tectonic Regime

(Flexure loading)

Subsidence Evolution

Associated Unconformities

(angular unconformity)

based on P. Vail, 1994

Fig. 33- In compressional tectonic regimes, such as foredeep basins, subsidence profiles clearly indicate periods of strong shortening (active thrusting). The associated unconformities are tectonically enhanced. When toplap (erosional hiatus) is not evident, the unconformities can be cryptic since, very often, the onlapping of the transgressive sediments of the new stratigraphic cycle are quite subtle.

Controlling Parameters

Identification of unconformities associated with extensional and compressional tectonic regimes are quite different. In extensional regimes, unconformities are generally cryptic except near the shelf break (fig. 27). In compressional regimes, unconformities are enhanced (fig. 33). The geometrical relationships between the chronostratigraphic lines underlying and overlying unconformities are clear and sharp. They allow an easy unconformity identification and its lateral correlation as well.

The seismic line illustrated in fig. 34 is representative of offshore New Jersey (Baltimore Canyon trough), which corresponds to a vertical superposition of a rift-type basin and a passive margin (Atlantic-type). Extensional tectonic regimes were predominant. The subsidence through time was mainly due to crustal extension (type-rift basin) and thermal cooling (passive margin). The results of COST B-2 well were used by Greenlee (1989) to calculate the eustatic fluctuations from stratigraphic data. The tectonic and total subsidence, the paleobathymetry, the long-term sea level, as well as the more likely subsidence mechanisms proposed by Greenlee (fig. 35) are:

- The total subsidence curve indicates the depth to the bottom of the well at any particular time.

- Decompacting the sediments and correcting for local isostatic compensation allow a calculation of the tectonic subsidence.

- To obtain accurate results, the subsidence curve must also be corrected for paleobathymetry and the datum adjusted to the long-term sea-level curve.

- Flexural loading due to the variation may also influence the tectonic subsidence curve in thickness of adjacent sedimentary units.

- To separate tectonic from eustatic effects, the subsidence curve obtained can be compared with theoretically calculated subsidence curves for various amounts of crustal stretching.

- From the difference between the load-corrected subsidence curve and the interpreted thermo-tectonic subsidence curve, the 1st order eustatic cycle can be estimated as discussed by Hardenbol et al. (1987).

Controlling Parameters

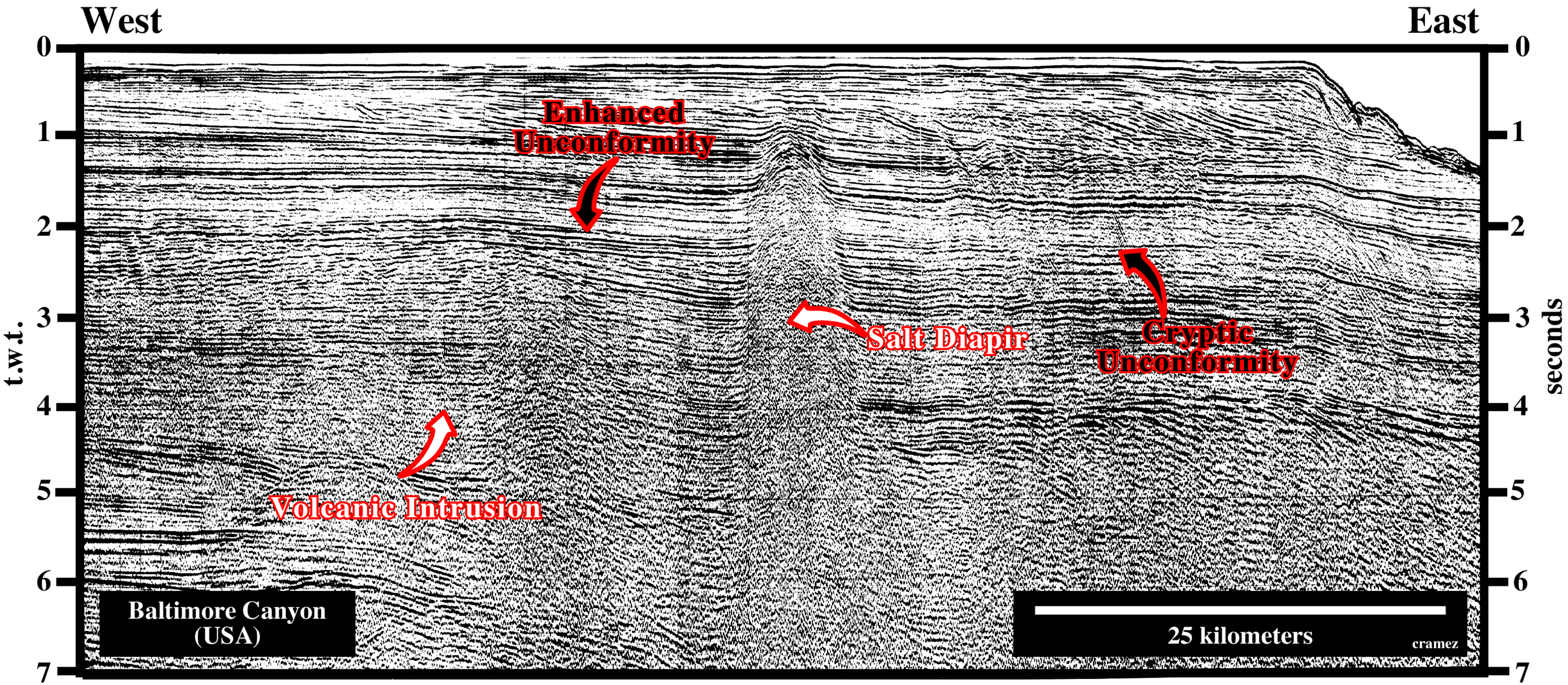


Fig. 34- On this seismic line from North America continental divergent margin, a volcanic intrusion locally enhanced a cryptic unconformity. In the upper part of the line, the forestepping (progradational) interval, which corresponds to the Cainozoic, is often used to illustrate the importance of eustasy in stratigraphy, since tectonic subsidence is quite insignificant. Notice that on this line the basement (SDRs) is quite high on the eastern part of the line. It is the eastern limit of the Mesozoic rift-type basin, of which the upper part is recognized in the central and western part of the line. Indeed, the salt diapir was emplaced between the basement and the rift-type basin.

Controlling Parameters

On the curves illustrated on fig. 35 Vail wrote:

> **"It shows a relatively high rate of subsidence during the basin type rift, and is followed by a normal thermal cooling subsidence after the opening of the Atlantic, 157 Ma. During the Aptian (116-109 Ma) thermal perturbation due to an igneous intrusion resulted in slight uplift (8). Normal thermal cooling was resumed after uplift. The thermo-tectonic subsidence curve shows tectonic events of middle hierarchical level, which start with increasing rates of subsidence. The first one extends from the late Triassic to late Jurassic (230?-157 Ma). The second one extends from late Jurassic to late Aptian (157-109 Ma) and the third from late Aptian to present (109-0 Ma). The same plate also relates the tectonic subsidence curve to variations in the paleobathymetry. Notice that there are four major transgressive-regressive facies cycles present. However, only three middle level tectonic events is visible one the thermo-tectonic subsidence curve. This is probably due to lack of stratigraphic resolution near the bottom of the well. Angular unconformities show that erosional truncation is present. They are indicated preceding the boundaries of the different stratigraphic intervals. Folding and faulting within the basin occurred during the four transgressive- regressive facies cycles. Normal faulting and other structures due to rifting were associated with the syntectonic phases of rifting, which preceded both the slow and rapid opening of the Atlantic. During the Aptian, magmatic activity induced doming".**

E) Terrigeneous Influx

The amount of sediments is mainly related with tectonics, eustasy and climate. Compressional tectonic regimes induce uplift increasing the amount of sediments available for deposition. Eustatic and relative sea level falls disrupt the equilibrium profile of the rivers. They increase the amount of sediments. The rivers are forced to incise to reach new equilibrium profiles. Climate is also an important factor not only in carbonate deposition but in sand-shale deposition as well. For a basin the terrigeneous influx changes in space and time, which makes it very difficult to correlate globally or even regionally. This is illustrated in fig. 35, where three different situations are assumed (same RSL rise, but different terrigeneous influx).

Controlling Parameters

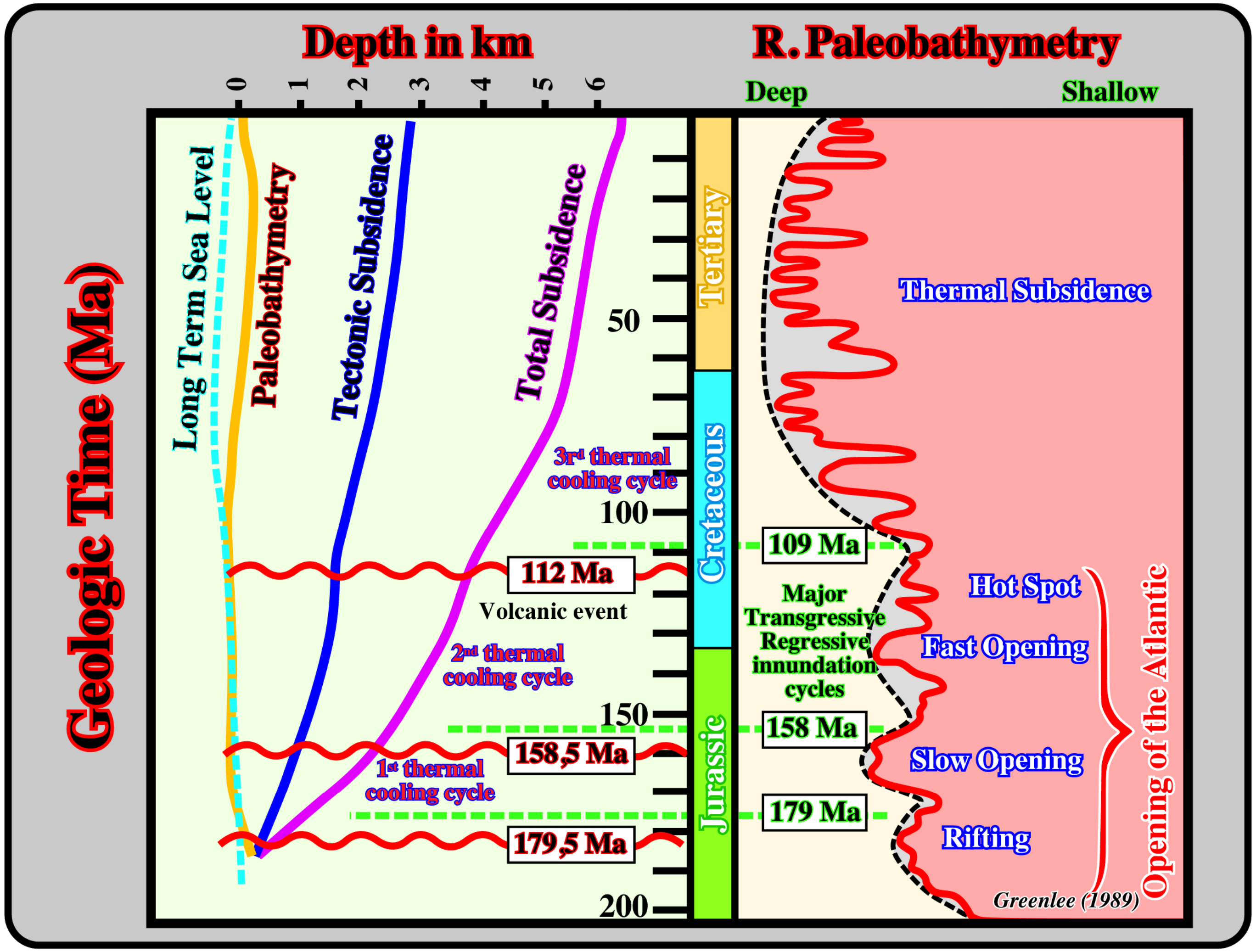


Fig. 35- Using the results of COST B-2 Greenlee calculated the eustatic fluctuations from stratigraphic data. The proposed tectonic and total subsidence, paleobathymetry, long-term sea level and the most likely subsidence mechanisms, have been corroborated by the exploration wells drilled on North Atlantic offshores.

Controlling Parameters

(i) In the first situation, the terrigeneous influx is low. The shoreline is displaced landward creating a backstepping geometry. The final result is a transgression.

(ii) In the second situation, the terrigeneous influx is high. The shoreline and the associated coastal deposits are displaced seaward. The internal configuration of bedding planes is progradational, which globally creates a forestepping geometry of the shoreline. The final result is a regression.

(iii) In the third situation, the terrigeneous influx balances the accommodation induced by the relative sea level rise. The shoreline and associated deposits are stationary.

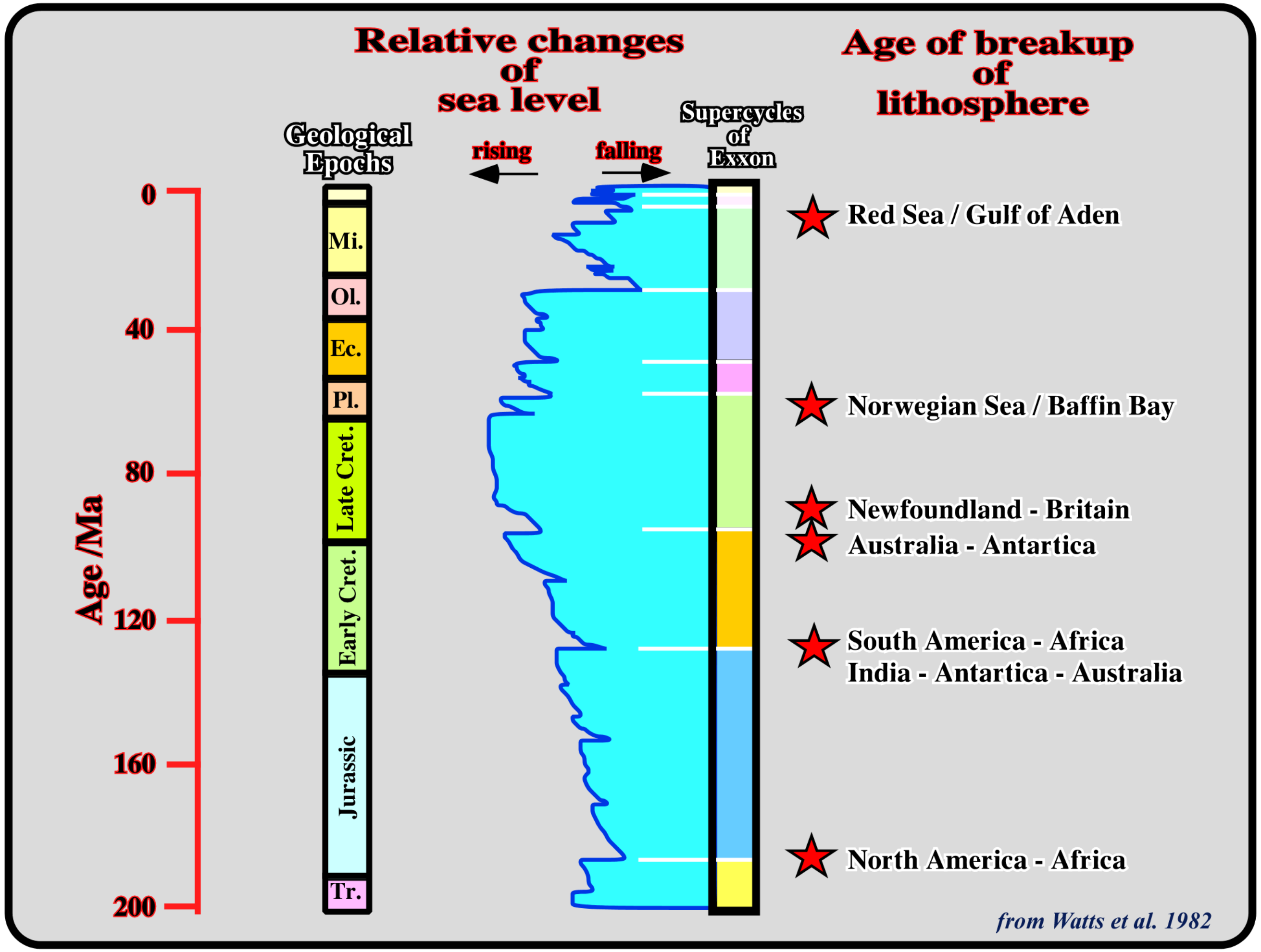
As terrigeneous influx changes in time and space, particularly near the mouth of large rivers, correlation of transgression / regression cycles are unlikely, even at basin scale.

Tectonics versus Eustasy

Since the Exxon team held that tectonics is not responsible for generation of sequence boundary unconformities1, several papers were published criticizing such a conjecture. Several geologists think that relative sea level changes can be also caused by continental tectonics that are regional to local in scope, and act over time periods of tens of millions to tens of thousands of years (possibly less).

“Tectonics of this type ... wrote Myall (1997)....
is driven primarily by plate tectonics processes. Extensional and contractional movements accompanying the relative motions of plates cause crustal thinning and thickening and changes in regional thermal regimes, and this leads to regional uplift and subsidence. These stresses and strains are generally primarily at plate margins but because of the rigidity of plates; they may be transmitted into plate interiors and affect entire continents. By their very nature these mechanisms of sea level change are regional, possibly even continental in extent, but cannot be global, because they are driven by processes occurring within or beneath a single plate or by the interaction between two plates. They affect the elevation of the plate itself, rather than the volume of the ocean basins or the water within them (next page).

Controlling Parameters



from Watts et al. 1982

Fig. 36- As depicted, the successive break-ups of the lithosphere seem to correlate with the major sea level falls of Exxon's chart. Indeed, as said previously, the smaller the number of lithospheric plates, the higher the volume of the oceanic basins. In addition, the onset of sea floor spreading following the break-ups, particularly the emplacement of the oceanic ridges (oceanic mountains), decreases the volume of the oceanic basins and so, assuming a constant water volume since the earth's birthday, the sea level rises.

Controlling Parameters

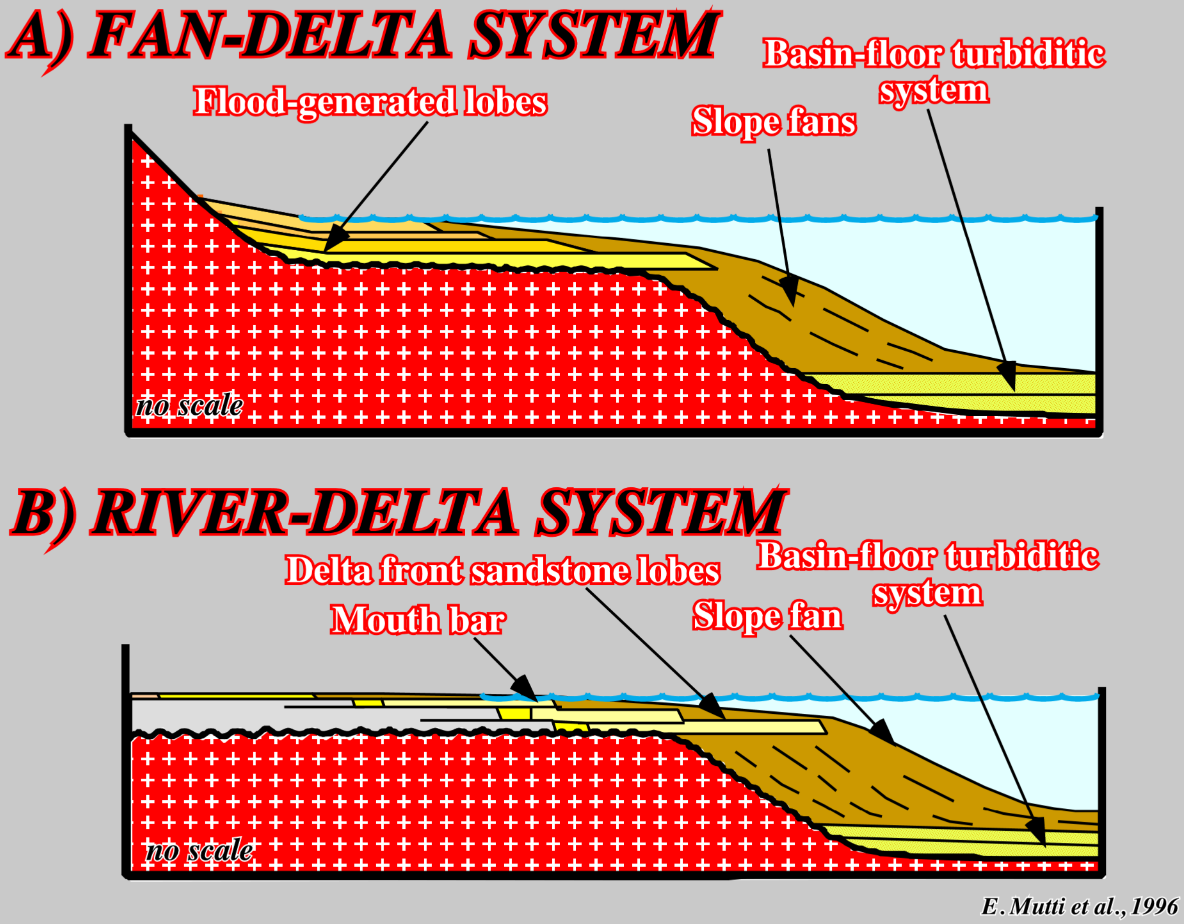
This category of sea level change is therefore not eustatic. However, they can simulate eustatic effects through the full range of geological episodicities over wide areas, and it is now thought by many researches that tectonic mechanisms were responsible for many of the events used to define the global cycle charts of Haq et al. (1987, 1988). An important additional point is that because the earth is finite, regional plate-tectonic events, such as ridge reordering or adjustments in rotation vectors, may result in simultaneous kinematics changes elsewhere. It is possible therefore for tectonic episodes to be hemispheric or even global in scope. However, such episodes would take a different form (uplift, subsidence, extension, contraction, tilting, translation) within different plates and even within different regions of a given plate. It is possible therefore those simultaneous events of relative sea level change occurring over wide areas but of varying magnitude and in the same or opposite direction could be genetically related”

Fig. 32, taken from Watts (1982), clearly illustrates that the timing of major rifting events correspond grossly with the onset of the major rising relative sea level of the global cycle chart of Vail et al. In fact, it is easy to recognize that the rifting between North America and Africa, which took place at the end Triassic, appears interlinked with the initiation of Jurassic sea level rise.

In the same way, the rifting between South America and Africa is coeval with the Cretaceous initiation of the sea level rise. The relation between rifting and sea level rise is also valid when Newfoundland and Britain, Norwegian Sea and Baffin Bay, or Red Sea and Gulf of Aden broke apart. In spite of the tectonic versus eustasy controversy, particularly in foreland basins, which will be discussed in detail in part III of this short course, I would like to include, what E. Mutti wrote on this subject, concerning tectonically active basins:

“Ancient fluvio-deltaic systems deposited in tectonically active basins are essentially built up intergradational fan-delta and river-delta systems dominated by catastrophic flooding. These systems and their component depositional elements cannot, therefore, be described and interpreted in terms of current sedimentological model based on “normal” fluvial and deltaic processes, facies and geomorphic settings derived from the study of modern environments. Despite this variability, all these sediments are characteristically composed of graded flood units in both alluvial and marine environments. The greatest preservation potential of individual flood units is found in the final marine depositional zones of each system considered. Ancient flood dominated fluvio-marine systems comprise huge accumulations of conglomerates, sandstone and mudstone facies whose origin and stratigraphic importance have been essentially overlooked in previous literature. These depositional systems can be understood only in terms of tectonically controlled physiographic settings characterized by small and medium sized fluvial systems with high elevation drainage basins and high gradient transfer zones located close to marine basins”

Controlling Parameters



E. Mutti et al., 1996

Fig. 37- In Mutti's fan-delta and river-delta system model the tectonic activity and catastrophic flooding is paramount. Indeed, these depositional systems can be understood only in terms of tectonically controlled physiographic settings characterized by small and medium sized fluvial systems with high elevation drainage basins and high gradient transfer zones located close to marine basins.

Controlling Parameters

In settings of this type, sediment flux to the sea can dramatically increase when climatic conditions provide sufficient amounts of water to produce catastrophic floods (fig.37):

- **These floods generate mixtures of water and sediment that can enter seawater with significant velocity. Sediment concentration produces hyperpycnal flows and related shelf-sustained turbiditic currents.**

- **The resulting depositional settings are dominated by flood related facies. They can develop in shelfal or deeper marine regions.**

- **Thick and laterally extensive successions of shelfal sandstone lobes with flood generated hummocky cross-stratification are the fundamental depositional element not only of fan-delta but river-delta systems as well.**

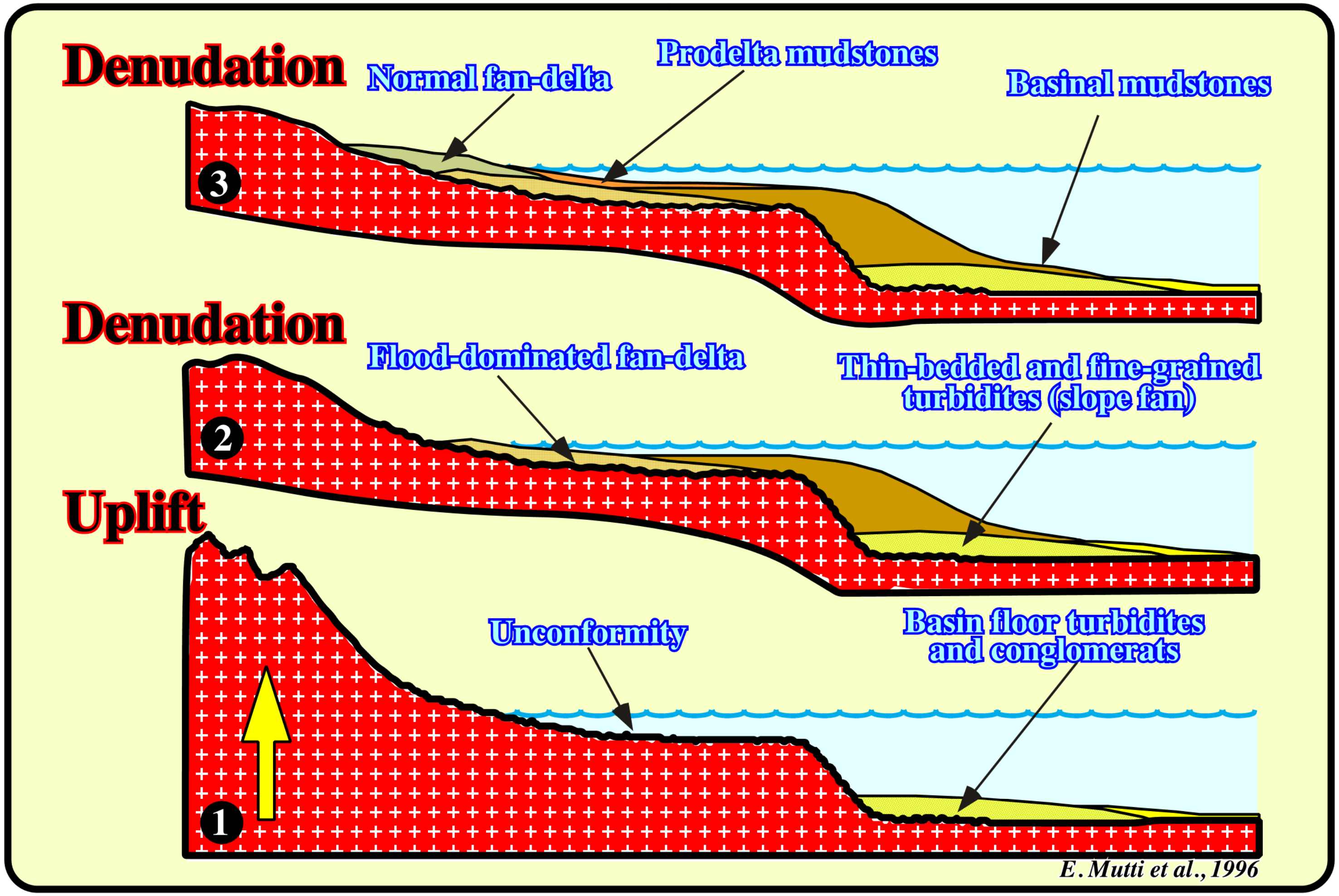
- **In terms of geometry, facies tracts, and high frequency cyclic stacking patterns, these lobes are essentially similar to deeper-water turbidite sandstone lobes.**

- **Shelfal sandstone lobes probably represent the only possible expression of fluvial-dominated delta-front sandstone facies. In the absence of flood generated hyperpycnal flows, river borne sands can only be redistributed in marine environments by waves and tides.**

Their overall stacking patterns and evolution of ancient flood-dominated fluvio-deltaic systems with time is apparently controlled by the initial uplift of the drainage basin, the rate of denudation, the gradient of each system, and the volume and the sediment concentration of individual floods, the later being a function of the amount of water and sediment made available to the system considered.

> **“A flood-dominated system of this type comes to an end when the sediment flux to the sea is progressively reduced to normal conditions. This occurs when relief and elevation drainage basins and related sediment availability, as well as the gradient of transfer zones have been substantially reduced through progressive denudation and sediment exportation to marine depositional zones. The occurrence of cyclic stacking patterns developed at different hierarchical orders is one of the most striking aspects of flood-dominated systems. The most complete record of this cyclicity is preserved in the final depositional zone of each system”.**

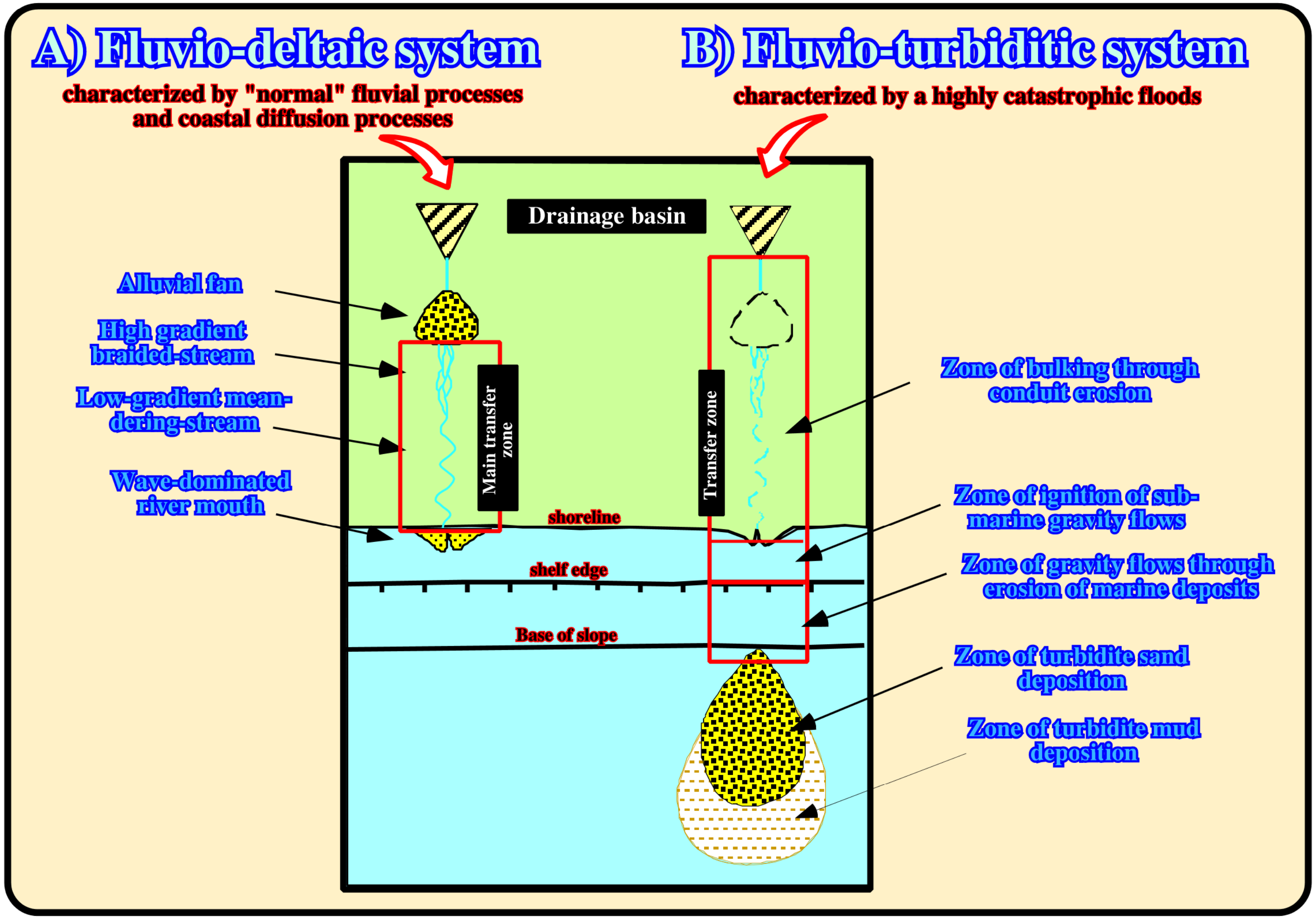
Controlling Parameters



E. Mutti et al., 1996

Fig. 38- These stacking patterns are apparently very similar to those which are thought to be characteristic of sequence-stratigraphic models (see later). Despite this apparent similarity, Mutti suggests that the overall vertical evolution of flood dominated systems is primary controlled by Davisian-type cycles, in which basal turbidite systems are overlain by a flood-dominated fluvio-deltaic system, which passes upward and landward into a normal fluvial or fluvio-deltaic system with time. Uplifting and denudation are responsible for flood-dominated and normal fan-deltas (Gilbert deltas).

Controlling Parameters



A) Fluvio-deltaic system

characterized by "normal" fluvial processes and coastal diffusion processes

B) Fluvio-turbiditic system

characterized by a highly catastrophic floods

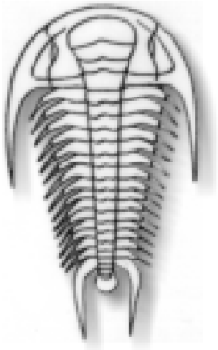
Fig. 39- In turbidite systems associated with highly catastrophic floods, it is important to take into account not only the drainage basin and the transfer zone, but also (i) the zone of ignition of submarine gravity flows, (ii) the zone of gravity flows through erosion of marine deposits (bypass zone) and (iii) the zones of deposition.

Controlling Parameters

“These stacking patterns are apparently very similar to those which are thought to be characteristic of sequence-stratigraphic models. Despite this apparent similarity, we suggest that the overall vertical evolution of flood dominated systems is primary controlled by Davisian-type cycles (fig. 38).

These cycles produced an overall forestepping backstepping succession recorded by a basal turbidite system (basin floor fan of sequence stratigraphy) overlain by a flood-dominated fluvio-deltaic system, which passes upward and landward into a normal fluvial or fluvio-deltaic system with time.

Higher-frequency stacking patterns developed within each of the above stages are essentially produced by forestepping-backstepping episodes of sand deposition, which are essentially controlled by cyclic climatic variation. The relationships between Davisian-type and higher-frequency climatic cycles and eustasy-driven cycles of relative sea level variations remain to be explored through careful stratigraphic, sedimentological and structural studies carried out without preconceived ideas. It is likely, however, that the eustatic control on flood-dominated sedimentation patterns of high gradient, tectonically active settings cannot generally compare with the importance of tectonics and related cycles of uplift and denudation”



Stratigraphic Cycles

Stratigraphic Cycles

Geologists now view earth history as a matter of evolution in which some changes are unidirectional (at least, in net effect), others are oscillatory or cyclic, and still others are random fluctuations, while the whole is punctuated by smaller or greater catastrophes. Stratigraphy is a typical example of a cyclic geological event. Exxon‘s geologists explained the cyclicity of Stratigraphy as a consequence of eustatic changes.

They assumed that:

1) Eustasy was the main parameter controlling the stratigraphy.

2) Each hierarchical eustatic cycle induces a correlative stratigraphic cycle.

However, one must not forget that the time duration of a eustatic cycle is always higher than the sum of sedimentary deposition time. In fact, one of the first things we learn in stratigraphy is, for instance, that the Cretaceous system in rocks is the equivalent of the Cretaceous period in time. But this is almost certainly not true. The completeness of the stratigraphic cycles is always lower than 1. The rock record is so episodic in its accumulation and so incomplete in its preservation that there have almost certainly been worldwide gaps during which no sediments were deposited, or eroded.

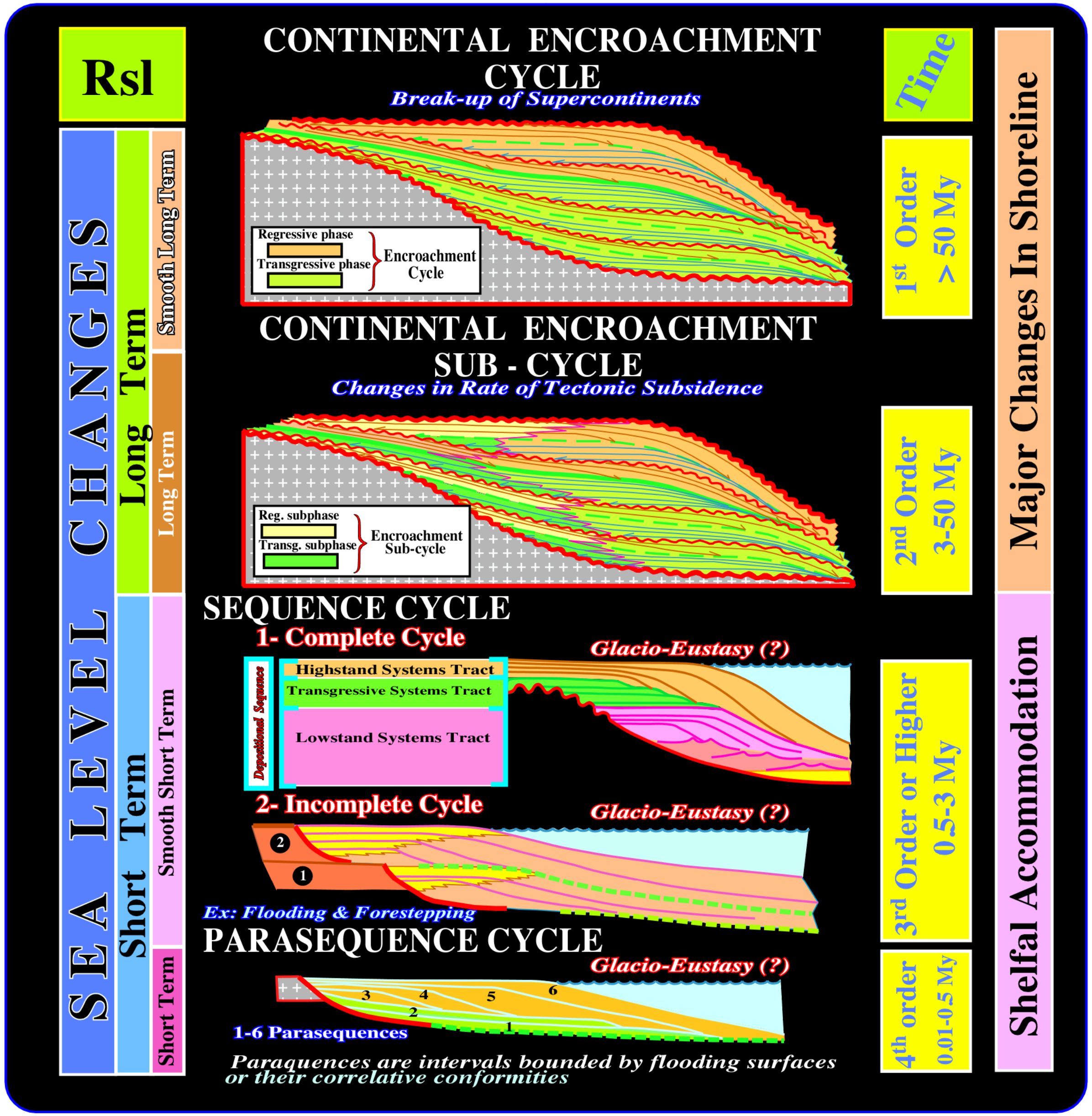
Four types of stratigraphic cycles (fig.40) are usually recognized in association with the different orders of eustatic cycles:

A) Continental encroachment cycles

B) Continental encroachment sub-cycles

C) Sequence cycles

D) Parasequence cycles



Stratigraphic Cycles

Fig. 40- The hierarchy of stratigraphic cycles proposed by Duval et al. (1993) takes into account four stratigraphic cycles: (i) Continental encroachment cycle, (ii) Continental encroachment sub-cycle, (iii) Sequence cycle and (iv) Parasequence cycle. These stratigraphic cycles are deposited during eustatic cycles of 1st, 2nd, 3rd and 4th orders, that is to say, eustatic cycles with time durations higher than 50 My, between 3-5 and 50 My, between 0.5 and 3-5 Ma and between 0.01 and 0.5 My.

Stratigraphic Cycles

A) Continental Encroachment Cycles

These cycles are associated with 1st order eustatic cycles (fig. 41 and 42). They are characterized by a succession of coastal onlap against the cratons. They fossilize the unconformity created by the aggregation of Supercontinents. Two continental encroachment cycles have been deposited since the beginning the Phanerozoic:

(i) The Palaeozoic cycle

(ii) The Caino-Mesozoic cycle

Both are recognizable in all continents. They are believed to be global. Taking into account that the Latest Proterozoic represents the time of slow encroachment with regression, we can say that:

1) During the Paleozoic cycle:

1.1) Cambrian represents the time of extensive encroachment with transgression.

1.2) Ordovician represents the eustatic high.

1.3) Silurian to Permian represents the time of restriction.

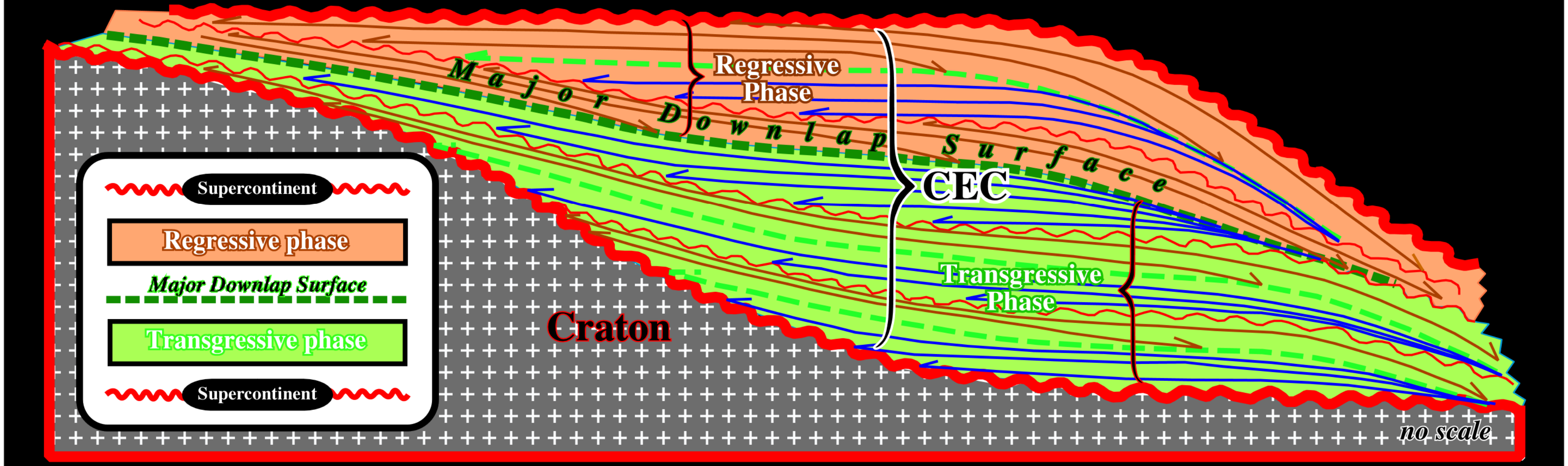
2) During the Meso-Cainozoic cycle:

2.1) Triassic represents a time of gradual encroachment of sediments onto the craton. Greatest thickness of non-marine sediments was deposited in grabens (rift-type basins) and bordering marine basins. This general pattern is believed to be caused by a slow relative rise of sea level due to slow long-term rise in eustasy. Non-marine rocks were widespread because sediment supply exceeded the space being created by slow relative rise, resulting in major regression.

Stratigraphic Cycles

CONTINENTAL ENCROACHMENT CYCLE

Break-up of Supercontinents



Truncated strata are commonly present below Continental Encroachment Cycles

Fig. 41- A continental encroachment cycle (CEC) is developed between break-up of a supercontinent and the formation of a new one. The transgressive phase, which globally has a backstepping, or retrogradational geometry, corresponds to the dispersion of the new continents, while the regressive phase, with a forestepping, or progradational geometry, corresponds to the gathering of the continents to form a new supercontinent. So, the transgressive phase is induced by a eustatic rise and the regressive phase is induced by a eustatic fall. A major downlap surface separates these sedimentary phases. Within each phase, a set of continental encroachment sub-cycles, bounded by unconformities, with transgressive and regressive sub-phases separated by downlap surfaces, is easily recognized.

Stratigraphic Cycles

Meso-Cainozoic CEC

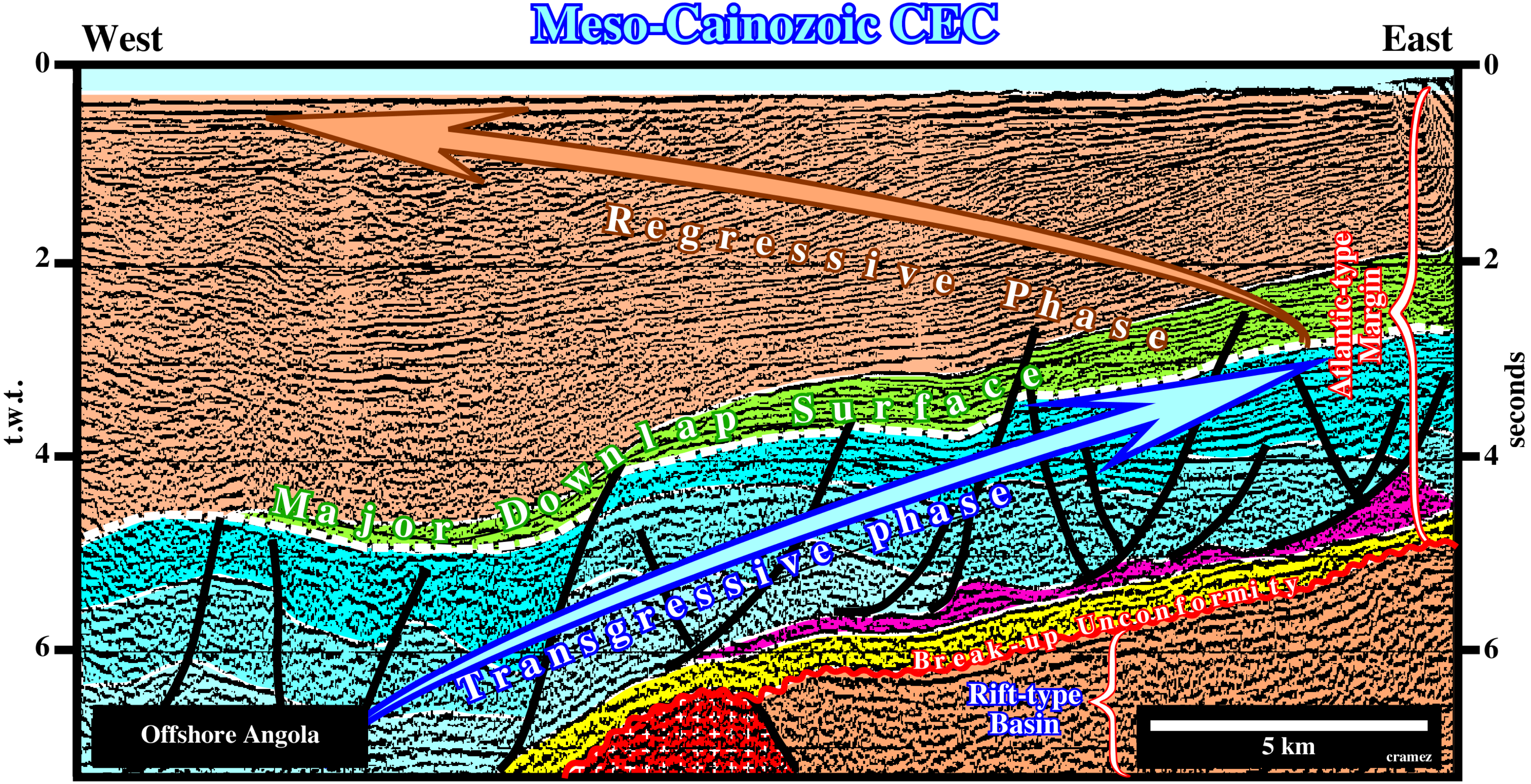


Fig. 42- This seismic line from offshore Angola illustrates the post-Pangaea, or Meso-Cainozoic, continental encroachment cycle continent (CEC), which is generally assumed to start with the break-up, that is to say, rift-type basins are excluded. The geometries of both stratigraphic phases are easily recognized, in spite of the salt tectonics in the transgressive phase. The major downlap surface (MFS 91.5 Ma), with which potential marine source-rocks are associated, limits the transgressive and regressive phases.

Stratigraphic Cycles

2.2) The Jurassic and Lower Cretaceous represent times of extensive encroachment of sediments on to the continental margins. These sediments are predominantly marine. During this time period, average relative sea level rose more rapidly due to an increase in the rate of rise of long-term eustasy. Marine rocks are dominant. Sediment supply did not keep up with the new space being created by more rapid relative rise, resulting in overall transgression.

2.3) The Lower Turonian is believed to have been the time of the maximum eustatic high.

2.4) The upper Cretaceous and Cainozoic are characterized by an overall gradual restriction of sediments to the continental margins and basinal areas. This pattern is believed to be caused by the slow long-term fall of the eustasy causing a decreasing relative rise and regression or relative fall and exposure.

B) Continental Encroachment Sub-Cycles

These cycles (figs. 43 to 45) are qlso associated with 2nd order eustatic cycles:

- They are characterized by unconformities induced by major basinward shifts of coastal onlap.

- The basinward shifts interrupt the continuity of continental encroachment associated with break-up of Supercontinents.

C) Sequence Cycles

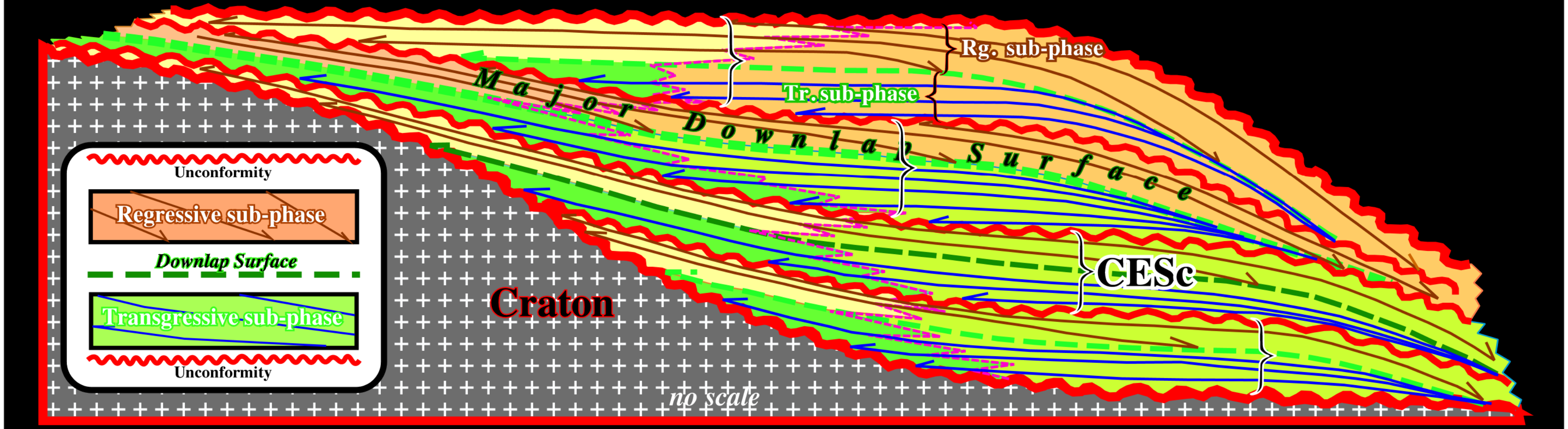
These cycles (figs. 46 to 49) are associated with 3rd order eustatic cycles.

- They are bounded by unconformities induced by changes in water depth, i.e. accommodation in the margins of basins.

Stratigraphic Cycles

CONTINENTAL ENCROACHMENT SUB - CYCLE

Changes in Rate of Tectonic Subsidence



Continental Encroachment sub-cycles are characterized by major downward shifts in continental encroachment.

Fig. 43- As illustrated, a continental encroachment cycle is composed ofcontinental encroachment sub-cycles (CESc), which are bounded by unconformities and composed of a transgressive and regressive sub-phase separated by a downlap surface. The transgressive sub-phase has backstepping geometry while the regressive sub-phase has forestepping geometry. Continental sub-cycles are induced by changes in the rate of tectonic subsidence which creates major downward, and basinward, shifts of coastal onlap. In certain petroleum basins, secondary potential source-rocks are associated with the downlap surfaces of continental encroachment sub-cycles.

Stratigraphic Cycles

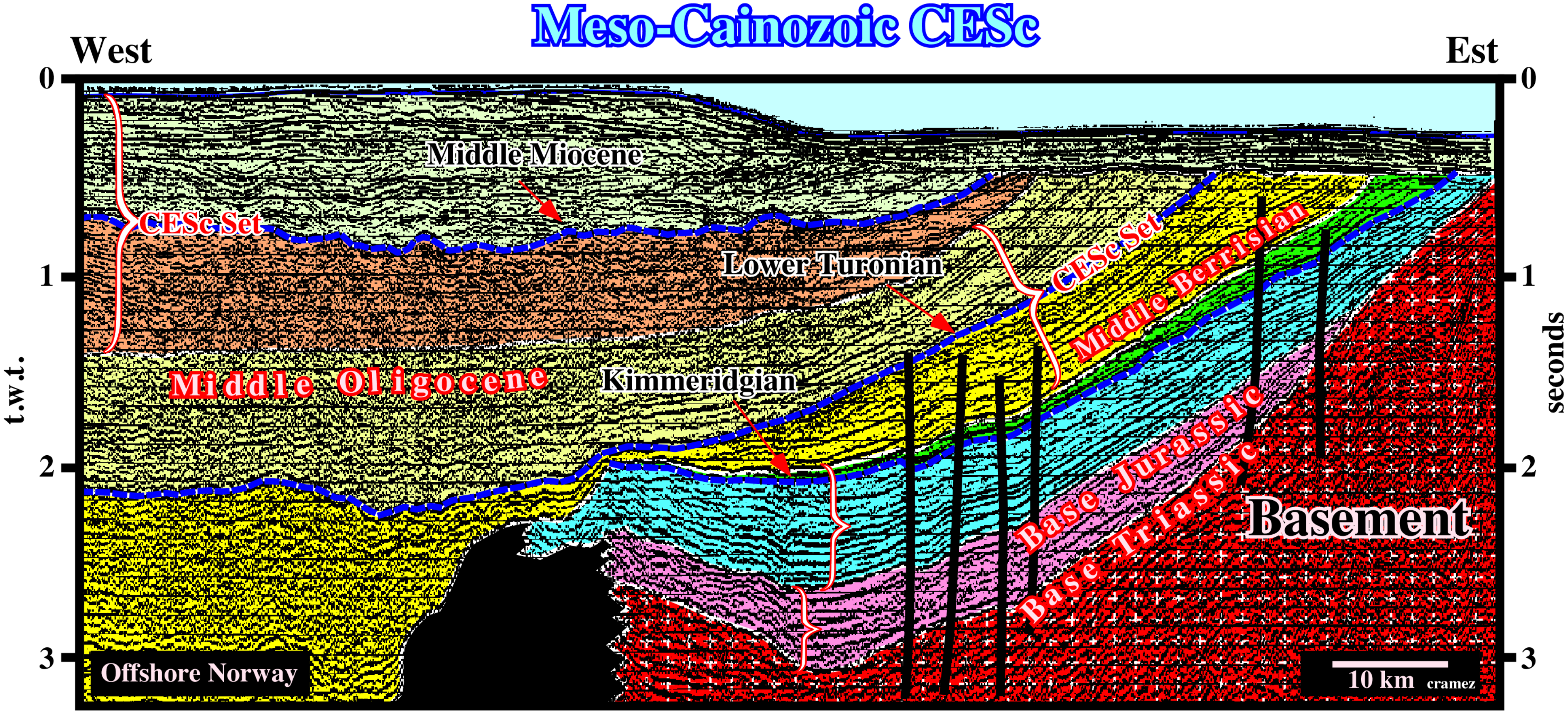


Fig. 44- On this line from offshore Norway, the seismic interpretation was performed in continental encroachment sub-cycles (CESc). However, just the more evident downward shifts of coastal onlap were identified and picked. So, one can say, the interpretation was done in continental sub-cycle sets. As illustrated, each CESc set is bounded by onlap and truncation surfaces, or correlative conformities, that is to say, by unconformities. A significant downlap surface can be recognized in each CESc set. Indeed, three downlap surfaces, with organic rich condensed stratigraphic sections, are evident: (i) Middle Miocene, (ii) Lower Turonian and (iii) Kimmeridgian. Taking into account isostatic rebound, which is obvious in the eastern part of the line, it is not a surprised that just the organic matter associated with the Kimmeridgian downlap surface reached maturation.

Stratigraphic Cycles

Meso-Cainozoic Continental Encroachment Sub - Cycles

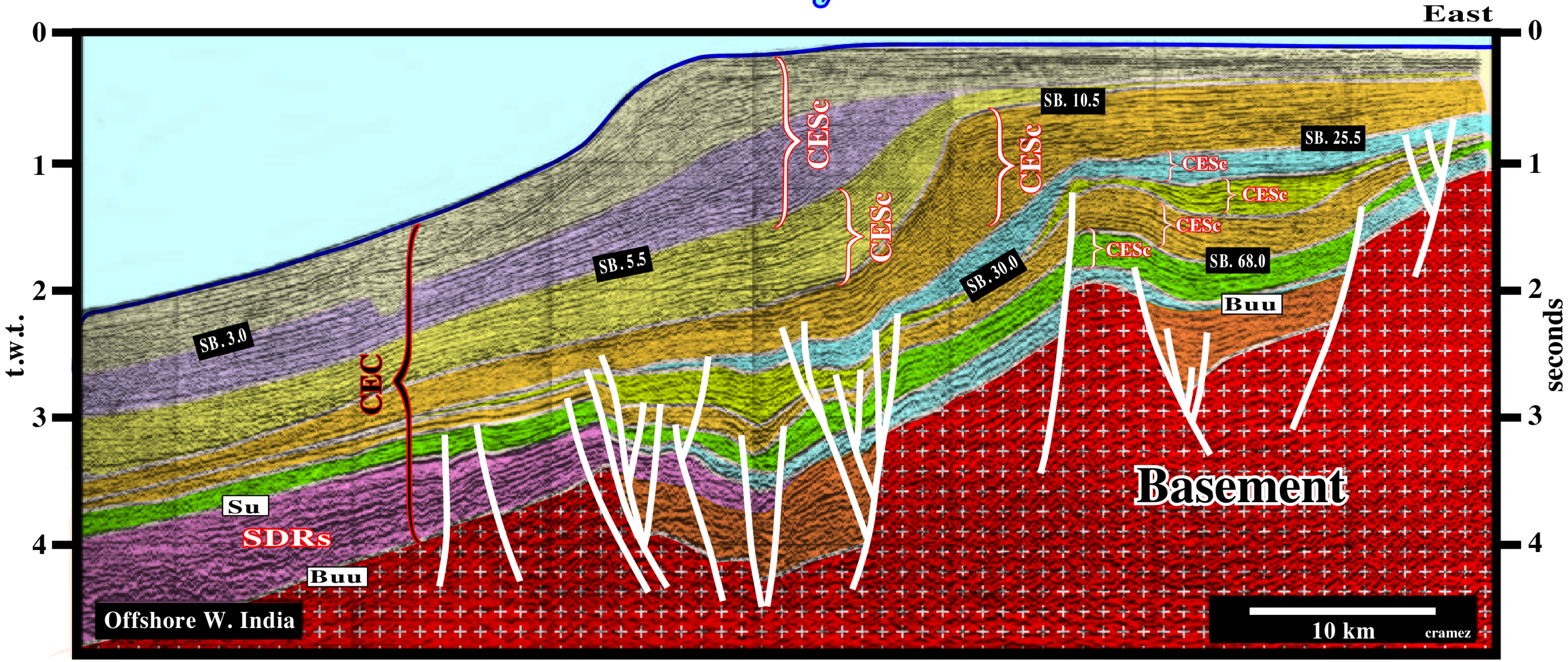


Fig. 45- On this line, within the post-Pangaea continental encroachment cycle (CEC), which is limited between the BU (break-up) unconformity and the sea floor, several continental encroachment sub-cycle sets can be recognized. The major unconformities bounding the CESc sets correspond to significant basinward and downward shifts of the coastal onlap. According to the stratigraphic signature proposed by P. Vail, and wells results, from top to bottom, the unconformities are: SB. 5.5 Ma, SB. 10.5 Ma, SB. 25.5 Ma, SB. 30 Ma and SB. 68 Ma. The term SB. 10.5 Ma means that the age of unconformity, which is a sequence boundary (SB), is 10.5 million years ago.

Stratigraphic Cycles

- Sequence cycles are bounded by regional onlap surfaces.

- Systems tracts, that is to say, linkage of contemporaneous depositional systems compose sequence cycles.

D) Parasequence cycles

These cycles are associated with 4th order eustatic cycle or higher.

- They are bounded by two consecutive flooding surfaces.

On this subject notice that:

(i) In deep water environments, with exception of parasequence cycles, all stratigraphic cycles are characterized by the onlap of turbidites and debris flows.

(ii) In shallower water settings, stratigraphic cycles are characterized by onlap of strata deposited in deltaic, coastal or fluvial environments.

(iii) Sub-aerial and submarine erosional truncations are commonly present below the boundaries of the cycles.

(iv) Toplap geometrical relationships, indicating sediment bypassing, are common under the boundaries of all stratigraphic cycles, particularly in areas of rapid progradation.

In spite of the scale problem, discussed next, and resolution of seismic data, we believe that in sequence stratigraphy, particularly when performed on seismic data, a hypothetico-deductive procedure (as proposed by K. Popper, 1934) is more appropriate than inductive procedures. In these notes, as you have probably already noticed, a discursive approach has been adopted. So, the different stratigraphic cycles must be studied in a decreasing hierarchical succession, i.e. from the cycles deposited during 1st order eustatic cycle downward to 3rd or 4th order.

Stratigraphic Cycles

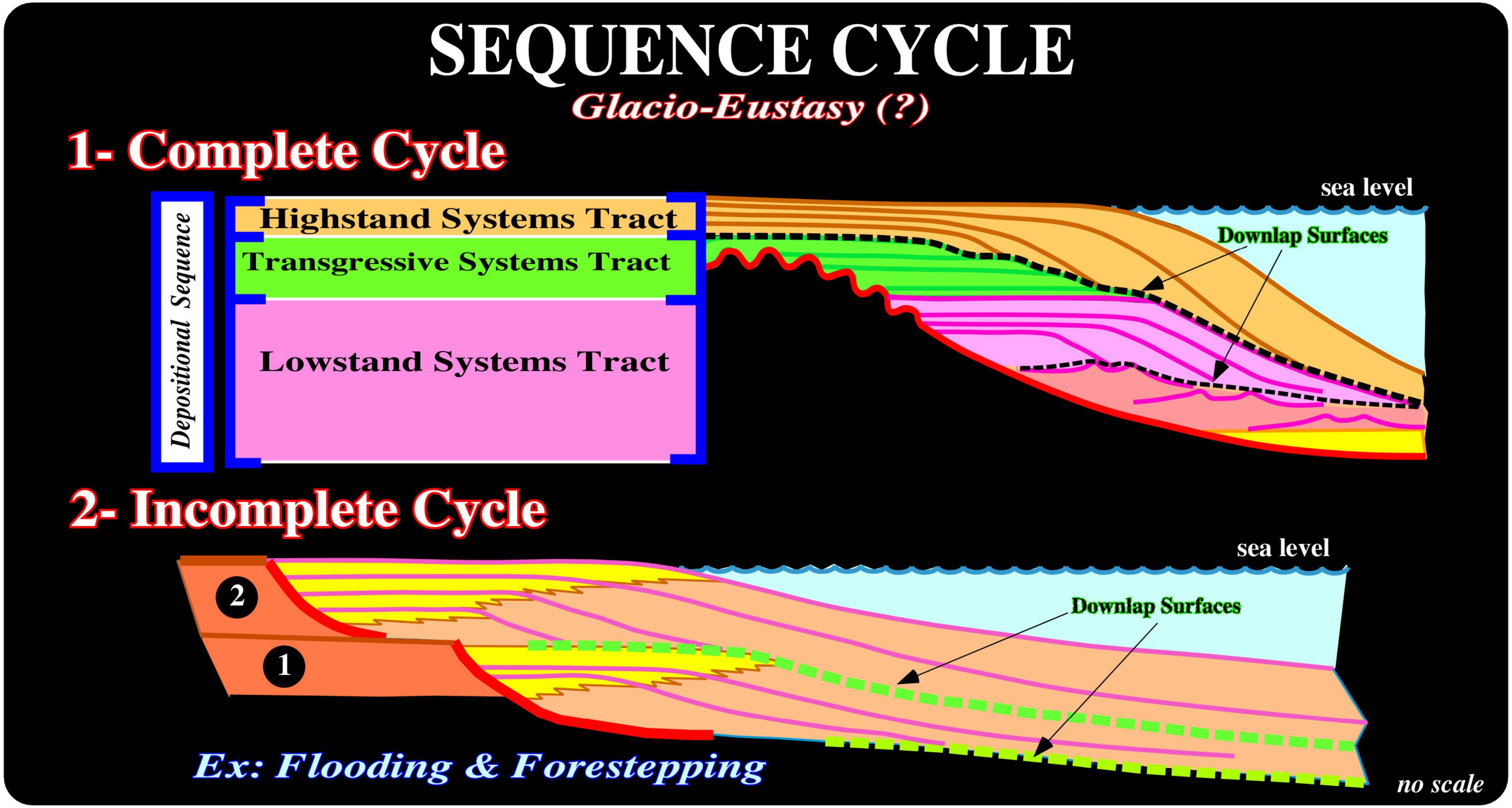


Fig. 46- Sequence cycles are associated with 3rd order eustatic cycles. They are bounded by unconformities, which are induced by relative sea level falls that either totaly or partially expose the shelf. So, they are defined by regional onlap surfaces. The difference of age between the bounding unconformities ranges between 0.5 Ma and 3-5 Ma. They are formed by a stacking of linked coeval depositional systems (systems tracts) and two downlap surfaces can be recognized. Sequence cycles, as illustrated above, can be complete (with all systems tracts) or incomplete.

Stratigraphic Cycles

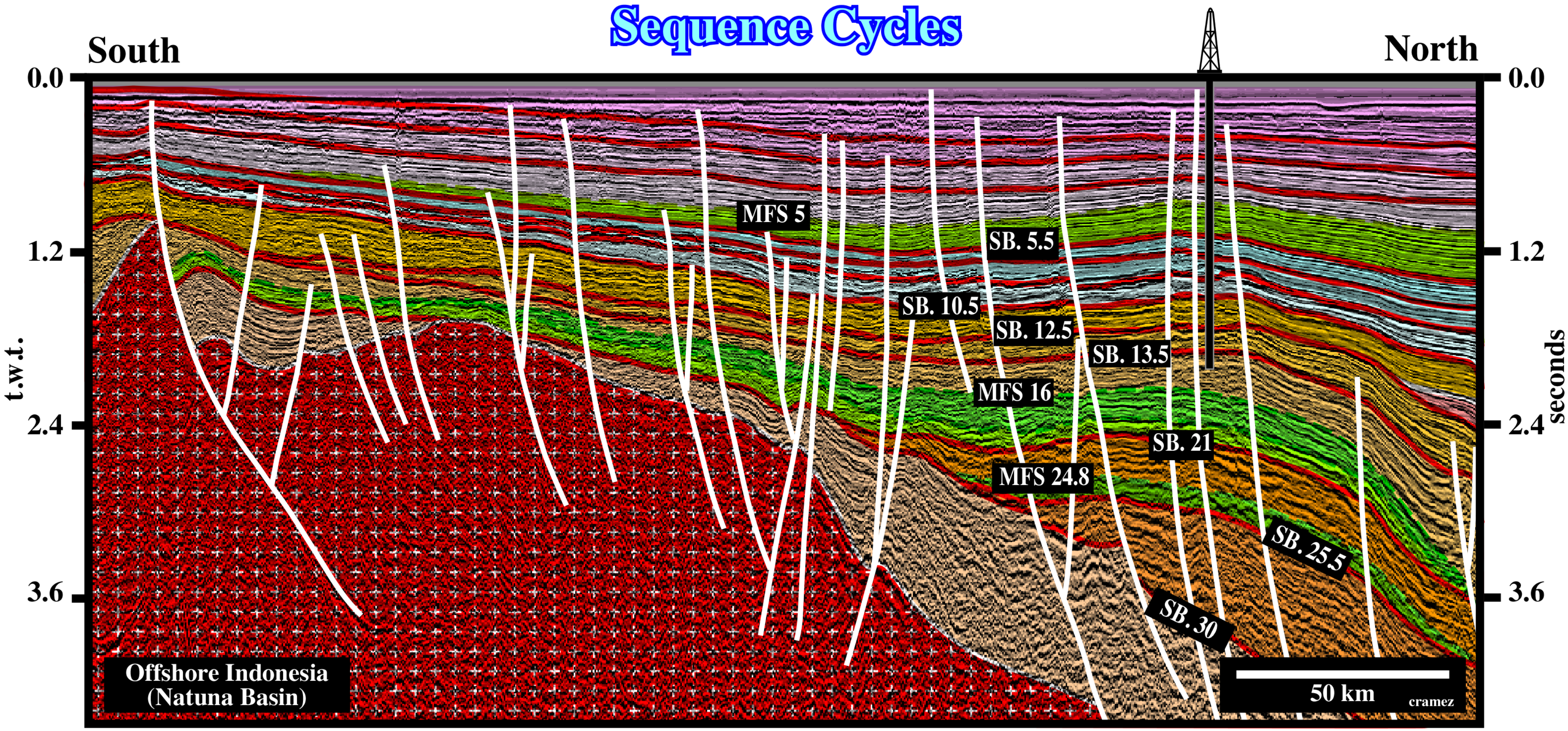


Fig. 47- On this line, the seismic interpretation was performed in sequence cycles. However, it is quite difficult, particularly due to the horizontal and vertical scales, to identify the systems tracts composing the different sequence cycles. Except for few a downlap surfaces, such as MFS. 5 Ma, MFS. 16. Ma and MFS. 24.8 Ma, which emphasize the major transgressive events of the Neogene, only the bounding unconformities have been picked. Some of them have been calibrated by the well's results (Lemang #1), while the age of the others is based on the stratigraphic signature of the area. Notice the age difference between consecutive unconformities is not higher than 3-5 My.

Stratigraphic Cycles

Sequence Cycles

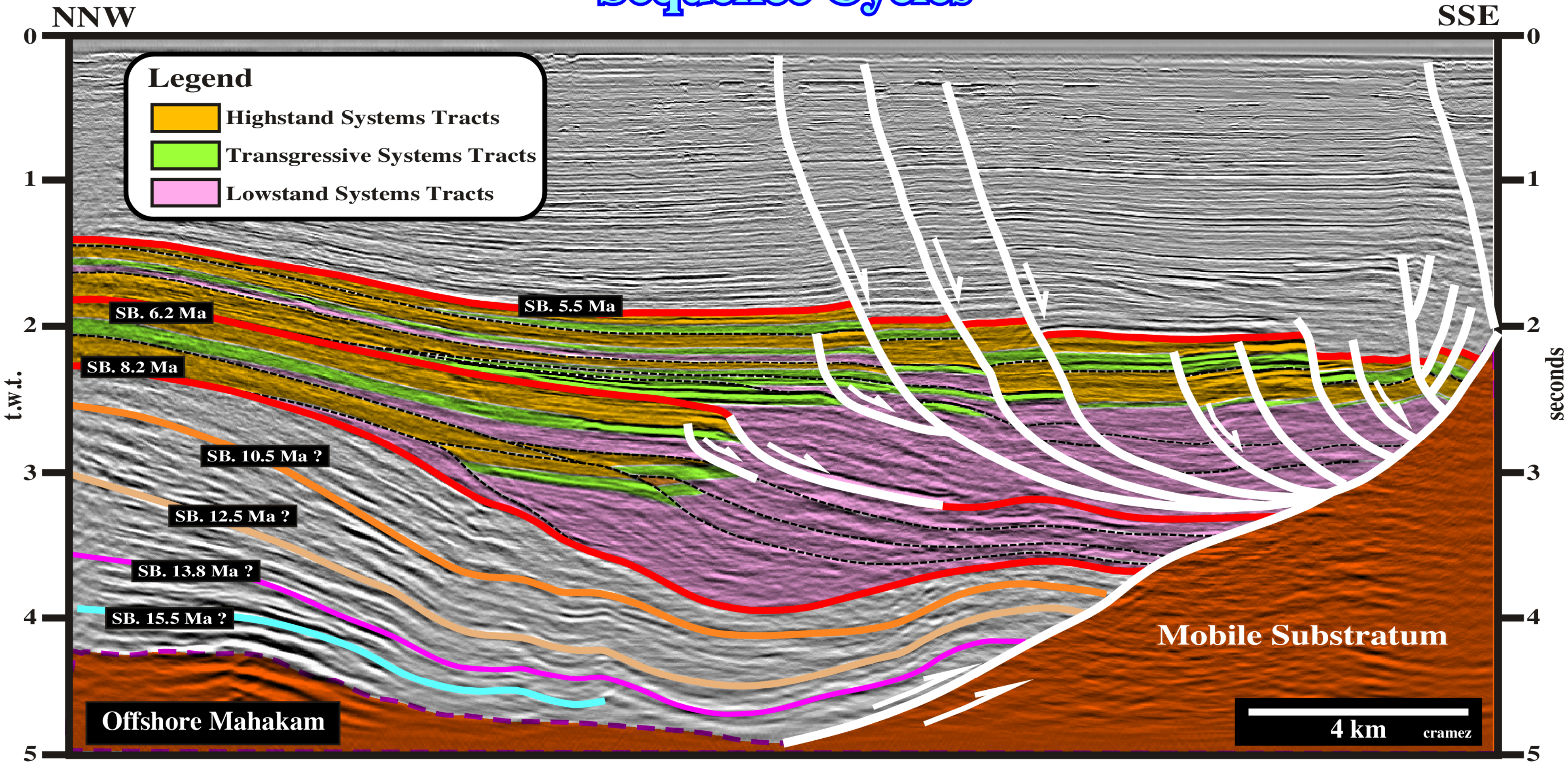


Fig. 48- On this line from offshore Kalimantan where the rate of sedimentation is quite strong, the picking of the sequence stratigraphic cycles and systems tracts is quite easy. In addition, as illustrated, between the sequence boundaries 5.5 Ma and 8.2 Ma, and taking into account the reflections terminations, it is possible tointerpret high frequency sequences. In spite of the fact that so far no basin floor fans have been drilled, the three uppermost unconformities are quite well calibrated and dated. However, the age of the lower ones are hypothetical and based on the stratigraphic signature of the Neogene recognized in SE Asia.

Stratigraphic Cycles

Sequence Cycles

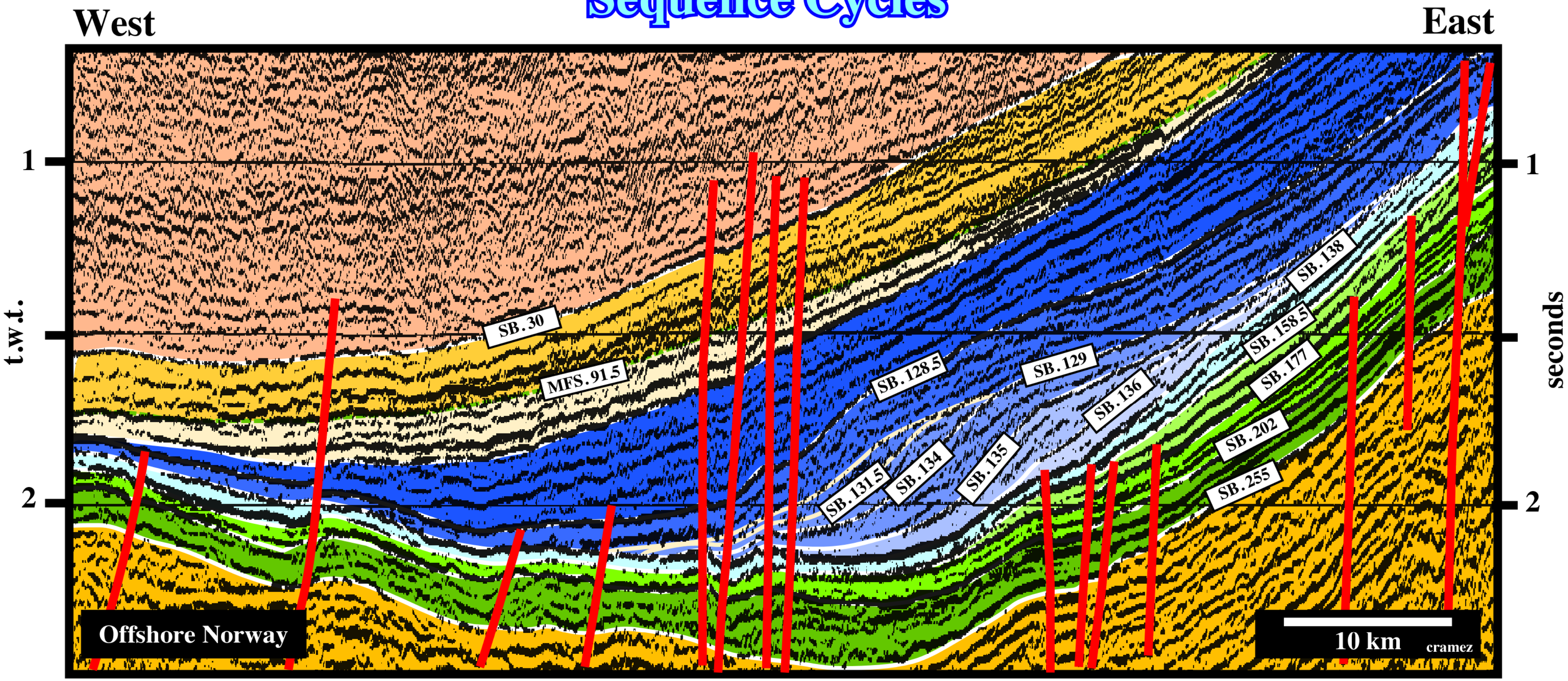


Fig. 49- On this line offshore Norway, the majority of the seismic sequences associated with the Kimmeridgian downlap surface seem to be incomplete. Indeed, between SB. 128.5 and SB. 138, six sequences can be recognized by reflections termination, but they seem just be composed of only forestepping systems tracts, most likely highstand systems tracts. The North Sea and offshore Norway source rocks are associated with the downlap surface along which all these Upper Jurassic sequences seem to terminate.

Stratigraphic Cycles

Sequence Cycles

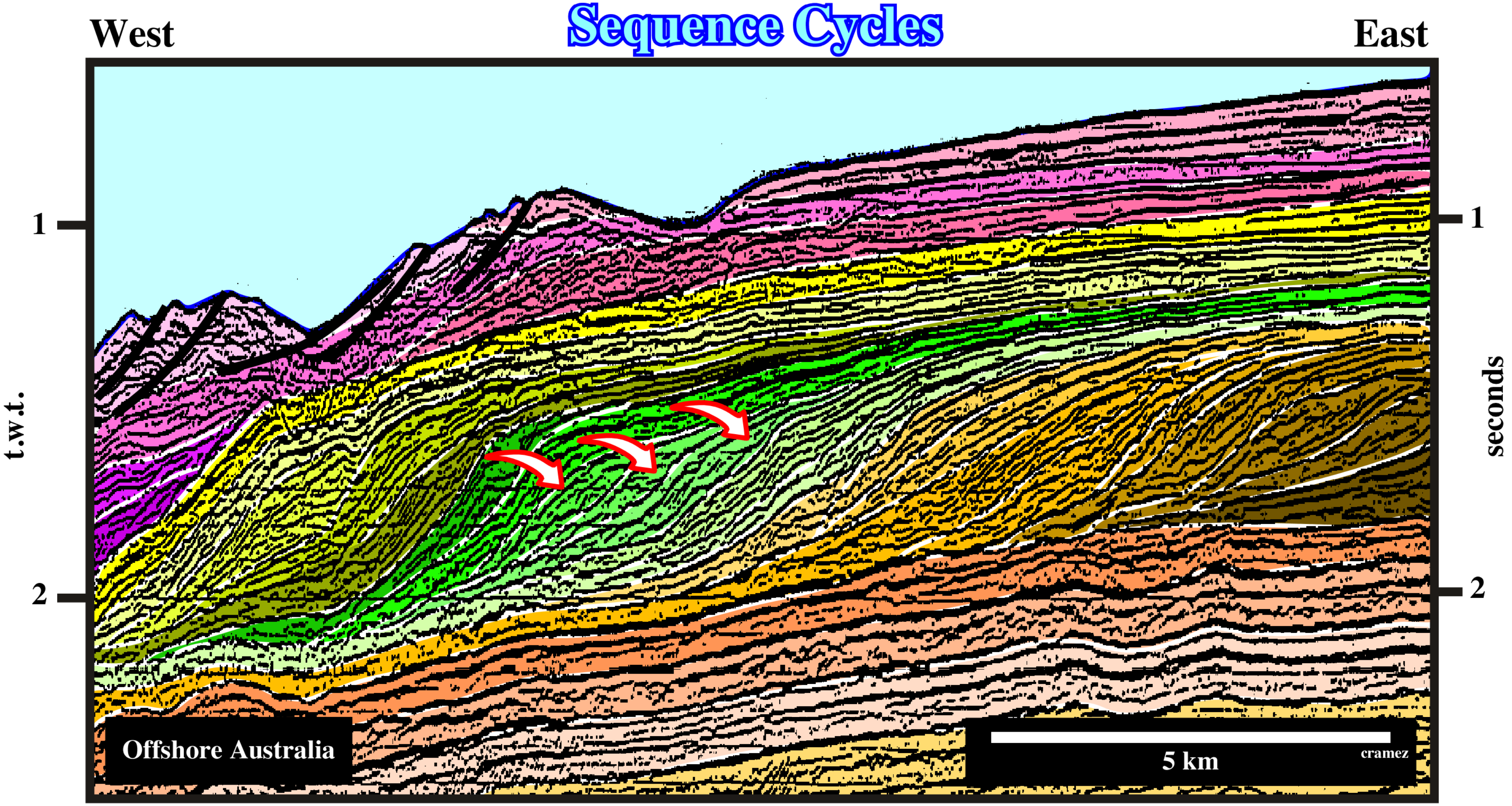


Fig. 50- When progradation is predominant, that is to say, when upbuilding is quite small in relation to outbuilding, very often, some of the sequence cycles are incomplete (some of the systems tracts are missing). In deed, on this seismic line from offshore Australia, it is evident that some sequences are incomplete; transgressive and highstand systems tracts are missing.

Stratigraphic Cycles

Sequence Cycles

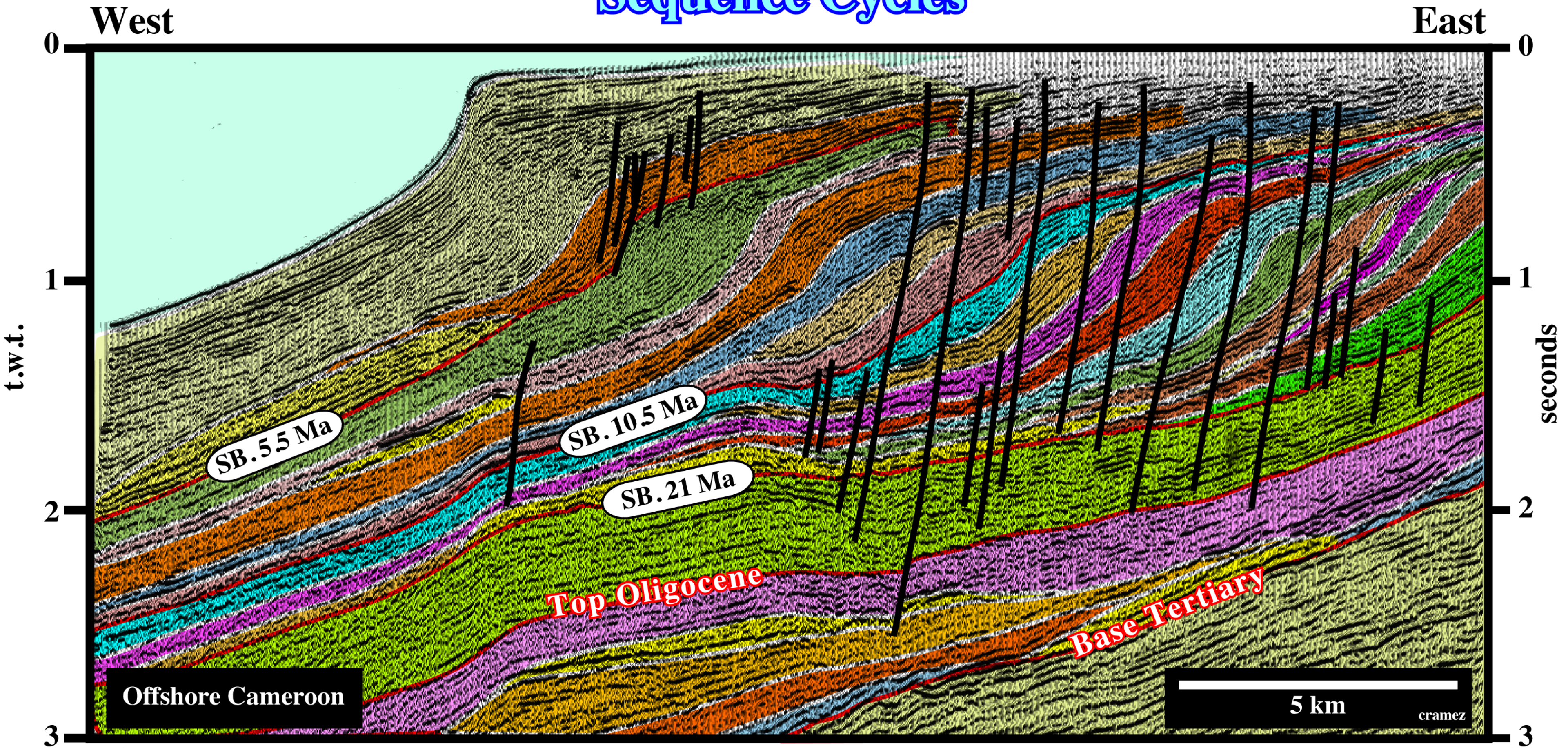
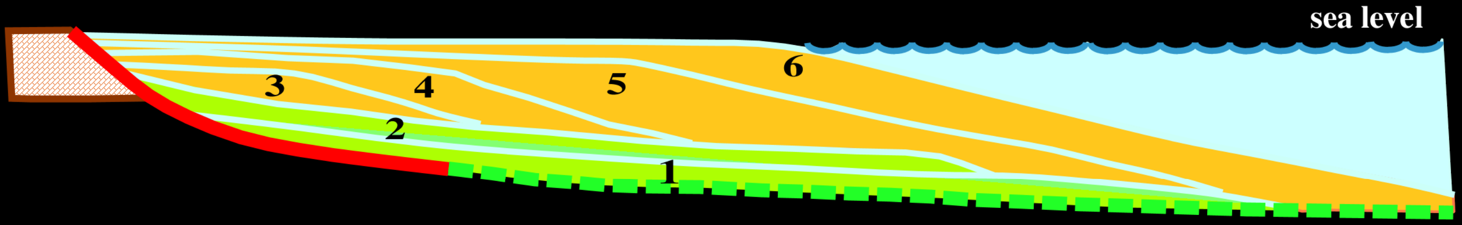


Fig. 51- On this interpretation three principal sequence sets are considered. They are bounded by the unconformities SB. 5.5 Ma, SB. 10.5 Ma and SB. 21 Ma. The majority of the distal sequence cycles seem complete, that is to say, seem to be composed by all systems tracts. However, taking into account the vertical scale, the individualisation, and picking of the systems tracts, is rather impossible. When upbuilding is significant, we guess that a sequence is complete. Contrariwise, when upbuilding is small, or inexistent a sequence is likely incomplete.

Stratigraphic Cycles

PARASEQUENCE CYCLE

Glacio-Eustasy (?)



1-6 are Parasequences

Parasequences are stratigraphic intervals bounded by flooding surfaces or their correlative conformities.

no scale

Fig. 52- As illustrated on this sketch, parasequences are stratigraphic intervals, bounded by flooding surfaces or their correlative conformities, which stack to form systems tracts. Their recognition is quite easy on the ground, but on seismic lines it is relatively difficult as illustrated on the next figure.

Stratigraphic Cycles

Parasequence Cycles

(are often under seismic resolution)

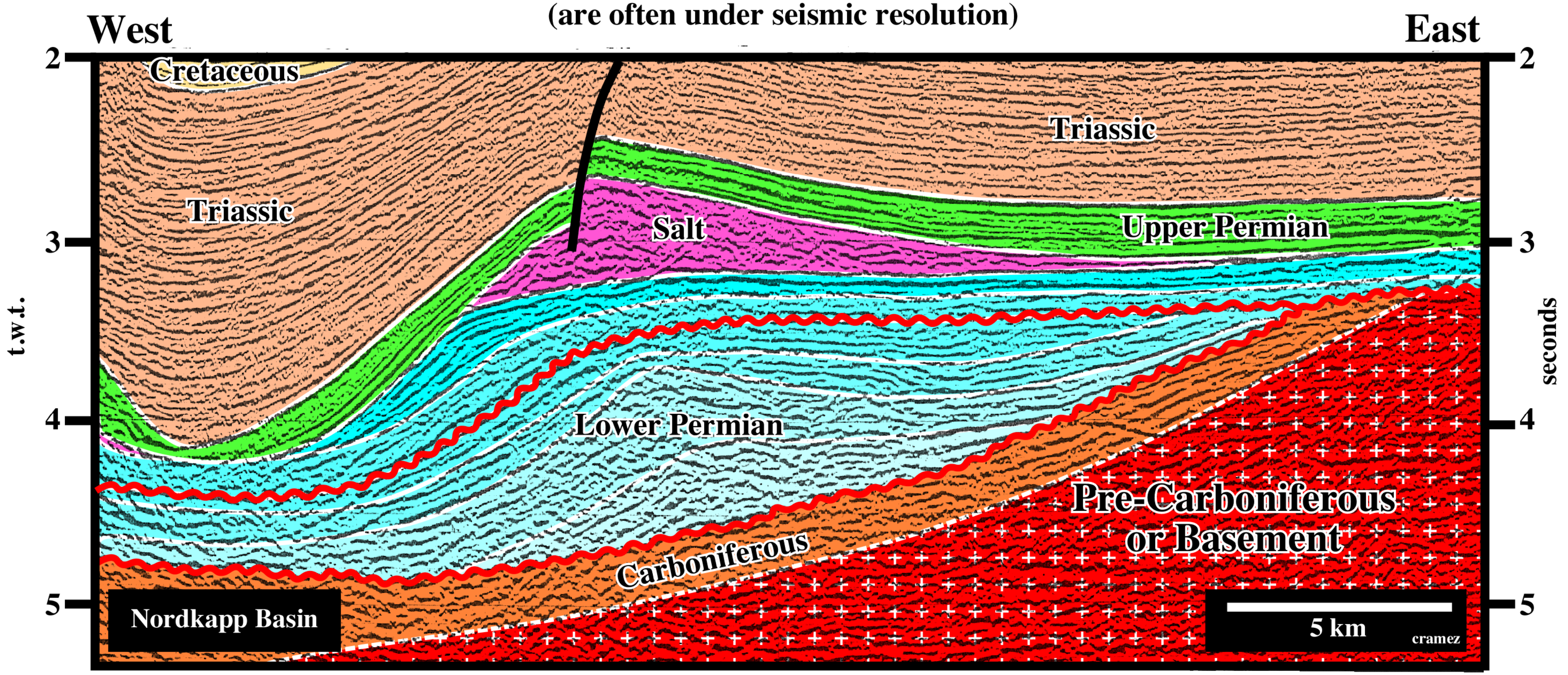


Fig. 53- As said previously, parasequences, which are limited between consecutive flooding surfaces, are easily to recognize on the ground and on electrical logs. Indeed, taking into account the scale of the seismic lines, and particularly the vertical time scale, only the major flooding surfaces can be recognized as illustrated on this seismic line by the Lower and Middle Permian flooding surfaces. However, the seismic interval between them does not correspond to parasequence. Actually do not forget that parasequences are deposited during 4th order eustatic cycles, which time duration ranges betwee, 0.01 and 0.5 My. So, even in areas with normal sedimentaion rates, their thickness is metric, that is to say, under seismic resolution.

Sequence Cycle Depositional Model

Depositional Model

The stratigraphic model proposed by the Exxon team assumes that:

Eustasy is the main factor driving the cyclicity of sedimentary deposits”

Figures 54 and 55 illustrate the classical sand-shale depositional model proposed by P. Vail and co-authors using Marco Polo software (1991). In this model the main geological parameters affecting the stratal patterns are assumed to be:

a) Eustasy.
b) Subsidence.
c) Accommodation.
d) Terrigeneous influx.
e) Climate.

They clearly emphasize that Stratigraphy to P. Vail is systemic, that is to say, global. Indeed, all parameters are interconnected and interdependent. Their interconnections corroborate the scientific “systems thinking” approach and Lovelock‘s Gaia hypothesis as well.

Several simplifications were used in this model (fig. 54), which attempts to explain the cyclicity and stratal patterns of sand-shale sedimentary intervals as recognized in the field, subsurface and seismic data:

1- A climate and a terrigeneous influx devoid of carbonate deposition.
2- A constant (in time and space) terrigeneous influx.
3- A gradual and linear basinward increasing of subsidence.
4- A 100 ky time interval between each chronostratigraphic line.
5- An aleatoric location of erosion features (incised valleys, canyons, etc.) during the major relative sea level falls.

Depositional Model

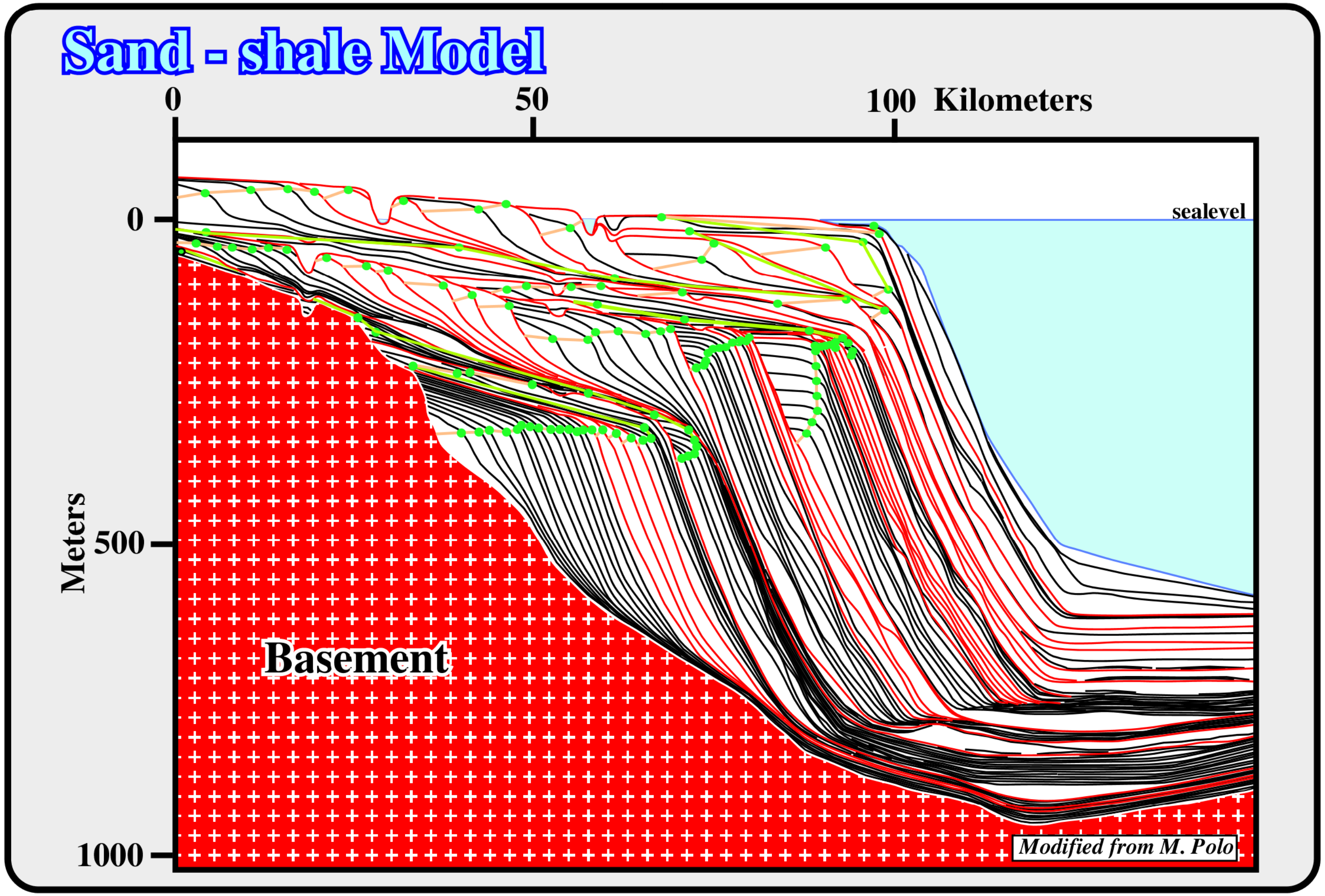


Fig. 54- Exxon's sequence model is here represented using Marco Polo software. The vertical and horizontal scales are quite different. The vertical scale is metric. The horizontal is kilometric. The vertical exaggeration is almost 100 times. Each line corresponds to a chronostratigraphic line. Their spacing is 100 ky. The red lines correspond to unconformities, that is to say, to relative sea level falls. The green dots underline the successive positions of the shelf breaks. In this model, terrigeneous influx is constant; in other words, the area between the consecutive chronostratigraphic lines is constant.

Depositional Model

These simplifications obey Occam's razor. They follow the principle used by Bak (1996): "**Observing details may be entertaining and fascinating but, in fact, we learn from generalities**". Indeed, on this subject, it is very important to reitorate:

(i) R. Magritte's purpose when he named his work of art "This is not a pipe" was to express the difference between "**being**" and "**representing**".

(ii) All geological structures are scale invariant, that is to say, without scale they cannot be correctly interpreted.

In figs. 54 to 56, the vertical and horizontal scales are different. They are both metric. However, they are quite different. The vertical exaggeration is almost 100 times the natural scale (1:1), as it exists in nature, that is to say, without magnification or reduction. With such an exaggerated model, it is evident that geometrical relationships between bedding planes (chronostratigraphic lines) clearly emphasized:

- **Onlap**:
  A base-discordant relation in which initially horizontal strata terminate progressively against an initially inclined surface, or in which initially inclined strata terminate progressively up-dip against a surface of greater initial inclination.

- **Downlap**:
  A base-discordant relation in which initial inclined strata terminate downdip against an initially horizontal or inclined surface.

- **Toplap**:
  Termination of strata against an overlying surface as a result of non-deposition (sedimentary bypassing) with perhaps only minor erosion. Each unit of strata laps out in a landward direction at the top of the unit, but the successive terminations lie progressively seaward.

Depositional Model

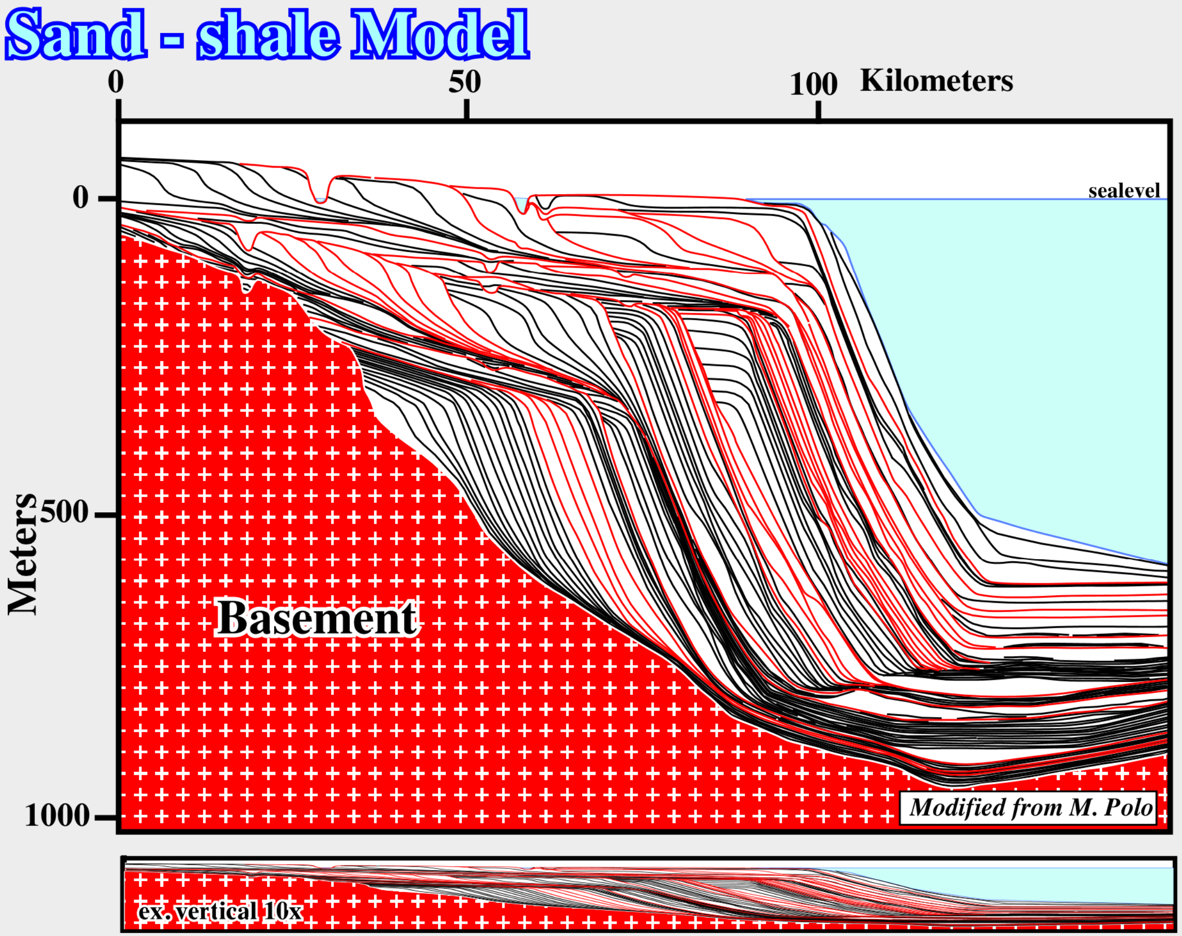
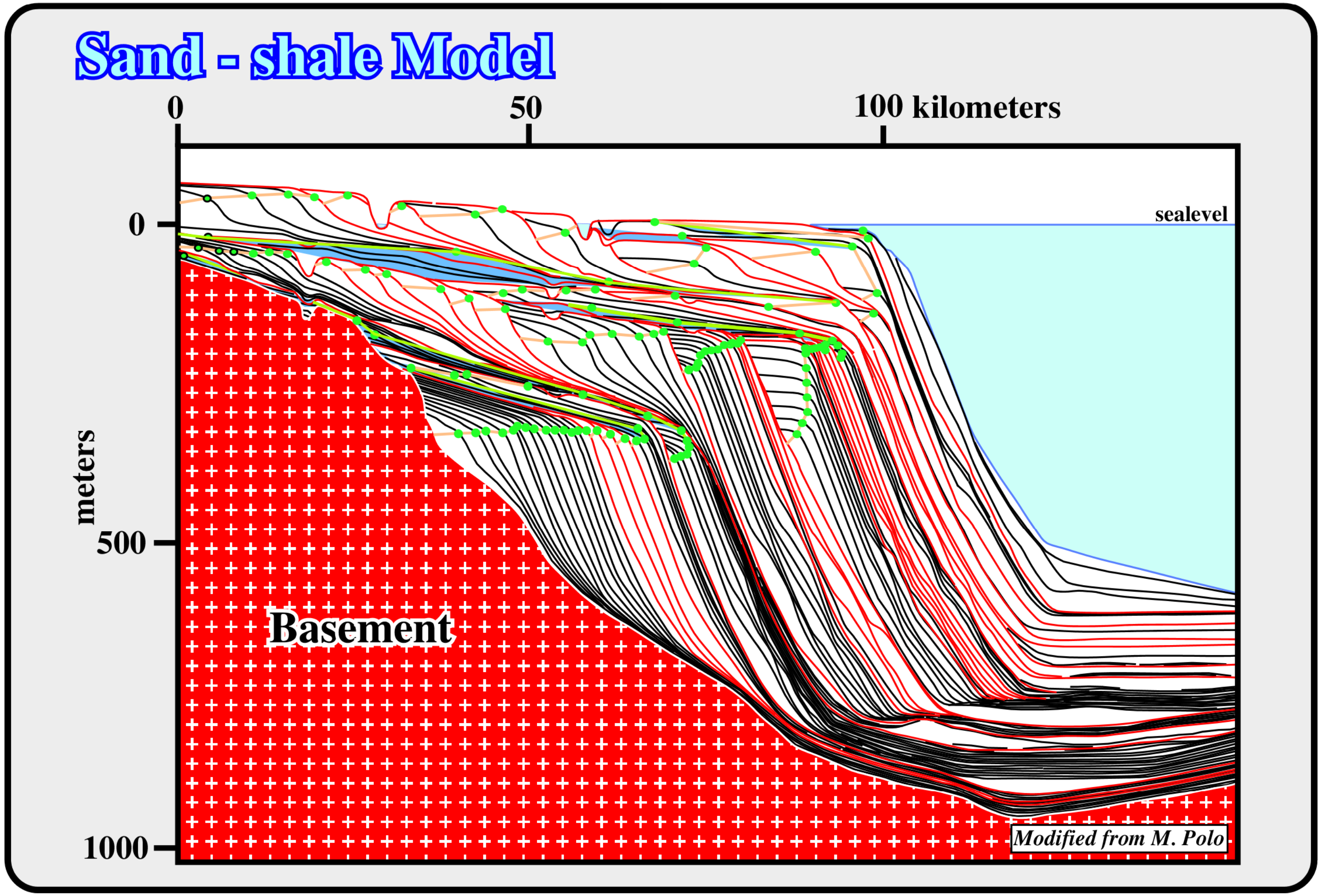


Fig. 55- Exxon's model is here represented at two different vertical scales. In the lower part, the model still is 10x vertically exaggerated. However, the majority of the geometric relationships between chronostratigraphic lines (or reflection terminations) cannot be recognized. Taking into account that the vertical exaggeration of a normal seismic line (time profile) ranges between 2 and 3, it is evident that seismic interpretations at the level of sequence cycles are only possible in areas with high depositional rates.

Depositional Model



Modified from M. Polo

Fig. 56- During regressive (forestepping) periods, sedimentary basins have no platforms. Shelf breaks and the depositional coastal breaks (roughly the shoreline) are coincident. Only during transgressive periods are platform environments developed as a consequence of backstepping of depositional coastal breaks. Subsequently, as the shorelines progressively move landward, the water depth of the platform increases.

Depositional Model

When Exxon's model is drawn at natural scale (1:1) or, even, with vertical exaggerations between 5 and 10 times, most of the geometrical relationships (or reflection terminations) cannot be recognized (Fig. 55). This feature raises several questions:

1) Under what conditions, can the Exxon sand-shale model be used on the interpretation of conventional seismic lines, knowing the vertical time scale, when converted in depth, has vertical exaggerations ranging between 2 and 10 times?

2) Are sea level changes the major factor of sedimentary cyclicity and the cause of discontinuities bounding the stratigraphic cycles?

3) Is the Exxon basic stratigraphic hypothesis valid in all sedimentary basins?

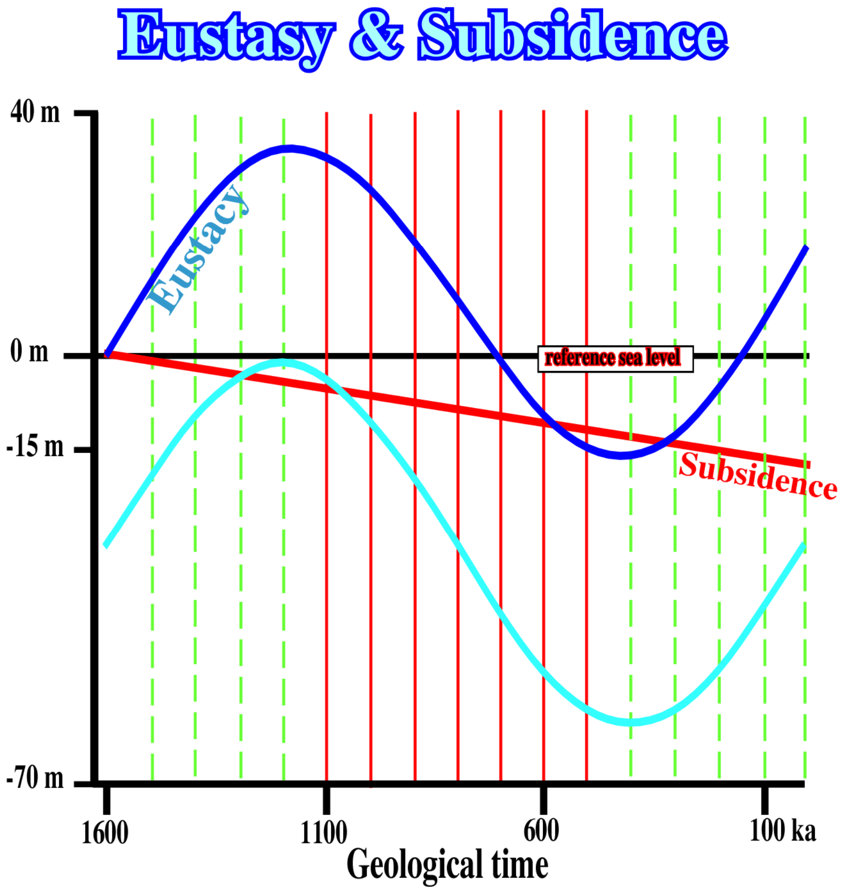
4) Are subsidence and terrigeneous influx rates smaller than sea level changes rates?

5) Are subsidence and terrigeneous influx rates smaller than sea level changes rates in basins associated with the formation of megasutures, such as back-arcs, foredeep and folded belts?

The Exxon carbonate depositional model is illustrated on fig. 58 using Marco Polo software. The parameters eustasy and subsidence are exactly the same as those used in the sand-shale model (figs. 54 to 56). The relative sea level curve is the same in both models.

The only difference is the sedimentary input. In the previous sand-shale model, the sediments are transported from the continent toward the sea and the terrigeneous input is conventionally taken as constant (the surface between two consecutive chronostratigraphic lines is kept invariable). In the carbonate model, the sediments are created in place by algal and reef production. Such an organic production is a function of water depth. The maximum of production ranges between 2 and 3 m (fig. 57) and it decreases progressively towards the bottom of the photosynthesis zone. Below this limit (roughly 80-100 meters), the absence of light prevents all algal production. Actually, algal production disappears between 30 and 40 meters of water depth.

Depositional Model



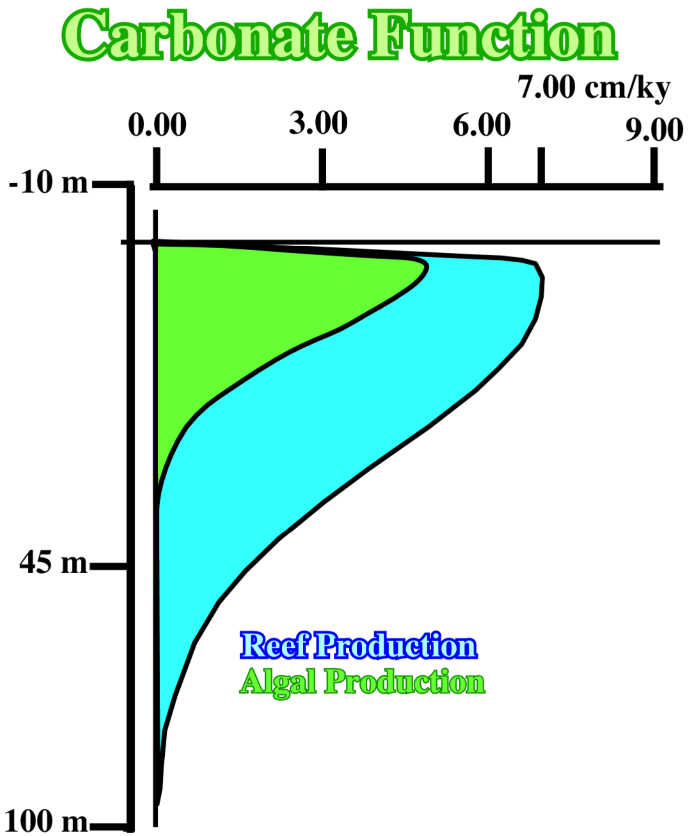


Fig. 57- To build the carbonate sedimentary model shown in fig. 58, we have used the eustatic curve (in blue) and the subsidence (in red) illustrated on the left. In the employedcarbonate function (on the right), the algal and reef production are maximal (5-7 cm/ky) near the surface at 2-3 meters water depth. At around 70-80 meters of water depth, there is no more reef or algal production.

Depositional Model

Reef growing becomes nil at the compensation depth, that is to say, at the lower boundary of the euphotic zone, which corresponds to the part of the ocean in which there is sufficient penetration of light to support photosynthesis:

(i) At first sight, the stratal patterns of the carbonate model look quite different from those associated with the sand-shale facies.

(ii) The geometrical relationships between the chronostratigraphic lines are the same.

(iii) Looking attentively, the same seismic surfaces, i.e. the surfaces defined by the reflection terminations are recognized, as well as the same systems tracts.

The same questions formulated previously for the sand-shale model are valid for the carbonate model. So, explorationists using these models should not forget that:

1) Numerical models contain closed mathematical components that may be validated, just as an algorithm within a computer program may be validated.

2) Finer scale structures and processes are lost from consideration, a loss that is inherent in a continuum mechanical approach.

3) Exxon' geologists assumed that the completeness of the stratigraphical interval deposited during a eustatic cycle of 3rd order was practically 100%. They assumed the sedimentary processes were active during the entire time interval, that is to say, sedimentation was a continuous process. Such an assumption is just not true. Indeed, the completeness of a stratigraphic interval is seldom higher than 20%. Sedimentary processes are discontinuous and catastrophic. In this perspective, one can say, Vail's sequence model is holistic. It forms a whole, in which the study of its parts (systems tracts) can only be approached when the organization of the whole is known. In other words, a sequence cycle is a whole, composed by different parts, which by itself is, at the same time, a part of larger wholes, that is to say, continental encroachment sub-cycles and continental encroachment cycles.

Depositional Model

Carbonate Model

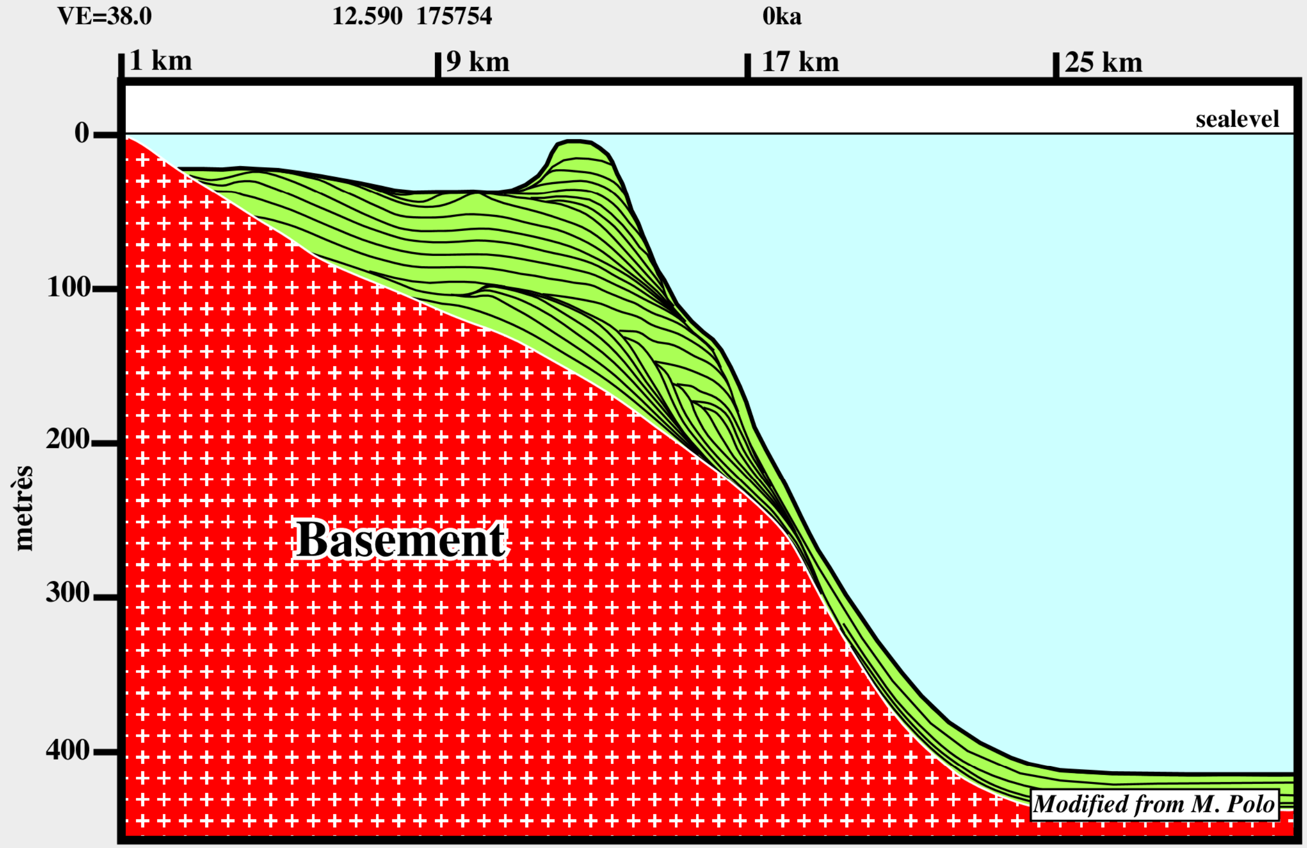


Fig. 58- The sedimentary carbonate model illustrated here was built using Marco Polo software and the same relative sea level curve as in the sand-shale model (fig. 54). Only, the terrigeneous influx was replaced by a carbonate function (fig. 57), in which algal and reef production are maximal (5 to 7 cm per 100.000 years) near the surface (2 - 3 meters water depth).

Sequence Depositional Model
Marco Polo Software

Sand - Shale
Model

Sedimentary Model

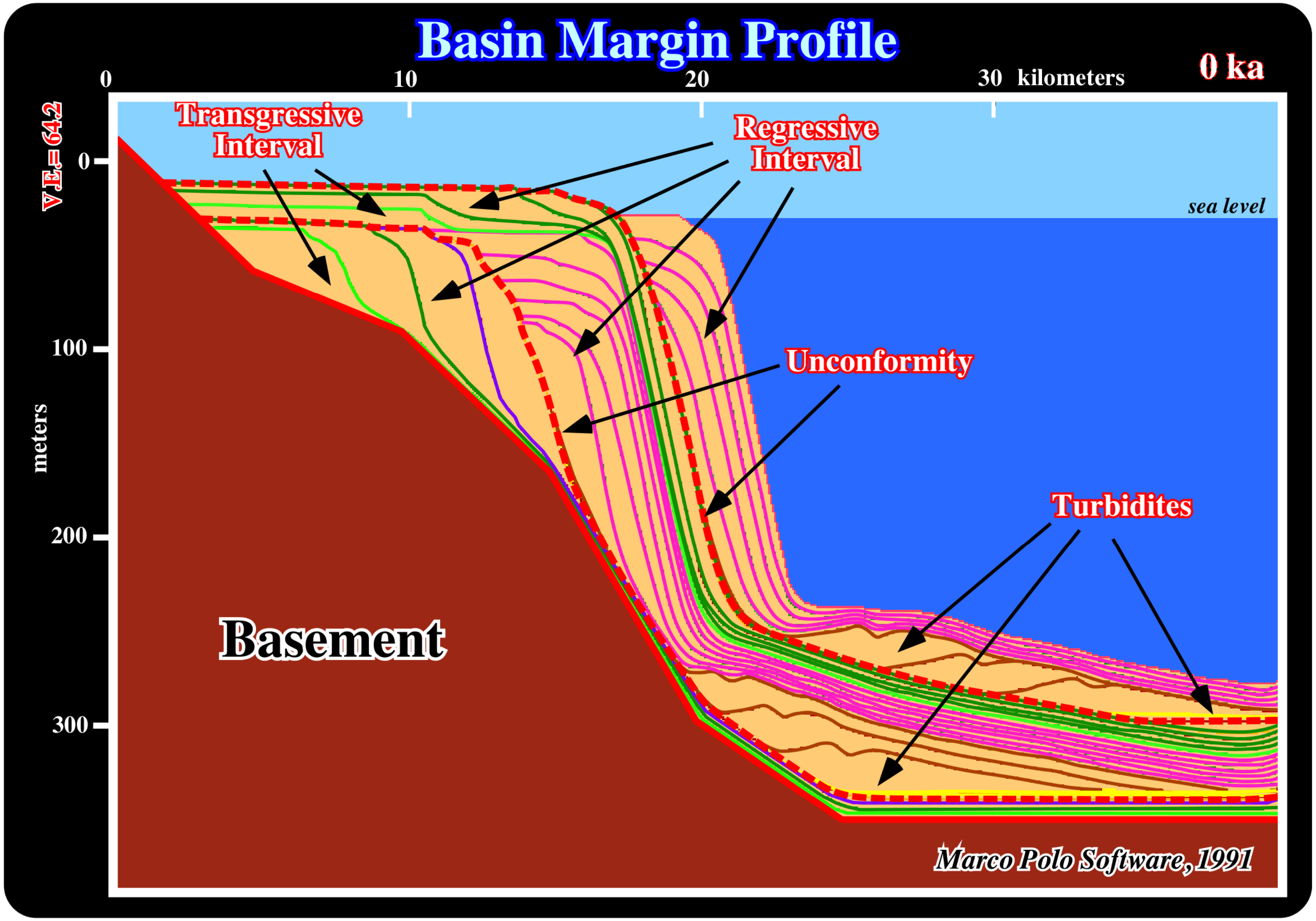


Fig. 59- The first thing a geologist must notice in this mathematical model is the vertical scale. In this particularly example, the vertical exaggeration is around 64 x, that is to say, far beyond the natural scale (1:1) and the vertical scale of the seismic lines, which generally ranges between 2 and 6 times. As you will see, all models illustrated on the next figures are vertically exaggerated. So, the geometric relationships between the chronostratigraphic lines are abnormally enhanced compared with those of the seismic data realm.

Sand - Shale
Sedimentary Model
Evolution

Model Variables

```
Report Version   2
 72392  11158
10000001
N° of Columns =200 Cell Spacing
= 150.00 m
Left Column =   5   Right Column
=200
Time slices from 3000 to 0. ka,
    with a timestep of 100. ky.
Timeslice trigger switch = 1.
Time Series

  Distance to next value   Depth
         .000000
               1.000            -50.000
               1.000            -40.000
               1.000            -30.000
               1.000            -20.000
               1.000            -10.000
               5.000              .000
               2.000             15.000
               2.000             30.000
               1.000             50.000
               1.000             65.000
               1.000             80.000
               1.000            110.000
               1.000            160.000
               1.000            190.000
               1.000            210.000
               1.000            220.000
               1.000            225.000
              -5.000            225.000
         -99.0000
```

```
Digital Sea Level File =  40
Digital Subsid. File = 999
Digital Subsid. History File  = 999
Digital Compact. Parameter File = 999
Digital Sediment Supply File = 999
Digital Erosion Rate File  = 999
Digital Bathymetry File =  41
Period  Amplitude  Phase  Asymt.   %
Cycle 1   6500.       .0     0.      0.   75.
Cycle 2   1600.     60.0     0.      0.   75.
Cycle 3    400.       .0     0.      0.   75.
Cycle 4    100.       .0     0.      1.   75.
Cycle 5     41.       .0     0.      0.   75.
Cycle 6     23.       .0     0.      0.    75.
Digitized sea level file used
          Exe3. Sl. text

  Age (Ma)      Depth
     .000          .000
     .100         7.000
     .200        12.000
     .300        15.000
     .400        16.500
     .500        16.500
     .600        15.000
     .700        12.000
     .800         7.000
     .900         2.000
    1.000          .000
    1.100         2.718
    1.200        11.306
    1.300        24.423
    1.400        40.000
```

```
      1.500            55.577
      1.600            68.694
      1.700            77.282
      1.800            79.983
      1.900            76.372
      2.000            67.019
      2.100            53.400
      2.200            37.665
      2.300            22.299
      2.400             9.728
      2.500             1.936
      2.600              .153
      2.700              .000
      2.800             1.000
      2.900             4.250
      3.000            11.000
    9999.990             .000

Digit. subsi. rates file used
Distance to next value
              Subsidence

     .00000
      4.000             1.100
      4.000             2.200
      4.000             3.300
      4.000             4.400
      4.000             5.500
      4.000             6.600
     -5.000             1.700
    -5.00000
```

Model Variables

Plotting equilibrium point
Subsidence Cycle Period = 1500. ky
Subsidence Cycle Phase = 0
Flexural Wavelength = 2 km
Effective Lith Thickness = 55 km
Taper Limit of Projection = 900 km
Loop Limit of Calculation = 1.
Density of the Mantle = 3340. kg/m3
Density of Water = 1030 kg/m3

Digitized subsidence factor file used

.000	.000
9999.990	.000

Sediment Supply Cycle Switch = 0
Maximum Sediment Supply = .01
Minimum Sediment Supply = .0015
Sediment Cycle Period = 1500
Phase = 270
Fraction derived from left = 1
Clastic Sediment Supply Switch = 1
Carbonate Sediment Supply Switch = 0
Digitized sediment flux file used

.000	.000
9999.990	.000

Pelagic product. constant 1.0 cm/ky
Reef product. constant 7.0 cm/ky
Width of Reef product. 40 m
Depth of Max. Reef product. 8 m
Distance of Reef production 1. km
Algal product. constant 5. cm/ky
Width of Algal product. 20 m
Depth of Max. Algal product. 2 m
Upper Lim. Clast. Poisoning .1 cm/ky
Time Step of Carb. product. 21 ky

Fluvial Plain Gradient .003
Coastal Plain Gradient .00001
ShoreFace Gradient .0079
Depositional Gradient .065
Barrier Island Height .0 m
Barrier Island Width 2000 m
Width of Coastal Plain 6. km
Depth Fairweather wavebase 10 m
ProDelta Suspension Dist. 5. km
Suspension Mixing
Depth Limit 200 m
% coarse sand 10
% volume traction transported 80.

Island Surface Gradient .000001
Tidal Plain Gradient .00099
Tidal Range 3 m
Back Reef Gradient .0070
Reef Top Depth 6 m
Bank Gradient .077
Rise Gradient .02
Silt Accomm. Rate (m/ky) .25
Silt/Clay Accomm. Rate (m/ky) .5
Silt/Coal Accomm. Rate (m/ky) 1.0
Coal/Silt Accomm. Rate (m/ky) 1.5
Coal Accommodat. Rate (m/ky) 2.0

Relative Sea Level Factor 1.0

Turbidite Volume Factor 1.0
Grad. Top of the Slope Fan .0079
Grad. Top of Basin Floor Fan .002
Slump Size Constant 200

Erosion switch = 0
where 1 = on, 0 = off
Erode Basement switch= 1
where 1 = on, =off
Headward erosion rate .01 km/ky
Surf. erosion rate 1 m/ky degree
Channel erosion rate 10. cm/ky
Channel Depth 4 m
Initial Channel Width .0 m
Channel Margin Gradient .10
Distance between Channels 10 km
Smoothing width is 100. meters

Digitized erosion rates file used

.00	
500.00	.00
-5.00	.00
-5.00	

Age (Ma)	Parameter ID	Value
-1.0	.00	.00

Plotted 31 Surfaces

SUCCESSFUL PLOT

Model RSL Analysis

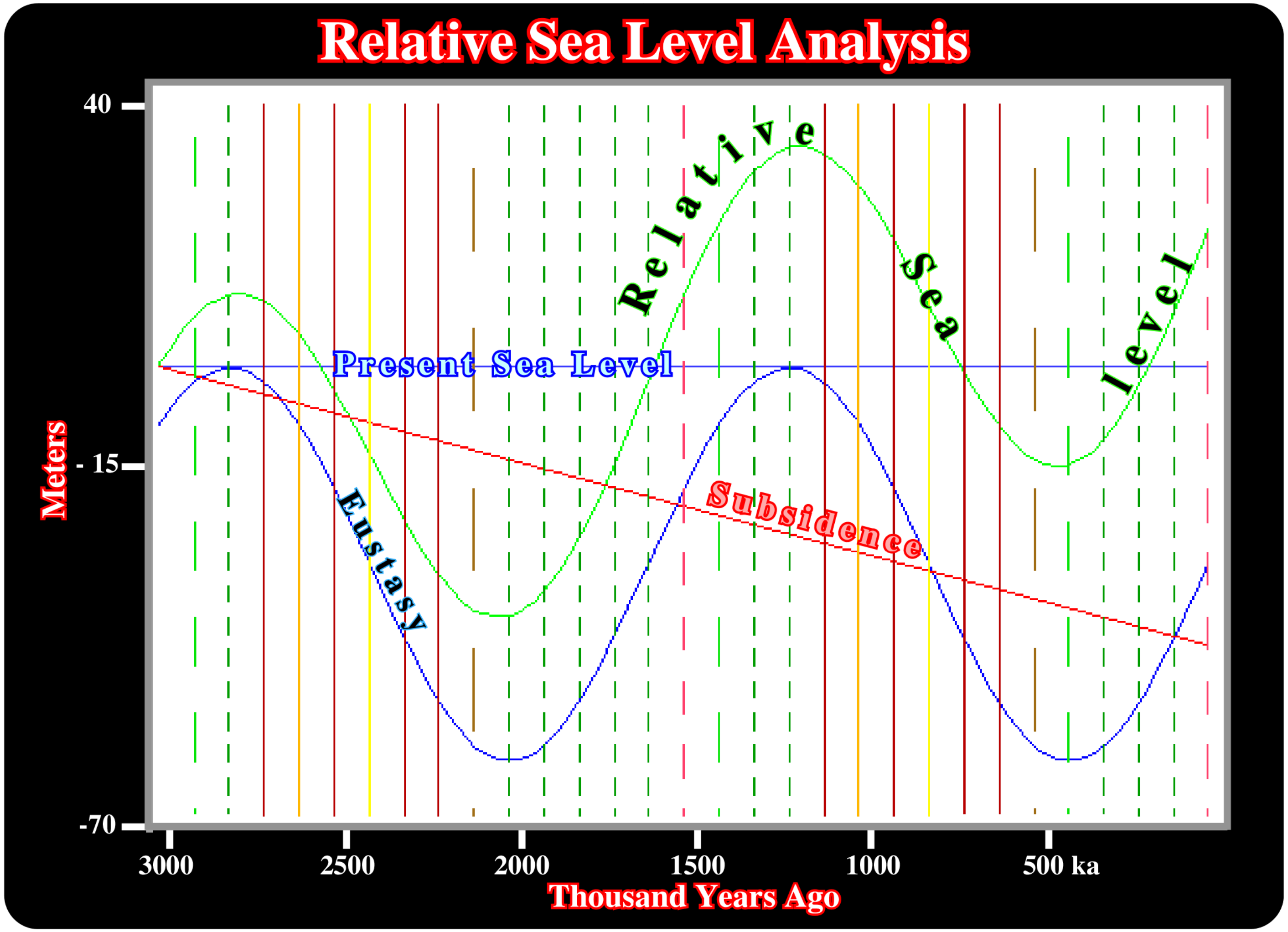


Fig. 60- The model's subsidence variable (in red) combined with the model's eustasy (dark blue) gives the relative sea level (in green), that is to say, the space available for the sediments, which controls the sedimentary evolution since 3.0 Ma to 0 Ma, as illustrated on the next figures. Notice, that in this model, the accommodation increases from 3 Ma till 2.7 Ma. Then, it decreases till 2.0 Ma. Then, it increases till 1.3 Ma and, finally, it decreases till 0.4 Ma to increases till 0.0 Ma.

Model Sedimentary Evolution

Marco Polo Software, 1991

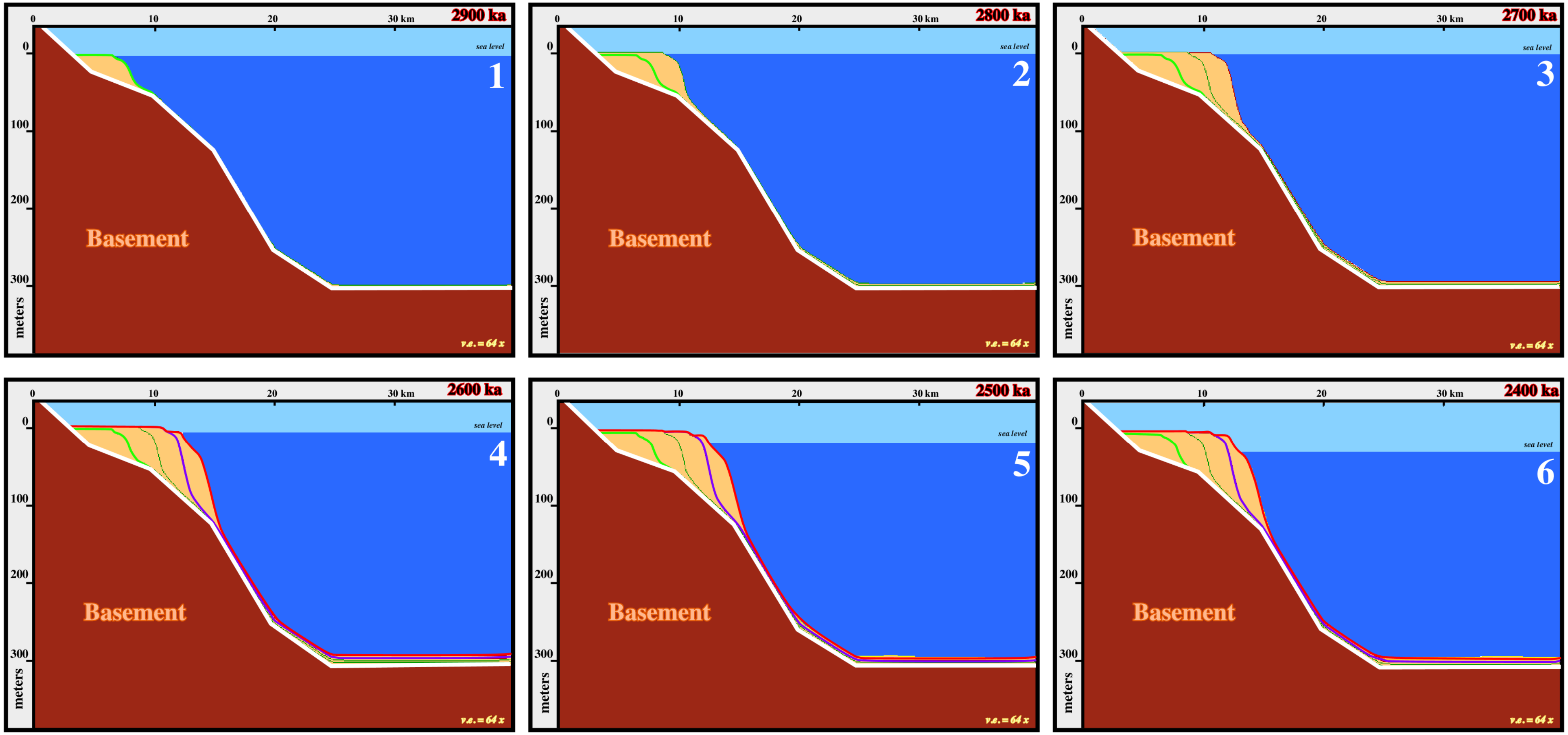


Fig. 61- Taking into account in the model, (i) each step represents the sediments deposited during 100 ka, (ii) the terrigeneous influx (area between two consecutive chronostratigraphic lines) is constant and (iii)there is no erosion, one can say: (a) in step 1, a transgressive interval (transgressive systems tract, TST) was deposited. Then, in steps 2 and 3, a relative sea level rise induced two regressive intervals (parasequences) forming a highstand systems tract (HST). A relative sea level fall took place between steps 3 and 4, creating a type II unconformity and a shelf margin wedge (SMW). Then, the relative sea level fell during steps 4, 5 creating an unconformity. A new sedimentary cycle started in 6, with the deposition of the lower member of the lowstand systems tract (LST), or, the basin floor fan (BBF).

Model Sedimentary Evolution

Marco Polo Software, 1991

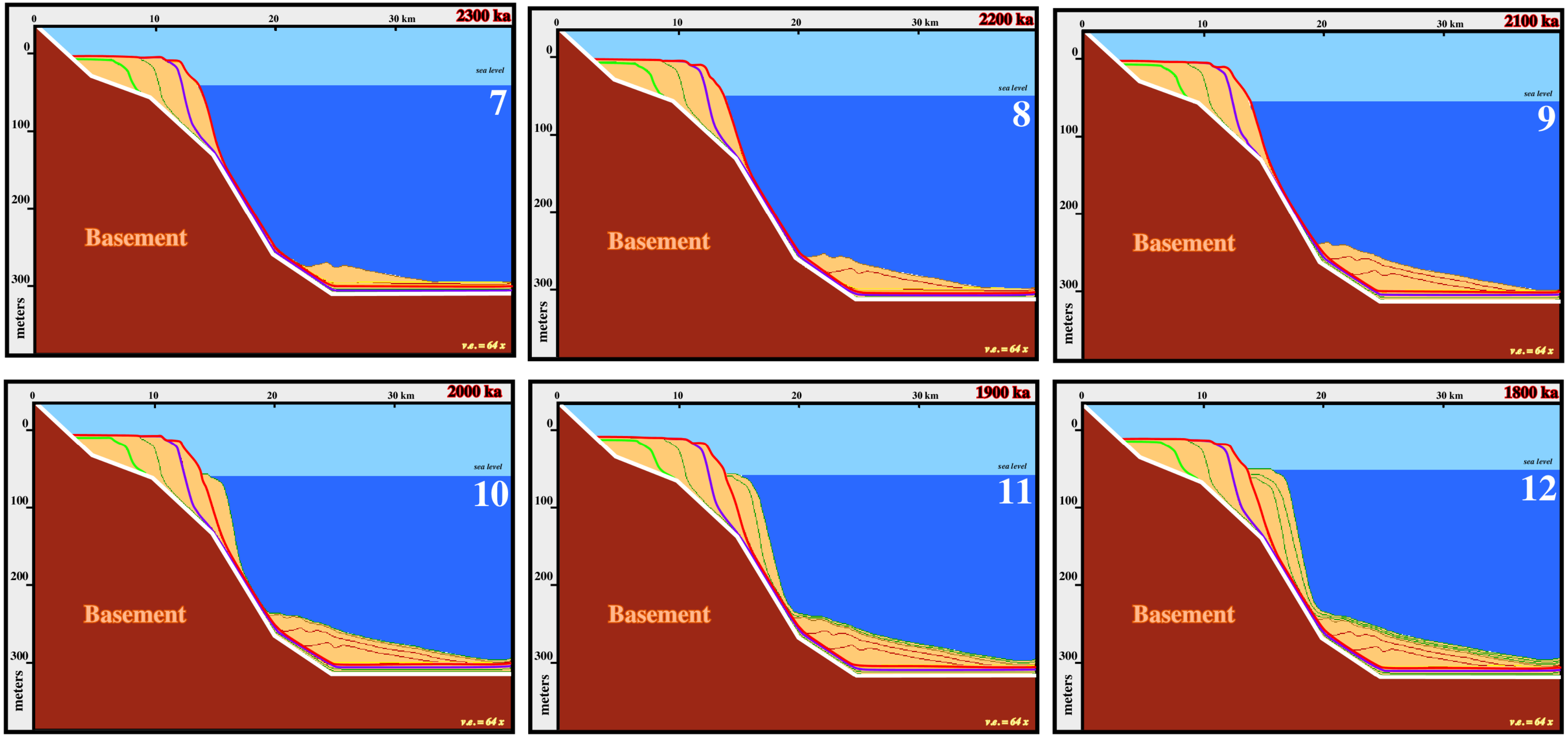


Fig. 62- In the new sedimentary cycle (sequence cycle) and overlying the basin floor fan (BBF), channel levee complexes of a slope fan (SF) were deposited during steps 7, 8 and 9. Then, since the relative sea level commenced to rise, the upper member of the lowstand systems tract (LST), that is to say, the lowstand prograding wedge (LPW) was deposit (step 10). During steps 11 and 12, relative sea level rose and so sediments in two LPW's parasequences were deposited.

Model Sedimentary Evolution

Marco Polo Software, 1991

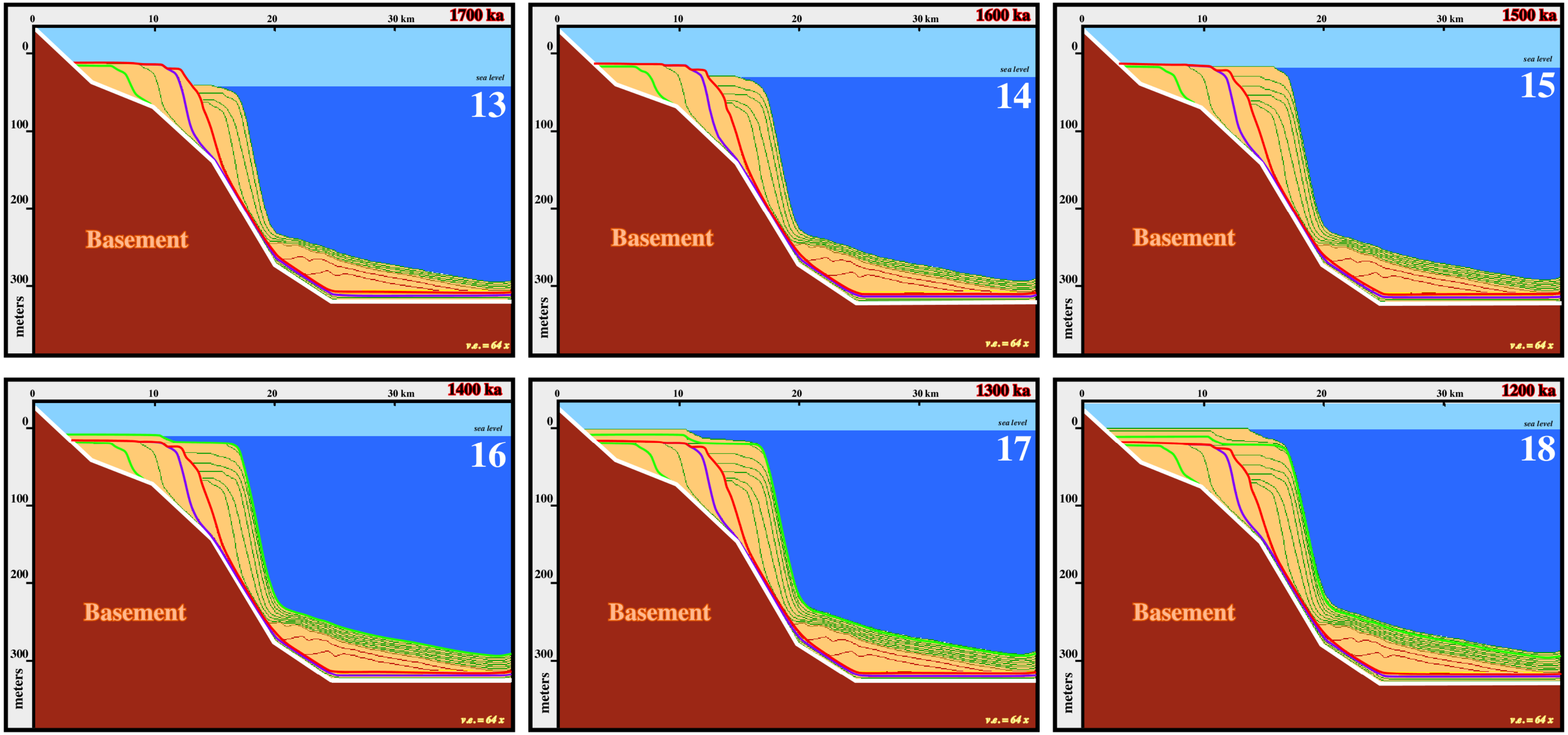


Fig. 63- During steps 13, 14 and 15, relative sea level rose and more parasequences of the lowstand prograding wedge (LPW) were deposited. Then, during step 16, the rate of relative sea level rise reaches its maximum and so the sea floods the exhumed shelf inducing a transgressive systems tract (TST). In steps 17 and 16, sea level rose, but in deceleration, so, a highstand systems tract (HST) started to deposit on the shelf, while in the deep parts of the basin starved conditions predominate.

Model Sedimentary Evolution

Marco Polo Software, 1991

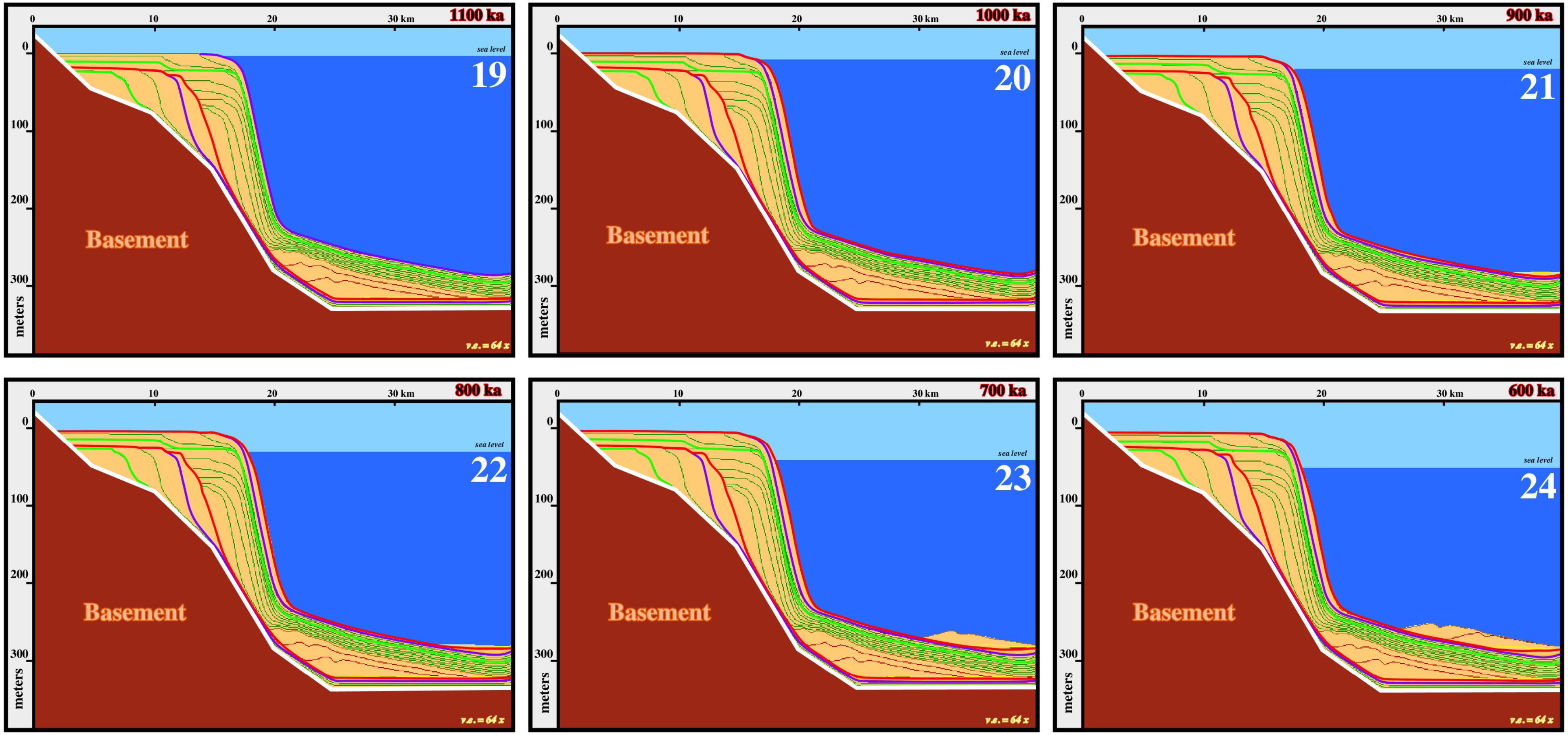


Fig. 64- In step 19, a small relative sea level fall created a type II unconformity and, in step 20, a shelf margin wedge (SMW) was deposited. In step 21, a relative sea level fall put the sea level below the coastal break, which was coincident with the shelf break (basin without shelf), creating a type I unconformity, which limits the sequence cycle. At the same time (minimum hiatus), in the deep parts of the basin a new sequence started (step 22) with the deposition of a basin floor fan (BFF), that is to say, the lower member of the lowstand systems tract (LST). In steps 22 and 23, channel-levee complexes, formed a slope fan (SF), deposited above the basin floor fan (BFF).

Model Sedimentary Evolution

Marco Polo Software, 1991

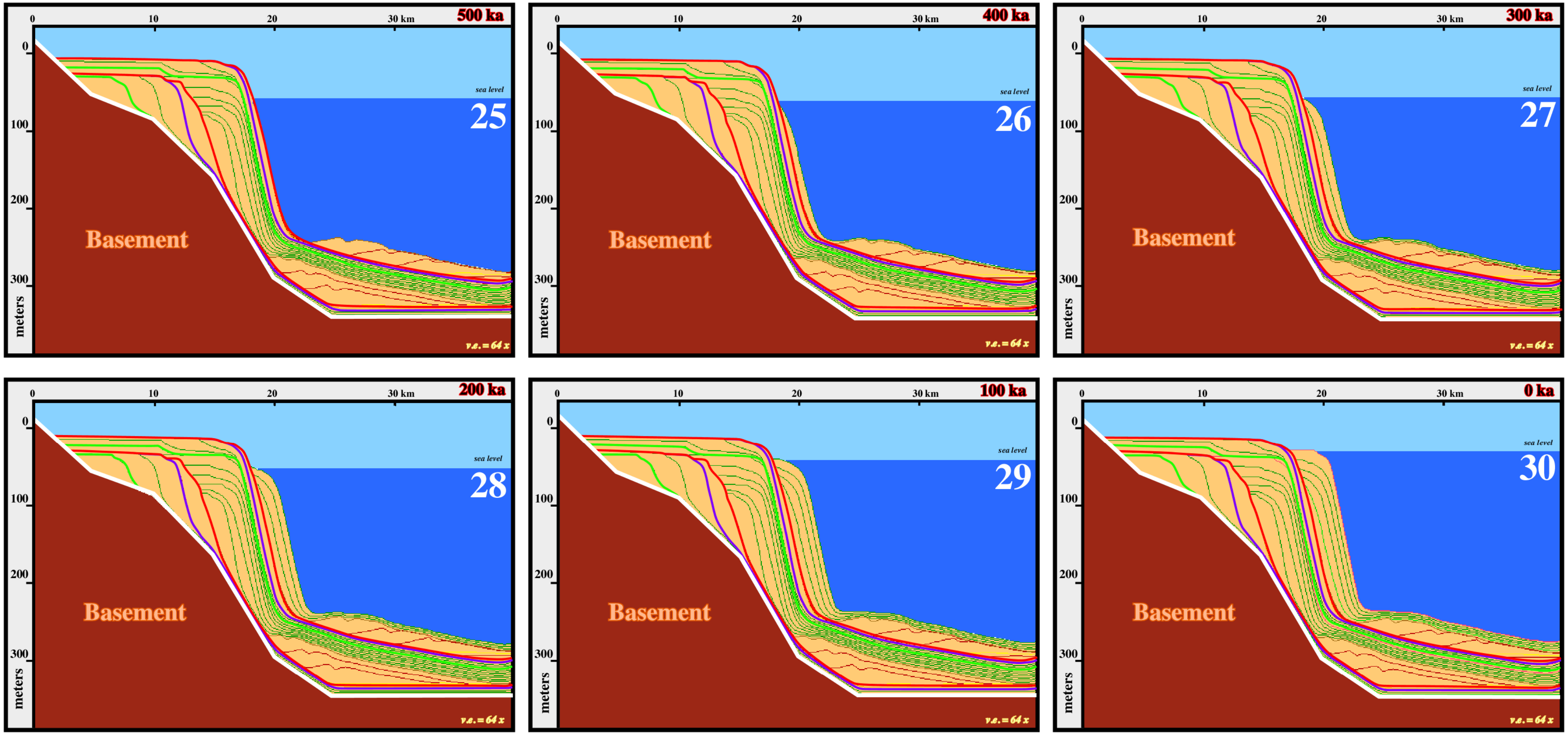
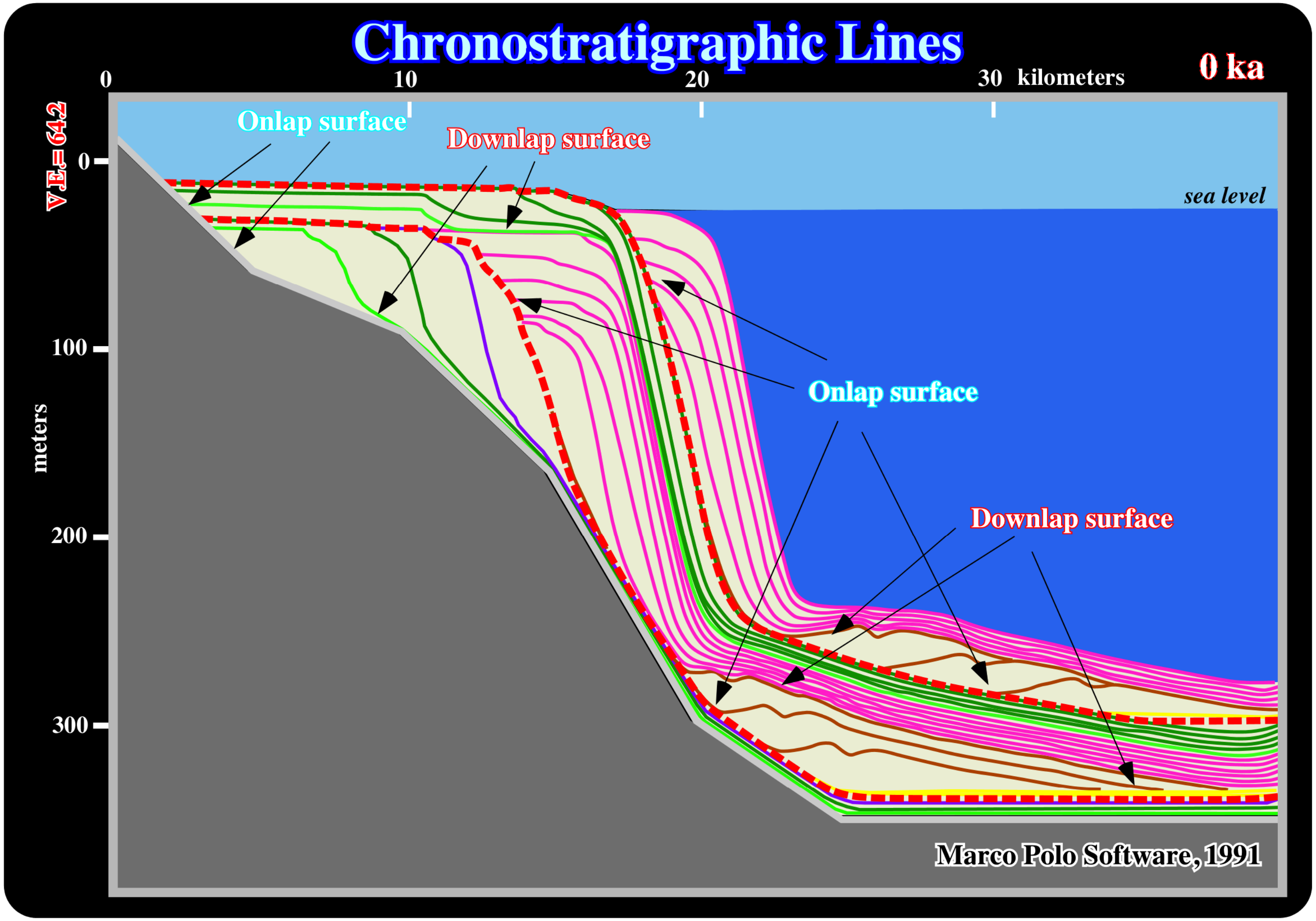


Fig. 65- After the deposition of the uppermost channel-levee complexes of the slope fan (SF), in step 25, relative sea level started to rise, in acceleration, and so the lowermost parasequences of the lowstand prograding wedge (LPW) commenced to deposit (step 26). Then, with the continuation of rise of relative sea level, during steps 27, 28, 29 and 30, the distal part of the LPW parasequences, progressively, fossilized, in downlap, the uppermost channel-levees of the slope fan.

Time Line Terminations



Marco Polo Software, 1991

Fig. 66- The geometric relationships between the different chronostratigraphic lines of the final step of the model (step 30, that is to say, 0 ka) are depicted above. Onlap and toplap surfaces define the type I unconformities (black), while downlap surfaces are easily recognized above slope fans (brown) and the lowstand prograding wedge (purple), as well as above the lower sequence boundary, in the proximal parts of the basin.

Model Chronostratigraphy

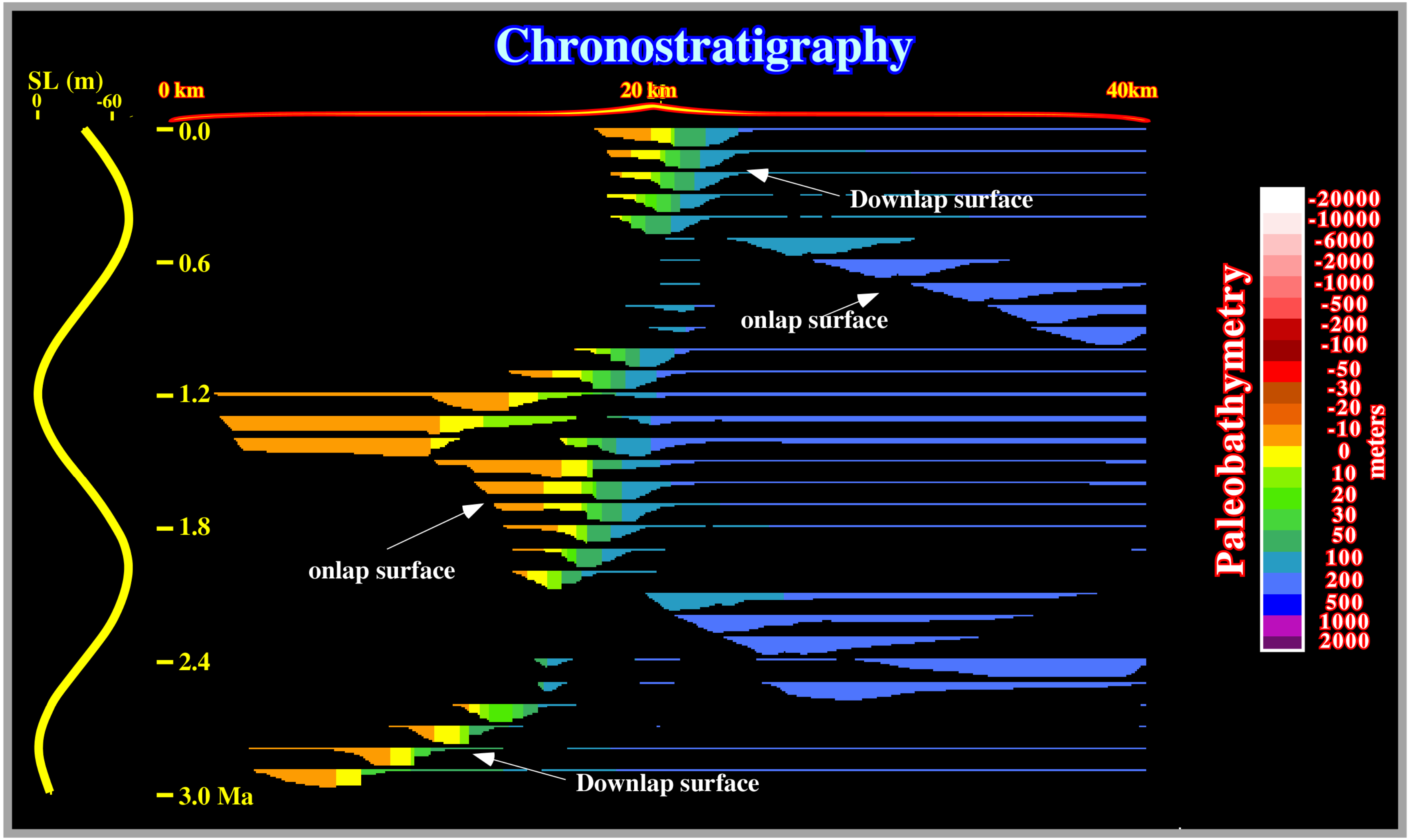


Fig. 67- On this chronostratigraphic chart the reflection terminations, the hiatus (mainly depositional), as well as, the paleobathymetry of the mathematical model are depicted. An example the major onlap and downlap surfaces are indicated. Admittedly, the paleobatymetry increases seaward, so the onlap surfaces of deep water sediments suggest basin or slope fans.

Model Sequential Stratigraphy

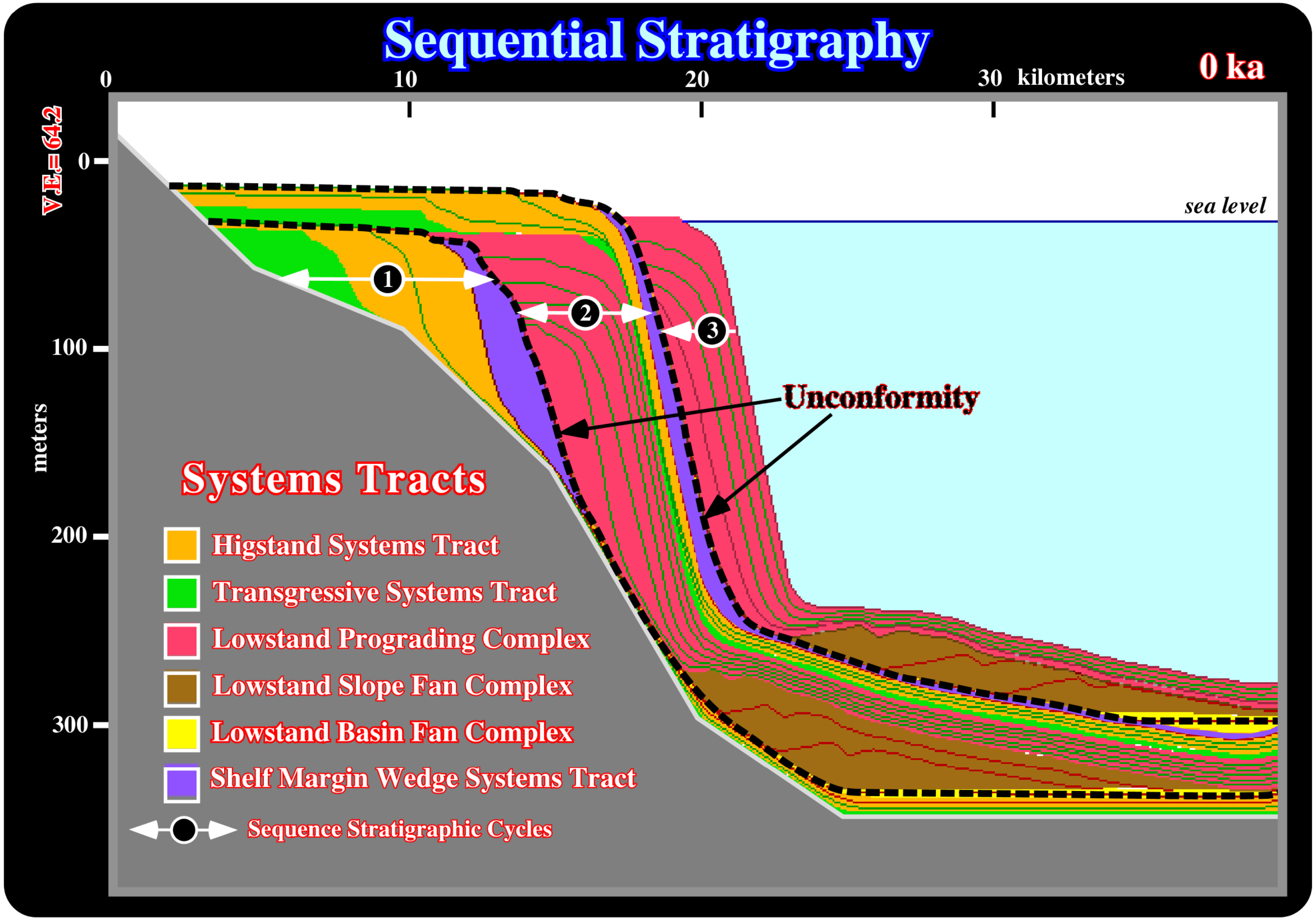


Fig. 68- The sequential stratigraphy of the mathematical model (3.0 - 0.0 Ma) put in evidence three sequence stratigraphic cycles. The oldest (steps 1-4) is incomplete. From bottom to top, a TST, a HST and a SMW compose it. The second (steps 5-20) is complete. It is composed of a LST (BBF+SF+LPW), a TST and a HST. The third (21-30), which is not yet finished, is only represented by a LST.

Model Depositional Systems

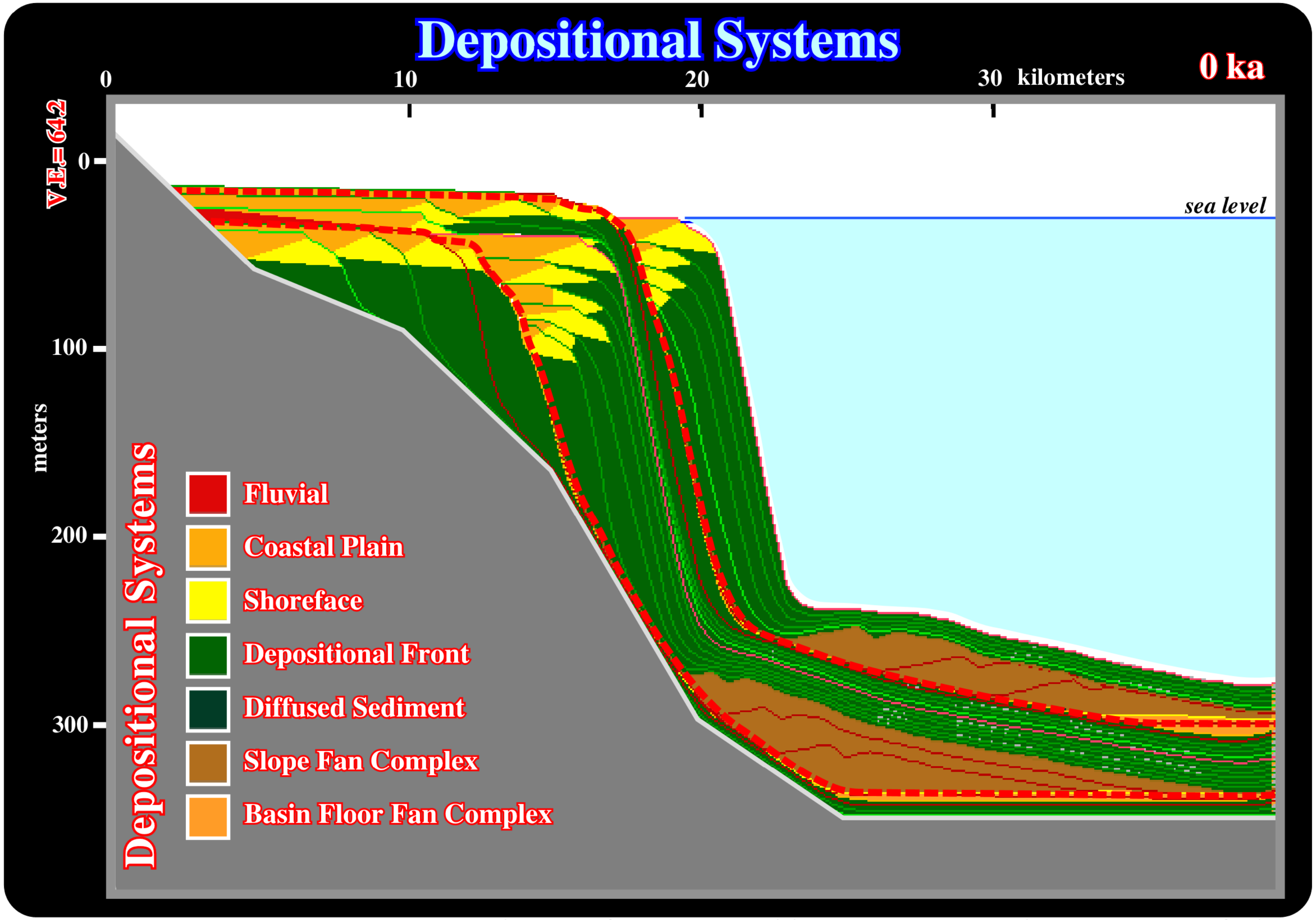


Fig. 69- As each systems tract correspond to a lateral linkage of coeval depositional systems, that is to say, coeval facies, environmental and lithological predictions can be advanced. In this sand-shale mathematical model, the following depositional environments can be predicted: (i) fluvial, (ii) coastal plain, (iii) shoreface, (iv) depositional front (slope) and (v) deep water (turbiditic deposits).

Model Facies

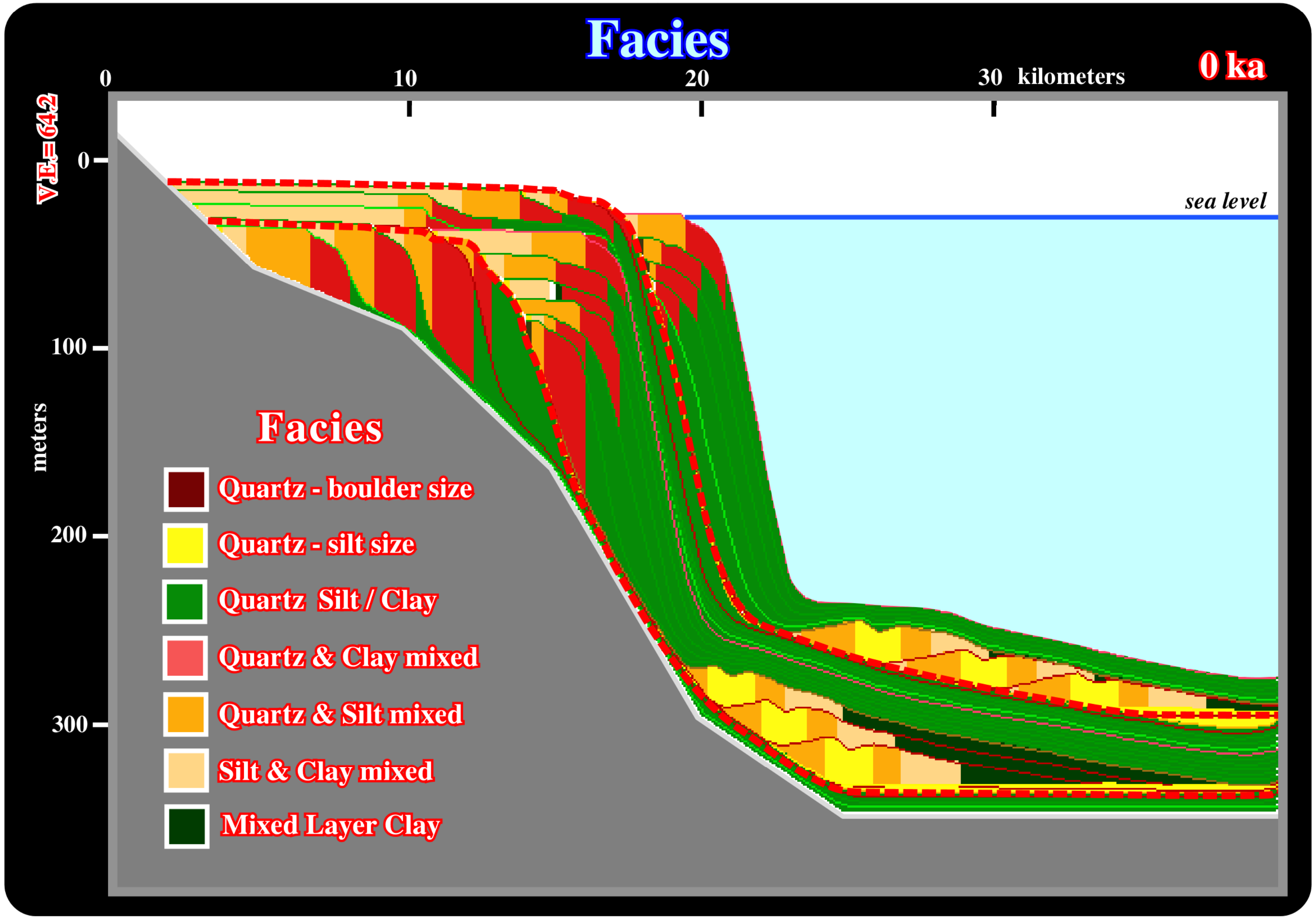


Fig. 70- Systems tractsare composed of lateral assemblages of depositional systems, which are characterized by typical lithologies and depositional environments. Admittedly, on seismic data, and particularly in absence amplitude and sedimentary anomalies, the recognition of sequence cycles, and associated systems tracts, is the best way to hypothesize the most likely location of potential reservoir-rocks.

Model Paleobathymetry

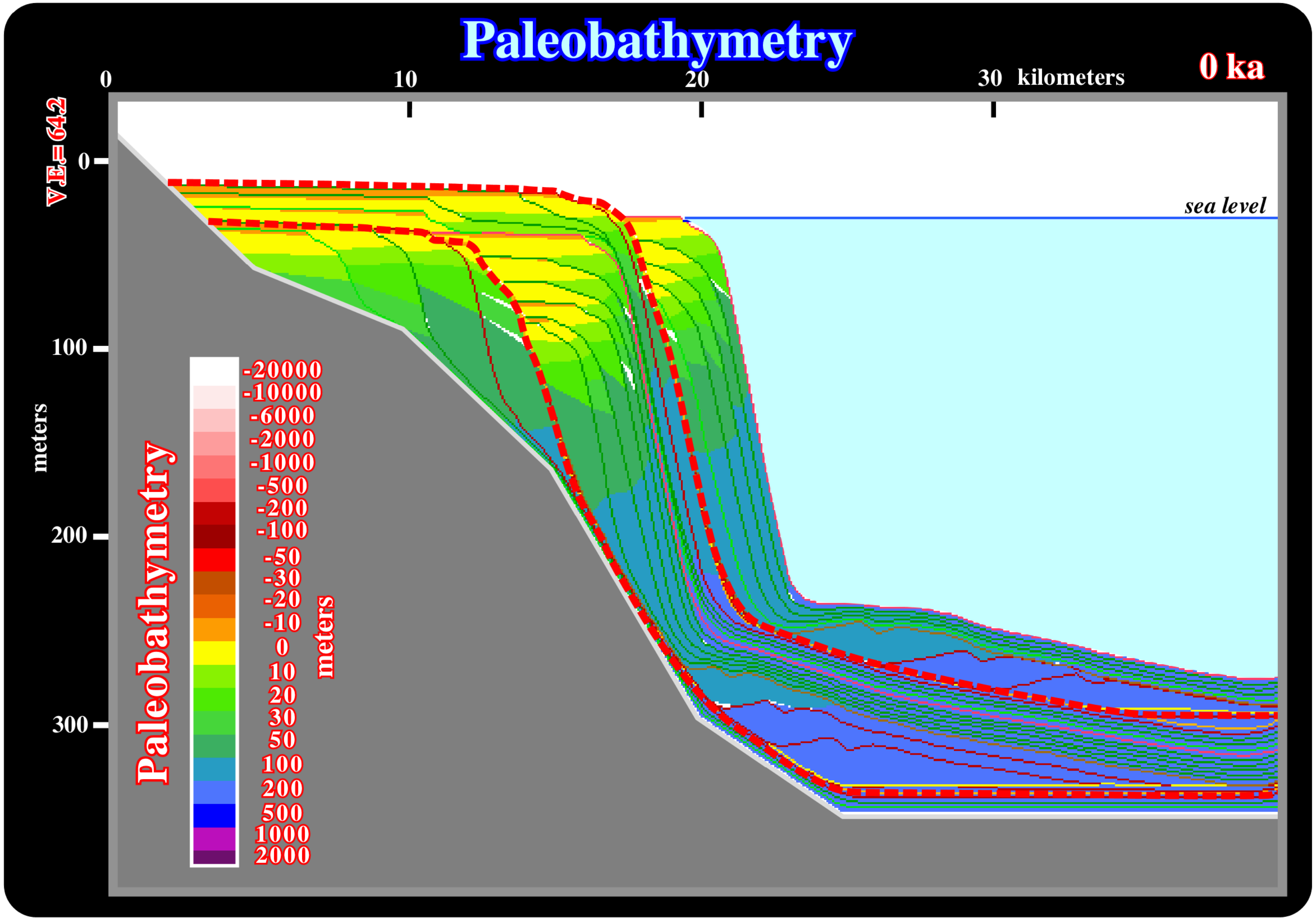
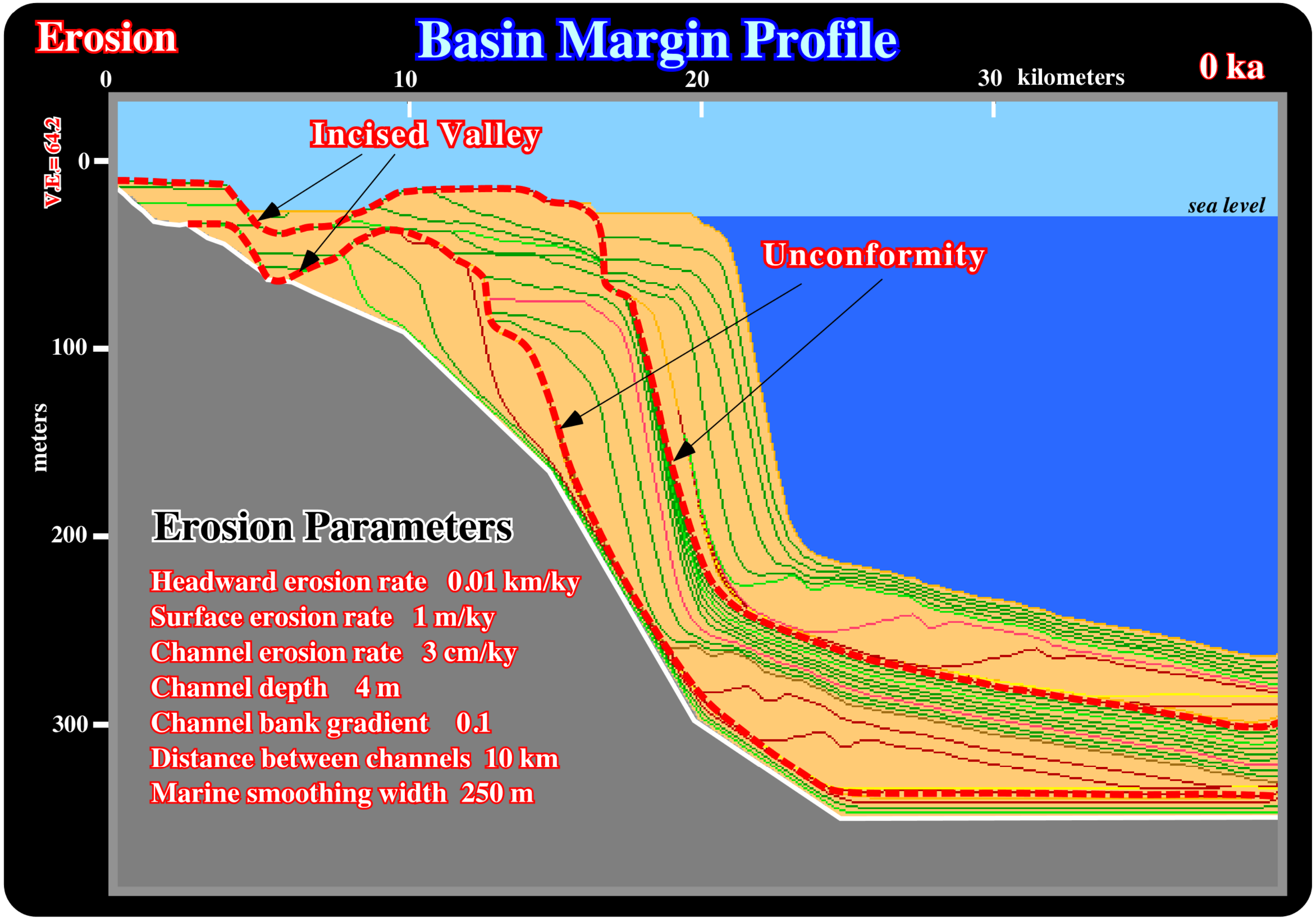


Fig. 71- The paleobathymetry, that is to say, the depositional water depth can be easily calculated (see exercises). Indeed, assuming that landward of the depositional coastal break, the paleo-water depth is zero, the coastal plain can be taken as a datum plane. Therefore, at a given point, the depositional water depth corresponds to the depth of the point in relation to the coastal plain.

Model Variables Impact

Model Variables Impact



Erosion Parameters

Headward erosion rate 0.01 km/ky
Surface erosion rate 1 m/ky
Channel erosion rate 3 cm/ky
Channel depth 4 m
Channel bank gradient 0.1
Distance between channels 10 km
Marine smoothing width 250 m

Fig. 72- In the previous mathematical model, erosion was ignored. Contrariwise, above, erosion was taken into account. Obviously, the picking of unconformities, particularly landward of the shelf break, is easier due to the presence of incised valleys (iv), which are mainly filled with LPW sediments. Seaward of the shelf break, where erosion is meaningless, there are no significant changes.

Model Variables Impact

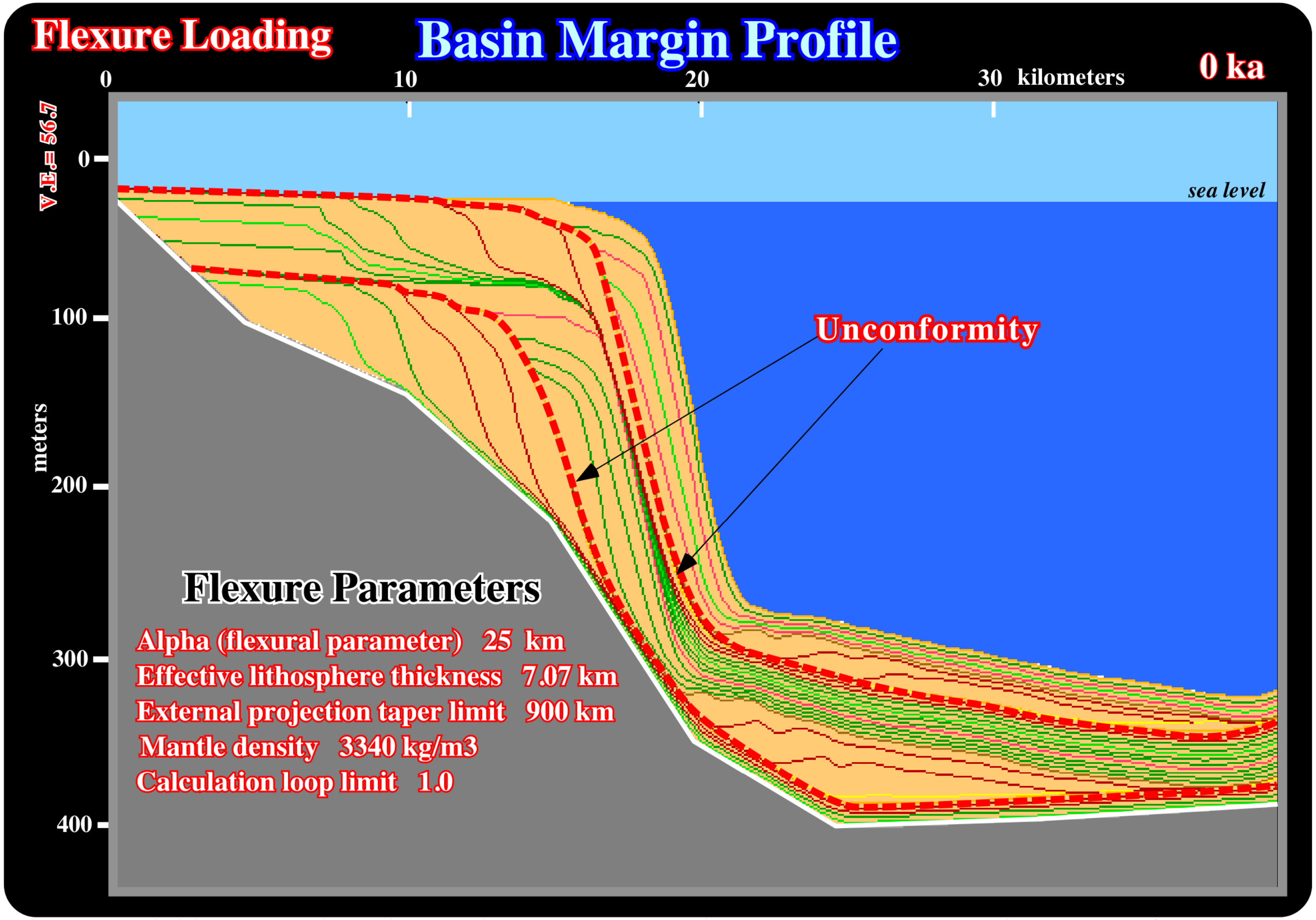


Fig. 73- In relation to the initial model, in which erosion was not taken into account, we have to introduce a flexure loading (see flexure parameters), that is to say, the flexure of the substratum induced by the weight of the sediments, which changes the total subsidence. Relative to the initial model, the LST's are less developed. Contrariwise, TST's and HST's , as illustrated in the next figures, are more developed.

Model Variables Impact

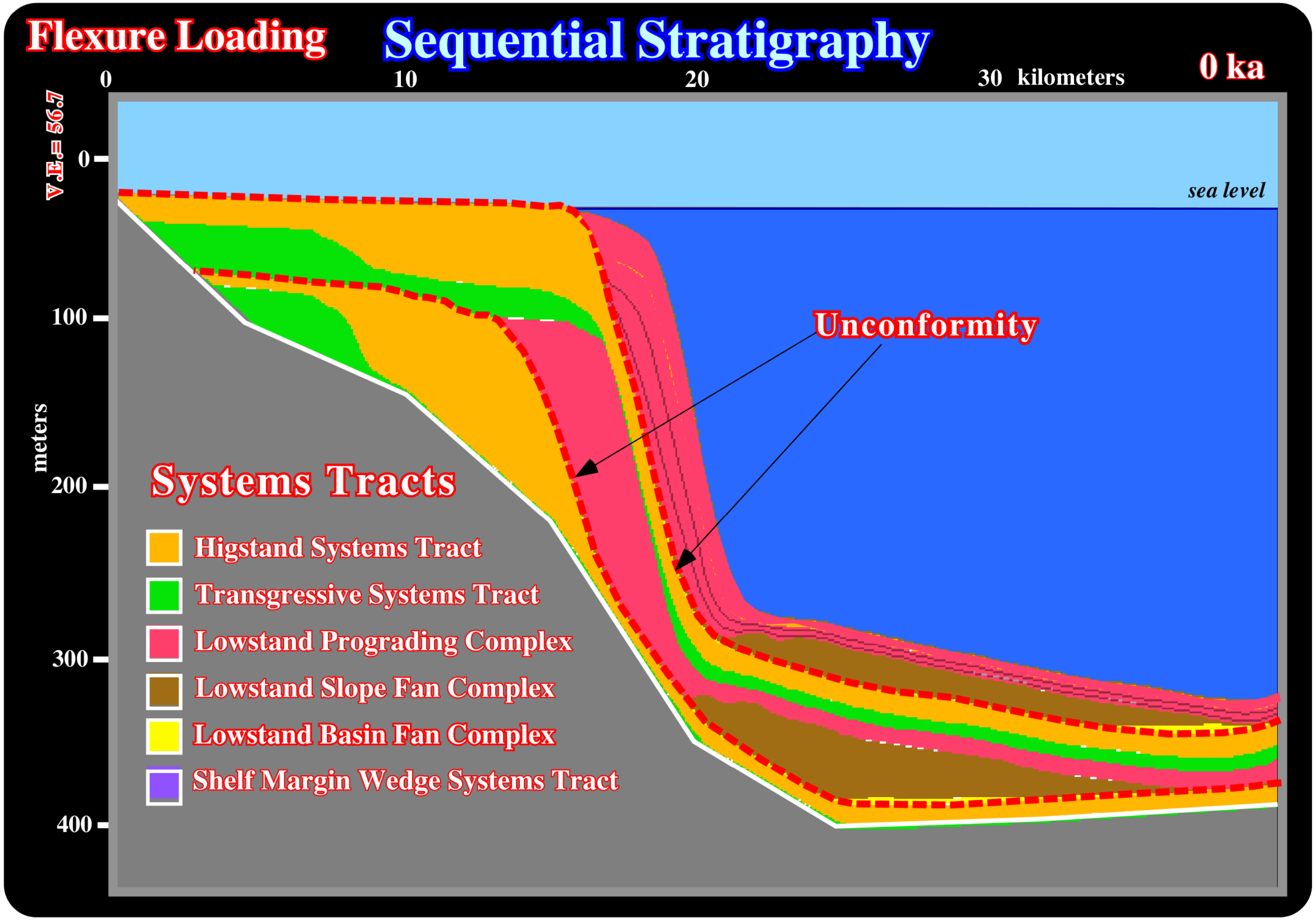


Fig. 74- In relation to the initial model, the introduction of flexure loading slightly reduces the development of the lowstand systems tracts. On the contrary, the transgressive (TST) and highstand systems tracts (HST) are better developed. Additionally, the backstepping geometry of the transgressive systems tracts, particularly in the second sequence cycle, are sharper.

Model Variables Impact

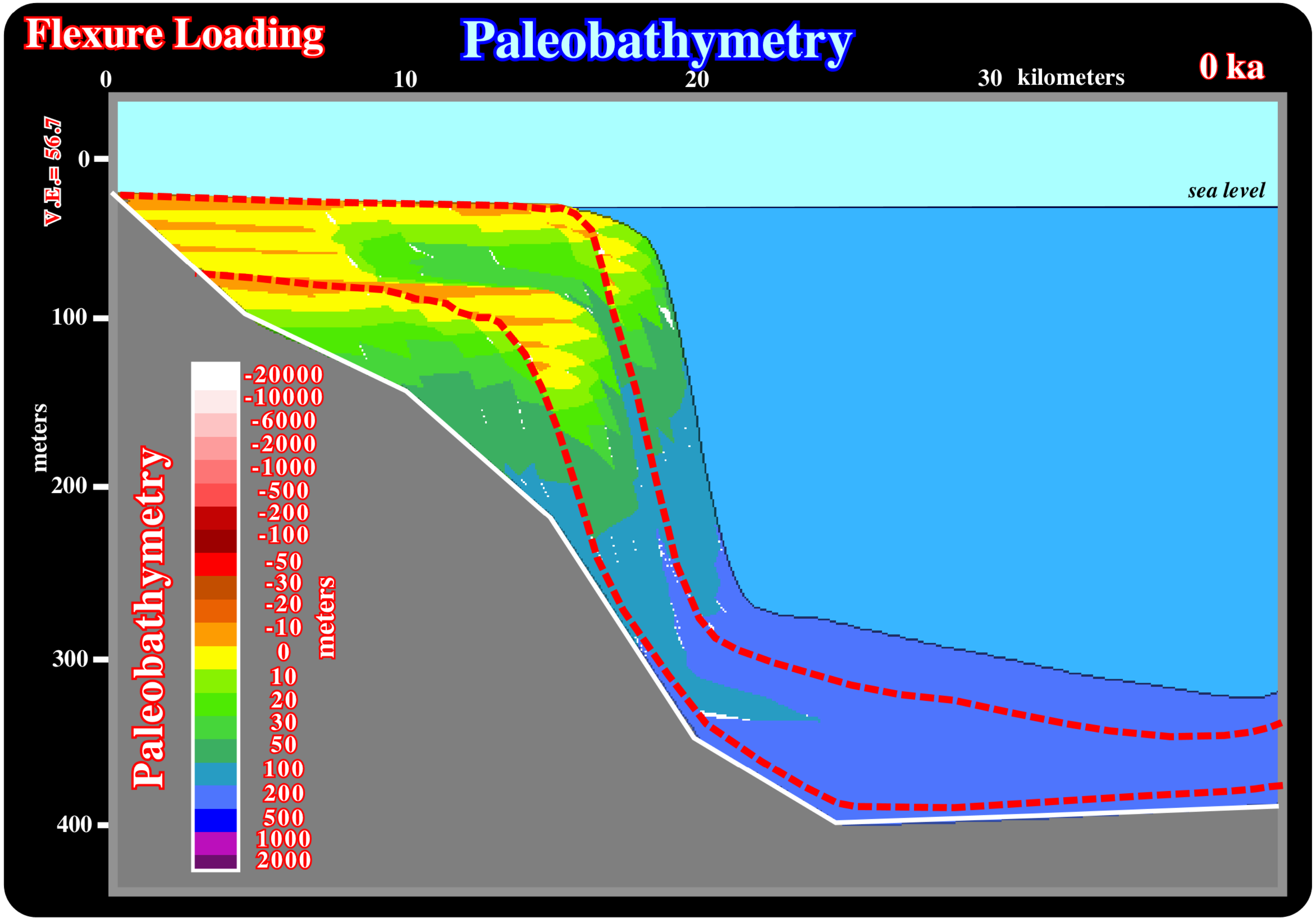


Fig. 75- The introduction of flexure loading in the initial model changes the paleobathymetry significantly. Indeed, in relation to the paleobathymetry illustrated in fig. 71 (no flexure loading), shallow water (coastal plain) deposits seem thicker. Also, shallow marine intervals look more developed. In the deep environments, there are no major changes.

Model Variables Impact

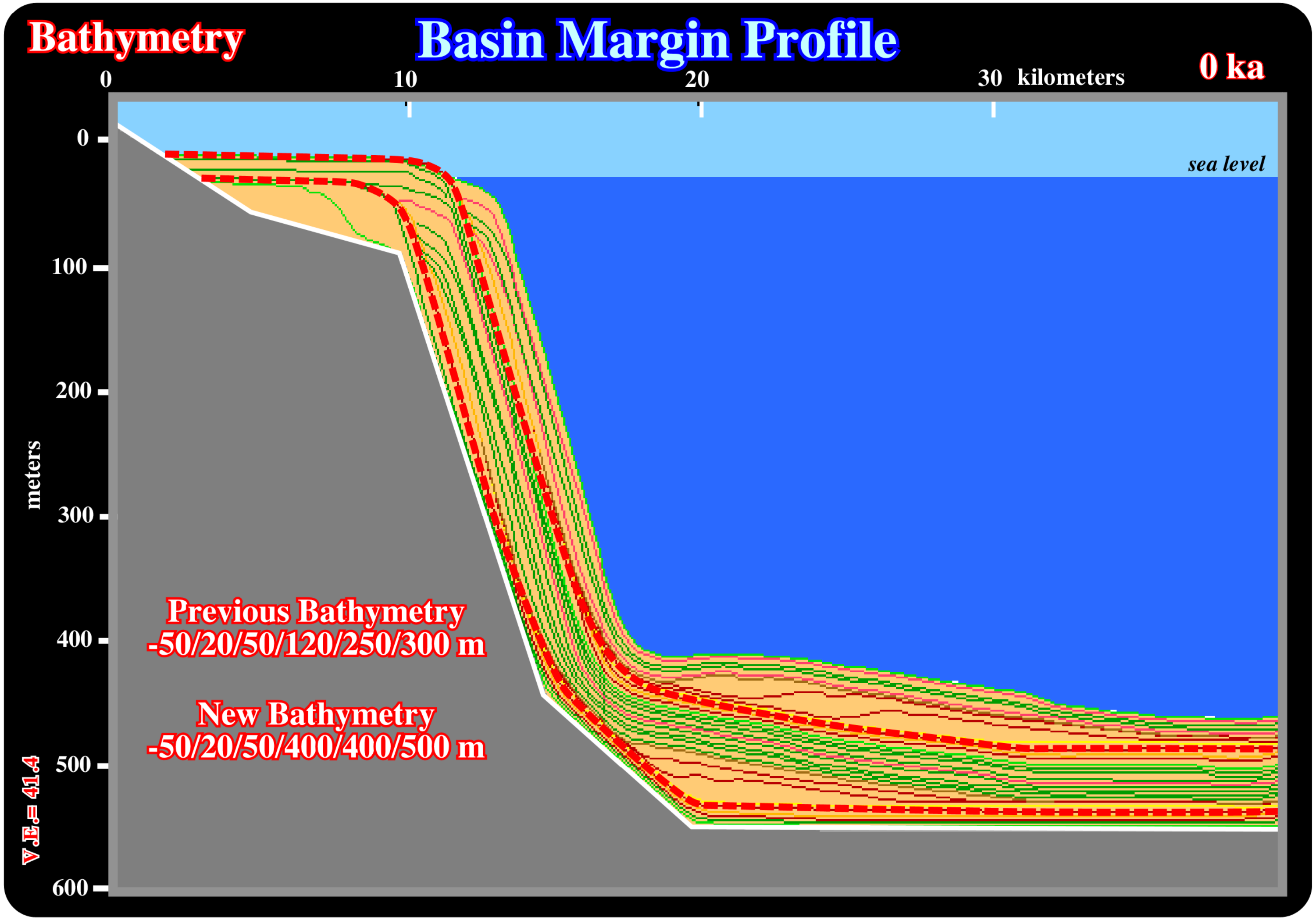


Fig. 76- As illustrated above, on this model, in relation to the initial model, we have changed the original bathymetry. The consequences of such a change are quite evident. Indeed, in spite of the fact that we were obliged to change the vertical scale, it important to notice that the outbuilding (around 13 km) is much smaller than in the original model (around 20 km, see fig. 71).

Model Variables Impact

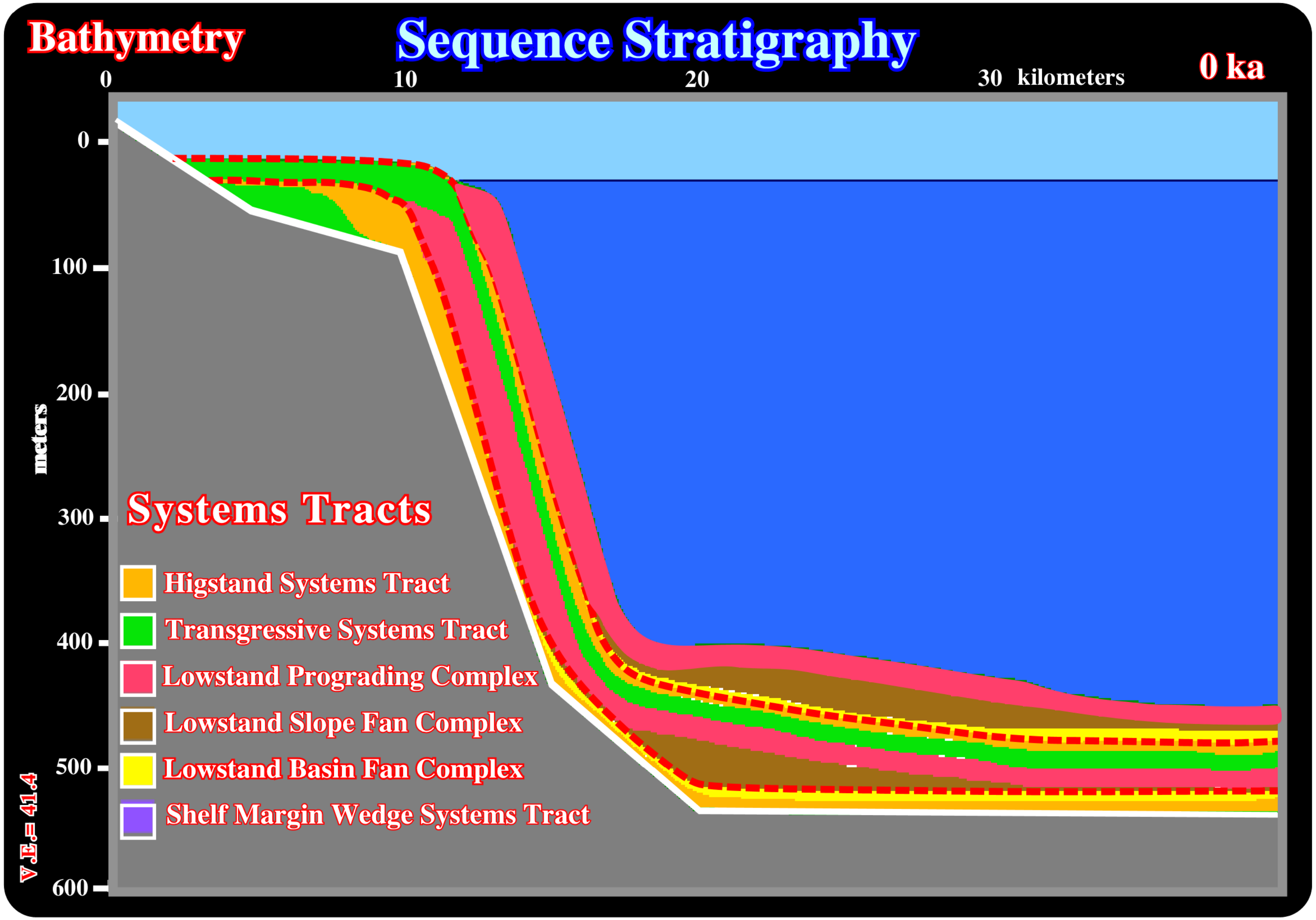


Fig. 77- In relation to the sequential stratigraphy of the initial model, changing the original bathymetry significantly modifies the position of the sequence boundaries as well as the development of the different systems tracts. It is interesting to notice highstand systems tracts are quite reduced.

Model Variables Impact

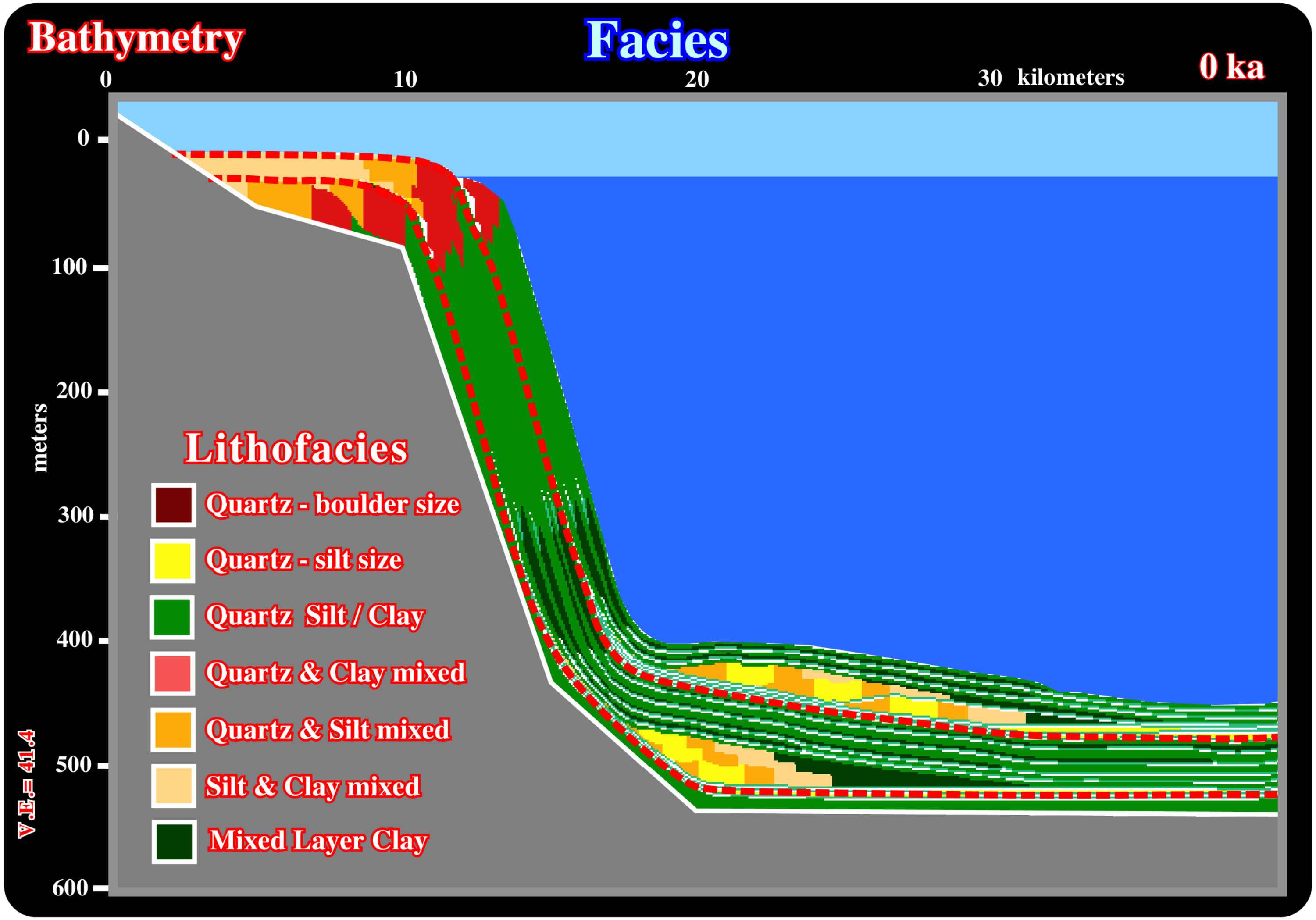


Fig. 78- The facies distribution follows the changes of the sequential stratigraphy depicted on fig. 77. The shallow water sediments are more restricted than in the original model. Contrariwise, the sandprone deep water sediments, and particular the basin floor fans, are more developed which balance the shallow water deficit. Note that in both models, the terrigeneous influx is the same.

Model Variables Impact

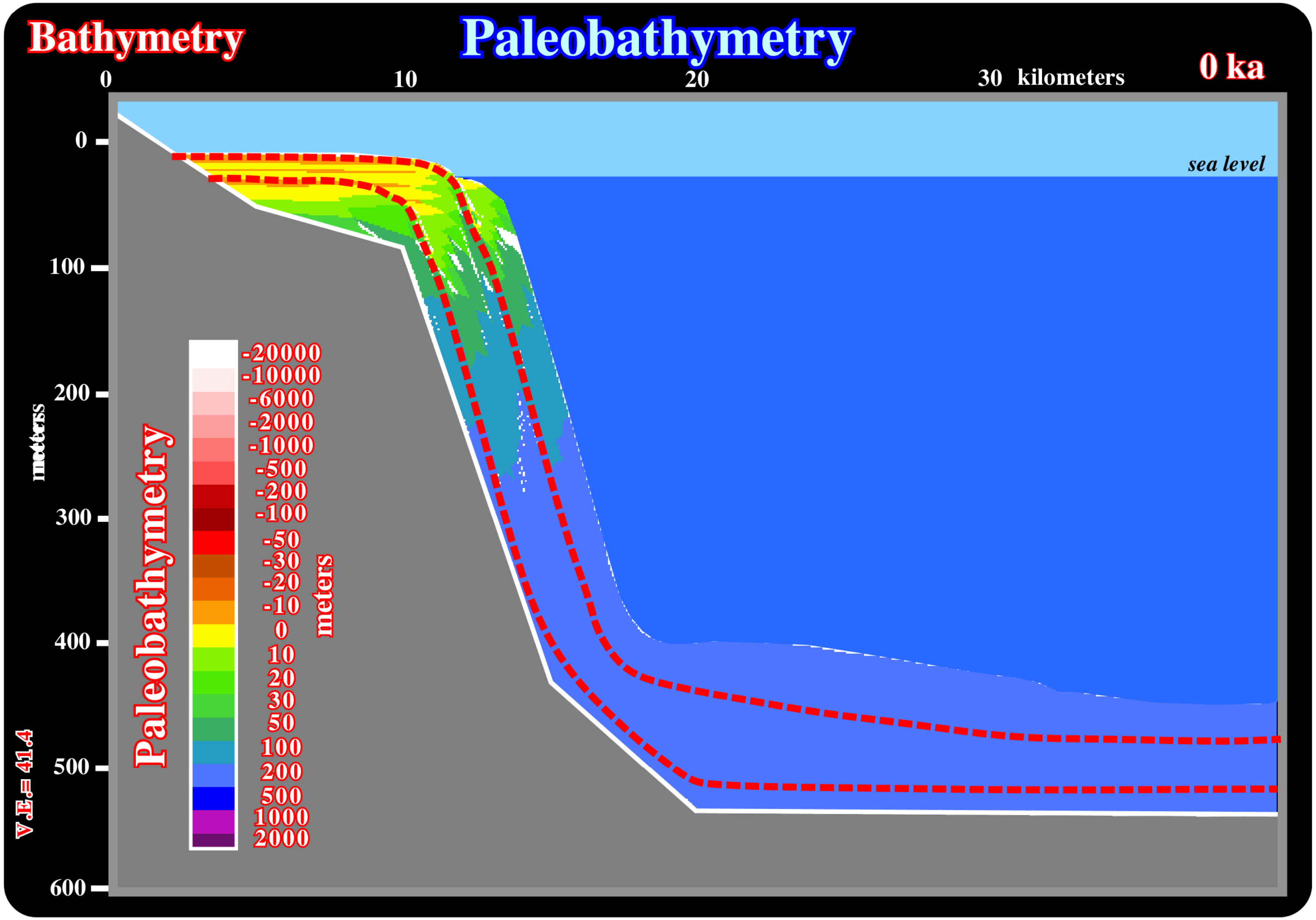


Fig. 79- Admittedly, changing the original bathymetry changed the depositional water depth. Indeed, taking into account the vertical scale, it is evident that shallow water sediments are much less developed than in the original model.

Model Variables Impact

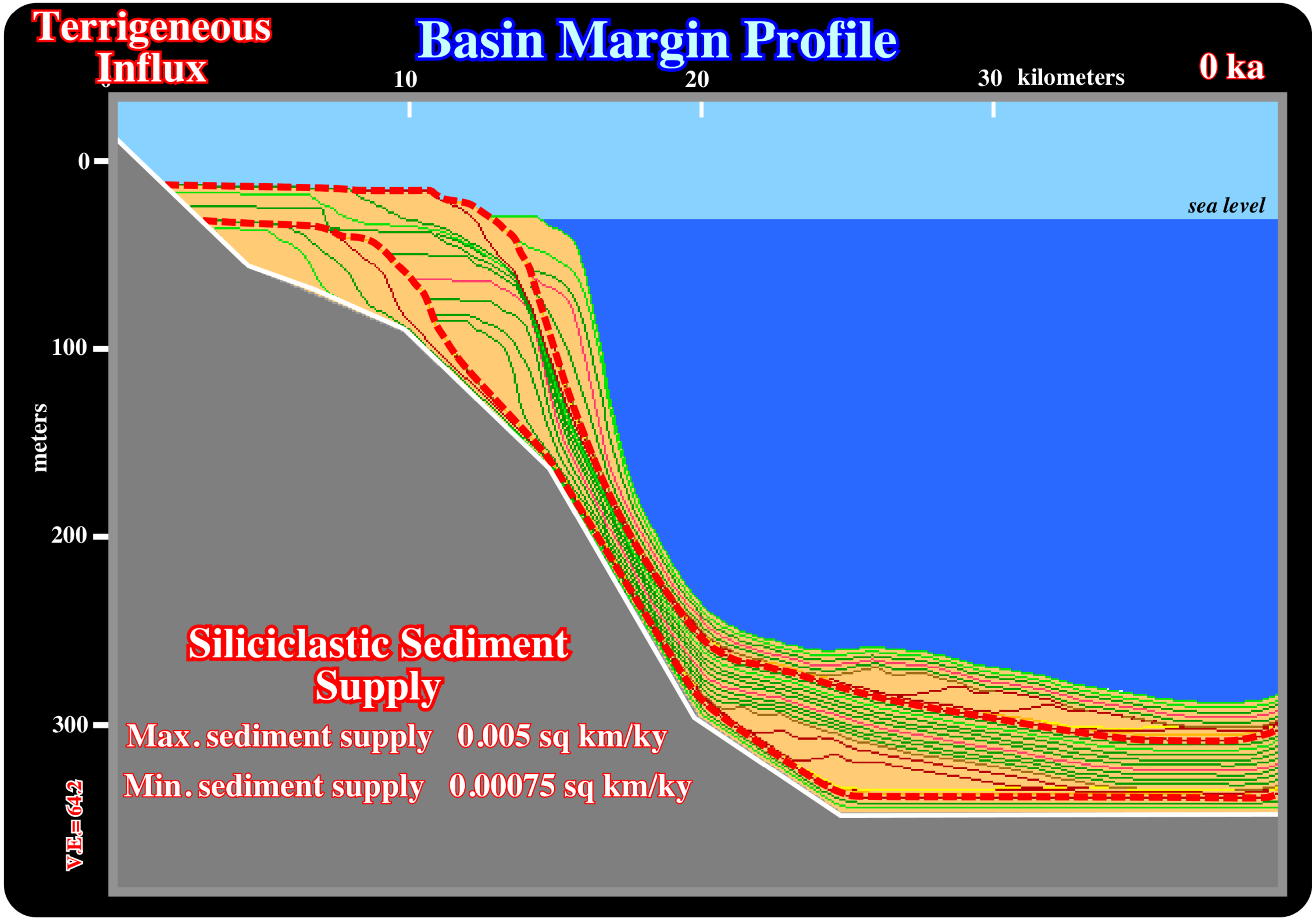


Fig. 80- On this model, the siliciclastic sediment supply was reduced 50% in relation to the initial one. Comparing both models (see fig. 71), the changes are quite evident. Fundamentally, the outbuilding of the shallow water sediments is here more reduced, as well as the upbuilding of the deep-water sediments. The geometry of unconformities and systems tracts is roughly the same.

Model Variables Impact

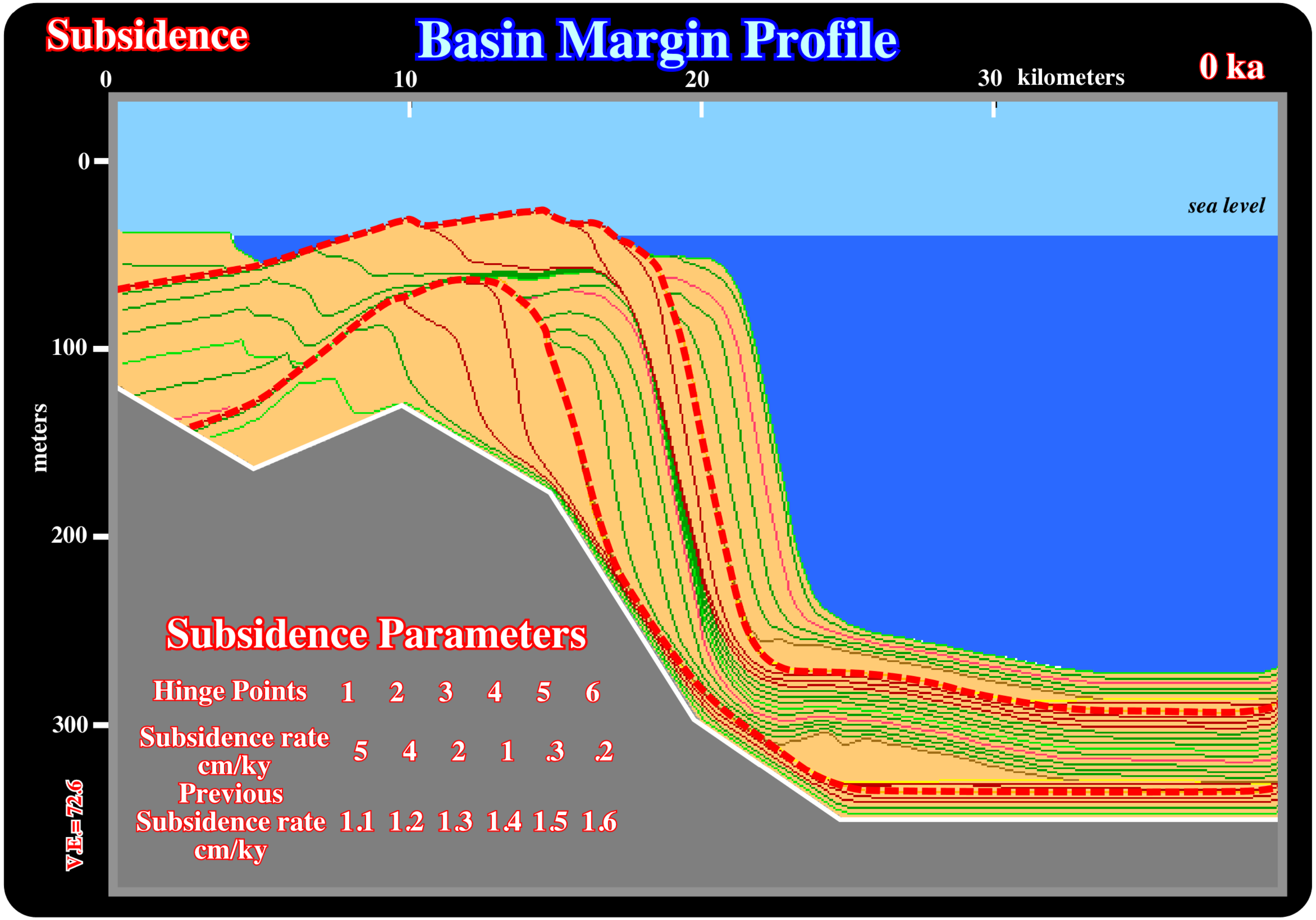


Fig. 81- On this model we have changed the subsidence. Indeed, as indicated above, we have introduced a seaward decreasing subsidence (5 / 4 / 2 / 1 / 0.3 / 0.2). The consequences of such changes are more than obvious. The geometry of the sequence boundaries is quite different as well as the sequential stratigraphy (see next figures). Notice that several type II unconformities can be recognized.

Model Variables Impact

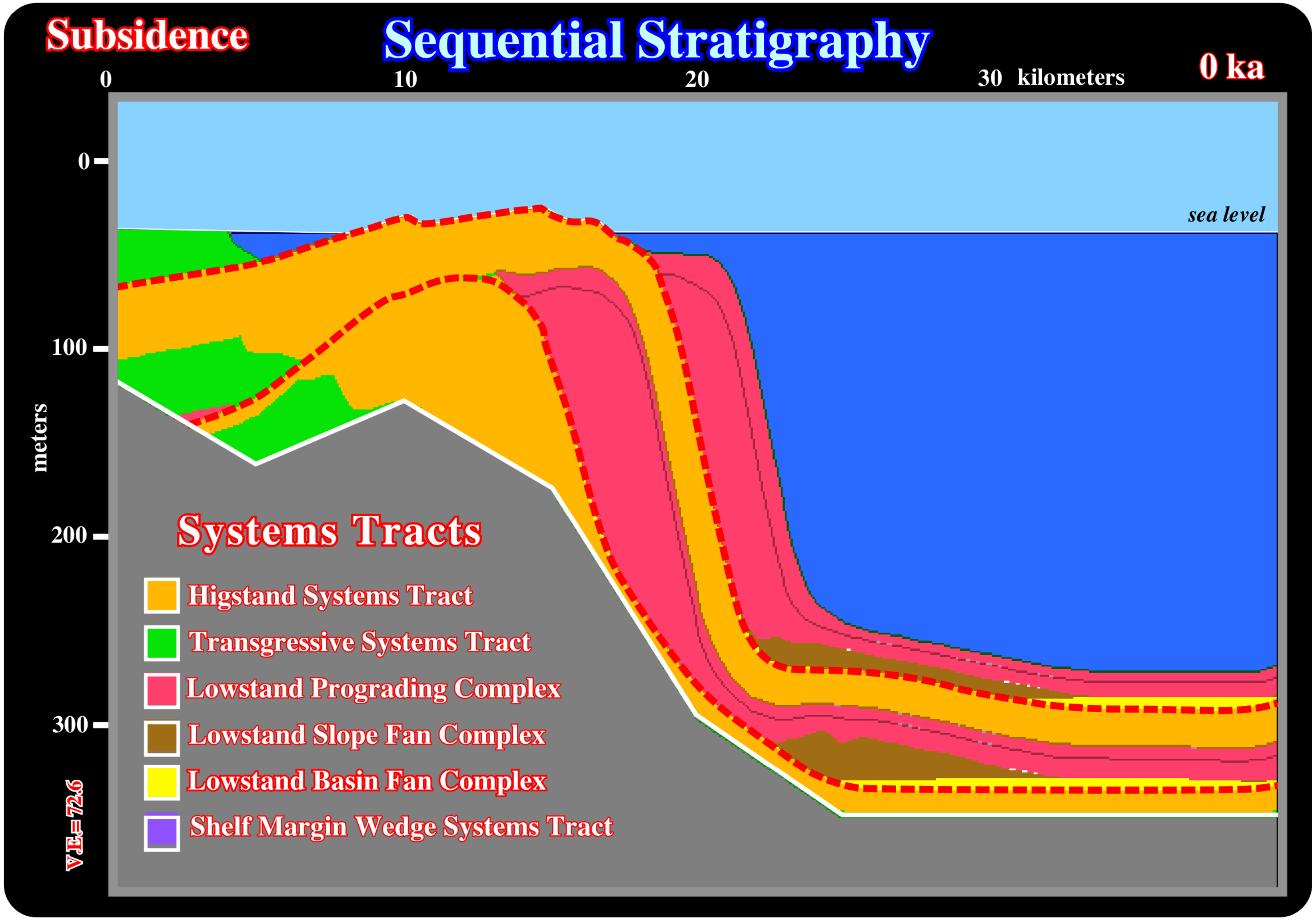


Fig. 82- From the previous figure, where the geometry of the chronostratigraphic lines is depicted, the above sequential stratigraphy can be deducted. Notice the development of the transgressive and highstand systems tracts, particularly in the proximal parts of the basin where the subsidence is higher.

Model Variables Impact

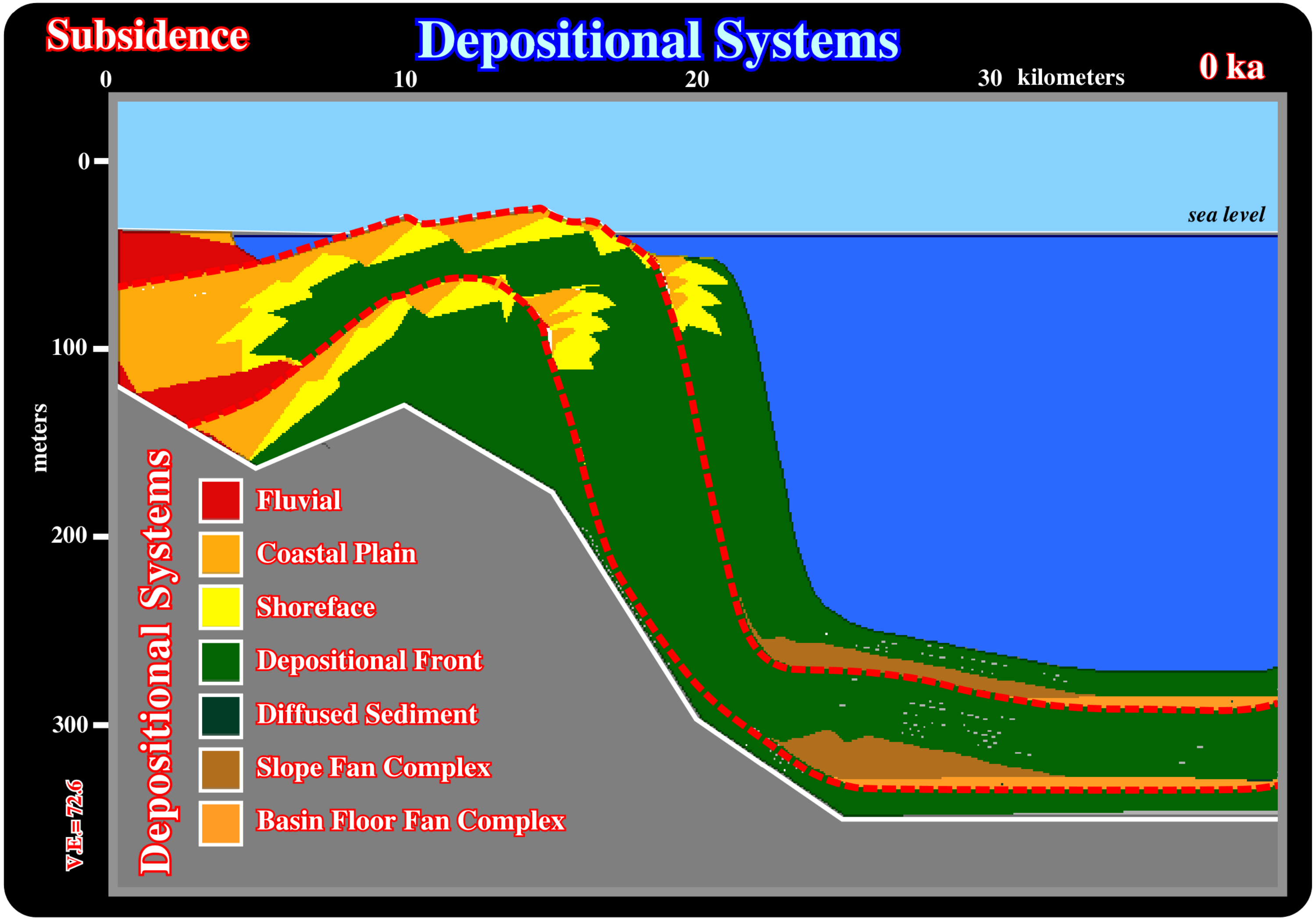


Fig. 83- The depositional environments illustrated on this figure can be easily deducted from the sequential stratigraphy shown in fig. 82, taking into account that the paleo-water depth, which can be calculated relative to the coastal plain, where the paleo-water depth is assumed to be zero (see fig. 85).

Model Variables Impact

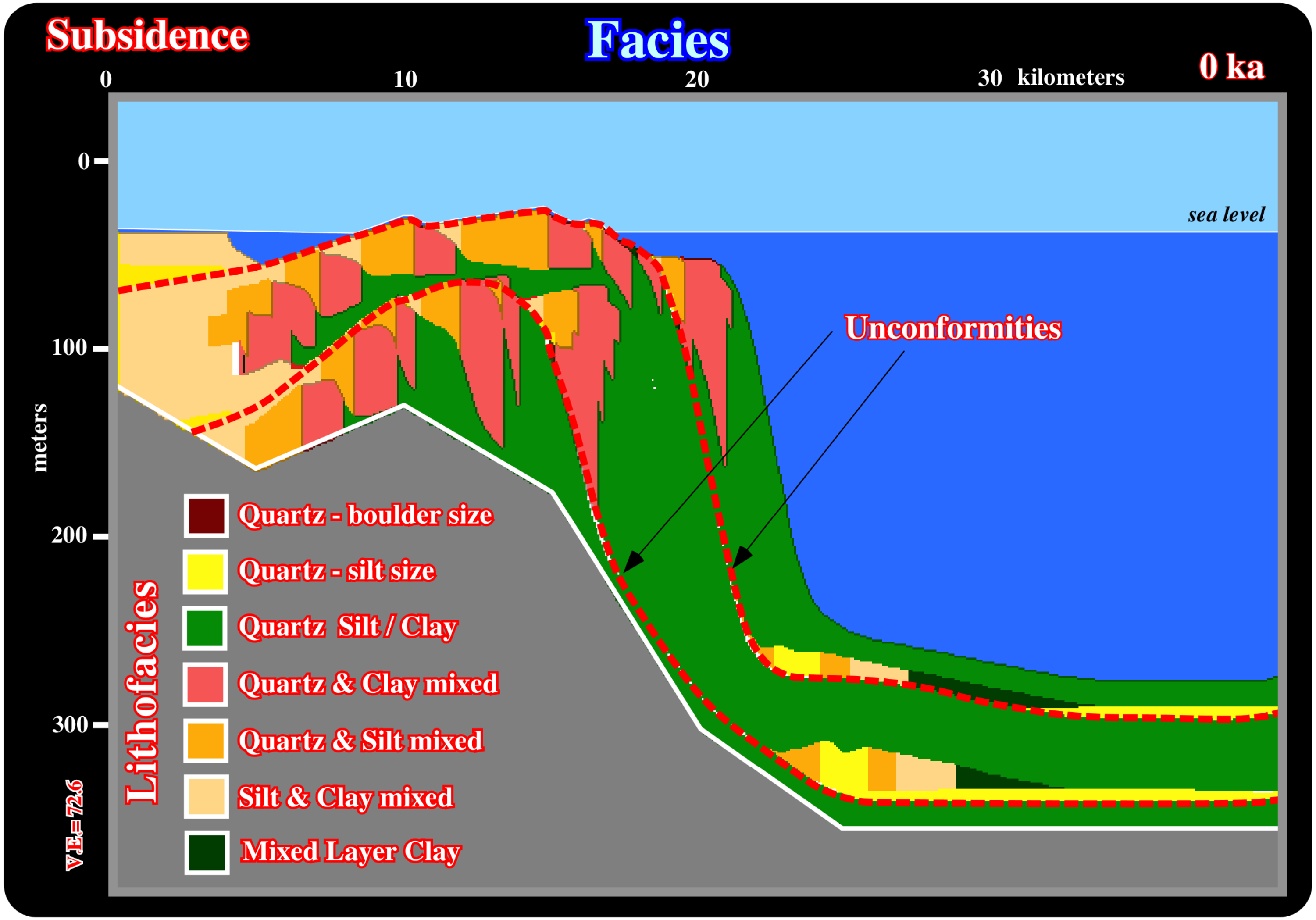


Fig. 84- The sequential stratigraphy and depositional systems, illustrated in figs. 82 and 83, suggest the lithology shown above. The potential sandstone reservoir-rocks are strongly associated with the unconformities, either by onlap or toplaping. Indeed, one of the advantages of sequential stratigraphy, which is based on unconformity picking, is reservoir prediction.

Model Variables Impact

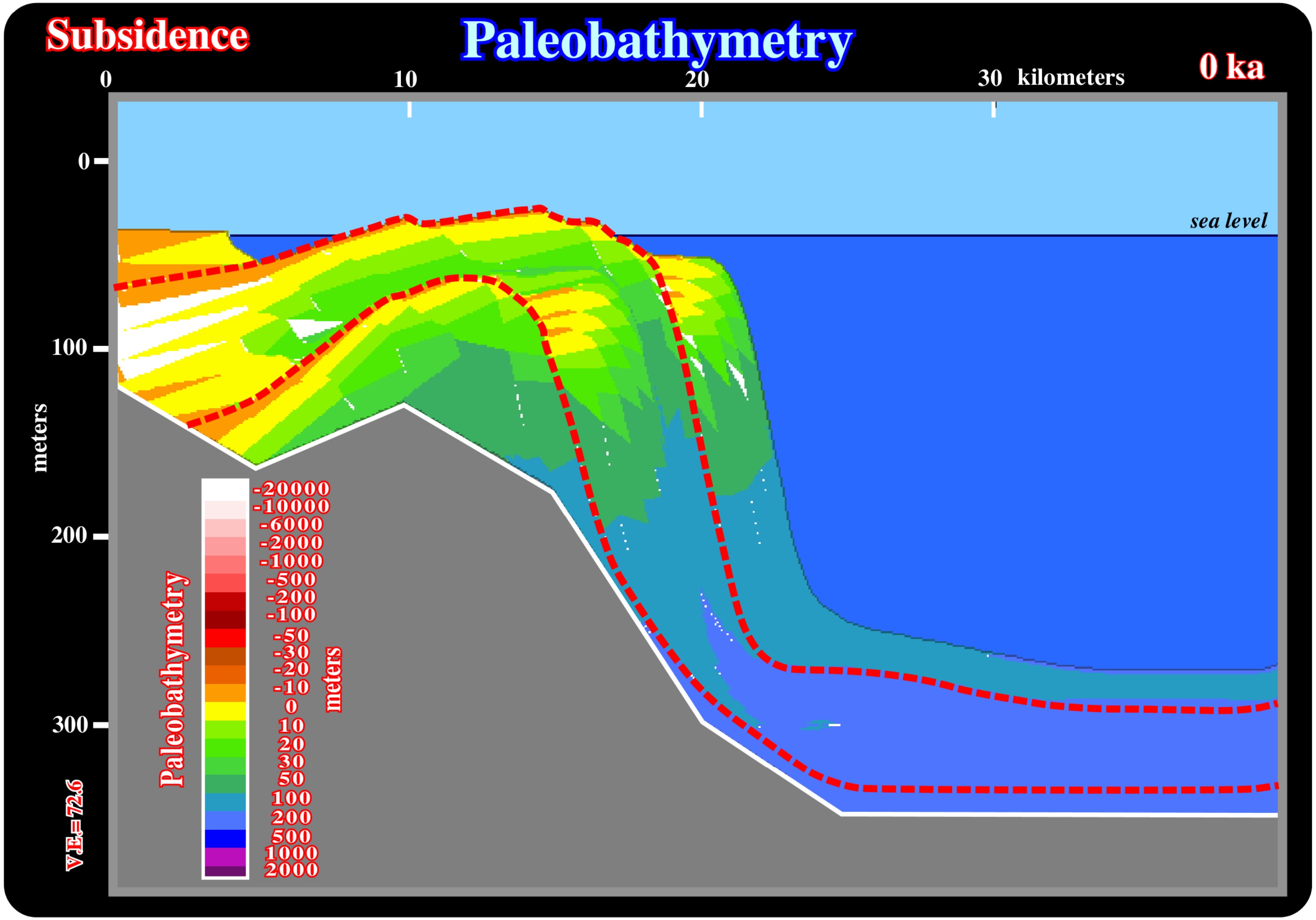


Fig. 85- This figure illustrates the paleo-water depth of the sedimentological model illustrated in fig. 81, in which the subsidence parameters were changed in relation to the initial model (fig. 68 and 71).

Carbonate Model

Carbonate Model

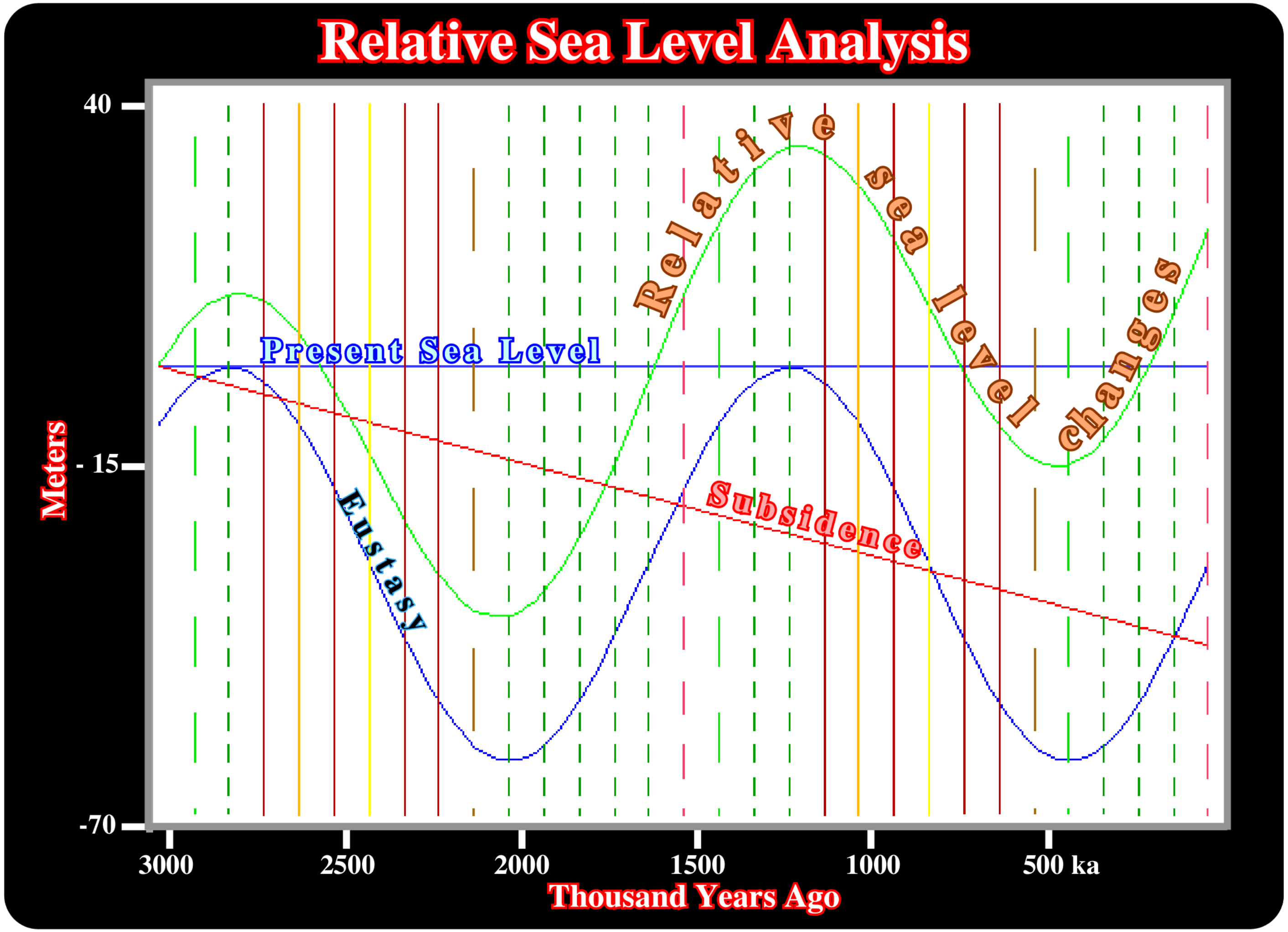


Fig. 86- The same subsidence and eustasy, that is to say, the same relative sea level changes as those used in the sand-shale mathematical model, were used in the mathematical carbonate model that will be shown in the next plates. Only the terrigeneous influx was changed by a carbonate function, which is illustrated in fig. 87.

Carbonate Model

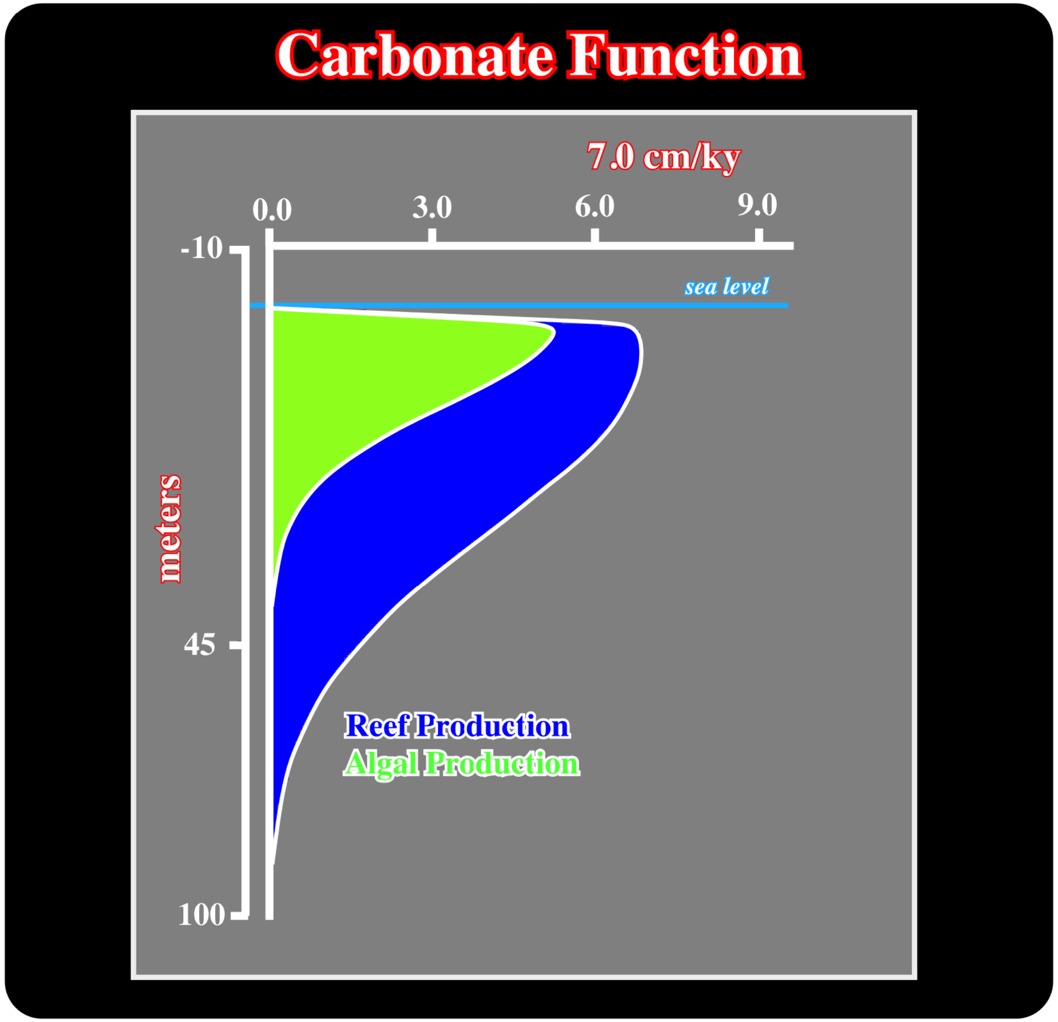


Fig. 87- This carbonate function was used in the carbonate model. In relation to the sand-shale mode, only this parameter replaced the terrigeneous influx, all other parameters are the same. Notice that in this carbonate function, the maximum of productivity is under a 3-10 m of water depth. On the other hand, algal production stops at 35 - 40 meters, while reef production becomes meaningless below 60 - 70 m of water depth.

Carbonate Model

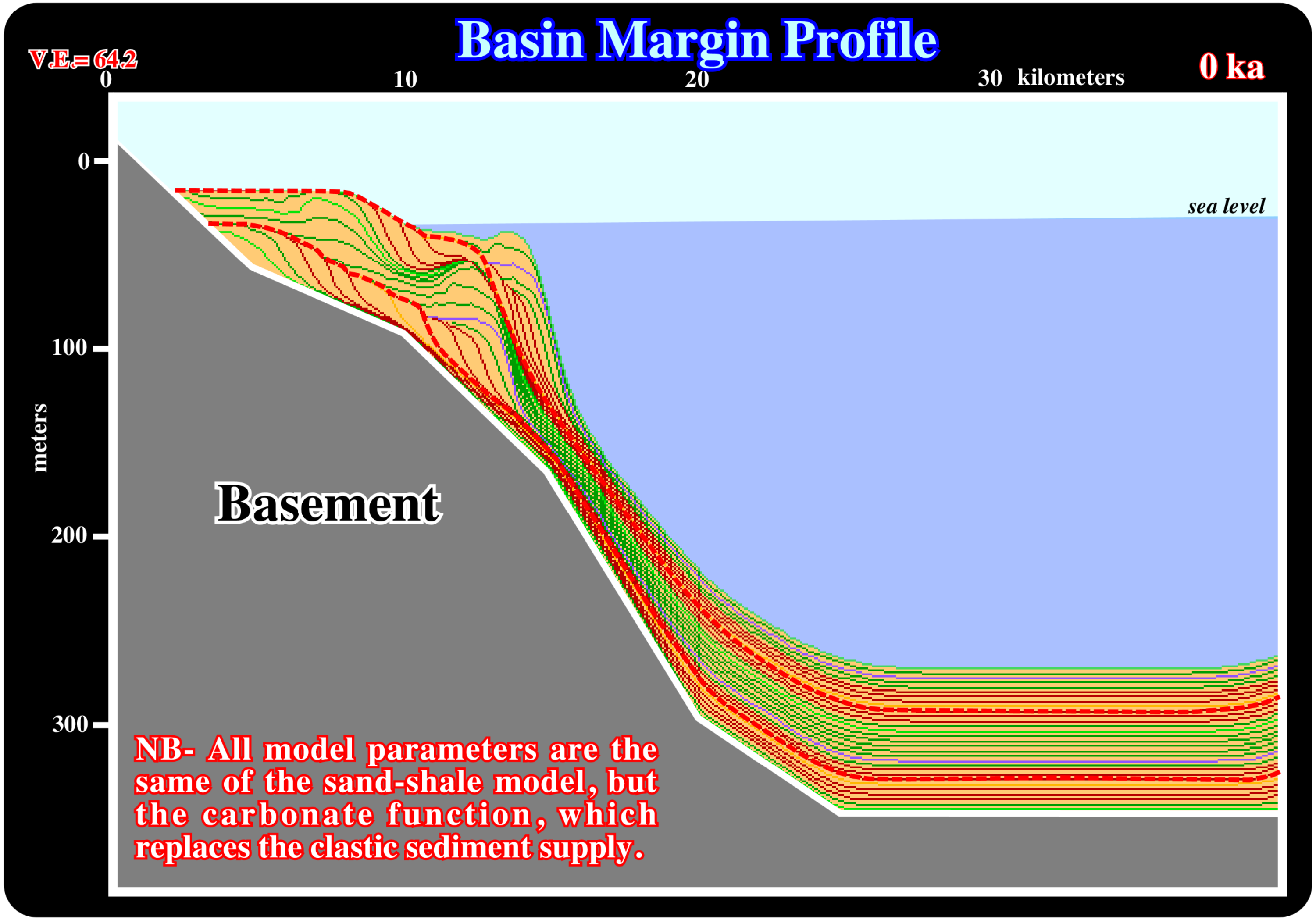


Fig. 88- The model response, when the terrigeneous influx is replaced by a carbonate function, is quite different from the sand - shale response. Indeed, the geometry of the chronostratigraphic lines changes completely. Such a change is particularly obvious in deep water. Indeed, the "gully wings" (channel levees complexes) of the slope fans were replaced by a parallel interval (pelagic limestones).

Sedimentary Model

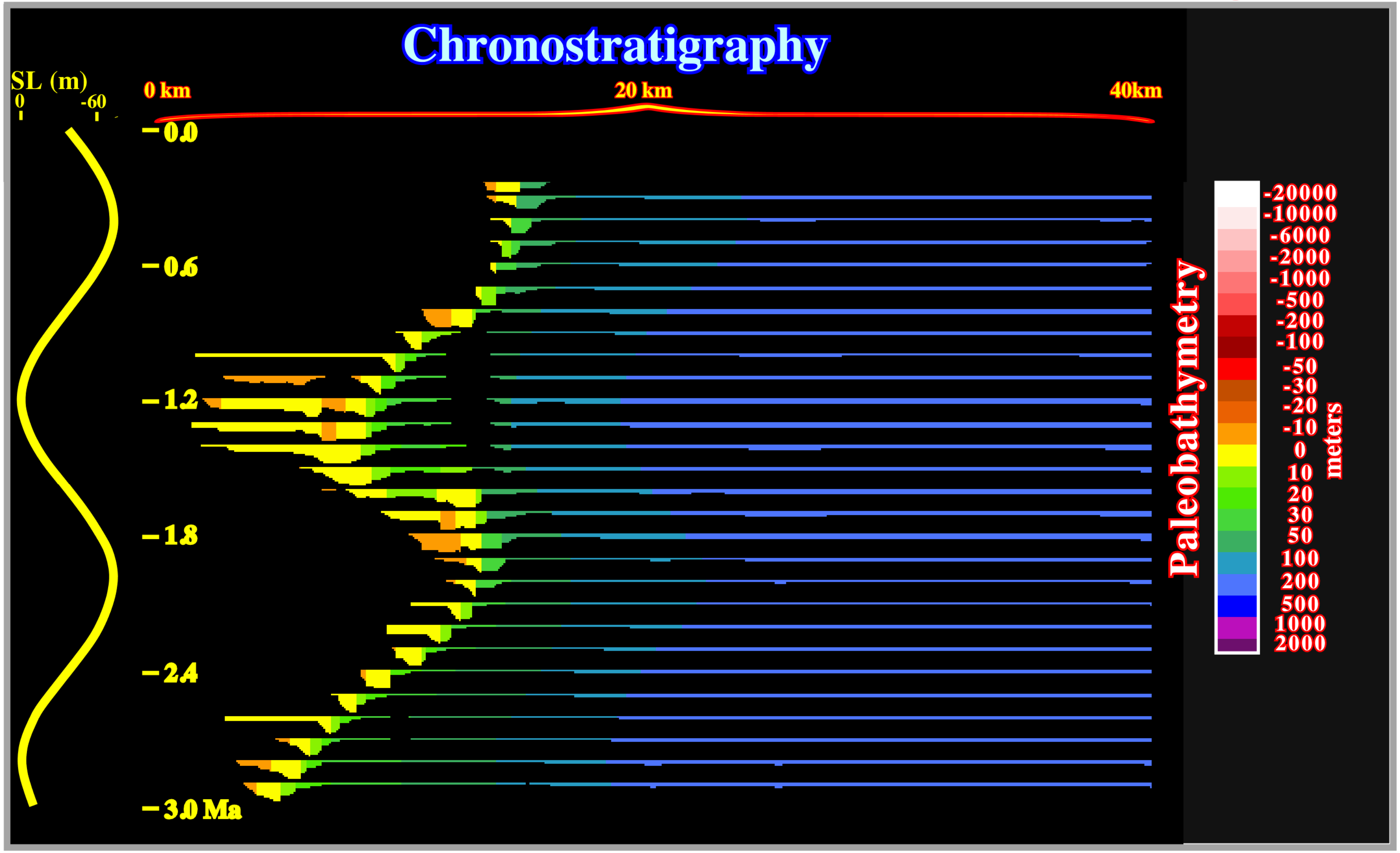


Fig. 89- The chronostratigraphy is also quite different from that of the sand - shale model. Indeed, downlap surfaces are much common, and there is no bypass zone. On the other hand, in deep-water environments, there are no onlap surfaces since there are no slope or basin floor fans.

Carbonate Model

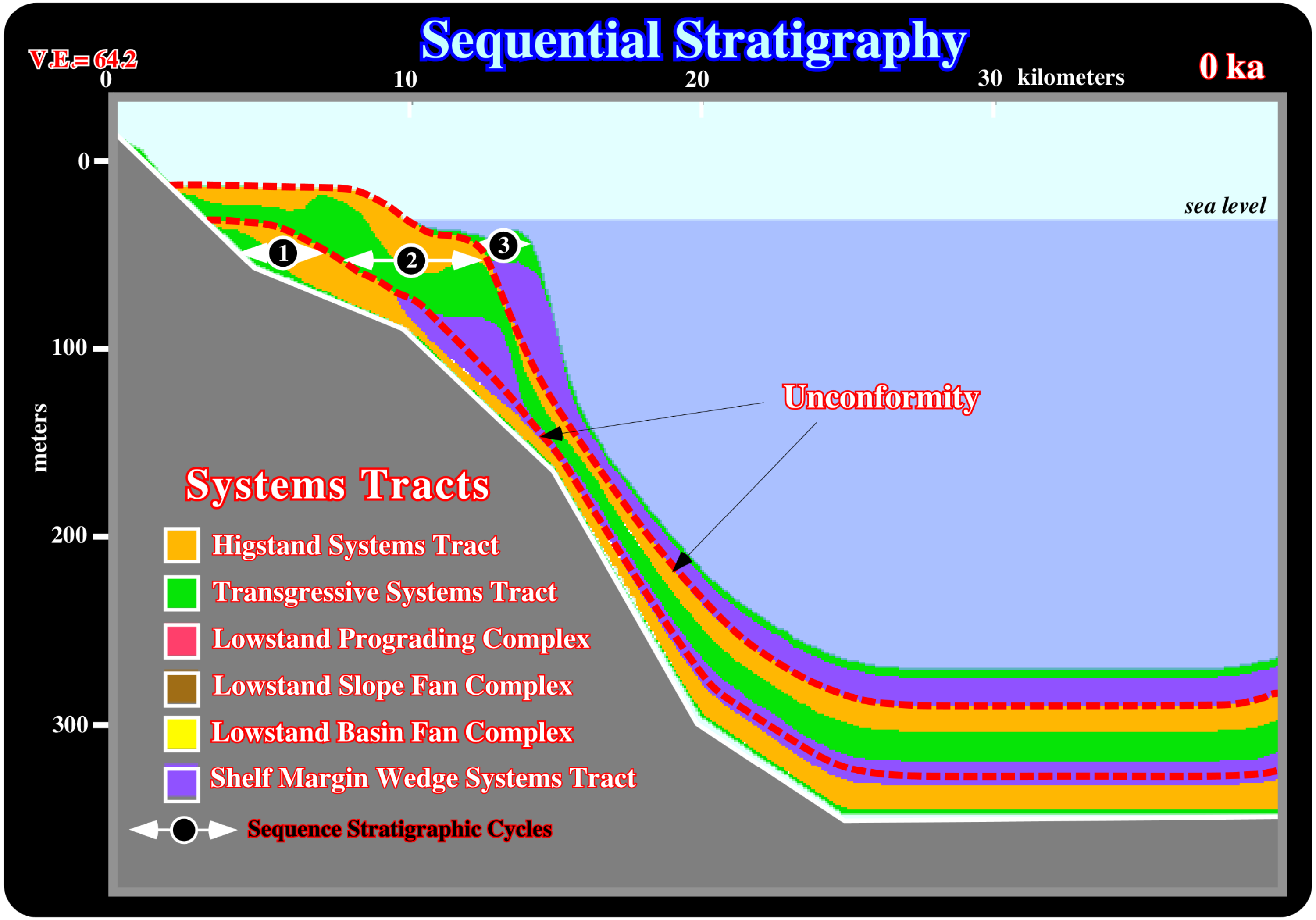


Fig. 90- The sequential stratigraphy of the carbonate model strongly suggests that the lowstand systems tracts (LPW, SF and BBF) are absent. On the contrary, the shelf margins wedge (SMW) is more developed than in the sand-shale model, as well as the transgressive systems tracts (TST).

Carbonate Model

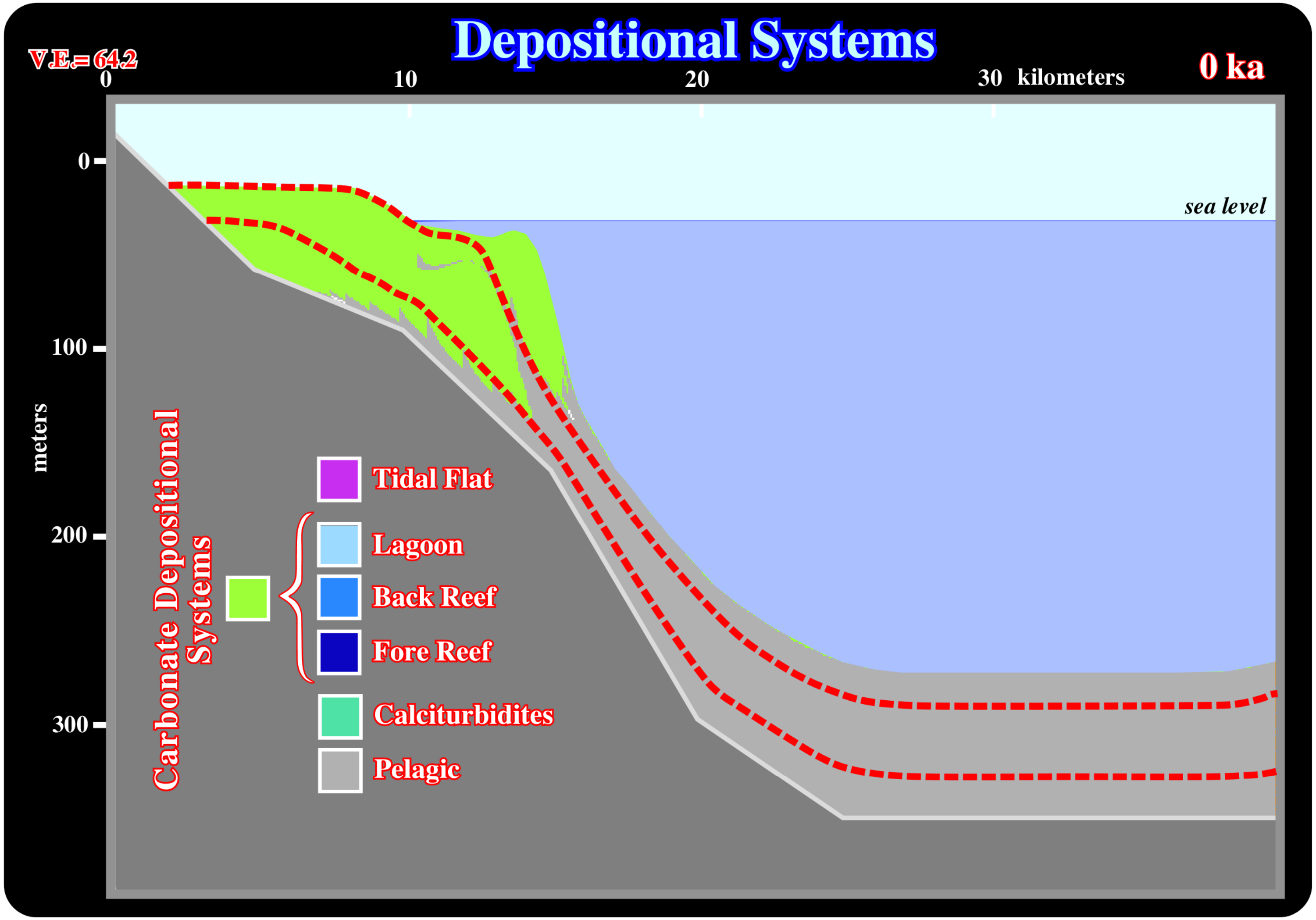


Fig. 91- In a carbonate model, the prediction of depositional environments is much more difficult than in the sand - shale model. So, we prefer to give just a rough idea of the limit between the pelagic sediments and the carbonate depositional systems, knowing that in such a term we include (i) lagoon, back reef and fore reef. In other words, I think the software does not work so well as in the sand - shale model.

Carbonate Model

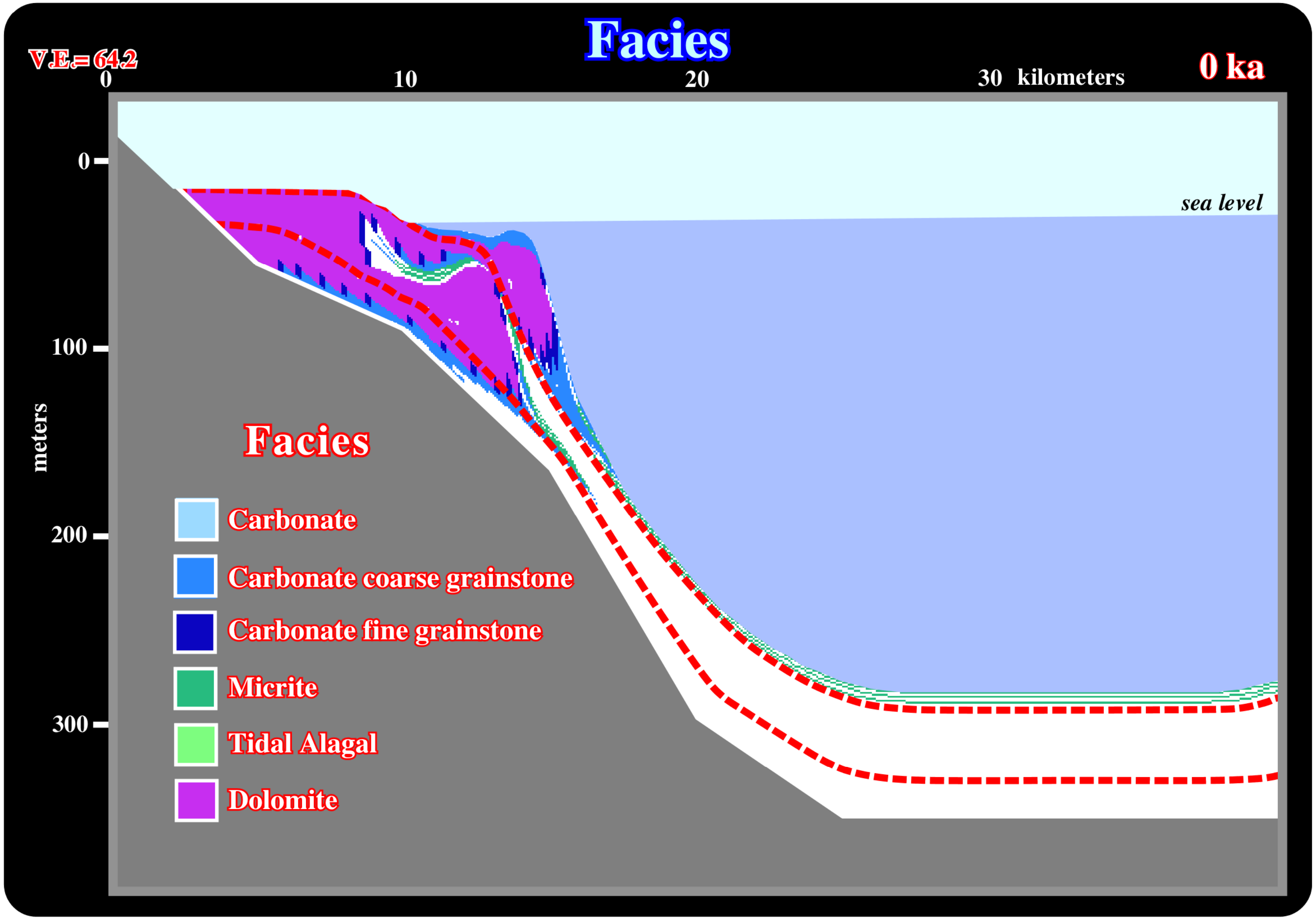


Fig. 92- As for the depositional environments (fig. 91), facies prediction is also very speculative, that is to say, the model results have been refuted several times. In fact, one can say that in a carbonate model, sequential stratigraphy, and particular environment and facies prediction, does not workas well as in a sand - shale model.

Carbonate Model

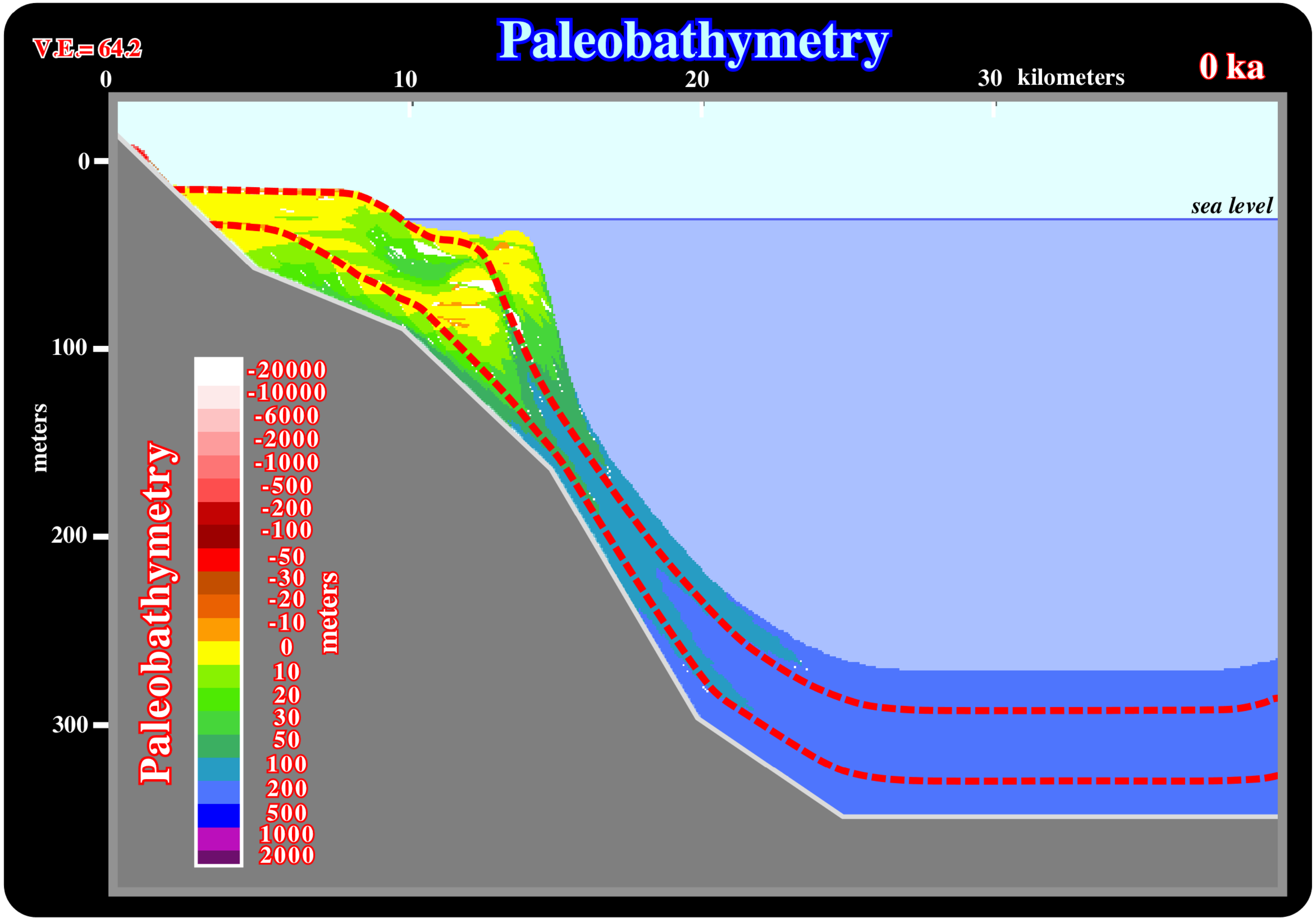
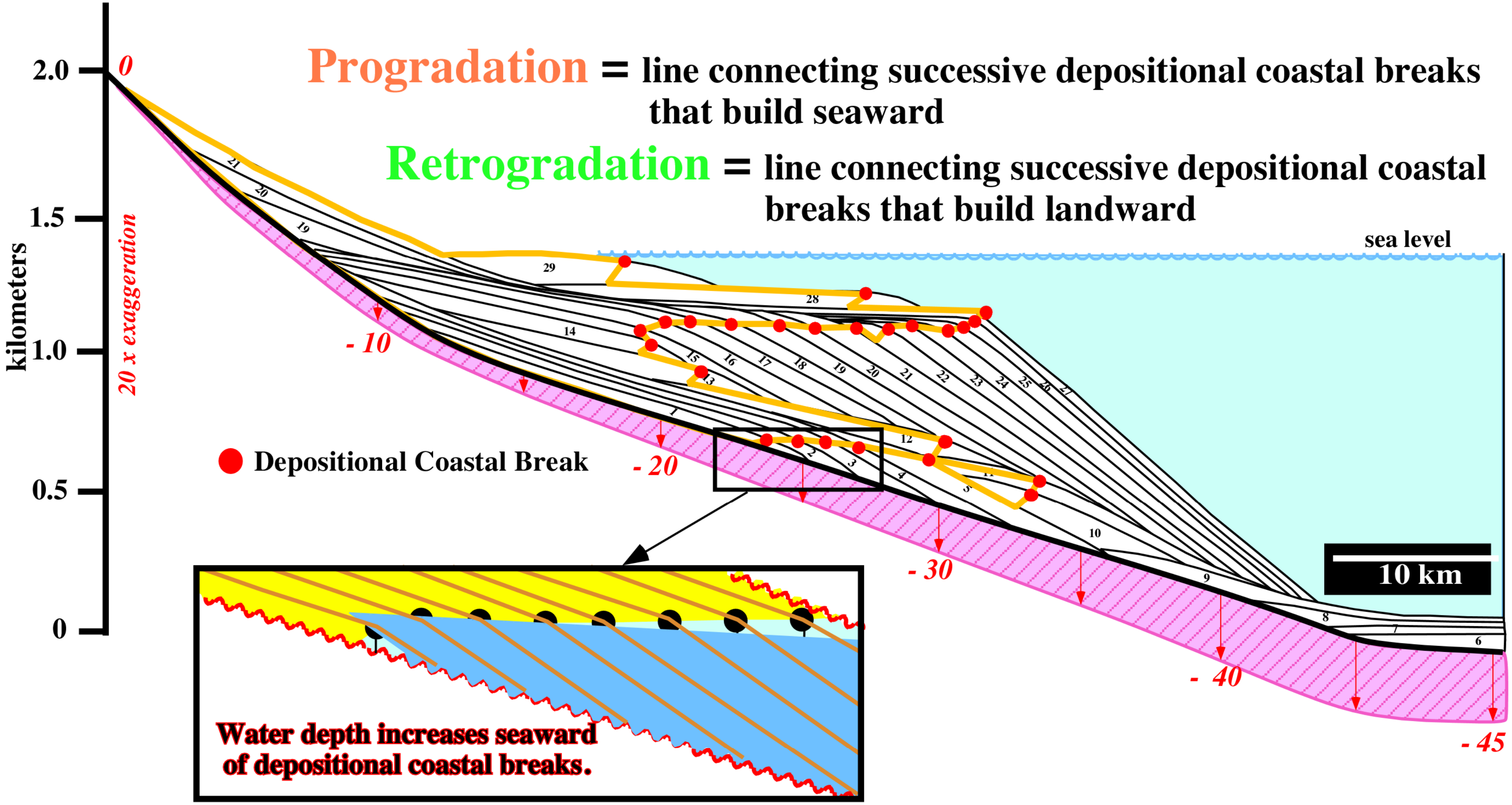


Fig. 93- Using the geometry of the chronostratigraphic lines and the sequential stratigraphy, the above paleobathymetry can be predicted. Admittedly, it strongly depends of the carbonate function used in the model.

Exercises

1) Depositional Coastal Break
2) Paleo - Water Depth
3) Accommodation Increasing
4) Bayline

Depositional Coastal Break



Progradation = line connecting successive depositional coastal breaks that build seaward

Retrogradation = line connecting successive depositional coastal breaks that build landward

● Depositional Coastal Break

Water depth increases seaward of depositional coastal breaks.

Fig. 94- On this mathematical model, the depositional coastal (sharp break in the dip of each chronostratigraphic line) is coincident with the shelf break except during the transgressive episodes (time lines 12, 13, 14 and 28, 29), during which the basin has a platform (shelf). Landward of the depositional coastal break the paleo-water depth is zero; therefore all space available (accommodation) is filled. Seaward of the depositional coastal break, the space available for the sediments is only partially filled, therefore a water depth is created. The water depth can be easily calculated as illustrated, that is to say, by taking the depositional coastal break as water depth zero.

Depositional Coastal Break

Exercise

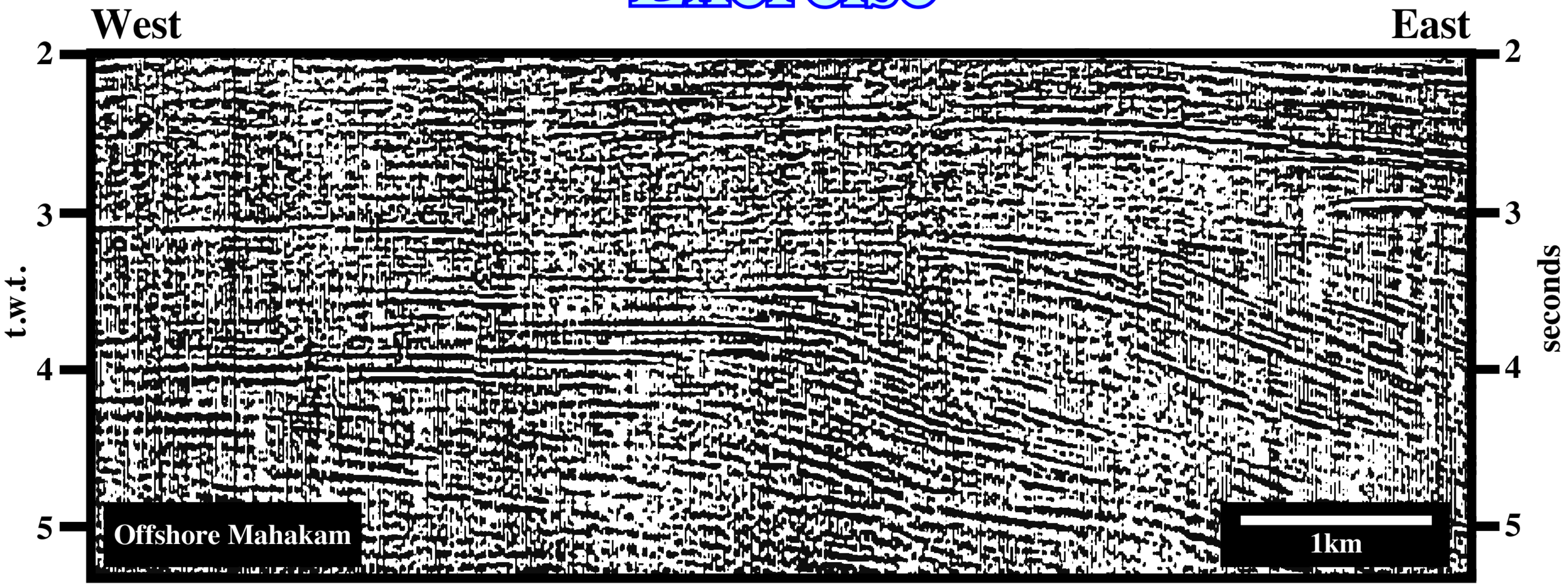


Fig. 95- In spite of the low quality of this seismic line, in which a regressive interval is globally predominant, try to pick the successive positions of the depositional coastal break (roughly coincident with the shelf break). Then, indicate the progradational and retrogradation displacements of the depositional coastal break. Finally, using these displacements propose the most likely location of the major unconformities. If you have problems, you can find a solution on fig. 96.

Depositional Coastal Break

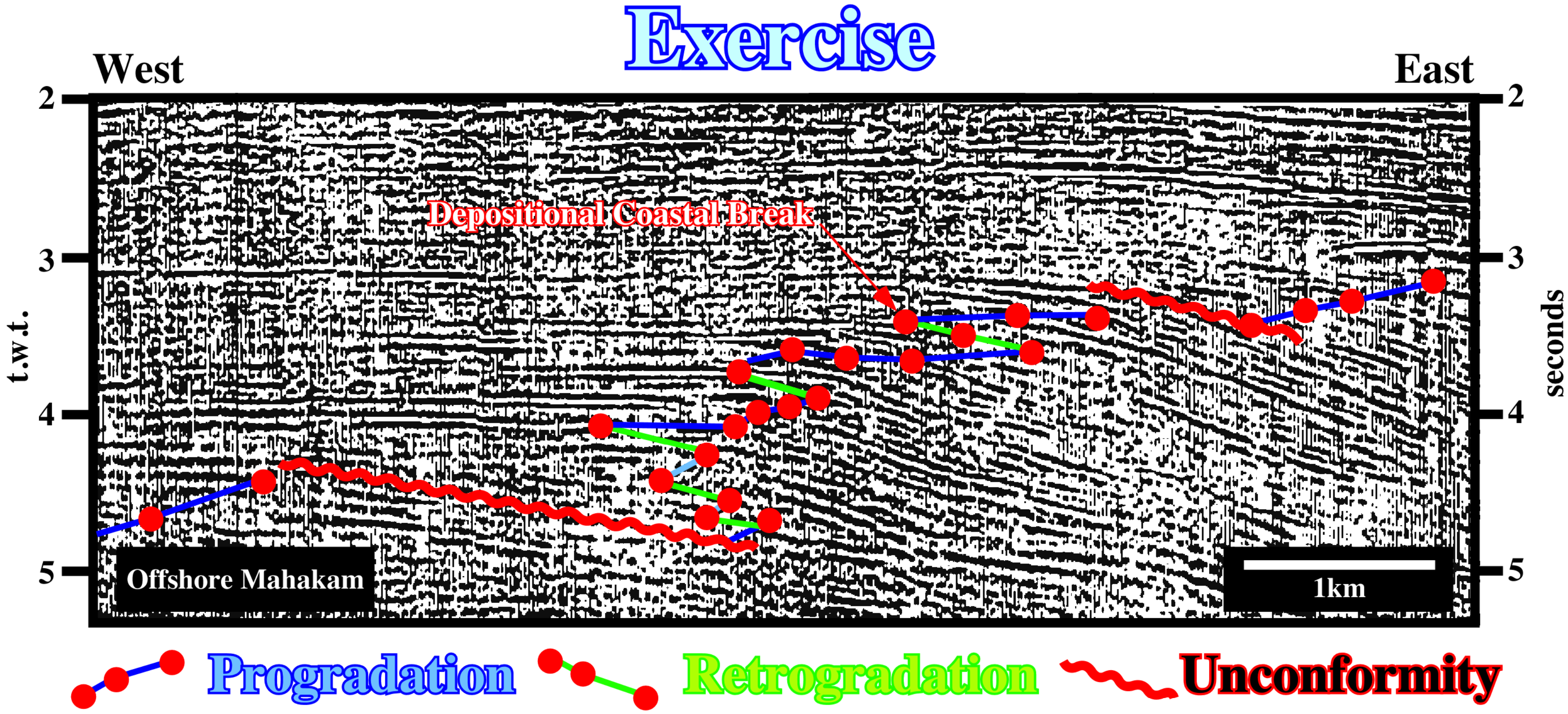


Fig. 96- Taking into account the seismic resolution, the most likely successive positions of the depositional coastal break is indicated by the red dots. Progradation happens when the depositional coastal breaks build seaward (blue line), when the depositional coastal breaks are displaced landward, retrogradation takes place. The more likely location of the major unconformities is emphasized by downward and basinward displacements of the depositional coastal break.

Paleo-water Depth

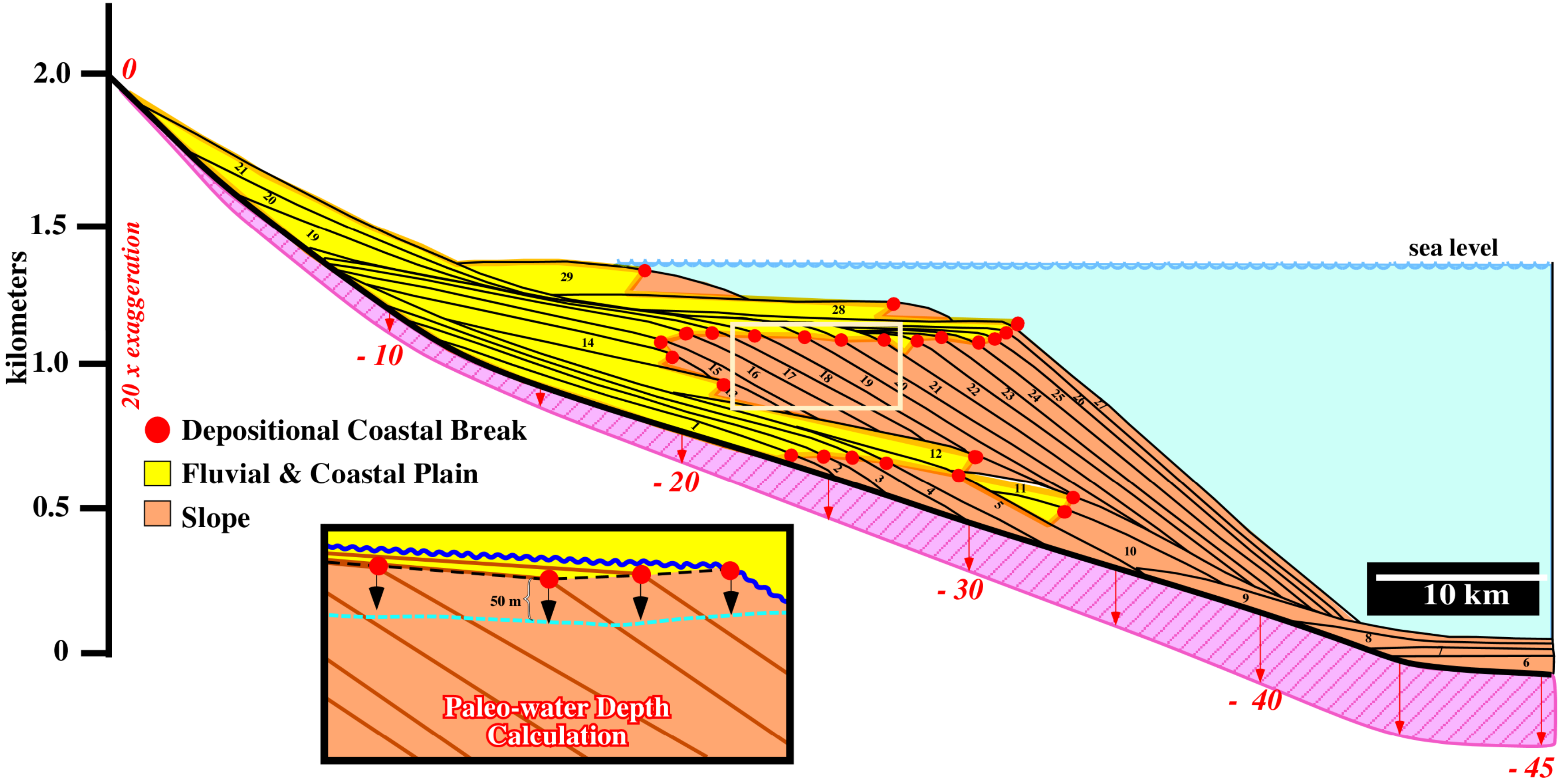


Fig. 97- As said previously, the paleo-water depth can be easy calculated. Indeed, assuming the paleo-water depth at the depositional coastal break is zero, at a given point seaward of the depositional coastal break, the depth of the point when measured perpendicularly to the coastal plain associated with the depositional coastal break, gives the paleo-water depth. The same can be done on seismic lines (see next figure).

Paleo-water Depth

Exercise

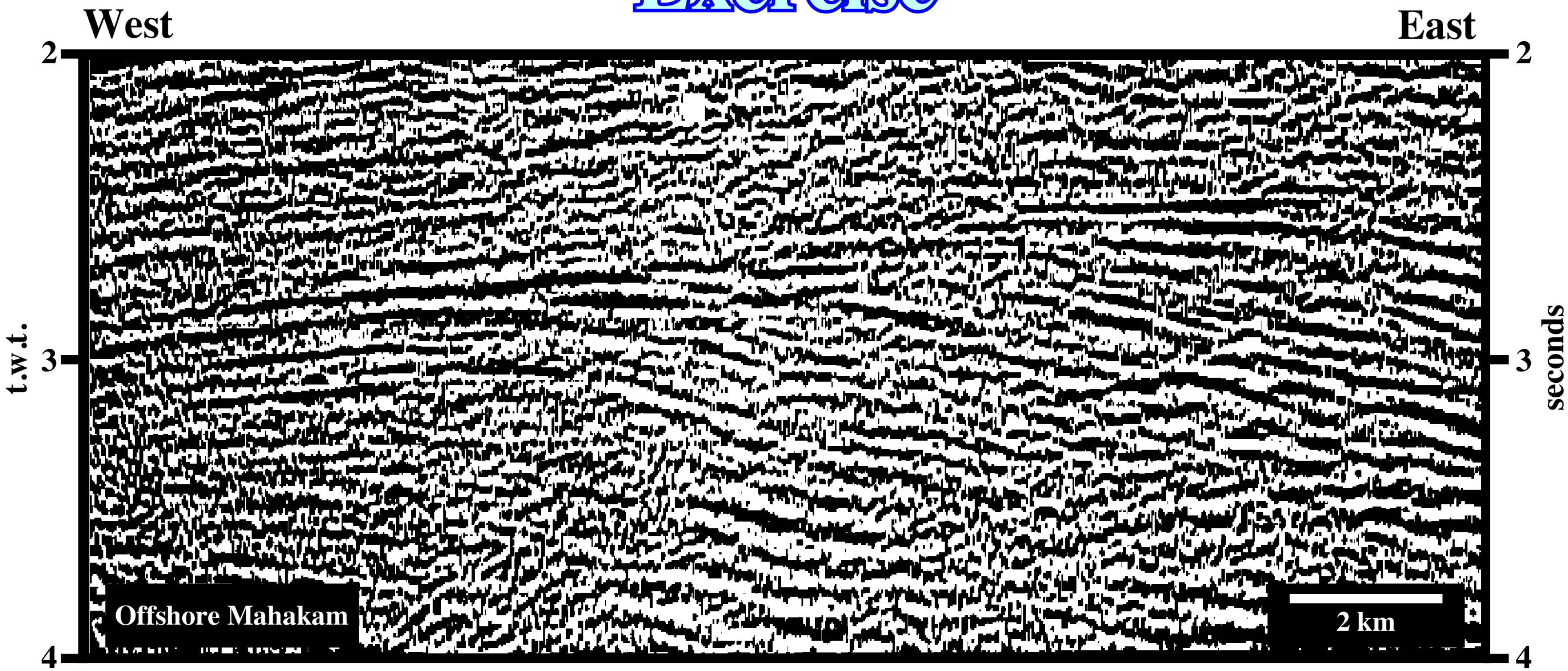


Fig. 98- On this seismic line, start to pick the most likely position of the depositional coastal break, which is roughly coincident with the shelf break, assuming that at such level the basin has no platform. Then, pick the area with 0.2 and 0.4 seconds (t.w.t.) of paleo-water depth. On the next page, we will find likely solution.

Paleo-water Depth

Exercise

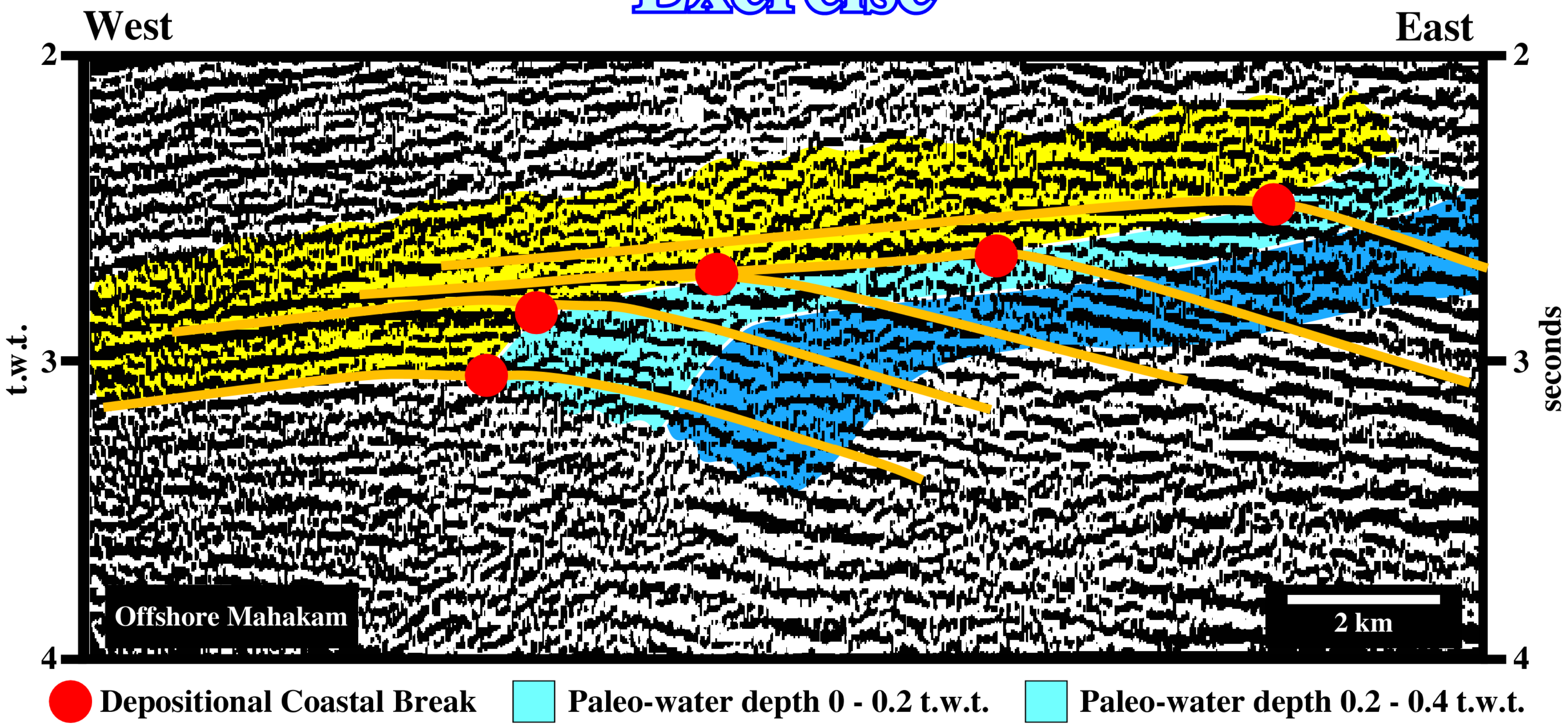


Fig. 99- The most likely solution of the previous exercise is presented above. For determining the paleo-water depth, you just need to find the depositional coastal break, where the paleo-water depth is zero, and then measure the time depth perpendicular to the coastal plain limited by the coastal break.

Accommodation

New Space = Relative change of sea level landward of depositional coastal Break

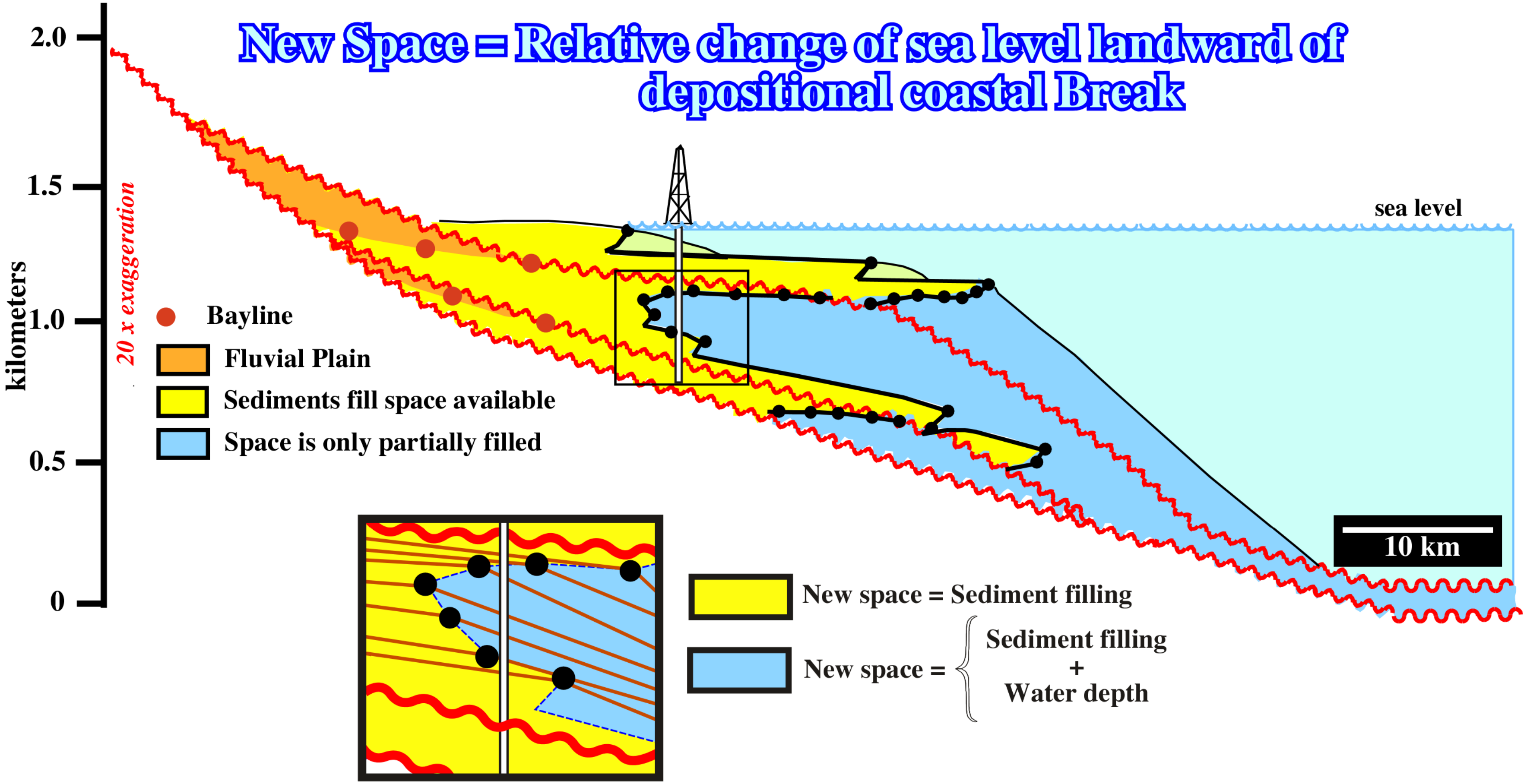


Fig. 100- Every time there is a relative sea level rise, the space available for the sediments, that is to say, the accommodation increases. However, landward of the depositional coastal break (or shelf break, when they are coincident), all new space is filled by sediments (if the terrigeneous influx is enough). Contrariwise, seaward of the depositional coastal break, only part of the new space is filled. In other words, seaward of the depositional coastal break, the new space is equal to the sediment deposits plus the water depth. So, knowing the thickness of the sediments deposited seaward of the coastal break and the water depth, which can be reckoned by micropaleontologic studies, it is possible to estimate the relative sea level change. Landward of the depositional coastal break, there is no major problems. The sediment thickness gives the space available, which corresponds to the relative sea level change.

New Space = Accommodation

Variation in sedimentary accommodation reflects the space made available for sediment accumulation through a combination of subsidence and sea level rise or fall. Whether this space is entirely filled depends on the rate of sediment supply to the basin. The key to sequential stratigraphy interpretation of well data, for instance, lies in the application of the accommodation concept to the interpretation of depositional environments.

P. Vail identifies the variations in sedimentary accommodation in several steps:

1) Locate the marine shale wedge.

In a siliciclastic section this wedge typically occurs on the shelf, where it is overlain and underlain by coarser sediments and extends laterally into the slope and basin. In a carbonate section, this wedge may be shales, marls or calcareous muds, and it is typically overlain by coarser clastic carbonates or by evaporites and underlain by transgressive carbonates.

2) In sediments deposited on the shelf, locate an overall fining and thinning upward pattern at the base of the marine shale wedge.

In siliciclastics these often form a bell shaped log pattern and reflect the retrogradation of successive parasequences as rapid sea level rise forces the shoreline away from the basin and across the shelf. In carbonates these variations may be less visible on logs and may require sample and core studies to recognize the fining upward pattern and the increase in depositional water depth.

3) In sediments deposited on the shelf, locate the overall coarsening and thickening upward patterns at the top of the marine shale wedge.

In siliciclastic deposits this often forms a funnel shaped pattern at the top of the marine shale wedge, representing progressive progradation of delta-front sands, followed by deltaic and fluvial sand-shale sections representing decreasingly marine conditions. Similar shallowing upwards facies patterns can be observed in carbonates through core and sample studies, aided by biostratigraphy.

Bayline

The bayline is the demarcation line between zones characterized by subaerial and marine accommodation

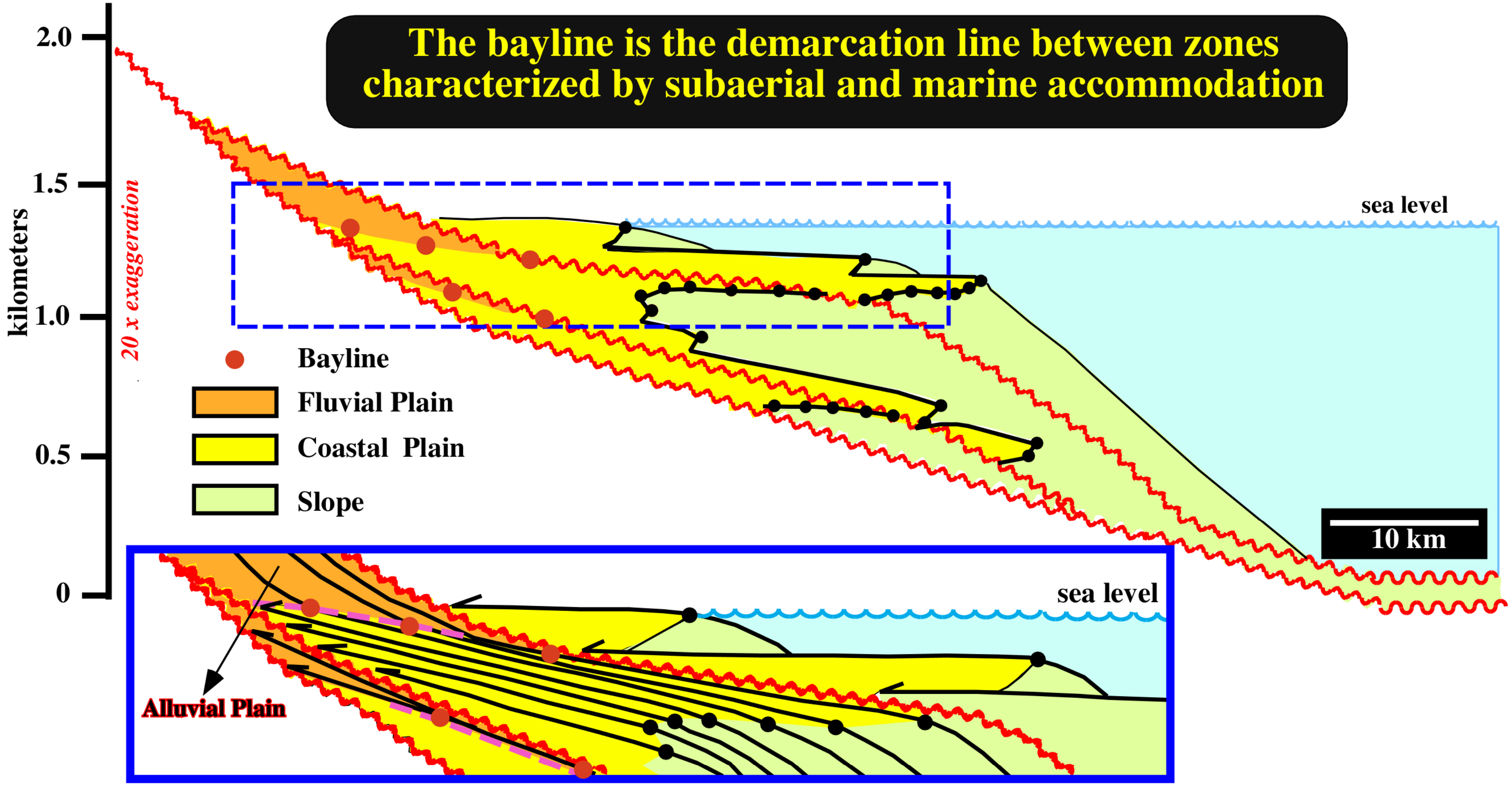


Fig. 101- In the majority of chronostratigraphic lines (depositional surfaces) there are three principal breaks: (i) bayline, limit between fluvial and coastal sediments, (ii) depositional coastal break, which separates coastal and marine sediments and (iii) shelf break, which limits shallow marine sediments (< 200 meters) from deep marine sediments (> 200 meters). As indicated above the bayline, which is quite difficult to recognize on seismic data, separates the alluvial plain from the coastal plain. Indeed, the change in dip associated with a bayline are so small that, very often, it is under seismic resolution. So the next examples are quite speculative.

Bayline

Exercise

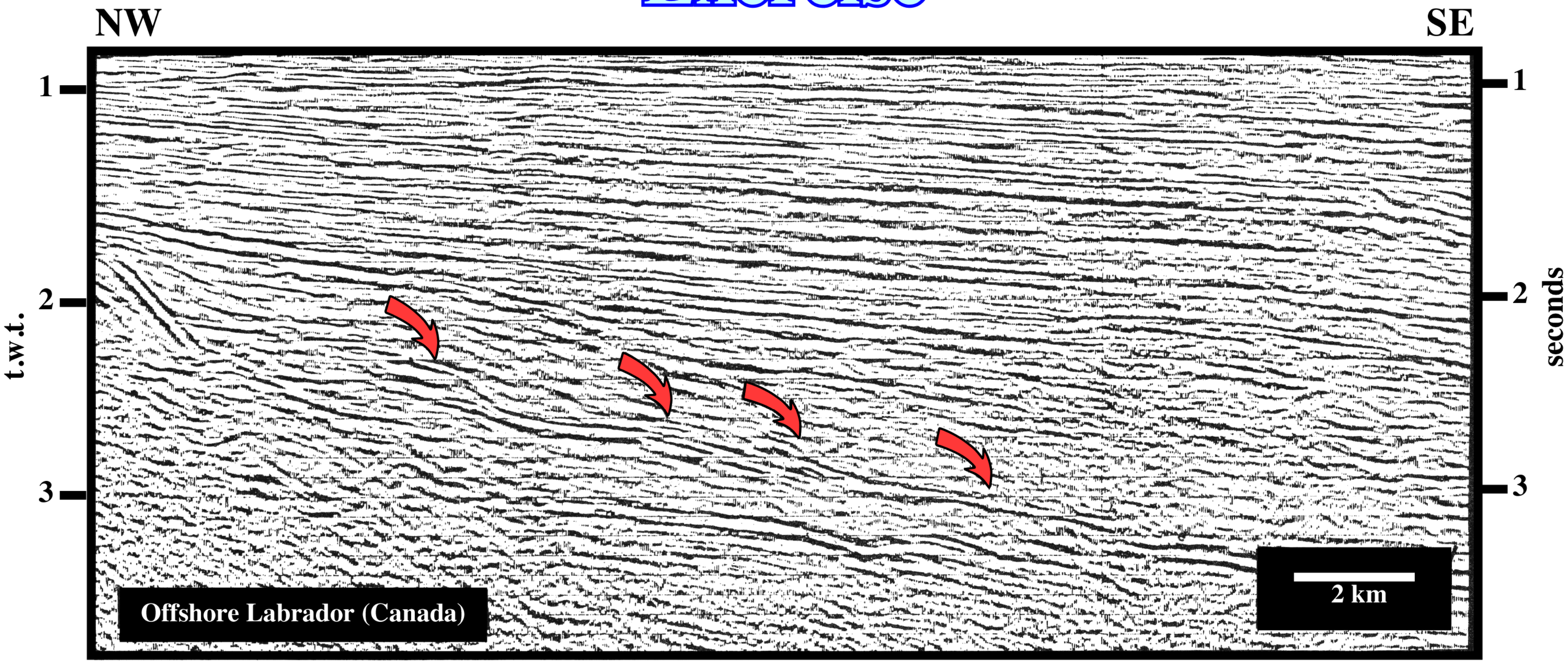


Fig. 102- Knowing that the arrows indicate the successive position of the depositional coastal break (which here does no coincide with the shelf break), try to pick the main unconformities and locate the bay line. Then, on the next page, see a possible solution and criticize both solutions, yours and mine.

Bayline

Exercise

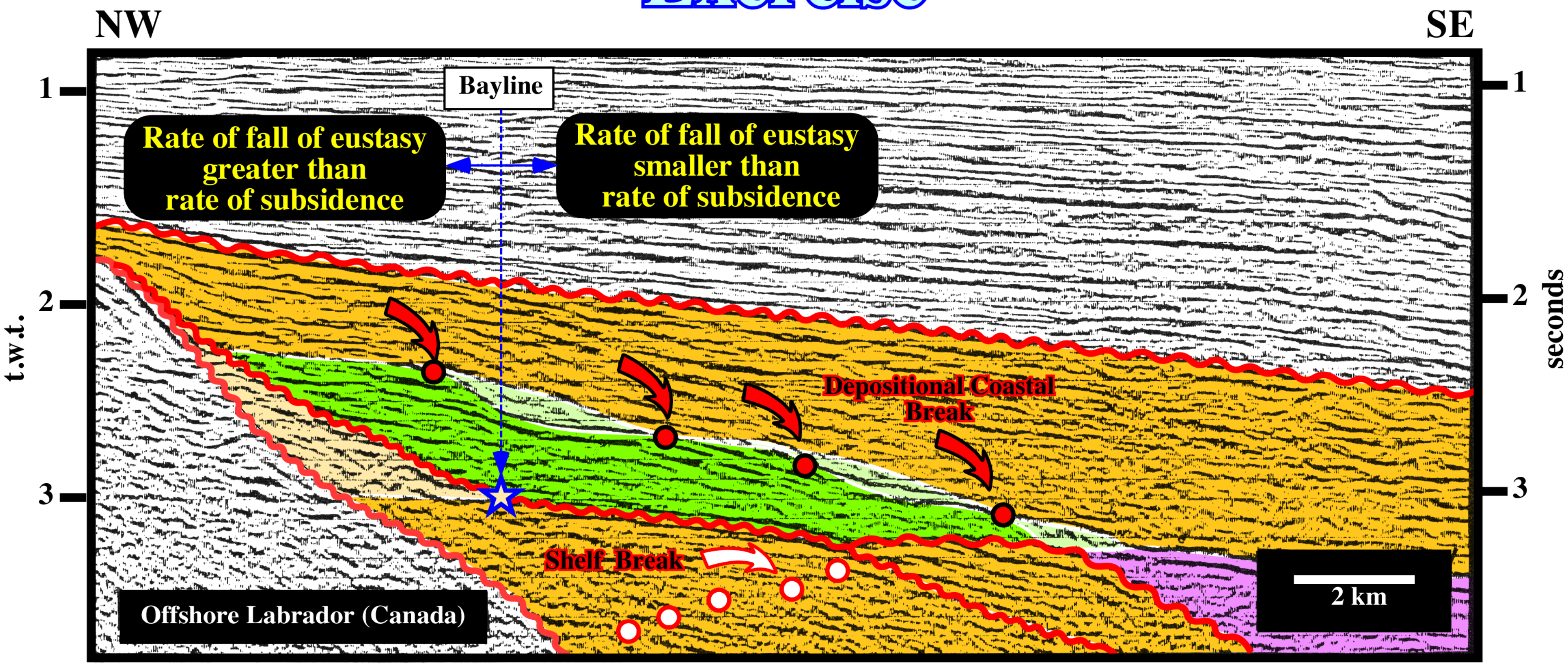


Fig. 103- Landward of the bayline, which separates the alluvial plain from the costal plain, the rate of fall of eustasy is greater than the rate of subsidence. On the contrary, seaward of the bayline, the rate of fall of eustasy is smaller than the rate of subsidence. The concept of a bayline (Posamentier, 1988), implies that this, rather than the shoreline, is the base-level point to which stream profiles are adjusted to. Also, it was assumed that a relative sea level rise or fall displaces the equilibrium point (point on the continental margin at which subsidence and sea-level change are in balance) landward or seaward. However, all these conjectures should be criticized, and must take into account tectonic activity, sediment supply and local relative.

Bayline

Exercise

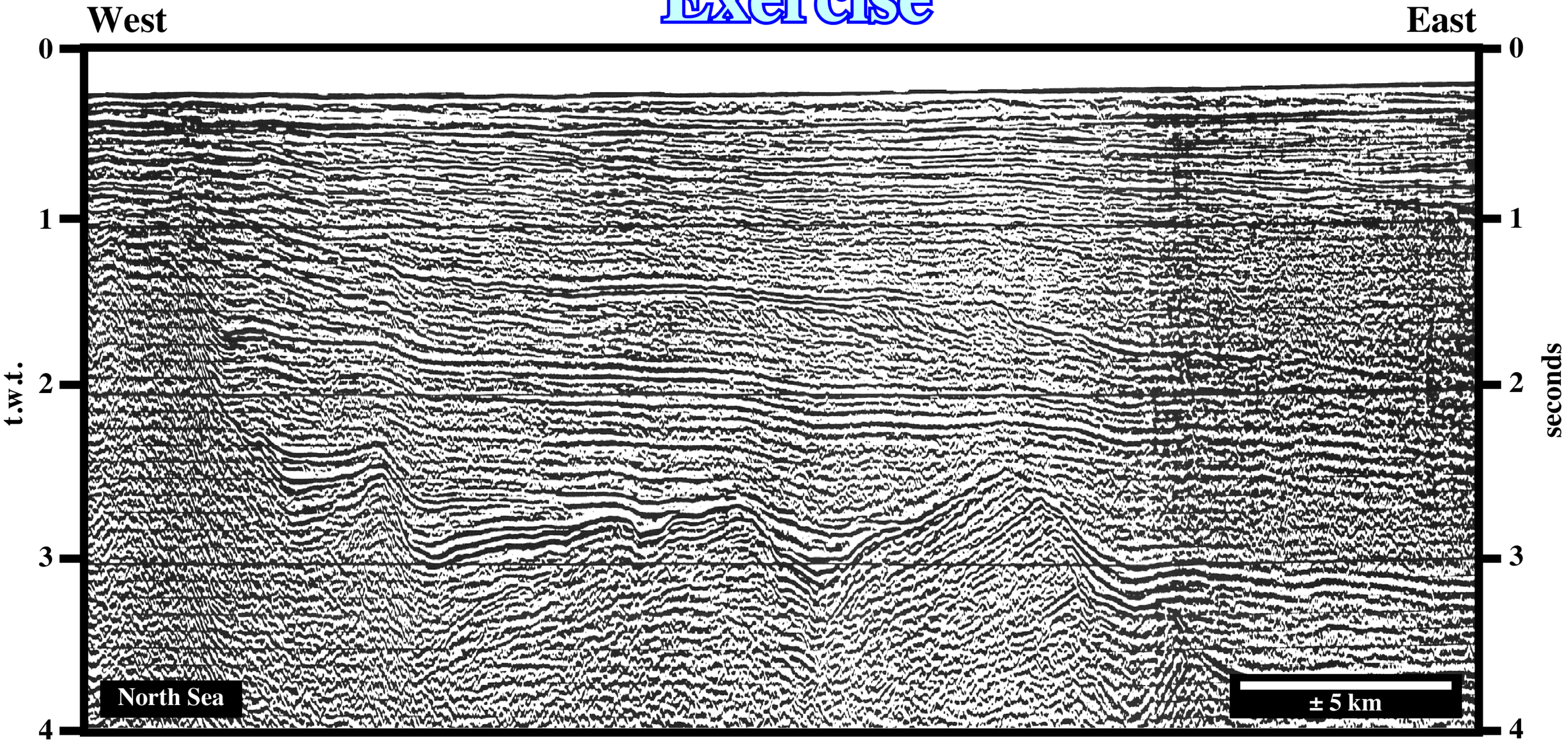


Fig. 104- Assuming that there is a bayline on this seismic line from North Sea, locate the most likely location. Take into account that a bayline, according to Posamentier (1988), is the demarcation line between fluvial and paralic/delta plain environments. Note that the concept of bayline has been severely criticized (Miall, 1977), particularly the conjecture that it corresponds to the base-level point to which streams profiles are adjusted.

Bayline

Exercise

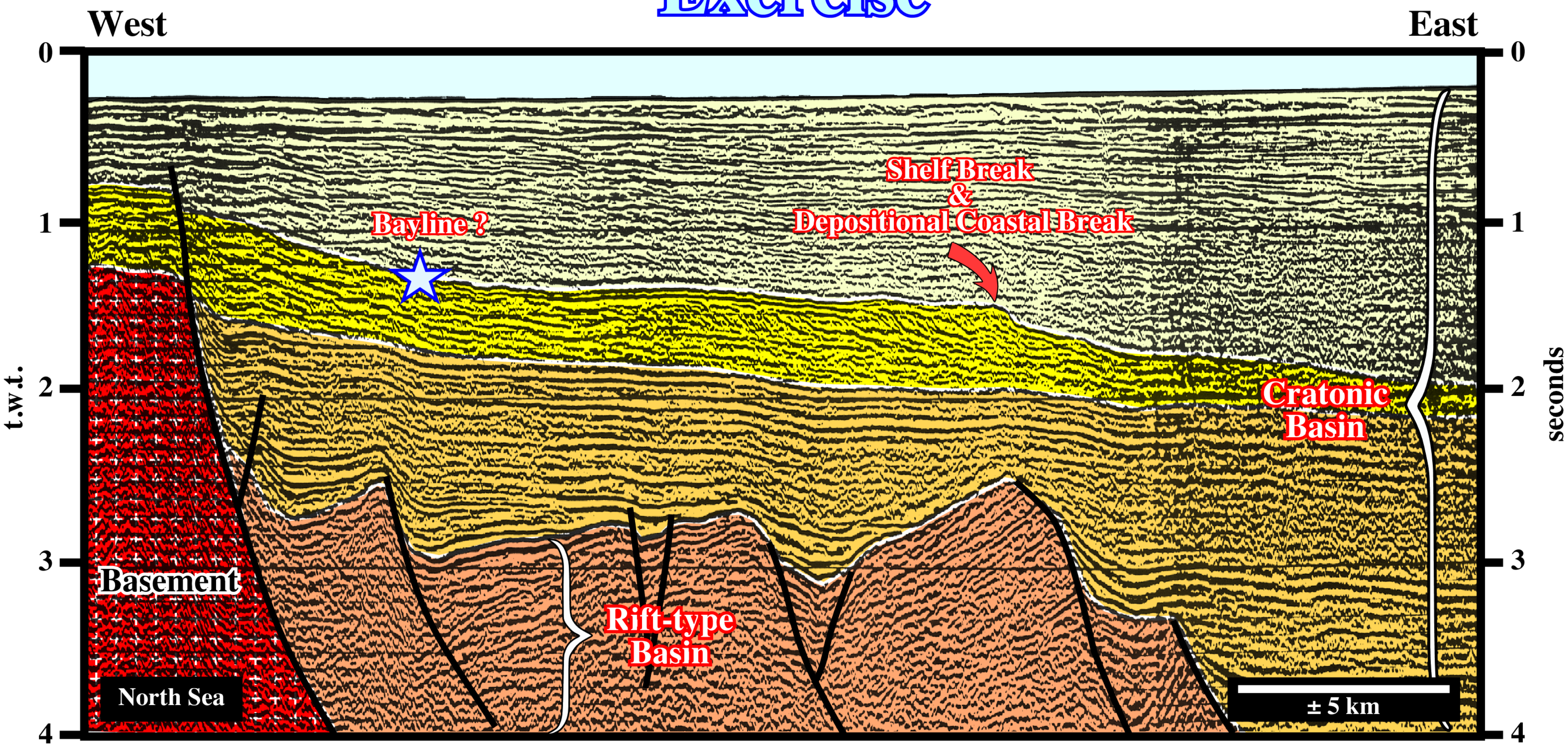


Fig. 105- I really don't think there is a bayline on this line. However, taking into account that it corresponds to most landward break of a depositional surface, the most likely location is underlined by the star. Actually, the upper unconformity of the regressive interval (in yellow) shows two sharp dip changes. On the other hand, as in a progradational interval, the depositional coastal break and the shelf break are coincident, there is a sligh chance that the landward break underlines the bayline.