Pitfalls' ABC
in
Hydrocarbon Exploration
(Argentina Petroleum Basins)

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Caveat :

The information and opinions contained herein are the sole responsibility of the author. They are not addressed to any particular oil company. They simply reflect what, in my opinion, should be avoided in scientific onshore or offshore petroleum exploration, particularly in the sedimentary basins of Argentina. The tentative geological interpretations of the seismic lines were conducted using the original seismic data. However, for confidentiality reasons, in these notes, the original seismic lines have been replaced by automated Canvas auto-traces.

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Foreword :

After conducting several geological assessments of the Proved and Speculative Petroleum Systems (using Magoon's terminology) in the South Atlantic basins, particularly in Argentina, we have realized that many geoscientists working in residual petroleum exploration propose naïve interpretations - not only in the tentative geological interpretations of seismic lines and electrical logs but also in geological models. In fact, several of them adopt a "Tabula Rasa"interpretation approach, erroneously assuming that observation precedes theory[1]. They shot seismic grids, particularly 3D seismic, to try to understand the geological and petroleum problems and not to test a geological idea or conjecture. They forget that all geological observation is theory laden. In addition, they try, always, to verify their inductive interpretations and not to refute them (in science, verification, corroboration and validation are not synonyms). Criticism as growth of knowledge being considered as politically incorrect, their interpretations are, often, quite controversial and even completely wrong.

Additionally, many geoscientists seem to have forgotten why seismic lines are used for stratigraphic and tectonic interpretations (seismic-stratigraphic interpretation). As a brief reminder, in the 1960s, geoscientists working in oil companies believed that the seismic reflectors visible on seismic lines (non-migrated) were associated with acoustic impedance contrasts created by the lithology (facies) of sedimentary intervals.However, when Exxon explored the offshore of Portuguese Guinea (now Guinea-Bissau), they drilled three exploration wells based on seismic interpretations (see Figure 1). The first well encountered the top of the reservoir rocks above an unconformity with Paleozoic rocks beneath. Before drilling the second well, which was located structurally in a lower position, Exxon geoscientists predicted that the reservoir sandstones should be found at a higher depth than in the first well. In reality, they were encountered significantly deeper. A similar discrepancy occurred in the third exploration well. Given the negative exploration and geological results compared to expectations, Exxon geoscientists reinterpreted and calibrated the seismic data. To everyone's surprise, they concluded that the seismic reflection associated with the top of the reservoir sandstones in the first well was two reflections above the top of the sandstones in the second well—and even higher in the third well (see Figure 2). As correlations between seismic and well data were difficult to refute, micropaleontological data strongly suggested that seismic reflectors follow time-lines (chronostratigraphic surfaces) rather than facies-lines (lithology), as was initially assumed.

For the first time, geoscientists recognized that: (i) Correlations between seismic reflectors and electrical logs follow real physical surfaces (bedding), which cut across the timelines of rock units. (ii) Seismic reflections do not follow the limits of geological formations (facies), where acoustic impedance contrasts occur, but instead follow stratification patterns—i.e., the real physical surfaces of rocks.The reaction of Exxon geoscientists was immediate

"Since seismic reflectors follow chronostratigraphic sedimentary packages rather than lithological sedimentary packages, seismic lines can be effectively used to conduct stratigraphic studies."

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[1]On this subject, it important do not forget that:

A) In the inductive approach, geoscientists start by making observations. Then, they invoke hypotheses. Their hypotheses can never be completed verified by posterior observations. On the other hand, very rarely do they try to refute them. The "scandal" of induction, as it is come to be known, is that observations are necessarily limited – you can't keep throwing rocks at windows forever in order to conclude that throwing a rock at a window it breaks. That is, the experimental method is "finistic" (M. Macrone, 1994). The swan metaphor of K. Popper is highly significant. In a slightly modified form, it can be expressed as follows: It is not because an Argentine geoscientist saw 2332 cute "mestiza" in Copacabana beach, that he has the right to say that all "mestizas" in Copacabana are cute (induced hypothesis). Just one less cute "mestiza" is enough to refute the induced hypothesis, even if he spends few days to find her. Actually, most geoscientists, just see what interests them, i.e., the cute ones.

B) In the rationalist or hypothetic-deductive approach, geoscientists try to solve problems by trial and error. When they have a problem, they advance a priori hypotheses. Then, they try to refute them by observations. These two scientific approaches are very different:

(i) In the inductive approach, a geoscientist can do all kind of jobs. He just needs to observe. Observations precede theory. If he does not know what a delta, or a deep sea fan, is, he can spend hours, weeks, even months looking at 3D seismic data, without understanding what he is looking for and what eventually he has mapped. The same is true for geoscientists that by challenge, or by unconsciousness, accept tasks for which they have not been trained. In addition, as the continuation of inductive reasoning is the verification of the induced hypothesis, he makes rarely progress. One does not progress seeking to demonstrate that he is right.

(ii) In the hypothetic-deductive approach, a geoscientist can only do the job for which he was trained. Observations are entirely dependent on the theory adopted by the observer. Theory precedes observation. In fact, for the rationalists, as K. Popper used to say, there is no such thing as instruction from without the structure, or the passive reception of a flow of information which impresses itself on our senses. All observations are theory-impregnated. There is no pure, disinterested, theory-free observation.

Such philosophic critical thinking strongly contrasts with the inductive thinking of Francis Bacon. Actually, Bacon was rightly worried about the fact that our theories may prejudice our observations. This led him to advise scientists that they should avoid prejudice by purifying their minds of all theories. Similar concepts are still held in several major oil companies. We belong to the geological community that thinks the deductive approach gives the better results in oil exploration. On the other hand, we also think knowledge of Geology began with observations, but we do not say that it derives from observations. Like empiricists, we agree that there are no innate geological ideas, but we also do not believe that all geological knowledge derives from observations. we prefer by far to change the order of the words and to say that all geological observations conform to the geological knowledge of the observer. New hypotheses are indispensable to the profitability and progress of hydrocarbon exploration particularly in mature basins. They are related to hypotheses put forth previously and not to knowledge of the geologist. For a young petroleum geologist, almost all hypotheses can be new. A continuous training of the "knowledge workers" as well as those who manage them, is prime importance (Drucker, P. F., 1993).

Thus was born Seismic Stratigraphy, which geoscientists later defined as a predictable succession of stratigraphic units - continental encroachment cycles, continental encroachment sub-cycles, sequence cycles, and paracycles (depositional system tracts) - delineated based on the internal geometry of seismic intervals of varying thickness and seismic surfaces (identified by reflector terminations). These units are deposited in response to changes in shelfal accommodation, or the space available for sediment on the continental shelf.

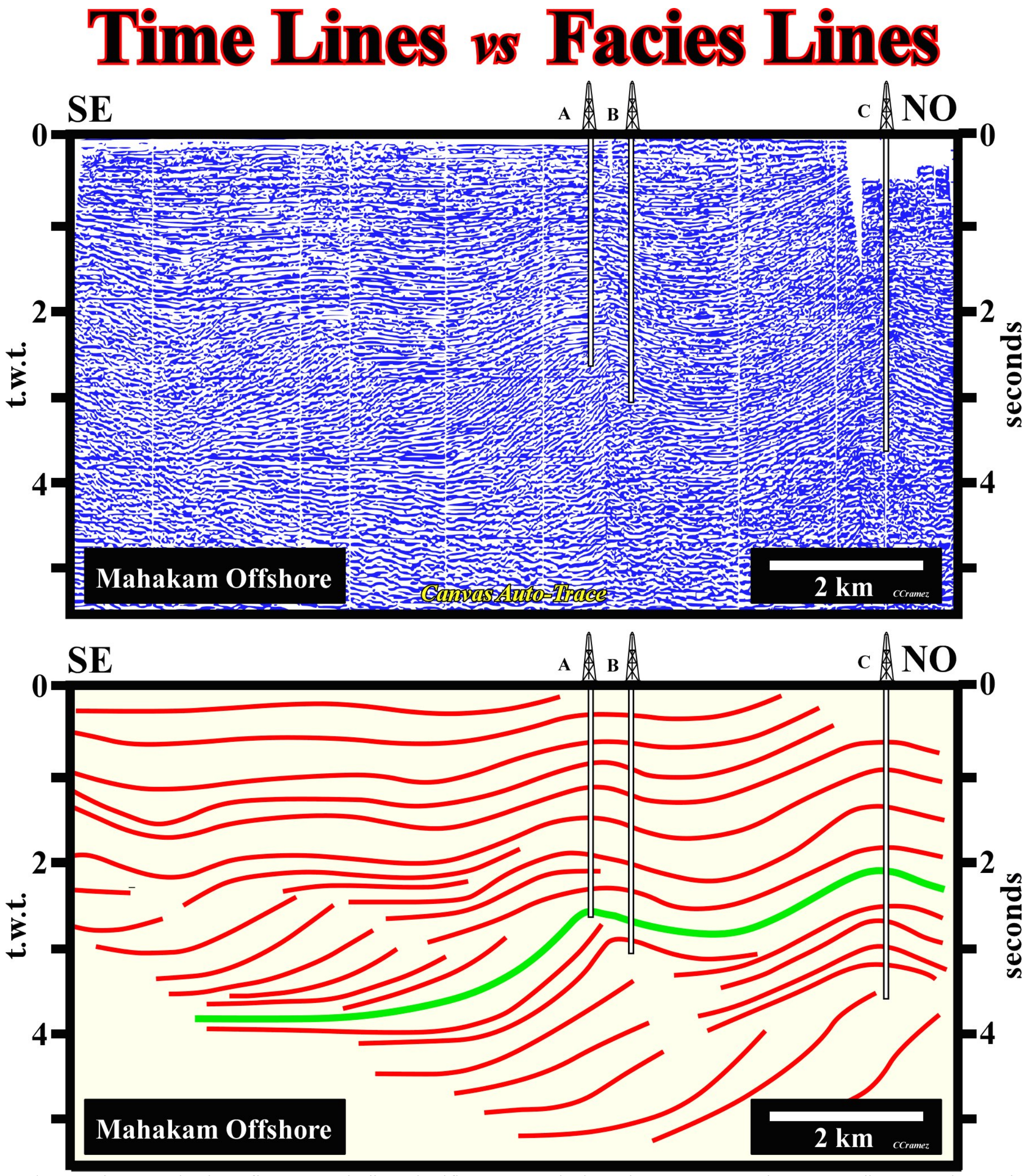

Figure 1 - In theory, seismic reflectors underline significant acoustic impedance contrasts between sedimentary intervals with different lithologies. In the sixties, when geoscientists oil companies started using seismic reflection data in oil exploration, the reflectors, as illustrated in this modern seismic line were interpreted as facies lines. At that time, the seismic lines (non-migrated) were completely different of the modern lines than any geoscientist, with a minimum of geophysical knowledge, can easily interpret. Obviously, this was not the case at that time. Indeed, the geological interpretation of seismic lines was made by geophysicists without any or little geological knowledge. Each reflector corresponded to an interface between different lithologies (shale-sandstone, sandstone-limestone, etc.). If on the above seismic line (used here to simulate the Exxon seismic lines shot during the petroleum exploration of Portuguese Guinea offshore), in which the reflectors were picked by colour pencil lines, the exploration well A recognised a limestone interval at the level of the green horizon, the same limestone level should be found in wells B and C, when the wells reached the green marker. It was with these ideas that Exxon's geoscientists expected recognise and, above all, follow on the seismic lines of the offshore Guinea-Bissau, the prograding delta front (reservoir-rocks), since the acoustic impedance of sandstones is much higher than that of the pro-delta clays or silts of the deltaic plain. However, as said in the text, after three exploration wells, Exxon's geoscientists calibrated the seismic lines in geological terms and concluded that the reflectors follows time-lines (chronostratigraphic surfaces) and not facies-lines (lithological changes).

All this allow geoscientists to stress that, generally, lithological predictions and, particularly, predictions of the most likely reservoir-rocks cannot be made by a simple glance at seismic lines (see chapter 13). They require an exhaustive methodological approach, i.e., a sequential stratigraphic interpretation of seismic lines, that certain geoscientists call Seismic-Stratigraphy, and not a naive inductive picking of the high amplitude reflections. On the other hand, the lithostratigraphy, as defined in the field and, particularly, on the base of geological formations, is not appropriate to be apply in the geological interpretation of the seismic lines. The reflectors follow chronostratigraphic lines.

Time Lines *vs* Facies Lines

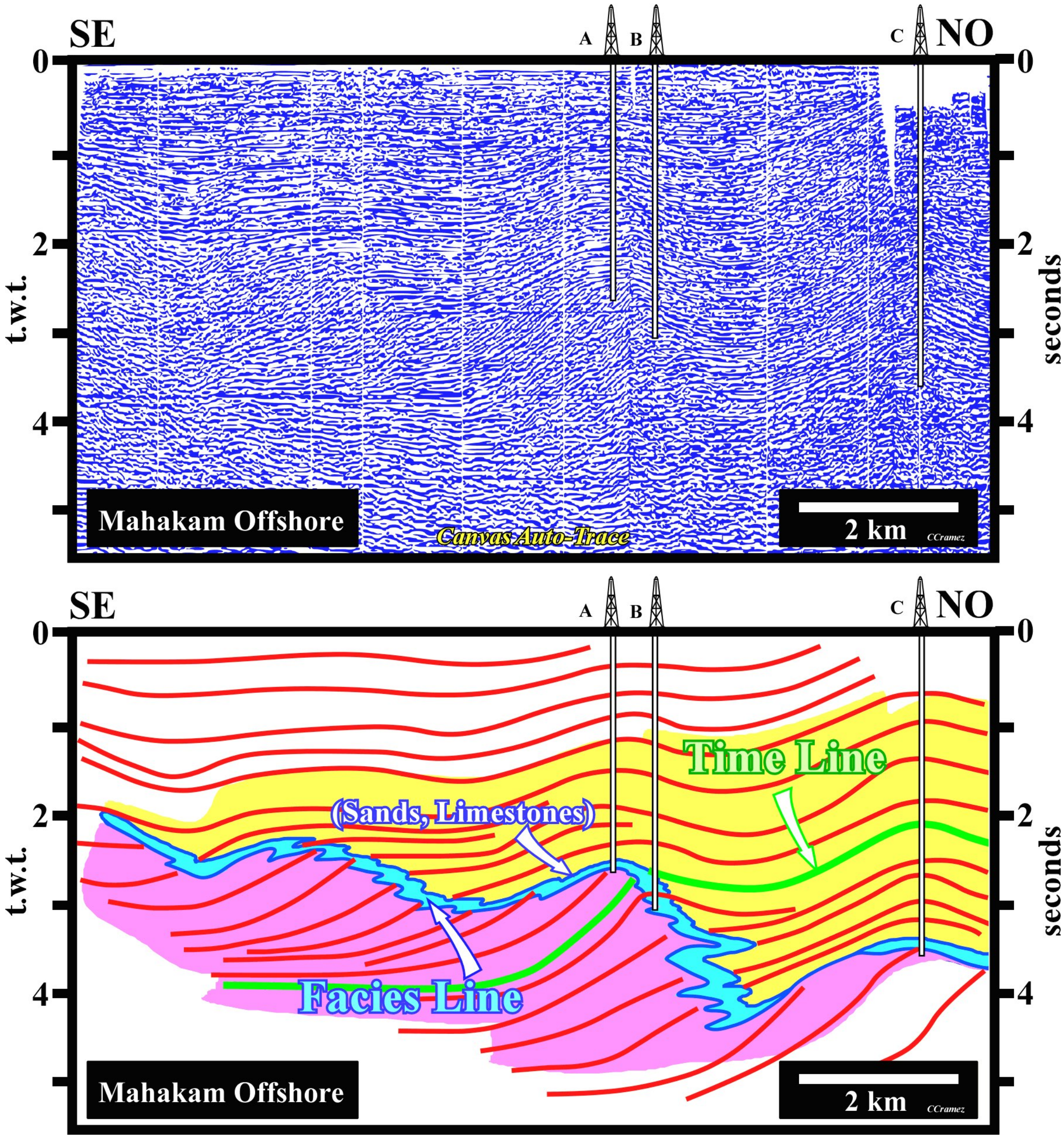

***Figure 2** – This tentative geological interpretation of the seismic line illustrated in Figure 1, based on the patterns of seismic packages and calibrated by the results of exploration wells drilled in the area, corroborates the conjecture that seismic reflectors follow time lines (chronostratigraphic surfaces) rather than facies lines (lithologic surfaces). In this interpretation, it is relatively easy to trace the successive depositional coastal breaks along the chronostratigraphic lines (time surfaces), which, in this particular case—where the basin has no shelf, from a seismic perspective—coincide with the continental breaks. Near the depositional coastal breaks, delta-front sandstones and bioherms (ancient organic reefs or mound-like structures built by a variety of marine invertebrates, including corals, echinoderms, gastropods, and mollusks) were deposited, while delta-plain sediments accumulated landward of the depositional shelf breaks (approximately corresponding to the shoreline). Seaward of the depositional coastal breaks, in the delta slope, which here forms the upper part of the continental slope, claystones were deposited. Considering lithology (facies), the acoustic impedance contrast associated with the blue interval (a facies line) should, in theory, correspond to a strong reflector on the seismic line; however, as seen in the clean seismic line (here represented by a Canvas auto-trace), no reflector is associated with this seismic impedance contrast. Instead, the reflectors correspond to chronostratigraphic surfaces, which cut across facies lines.*

On these notes, we will summarize the main misunderstandings and seismic pitfalls[2] (interpretation traps) that obscure the recognition of petroleum systems[3], which can easily be avoided, particularly in the evaluation of the remaining petroleum potential of onshore and offshore Argentina.

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[2] Pitfalls can be induced by (i) changes in interval velocity, (ii) the geometry of the reflector, (iii) recording, and (iv) playback (software programs retrieving time series of seismic data). While regional interval velocity changes seldom pose significant problems, abrupt velocity variations due to sudden structural changes can have disastrous consequences if not recognized. Common pitfalls include: (a) reverse faults, which create pull-ups; (b) normal faults, which create pull-downs; (c) reefs with underlying pull-ups; and (d) surface or seafloor irregularities that cause coincidental subsurface reversals. Depth sections can be used to mitigate these pitfalls, provided that they are not, in themselves, misleading.

[3] A petroleum system describes the genetic relationship between a pod of active source-rock and the resulting oil and gas accumulations. The petroleum system has a stratigraphic, geographic, and temporal extent. Its name combines the names of the source rock and the major reservoir-rock and also expresses a level of certainty— known, hypothetical, or speculative.

1) Classification of the Sedimentary Basins

Bally and Snelson (1980), using the realms of subsidence, proposed a classification for sedimentary basins (Figure 3). This classification provides a useful framework for understanding the different potential petroleum systems present in geographic depositional depocenters. The mechanisms of subsidence and eustatic change vary over time and space. Sedimentary depositional depocenters, such as the Neuquén and Colorado basins (located onshore and offshore Argentina, respectively), often correspond to a vertical stacking of different sedimentary basins, each with distinct accommodation characteristics and petroleum system parameters.

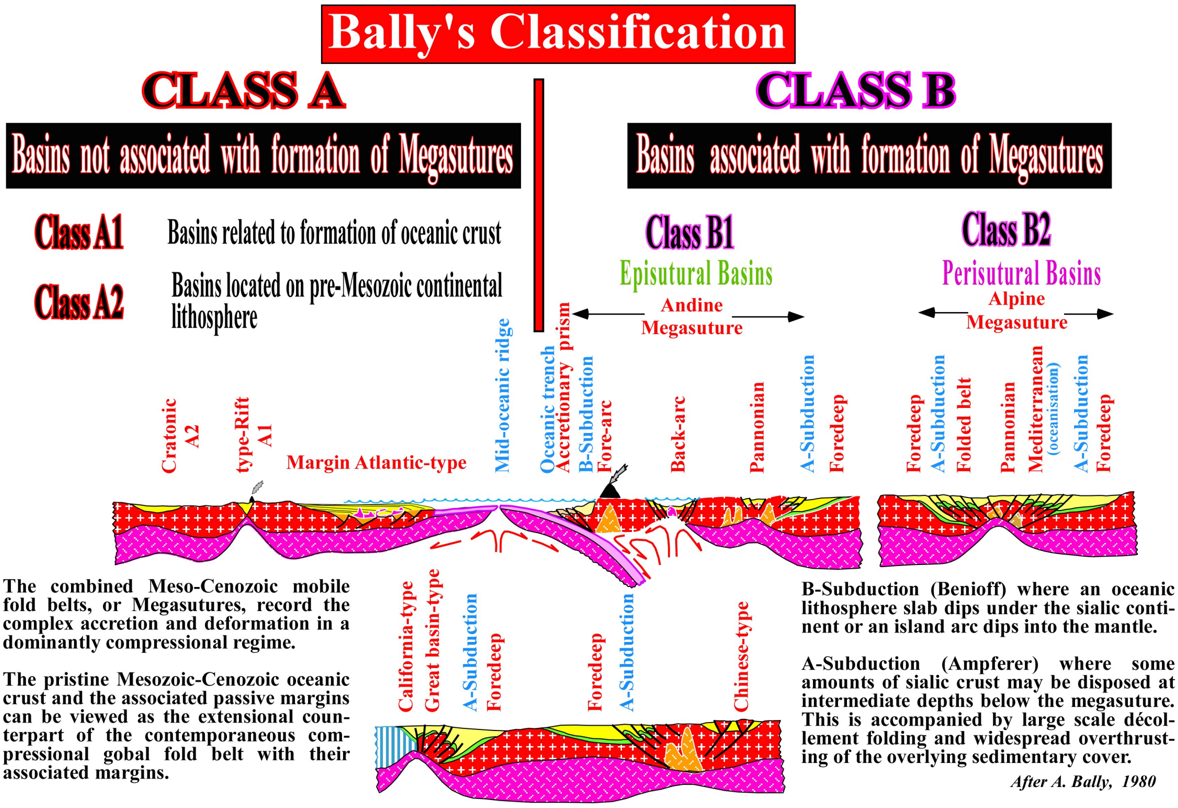

***Figure 3** – In this classification, there are two main families of sedimentary basins: (i) Basins not associated with the formation of mega-sutures (Class A), where extensional tectonic regimes (lengthening) dominate, and (ii) Basins associated with the formation of mega-sutures (Class B), where compressional tectonic regimes (shortening) prevail. Class A basins can be related to the formation of oceanic crust, as seen in Rift-type Basins and overlying Divergent Margin-type Basins, or they can be located on continental lithospheric infrastructure, as in the case of Cratonic Basins. Rift-type basins are primarily characterized by differential subsidence, which results in their half-graben geometry. Divergent margin-type basins (both Atlantic and non-Atlantic) exhibit increasing seaward thermal subsidence, which is responsible for their seaward-dipping fusiform geometry. Cratonic basins are mainly controlled by thermal subsidence, giving them their characteristic sag geometry. Class B basins can be Episutural (located inside the mega-suture) or Perisutural (located around the mega-suture). Episutural basins, such as Fore-arc and Back-arc basins, are associated with B-subduction zones (Benioff-type), while perisutural basins, such as Foredeep basins, are associated with A-subduction zones (as seen in the Alpine and Andean regions). Back-arc basins develop in two sub-basins (often called phases). The lower sub-basin, formed during lithospheric extension in the overriding plate of a B-subduction zone, closely resembles a rift-type basin, as the dominant subsidence mechanism is differential (half-graben geometry). The upper sub-basin, controlled by thermal subsidence, resembles a cratonic basin, where most accommodation space is created by sagging (tectonics), while eustasy primarily controls the cyclicity of sedimentary intervals. Potential source rocks can be found in both sub-basins. In the lower sub-basin (rifting phase), potential lacustrine source rocks are often present, especially when accommodation created by extension is not completely filled by terrigenous influx, allowing the formation of a water column (i.e., a lake). This setting promotes parallel infilling, which is easily recognized on seismic lines by the parallel internal configuration of lacustrine intervals. In the upper sub-basin (sag or cratonic phase), potential marine source rocks are typically associated with lower-middle segments of deltaic progradation, particularly along downlap surfaces (generally secondary). Foredeep basins, associated with A-subduction zones(Ampferer-type), form through flexural subsidence induced by the loading of successive thrust faults from the fold belt. Over time, the fold belt becomes the principal provenance of terrigenous influx. In these basins, potential source and reservoir rocks are often linked to progradational shelf (platform) intervals. Potential turbiditic intervals, which onlap the basal unconformity of the foredeep basin, may also be present, particularly during the initial phase of flexural subsidence. In onshore Argentina, back-arc basins are Triassic–Jurassic in age and are covered by foredeep basin sediments from the Early Cretaceous onward. Additionally, Jurassic–Lower Cretaceous rift-type basins, formed during the extension of Pangea's lithosphere (before its breakup, the most significant geological event in the South Atlantic realm), are present in coastal and offshore areas. These basins underlie the overlying Western South Atlantic Divergent Margin, which was deposited during the opening of the South Atlantic (seafloor spreading). Following the breakup of Pangea, thick subaerial lava flows were deposited immediately above distal rift-type basins (near the breakup zone) and below clastic margin sediments. Some geoscientists include these subaerial lava flows within the margin itself and refer to it as a volcanic margin.*

The accommodation mechanism, that is, the manner in which space is created for sediments through the combined effects of subsidence and eustasy, and particularly the amount of space available, varies from basin to basin. This has significant implications not only for the distribution of reservoir and source rocks but also for the development of non-structural traps. As illustrated in Figure 4, on seismic lines, the stacking of different types of sedimentary basinsfrom Bally's classification, forming the stratigraphic column, is relatively easy to recognize. Such recognition is far more useful for identifying and analyzing potential petroleum systems than the meaningless basin partitioning based on local geological formations, which is often used by naive, inductive geoscientists.

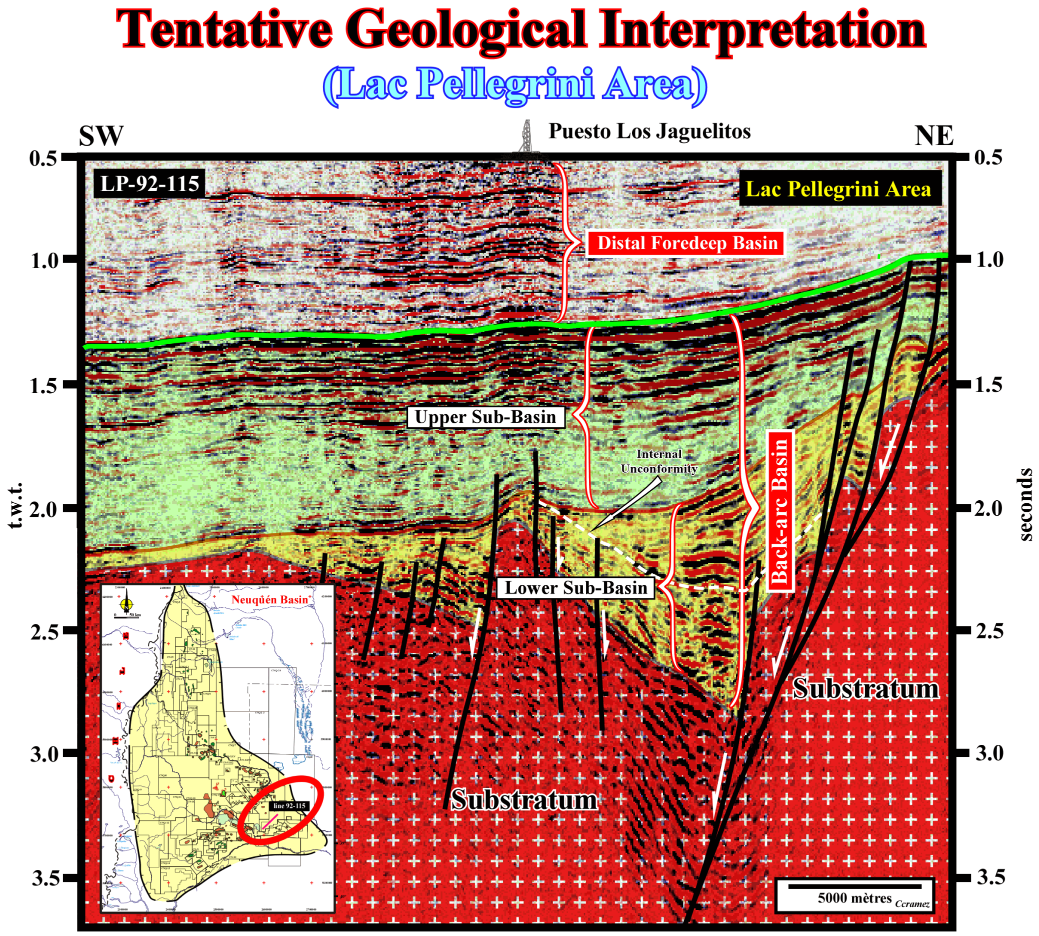

***Figure 4** – On this tentative geological interpretation of a seismic line from the Neuquén geographic basin (see location on the map in the lower-left corner of the plate), a geoscientist with prior knowledge of the geology of the Neuquén areaand Bally's basin classification can easily recognize, from bottom to top: (i) the Paleozoic sedimentary Pangea lithosphere (substratum), since southward of a line from Córdoba to Buenos Aires, the infrastructure of the Meso-Cenozoic sediments consists of the Paleozoic mega-suture rather than the Precambrian mega-suture, as is the case northward; (ii) the lower sub-basin (rifting phase) of the back-arc basin, where a significant unconformity is suggested by an onlap seismic surface defined by reflection terminations; (iii) the upper sub-basin of the back-arc basin (sag or cratonic phase); and (iv) the distal part of the foredeep basin (eastern section). The geometry and internal configuration of the lower sub-basin of the back-arc basin strongly suggest differential subsidence and volcanic-clastic infilling below the onlap seismic surface (unconformity), with lacustrine sediments deposited above, indicating the potential presence of lacustrine source rocks. The internal configuration of the upper sub-basin of the back-arc basin (sag or cratonic phase) suggests thermal subsidence, with sediments deposited in a shallow marine environment (platform sediments), some of which exhibit a clear progradational geometry, implying the possible presence of adjacent potential reservoir and source rocks, highly favorable for the development of non-structural traps. The presence of foredeep sediments in this area contributes primarily to the maturation of organic matter within the potential source rocks of the back-arc basin.*

Nevertheless, Bally's classification, like all other basin classifications, does not allow for the prediction of hydrocarbon volumes generated and preserved within different families of sedimentary basins. However, it provides a structured approach that guides geoscientists to make geological observations controlled by plate tectonics, which is fundamental to any advancement in oil exploration.

The application of this basin classification, in combination with a sequence stratigraphic interpretation of seismic lines, has immediate benefits for evaluating the remaining petroleum potential of geographic depositional depocenters, particularly in regions where structural petroleum exploration is mature or over-mature, as is the case for all Argentine back-arc basins. In fact, this combination enables a more accurate assessment of petroleum system parameters, facilitates the identification of potential non-structural traps (such as stratigraphic traps and morphological traps by juxtaposition), and allows for the rapid identification of key petroleum parameters, particularly those that could alone determine the viability of a basin or prospect from a petroleum exploration standpoint.

Geoscientists must try, for each type of sedimentary basin considered in a given depositional area, to characterise, in regional terms, the various petroleum parameters and emphasising those that look most important:

(i) Source-rock (presence and maturation);
(ii) Reservoir-rock (presence and characteristics);
(iii) Trapping;
(iv) Migration;
(v) Retention.

Assuming, for instance, the presence of source rocks (with organically mature matter) in a sedimentary basin associated with a mega-suture, the principal petroleum parameter - the killer parameter in conventional structural exploration -is migration (its age and type). Since the basin is situated in a globally compressive tectonic realm, sooner or later, the sediments, including any pre-existing extensional structures, will undergo shortening. Therefore, in this type of basin, the age of hydrocarbon migration relative to tectonic shortening is the key petroleum parameter, as migration must postdate potential trap formation for hydrocarbons to be successfully retained.

When structural petroleum exploration is mature or over-mature, meaning that the vast majority of structural traps(four-way dip closures) have already been tested (drilled), it does not mean that there is no more petroleum left to be discovered. Rather, it indicates that geoscientists must adopt a different exploration approach, primarily based on detailed sequence stratigraphic interpretations (P. Vail) and/or genetic stratigraphic interpretations (W. E. Galloway) within the different realms of subsidence, that is, within the various types of Bally's sedimentary basins - providing yet another reason to adopt this classification.

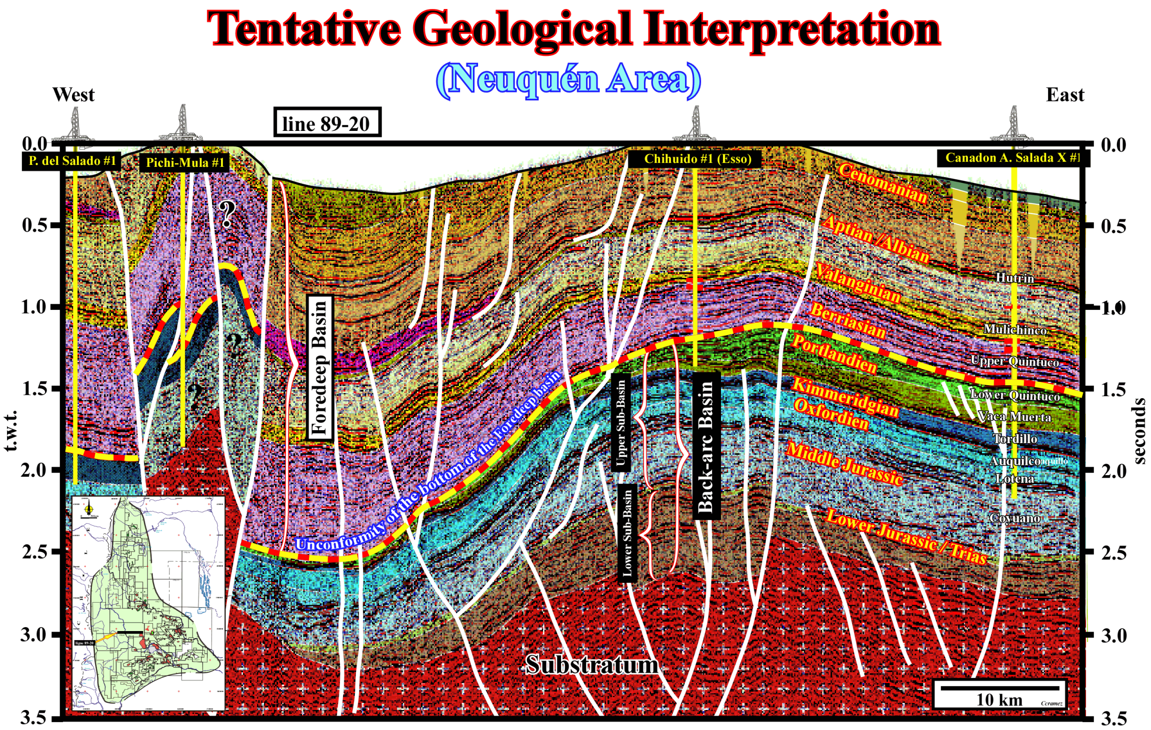

Figure 5 – On this tentative geological interpretation of a seismic line from the central part of the geographic Neuquén Basin (passing through the Chiuido #1 well location), the geoscientist who performed the interpretation not only identified, on the seismic line, the two types of sedimentary basins that compose the depocenter, positioned above the substratum, but also proposed a sequential interpretation in terms of continental encroachment sub-cycles. Additionally, by using the results from the Canadón A. Salada X-1 well, it became evident that seismic calibration in terms of geological formations is meaningless, particularly regarding the Quintuco and Vaca Muerta Formations. In fact, the Upper Quintuco Formation lies above the basal unconformity of the foredeep basin, meaning it belongs to the foredeep, while the Lower Quintuco Formation belongs to the upper sub-basin (sag or cratonic phase) of the back-arc basin. Furthermore, it is evident that the Vaca Muerta Formation, which is the major source rock in the area, corresponds only to the lower segment of Upper Jurassic progradations, which are easily recognizable on seismic data. Consequently, this formation does not represent a chronostratigraphic interval but rather a lateral stacking of diachronic intervals rich in organic matter. A simple glance at the seismic data strongly suggests the presence of several other lateral diachronic intervals, not only in the upper sub-basin of the back-arc basin but also in the foredeep basin. The basal unconformity of the foredeep basin is clearly visible on this seismic line. Like all other unconformities, it represents an erosional surface. In the proximal area (i.e., near the fold belt), this unconformity is characterized by the onlapping of foredeep deep-marine sediments against the tilted back-arc sediments. In the distal area, it is mainly characterized by the toplapping of shallow-water sediments from the back-arc basin, where toplaps result from the outward migration of the bulge anomaly. In fact, in the distal area, the progradation of foredeep sediments preserving the erosional surface is not always very evident, as the angle of the slope is too small. It is also worth noting that in certain seismic lines from this area, immediately overlying this unconformity, there is a complex downlap surface marking the distal terminations of foredeep sediment progradation.

As in the Neuquén area, where the vast majority of structural traps (four-way dip closures, in which the maps of the reservoir top and sealing rocks are interchangeable) have already been tested, the remaining petroleum potential is primarily associated with non-structural traps (stratigraphic, morphological, and morphological by juxtaposition), particularly in areas where a non-negligible hydrodynamic component is present. To effectively target these non-structural traps, the cartography of the boundaries of different basins

and sub-basins, particularly using seismic lines, represents the first step in the remaining exploration process. This type of cartographic analysis is often challenging for junior geoscientists. However, considering that these basin boundaries correspond to genetic changes in subsidence (lengthening, thermal contraction, and flexural subsidence), they can be recognized indirectly through careful seismic interpretation.

A priori, one can say:

a) When subsidence is due to lengthening (half-graben or rift-type basins), the sedimentary fill is predominantly non-marine and, at the seismic scale, it is mainly aggradational. The progradation of a deltaic depositional system is likely the simplest geological mechanism of infilling. However, on conventional seismic data, the depositional sedimentary breaks associated with deltaic progradation are often below seismic resolution.

b) In a back-arc basin (thermal contraction), the sedimentary infilling is predominantly aggradational, meaning the internal configuration geometry is mainly aggradational rather than progradational. The progradation of deltaic depositional systems is likely the simplest geological mechanism of infilling. However, on conventional seismic data, depositional sedimentary breaks associated with deltaic progradation are only clearly evident when the basin lacks a shelf, meaning the delta slope reaches depths of 100–200 meters.

c) When subsidence is flexural, sedimentary prisms develop, with their progradation controlled by tectonic loading. Only in the proximal and deep areas of foredeep basins (i.e., in the turbiditic realms) does the geometry remain aggradational. On seismic data, the lower boundary of foredeep basins, marking the onset of flexural subsidence, is often underlain by a major downlap surface, visible as distal reflection terminations due to the successive progradation of sedimentary prisms away from the fold belt.

Summing up : When using seismic data, geographic depositional basins such as the Neuquén Basin or San Jorge Basin must be subdivided in time and space based on the genetic changes in subsidence (lengthening, thermal contraction, flexural subsidence, etc.) rather than relying on geographic, inappropriate, or meaningless classifications (e.g., rift, post-rift, synrift, sag) or geological formations such as Vaca Muerta, Quintuco, etc..

2) Geological Interpretation is Scale Dependent

Despite the fact that all geologists understand that in Geology, the scale is 1:1 (natural scale), geoscientists working in oil companies often tend to overlook this principle, frequently producing documents without scale or tentative geological interpretations that fail to consider the scale of observed features. Additionally, they often neglect the effects of scale exaggeration in their working data, such as geological cross-sections, depth seismic sections, and time seismic lines. On this subject, the figure below (Figure 3), proposed by Sitter in 1974, is highly significant.

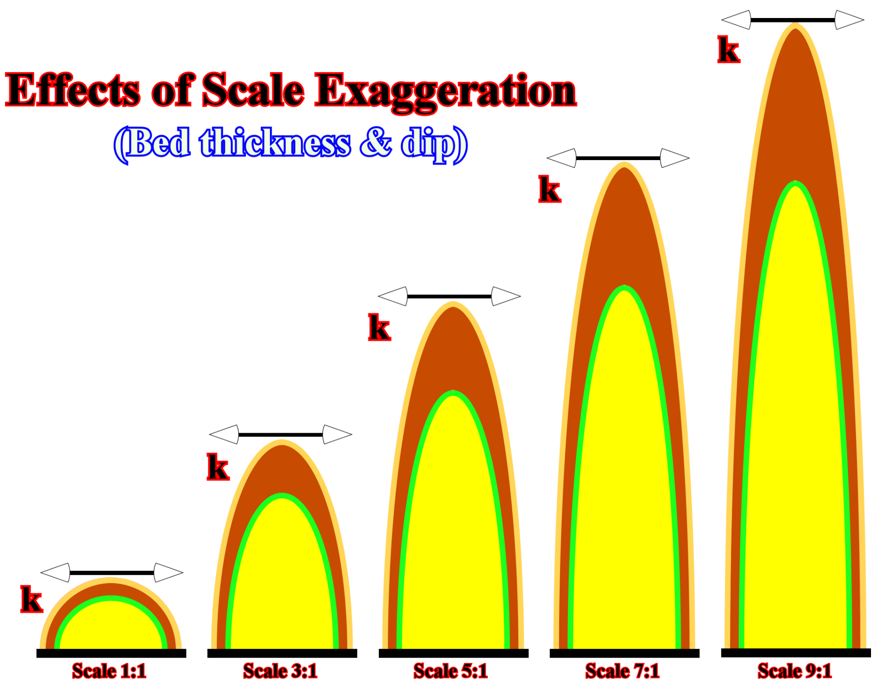

Figure 6 – The appearance of an ideal isopach anticline (shortened structure) or an antiform (lengthened structure without significant normal faults at the top) as observed in the field (scale 1:1) can vary significantly when represented on paper (A4 = 21 cm × 29,7 cm), depending on the vertical exaggeration applied by the geoscientist. The thickness and dip of the beds are strongly altered by this exaggeration (after Sitter, 1974).

How often is a proposed tectonic inversion (where low structural points become high structural points and high structural points become low structural points, as in a salt-induced turtle-back structure) refuted (falsified) simply because the geoscientist overlooked the fact that a greater thickness interval at the top of an antiform structure could be purely due to vertical scale exaggeration, as illustrated in Fig. 6.

The same issue applies to the dip of beds and the dip of fault planes, whether on geological cross-sections (Figure 7) or on seismic lines (Figure 6). In all tentative geological interpretations, geoscientists must always remember that the fault plane dips predicted by Anderson's fault theory (normal faults ~60°; reverse faults ~30°; strike-slip faults ~90°, with common exceptions for thrust faults and low-angle normal faults, which are mechanically unfavorable) are only valid in documents at natural scale (1:1), as illustrated in Fig. 7.

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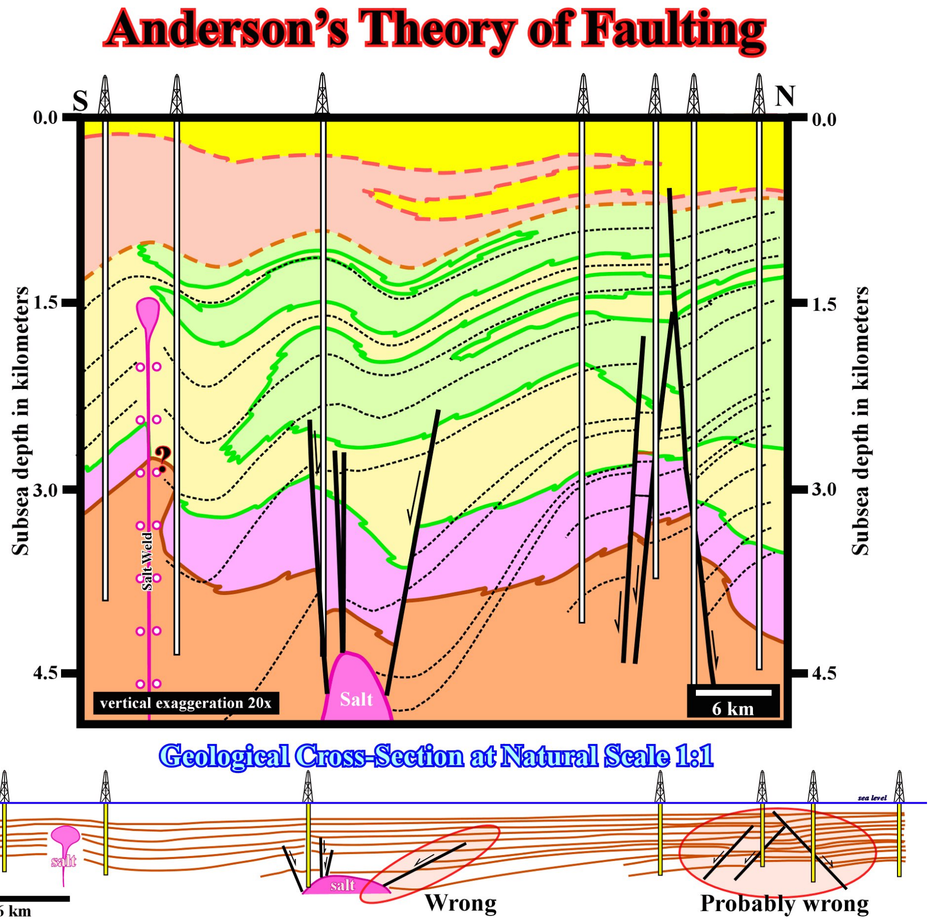

Figure 7 – The above original cross-section, taken from a non-confidential geological publication, illustrates the dangers of ignoring scale exaggeration and highlights how fragile (easily falsifiable) an uncritical geological cross-section or a tentative seismic interpretation can be. Although the original geological cross-section is in depth (with both vertical and horizontal scales in metric units), the vertical exaggeration is approximately 20× (twenty times). Theoretically, this means the fault planes should appear nearly vertical, which is not the case in the interpretation shown. Particularly striking is the dip of the four northern faults. A simple conversion of this cross-section to natural scale (1:1) clearly invalidates the fault plane traces, as they fail to conform to Anderson's fault theory—the fault angles are far shallower than the expected ~60° for normal faults. Notice that these faults are described as normal faults, which seems plausible given that they were induced by sedimentary extension caused by salt diapirism. In reality, the supra-salt structures are antiforms (extensional structures) rather than anticlines (compressional structures). Beyond the dip of the faults, the proposed cross-section is further invalidated by the rectilinear geometry of the fault planes. If these faults are relatively old, meaning they formed before compaction of the sedimentary column, which consists of a sand–shale succession, then the fault planes should not be rectilinear. Even if the original geometry (before compaction) of the fault planes was relatively straight, post-compaction adjustments would lead to variable dips, with shallower dips in more compactable shale intervals and steeper dips in less compactable sand intervals. This effect results in rollover structures (antiforms) in the hanging wall, juxtaposed against the less compactable (sand-prone) intervals. This rollover geometry is frequently used in sand–shale depocenters, such as in the Gulf of Mexico, by many geoscientists to predict potential sand-prone reservoir intervals in the footwall, which may form morphological traps by juxtaposition (incorrectly referred to as "traps against faults" by many geoscientists). In the footwall of a normal fault with opposite dip direction (where the fault plane dips opposite to the strata), the geometry is favorable for trapping hydrocarbons by juxtaposition—specifically, where a footwall reservoir rock is juxtaposed against a hanging wall sealing rock. However, the success of such an interpretation relies on accurately locating potential reservoir-prone intervals in the footwall. Theoretically, the most likely footwall reservoir intervals (i.e., less compactable sand intervals) correlate with the steeper segments of the fault plane trace. Summing up, one can say that in the field and especially on seismic data (where interval velocity increases with depth), there are no pre-compaction rectilinear faults. Additionally, the dips of fault planes—after accounting for dip variations caused by sedimentary compaction—must still conform to Anderson's fault theory.

The effects of scale exaggeration are also quite evident on seismic lines, not only because the vertical scale is in time, which is completely different from the horizontal scale (which is in metric units), but also due to display reasons. In practice, most conventional seismic lines (both in time and depth domains) have a vertical scale exaggerated by a factor of 3 to 5, as illustrated in Figure 8. Consequently, as mentioned earlier, the dips and thicknesses observed on seismic sections do not represent their true values. Additionally, as will be shown later, the thickness of a seismic interval is also affected by lateral variations in interval velocity, particularly in cases where there is a lateral facies change (change in lithology).

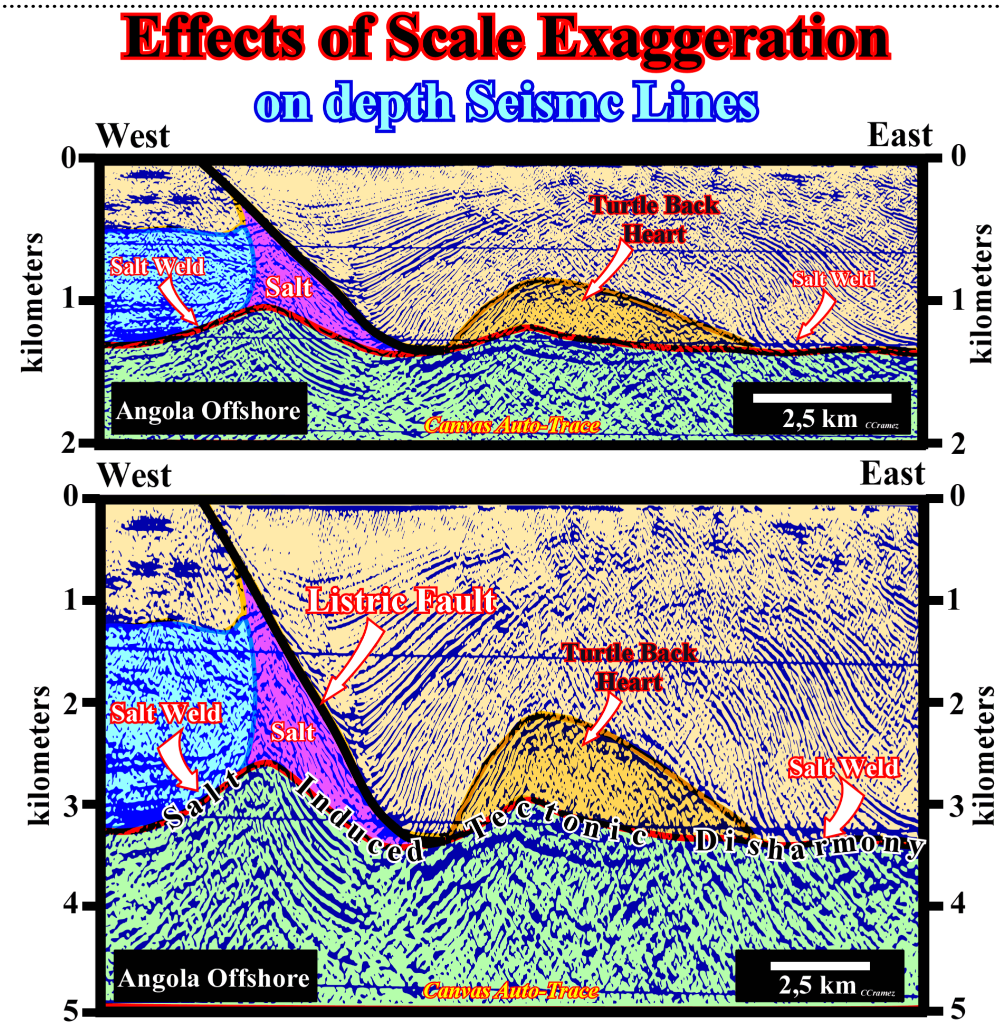

Figure 8 – Both seismic lines are in depth to eliminate the seismic pitfalls nduced by the time vertical scale of conventional seismic lines, which will be discussed later. However, it is important to note that this time-to-depth conversion is not perfect. The tectonic disharmony induced by the salt interval (present in this offshore area) should be approximately horizontal rather than undulated. The same applies to the seismic reflectors underlying the salt roller beneath the listric fault (the term listric fault is used here synonymously with curvilinear fault). By definition, a listric fault is a curvilinear fault that exhibits normal fault geometry in the upper part and reverse fault geometry in the lower part, as observed in slumping. The seismic line on the right is at natural scale (1:1), where the horizontal and vertical scales are equal, meaning that the dips of the seismic reflectors and the dip of the fault plane bordering the depocenter above the turtle-back structure are true to reality. In contrast, the seismic line in the lower part has a vertical scale exaggerated by a factor of 2.5× relative to the horizontal scale. As a result, the thickness between chronostratigraphic lines (reflectors) and the dip of the reflectors are artificially exaggerated and do not represent their actual values.

If a geoscientist (observer) does not know the scale of the observed, all proposed geological interpretations will be wrong (serendipity exists, but it is uncommon). This is particularly true when a geoscientist tries, tentatively, to interpret seismic data, in geological terms, in a naive personal manner. Never forget that you do not see with your eyes by with your brain. In fact, just before, when you looked at the tentative geological interpretations of the seismic lines illustrated in figure 8, electromagnetic waves, in the form of white light, illuminated the tentative interpretations. Part of the white light was absorbed and part reflected. Specific wavelengths entered your eyes, stimulating the retinal cells, causing complex chemical and electrical changes in your brain and end up at the visual centre at rear of your brain. So you see with your brain an internal representation of the tentative interpretations and not the reality. If your brain had already stocked an image of a turtle back, in other words, if you know what is a salt induced turtle back structure, you easily recognise it on the tentative interpretation. On the contrary, if you brain has not yet in stock the image of a turtle back, i.e., if you do not know, a priori, what is a turtle back structure, you can look at the tentative interpretations during hours and you never see a turtle back. In fact, you see just what you know or, in philosophic words, Theory precedes Observation. By the same token, the clean seismic lines used on the tentative interpretations, that is to say, the seismic lines not interpreted, represent, in time, a copy of the reality. On the other hand, not every geoscientist sees the same colours that you saw on theses tentative interpretations (adapted from Robinson, D. 2005).

You can easily test the following conjecture[4] : "If a geoscientist (observer) does not know the scale of the observed (seismic line, for instance), all proposed geological interpretations will be incorrect. » using Figure 9 by following these steps:

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[4] A geological hypothesis or conjecture can be refuted, corroborated or validated, but never verified. Corroboration is not synonym of verification. In fact, a hypothesis can be corroborated by observations and experimentations, but it can never be verified. The truth in science does not exist. Actually, it is impossible to demonstrate the truth of any proposition, except in a closed system. Geological models are never closed systems. Observation and measurements have both independent and dependent variables. They are laden with inferences and assumptions.

(i) First, look at Figure 9, but ignore the tentative geological interpretation of the seismic line with scales (do not cheat).

(ii) Using the tentative geological interpretation on the left side (seismic line without scales), try to propose a geological interpretation for the progradations within the yellow interval.

(iii) Finally, refute your interpretation by comparing it with the seismic line illustrated on the right side of the figure, which includes scales.

This simple exercise demonstrates how lack of scale awareness can lead to misinterpretations, reinforcing the critical role of scale in geological analysis.

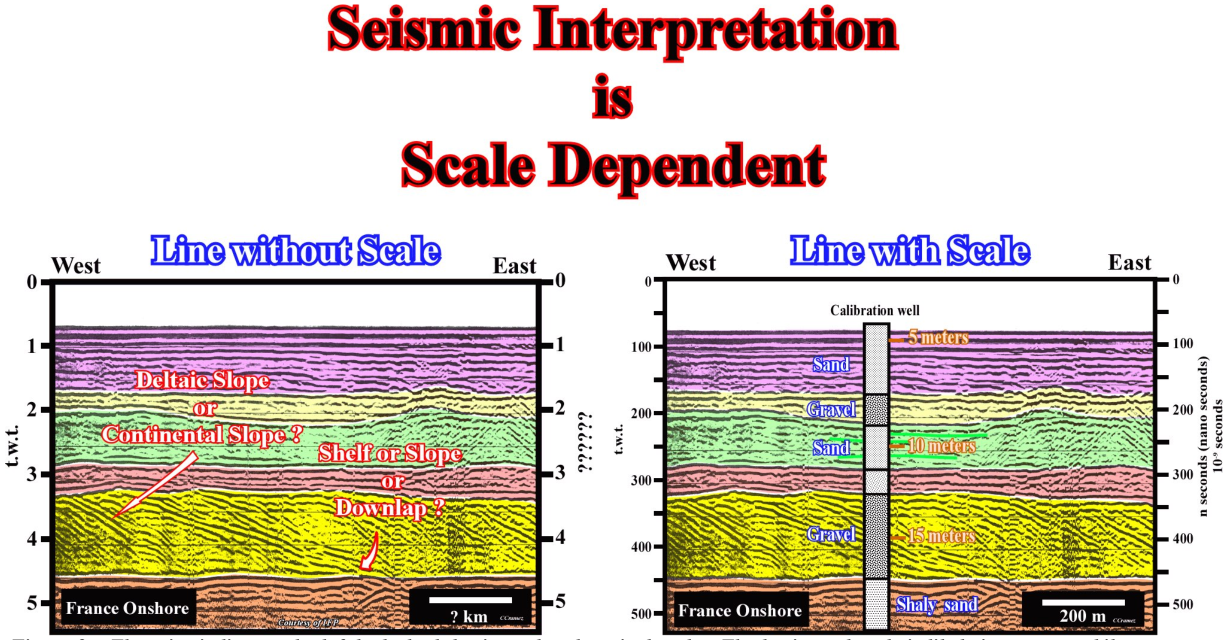

Figure 9 – The seismic line on the left lacks both horizontal and vertical scales. The horizontal scale is likely in meters or kilometers, while the vertical scale is generally in time (most often in seconds). Any tentative geological interpretation of this seismic line, particularly concerning the dipping reflectors, would be nothing more than a guess, with a high probability of being refuted by new data. Without knowing the slope amplitude of the oblique progradations (no upbuilding, only outbuilding) visible within the yellow interval, a geoscientist cannot determinewhether these progradations correspond to deltaic slopes, continental slopes, or other depositional slopes. By examining the seismic line on the right, the geoscientist can identify that the horizontal scale is approximately 200 meters and that the vertical scale is in nanoseconds (a typical vertical scale for ground-penetrating radar (GPR) data). With this information, they can hypothesize that the progradations correspond to oblique stratifications, a hypothesis that is not falsified by the results of the well located on the seismic profile.

In order to interpret seismic data in geological terms, the data must always have a scale (preferably a graphic scale), and the geoscientist must know which geological realm the data belongs to: (i) Microscopic, (ii) Mesoscopic, or (iii) Macroscopic.

The microscopic realm, as the name suggests, is the domain of objects and events smaller than those visible to the naked eye. It is the domain of optical mineralogy and petrography, where geoscientists study thin sections—laboratory preparations of rock or mineral samples approximately 30 µm thick.

The mesoscopic realm, as defined by C. E. Wegmann (1950), is the domain of continuity as observed in outcrops, where geological features can be seen in lateral continuity. In physics, the mesoscopic scale is a sub-discipline of condensed matter physics, dealing with materials at an intermediate length scale—between atomic structures and materials measuring in micrometers. In geology, the mesoscopic realm is a direct consequence of the principle of lateral original continuity, which states that "sedimentary layers are deposited in lateral continuity." However, this principle acknowledges that lateral continuity may disappear due to erosion or tectonic movements. Sediments are originally connected at the time of deposition but may later become separated due to processes such as river valley formation. Unconformity time gaps may represent prolonged subaerial exposure with minimal erosion, localized valley/channel downcutting, uplift and major erosion of strata, or submarine erosion by turbidites, slumps, or ocean currents. This discontinuity, which defines the limits of the mesoscopic scale, is widely recognized today but was difficult to explain in the 17th century.

The macroscopic realm is the domain of geological and seismic maps, as well as seismic lines, where geological and seismic features generally lack continuity. This discontinuity is particularly evident in seismic data, where sequence cycles and continental encroachment sub-cycles cannot always be traced continuously. Similarly, seismic reflectors (chronostratigraphic surfaces) and unconformities (erosional surfaces) are often disrupted by lateral changes in acoustic impedance. Given that geological features exhibit self-similarity and scale invariance, it is at the macroscopic realm—when working with seismic data—that geoscientists must avoid realm misunderstandings. For example, they must not mistake an oblique stratification (mesoscopic realm) for a deltaic slope (macroscopic realm) or a continental slope.

> **Summing up** : Geoscientists should never work with seismic lines or geological maps that lack scale and location. Likewise, they should avoid presenting or including geological or seismic data without scale in reports or presentations (except for confidentiality reasons). All tentative geological interpretations must be falsifiable (scientific) rather than metaphysical—i.e., they should not be statements that are always right, such as "all source rocks are rich in organic matter." If interpretations are not falsifiable, neither the geoscientist nor the company they work for will make progress in petroleum exploration. A geoscientist must constantly challenge their own interpretations and allow others to do the same. However, for this to happen, the correct scale and location must always be included in the data—because "Petroleum exploration knowledge progresses by trial and error."

2.1) Deltaic and Continental Slopes

A deltaic slope is generally defined landward of the shelf break, within the platform, at a water depth of less than 200 meters. In contrast, a continental slope extends from the continental margin to the beginning of the ocean basin, at depths greater than 200 meters. Using modern deltas (Niger, Rhône, Rhine, and Mississippi) as references, the length of deltaic plains (a) and delta slopes (b), as well as the height of the delta (4) and the delta slope (3), are quite significant—particularly the latter two—as illustrated in Figure 10.

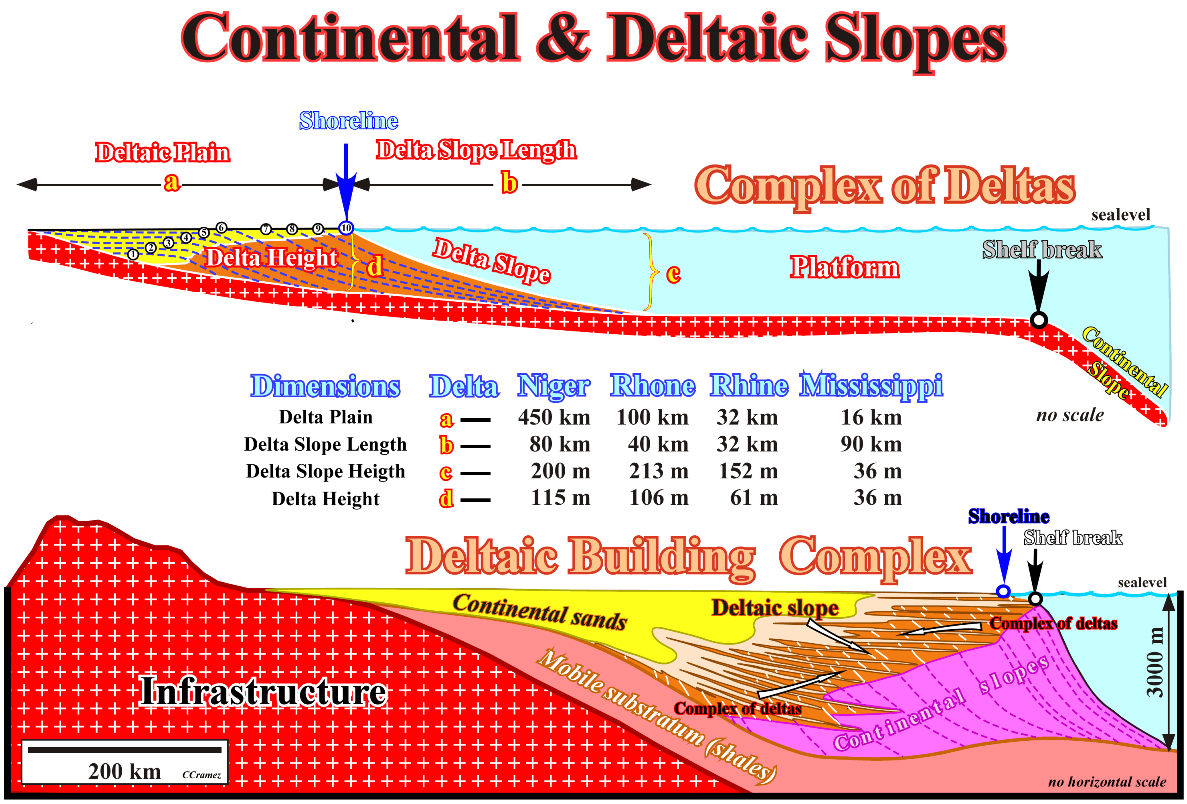

Figure 10 – The height of a delta rarely exceeds 100 meters, whereas the thickness of a deltaic building complex (a vertical stacking of delta complexes, i.e., lateral accretions of deltas) can exceed 3000 meters. In other words, the height of deltaic progradation rarely surpasses seismic resolution, while the height of a continental slope progradation is well above seismic resolution. In highstand geological conditions, deltaic progradations, which can be oblique (no upbuilding, only outbuilding) or sigmoidal (both upbuilding and outbuilding), occur landward of the shelf break (summit of the continental slope, coincident with the basin edge). In lowstand geological conditions, deltaic progradations occur seaward of the basin edge, as the basin has no shelf. As illustrated in the upper sketch, when a sedimentary basin has a shelf (i.e., a continental platform with water depths between 0 and 200 meters), which always happens during the transgressive systems tract of a sequence-cycle, the shoreline is landward of the shelf break, and a condensed stratigraphic section, deposited under starved sedimentary conditions, may be present between the bottom of the pro-delta (delta slope base) and the shelf break. Under such conditions, delta slopes are completely disconnected from continental slopes (landward), which is not the case when the shoreline is near or coincides with the shelf break, meaning the basin has no shelf. Within a sequence-cycle, starting from the onset of highstand systems tracts, the continental platform narrows progressively as the shoreline approaches the shelf break. In a deltaic building complex (a vertical stacking of delta complexes), as illustrated in the lower geological sketch, one can say that, globally and especially in seismic data (where resolution is approximately 30–50 meters), the basin has no shelf, as the shoreline is nearly coincident with the shelf break (also the basin edge). Under these conditions, delta slopes are often connected to the uppermost part of the continental slope. However, in detail and particularly at a natural scale (in the field), it is evident that each relative sea level rise creates a temporary shelf, which is rapidly filled by the progradation of deltaic systems until the next relative sea level rise. Between each paracycle within a sequence-cycle, there is no relative sea level fall, but rather a stillstand of relative sea level, during which the shoreline progrades seaward, depositing deltaic systems. Consequently, when a geoscientist identifies lowstand conditions on a seismic line (a basin with no shelf), they cannot assume the absence of shelf deposits (e.g., deltaic systems). These deposits may be present, but their thickness could be below seismic resolution.

On seismic lines, delta slopes are often below seismic resolution, whereas continental slopes are well above it. However, in the absence of scale, their self-similarity makes differentiation a challenging and, in many cases, impossible task [5]

The next Canvas auto-trace of a seismic line shot in onshore Texas (Figure 11) illustrates the outbuilding of the Late Cretaceous Woodbine complex of deltas. The deltas forming this complex are destructive deltaic systems with progradational channel-mouth bars. Woodbine deltaic systems are often classified as marine-influenced due to the poor development of constructional sequences, the formation of embayments and associated strand-plains[6], the presence of well-developed coastal barriers proximal to areas of maximum discharge, relatively thin pro-delta facies, and a high sand-to-mud ratio with poorly developed muddy delta plain aggradational deposits. However, these deltas are not classified as marine-influenced.

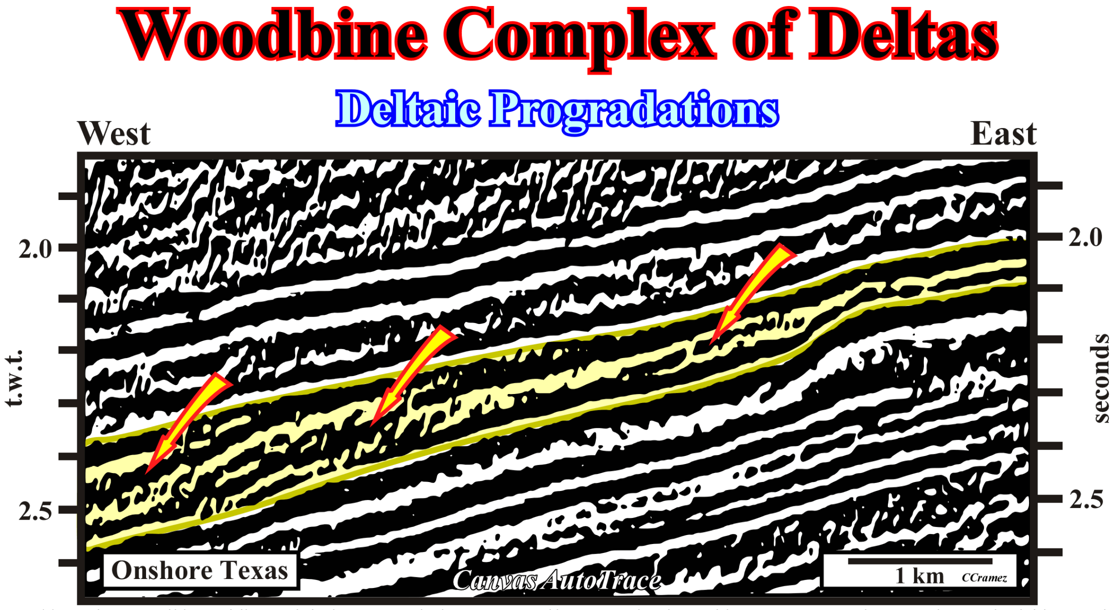

Figure 11 – The Woodbine oblique deltaic progradations are easily recognized on this auto-trace. They are located within a seismic interval bounded by two unconformities induced by two relative sea level falls, which created two erosional surfaces. In sequence stratigraphy, this seismic interval (colored in yellow) likely corresponds to a sequence-cycle, provided that the age difference between the two unconformities is less than 3–5 million years. Its maximum thickness (at least in this seismic line) is around 200 milliseconds (double time), which excludes a continental slope interpretation for the internal dipping reflectors responsible for the oblique configuration. Such a realistic sequence-cycle is formed by the lateral accretion of stratigraphic paracycles, which themselves consist of the lateral accretion of depositional systems. The oblique internal configuration results from the lateral accretion of paracycles, characterized by significant outbuilding (progradation) and minimal or no upbuilding (aggradation) of the shoreline, often associated with the lateral accretion of deltas (complex of deltas). Each delta, represented by an oblique progradation (time line), corresponds to a depositional systems tract, generally composed of three different depositional systems (pro-delta, delta front, and delta plain). Each depositional system is characterized by its distinct lithology and associated fauna. Based on this figure and Figure 10, we can conclude: (i) Each progradation represents a delta; (ii) Each delta, emphasized by a progradation (here oblique), is generally composed of three coeval and genetically related depositional systems; (iii) Each depositional system is characterized by a distinct lithology and fauna; (iv) A lateral accretion of deltas forms a complex of deltas; and (v) A vertical stacking of delta complexes forms a deltaic building complex.

Theoretically, delta depositional systems are relatively complex; however, they can be summarized into three main environments: (i) Pro-delta (bottom-set), (ii) Delta front (fore-set), and (iii) Delta plain (top-set). Generally, and particularly in the deltas of the Woodbine complex, the pro-delta represents the deepwater portion of the deltaic system. It consists of muddy facies with varying amounts of marine fossils and intermittent fine sands, as the pro-delta environment transitions into the delta front. The pro-delta is characterized by a coarsening-upward lithological succession, where muddy lithology progressively grades into sandier lithology of the delta front. The pro-delta front muds tend to transition into interbedded, flat-laminated sands. Delta progradation can result in delta plain lithologies overlying the delta front sands; however, delta front sands can be eroded by the progradation of the channel over the mouth bar. The facies of the pro-delta environment greatly depend on sediment transport, deposition, and reworking processes. The delta front is the zone of most abundant sedimentation and progrades outward over the pro-delta muds. It consists of a slope of offlapping clinoforms, which gradually grades into the sandier facies of the delta plain. The delta front is more strongly influenced by fluvial sedimentation than the pro-

[5] In fact, for a long time, I have noticed that when a geoscientist responsible for geological interpretation of seismic dataspeaks about deltaic progradations, they often mean continental progradations. If you don't believe me, test this conjecture yourself. The next time you are having lunch with your colleagues (also geoscientists) in the canteen, casually ask them: "What is the height of a delta?" You will likely be surprised by their answers. If you are still unconvinced, follow up by asking: "Is a delta deposited during highstand or lowstand geological conditions?" (i.e., when sea level is above or below the seaward edge of the continental platform, if one exists). Then, ask: "Does a delta form when the relative sea level falls or rises?" After listening to their responses, do not immediately draw any conclusions.

[6] A strand plain or strand-plain is a broad belt of sand along a shoreline, characterized by a surface with well-defined parallel or semi-parallel sand ridges separated by shallow swales. A strand plain differs from a barrier island in that it lacks lagoons or tidal marshes, which typically separate barrier islands from the shoreline to which the strand plain is directly attached. Additionally, the tidal channels and inlets that cut through barrier islands are absent in a strand plain. Strand plains typically form through the redistribution of coarse sediment by waves and longshore currents on either side of a river mouth. As a result, they are considered part of a wave-dominated delta.

delta environment. It contains sands, silts, and muds, which overlie the mudstones of the pro-delta, forming flat to wavy-laminated, coarsening-upward sandsinterbedded with silts and muds. The delta plain is the emergent portion of the deltaic system, where sedimentation occurs in distributary channels, levees, splays, lagoons, tidal flats, and marshes. It consists of sands, silts, and clays, with organic matter, coal, or peat present in marsh environments.

As stated previously, continental slopes are characterized by large and tall progradations, which are easily recognized on seismic lines, as illustrated in the next tentative geological interpretation (Figure 12). Their geometry is generally sigmoidal, with significant upbuilding and outbuilding between successive progradations deposited during a decelerated relative sea level rise.

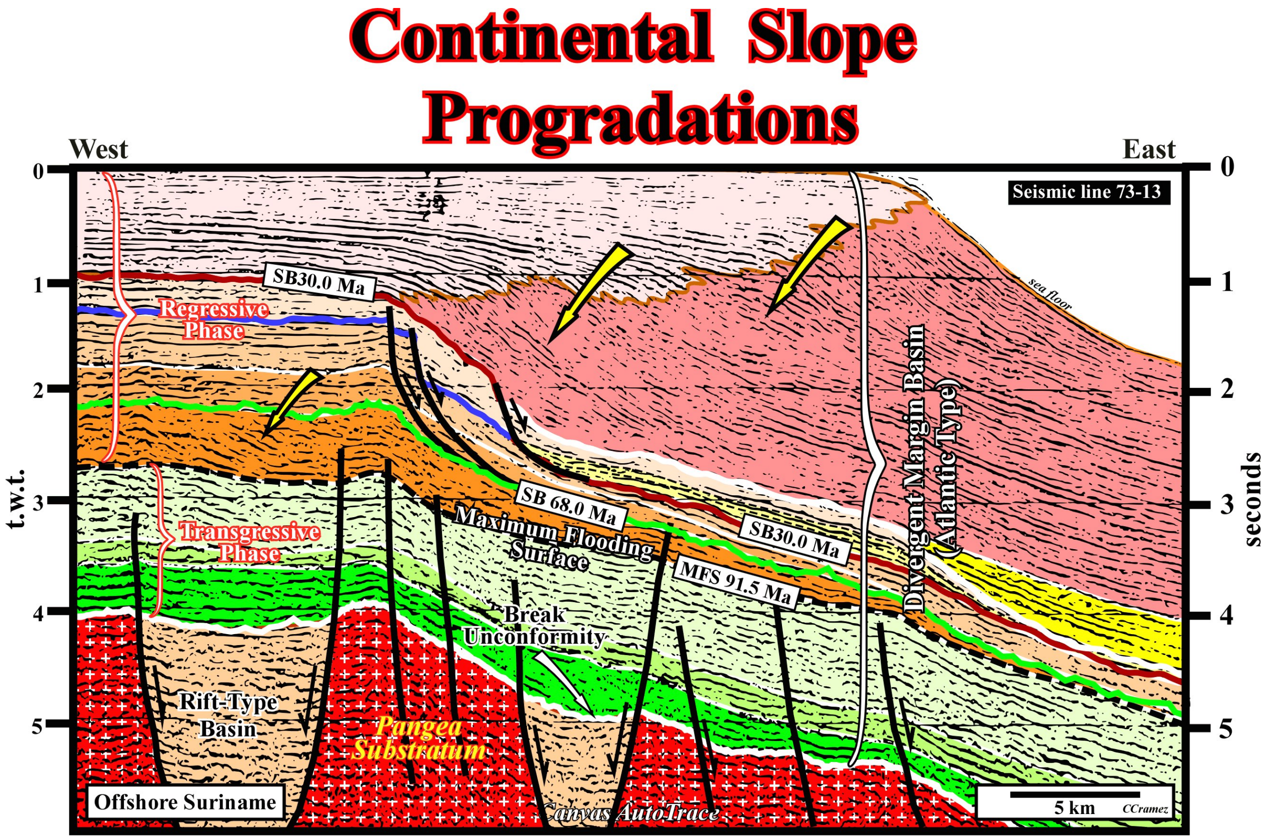

Figure 12 – This tentative geological interpretation of a seismic line offshore Suriname illustrates well-defined continental slopes within the regressive phase of the post-Pangea continental encroachment stratigraphic cycle. This stratigraphic phase, deposited during the first-order eustatic cycle, exhibits a progradational geometry. In contrast, the transgressive phase (represented here by the seismic interval in green tones) displays an aggradational geometry. The aggradational transgressive phase is deposited during the rise of eustatic sea level (not relative sea level), whereas the progradational regressive phase corresponds to the fall of eustatic sea level. These stratigraphic phases are separated by a maximum flooding surface (MFS) dated at 91,5 Ma. Continental slope progradation becomes particularly significant after the Oligocene unconformity (SB 30,0 Ma). The relative sea level fall associated with this unconformity appears to be driven by the formation of the Antarctic ice sheet, which covers approximately 98% of the Antarctic continent and represents the largest single mass of ice on Earth. Notably, after the Oligocene unconformity, the basin appears to lack a shelf, meaning the shoreline was roughly coincident with the continental break. However, as previously noted, transgressive episodes with a relatively shallow continental platform are likely, though their thickness falls below seismic resolution.

In a relative sea level cycle, the relative sea level rise initially accelerates (e.g., 2, 5, 9, 15 meters, etc.) until reaching an inflection point, where the first derivative of the relative sea level curve is positive. Beyond this point, the rise continues but at a decelerating rate (e.g., 20, 18, 14, 9, 3, 0 meters) until the level stabilizes and begins to fall. Between the inflection point and the onset of the fall, the first derivative of the curve is negative. Excluding turbiditic deposits, which accumulate during relative sea level falls, all other marine depositional systems - particularly those forming on the shelf—require a relative sea level rise, meaning an increase in accommodation space (the space available for sediment deposition). When a geoscientist states that during a global sea level rise, the shoreline shifts landward and during a sea level fall, it moves seaward, they must recognize that this statement is strictly valid during a first-order eustatic cycle. In such cycles, sea level changes result from variations in the volume of the oceanic basins, driven by the breakup and subsequent agglutination of supercontinents (Wilson's cycle). When the shoreline shifts landward, geoscientists refer to this process as transgression, whereas a seaward shift is termed regression.

Certain geoscientists, such as C. Emiliani, also use the term ingression to describe a broad marine advance over a continental area:

"The Middle and Late Jurassic saw the widening of the South Atlantic rift and the creation and expansion of rift-type basins between western Gondwana (South America–Africa) and eastern Gondwana (Madagascar–Seychelles–India–Australia–Antarctica). As a result, a significant ingression took place."

When a geoscientist uses the depositional coastal break as a reference, they typically refer to transgression (retrogradation of the shoreline and associated coastal deposits) and regression (progradation of the shoreline and associated coastal deposits). However, when using sea level as a reference, they use the terms ingression (when the sea advances) and egression (when the sea retreats).

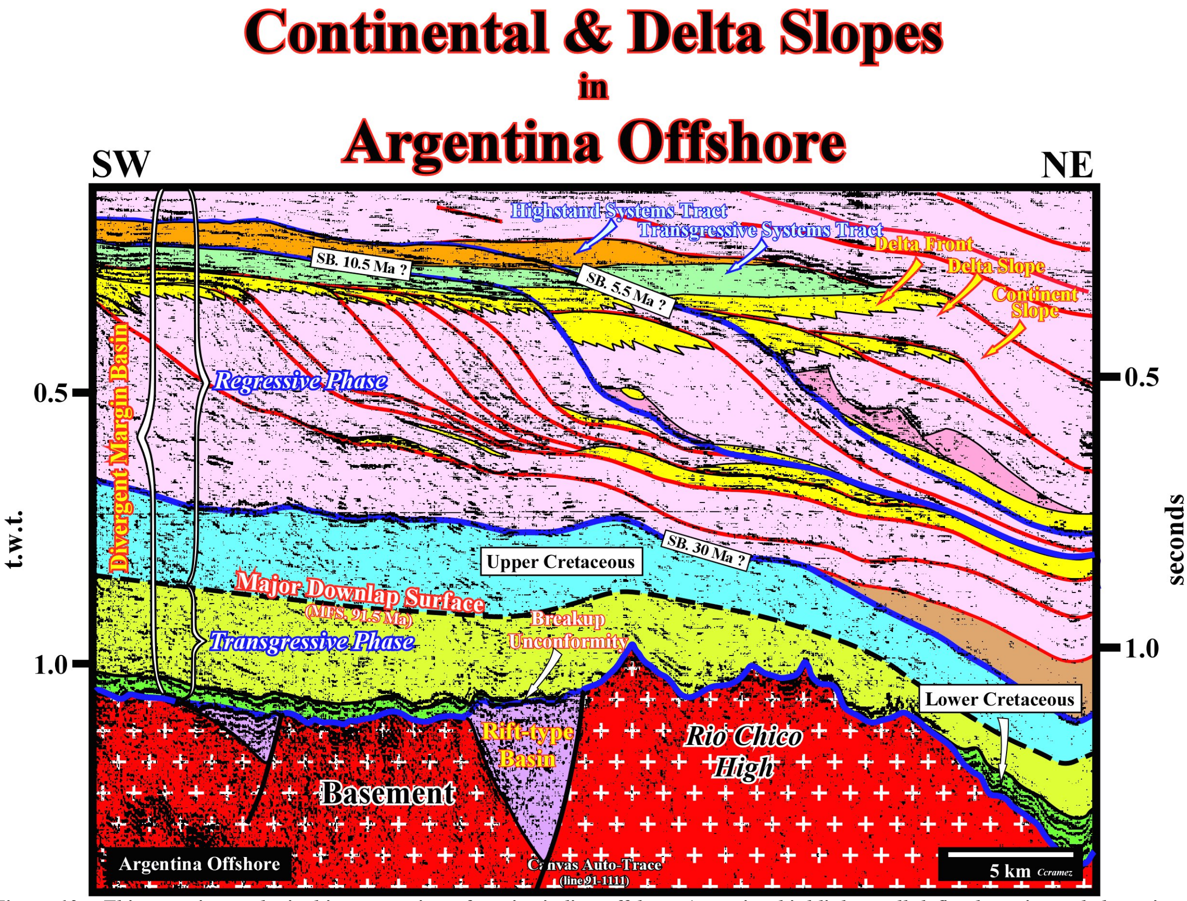

Figure 13 – This tentative geological interpretation of a seismic line offshore Argentina highlights well-defined continental slopes in the upper part of the regressive phase of the post-Pangaea continental encroachment stratigraphic cycle. Although the amplitude and, in particular, the height of the progradations are not excessively high, they exceed typical delta slope standards. However, as suggested by this interpretation, the progradations developed during a lowstand geological setting, meaning the basin lacked a continental platform (no-shelf), and turbiditic depositional systems are easily recognized along and at the base of the continental slope (slope fans and basin floor fans). Under these geological conditions, the shoreline (depositional coastal break) was approximately coincident with the continental break. Subsequently, delta plains, delta fronts, and delta slopes (pro-deltas) were deposited atop the continental slope, as illustrated above. Some delta plains are overlain by transgressive systems tracts, while others are covered by highstand systems tracts.

Within a sequence cycle (deposited during a third-order eustatic cycle with a duration ranging between 0.5 My and 3–5 My), highstand systems tracts are deposited when relative sea level rises in deceleration. At the beginning of this phase, the continental slope is relatively small, as the shoreline remains far from the shelf break due to the presence of a shelf. Gradually, the continental slopes become more pronounced until the basin no longer has a shelf. At this stage, at least from a seismic perspective, the shoreline is positioned near the shelf break. Subsequently, the progradation of the shoreline depends, among other factors, on the stability angle of the slope. If the critical angle is exceeded, slumping at the continental break (where there is no longer a shelf, making the term shelf-break inapplicable) can trigger turbiditic deposits, which act to reduce the slope angle and restore conditions for continued shoreline progradation.In certain continental margins, upwelling currents induced by Ekman transport[7] (the horizontal movement of surface ocean water layers due to wind-driven friction) can partially erode the continental slope, contributing to the destabilization of the continental break.

2.2) Deltaic Slopes in Argentina Basin

Examples of deltaic slopes were selected from two Argentine geographic basins: (i) the Malvinas Basin (Fig. 14), located offshore, and (ii) the Neuquén Basin (Fig. 15 and 16), located onshore.

a) Geographic Malvinas Basin

[7] The wind blowing over the ocean drives the movement of the surface water layer; however, the Coriolis force deflects this movement to the right in the Northern Hemisphere and to the left in the Southern Hemisphere, resulting in a clockwise rotation in the south. This deflection, transmitted downward through viscosity, creates a mean transport of water and suspended material away from the axis of the surface winds, a process known as Ekman transport.

The geological setting of the North Malvinas Basin can be summarized as follows:

1- During the terminal Paleozoic, the deposition of the Gondwana Sequence was characterized by very low magmatic activity and significant sedimentary shortening, associated with the Pan-African–Brazilian orogeny. The predominant structural alignments followed a NNW-SSE orientation.

2- From the Triassic onward, the dominant tectonic regimes were extensional, accompanied by intense magmatic activity. These changes marked the initial phases of the breakup of the southern portion of Pangaea (Gondwana). During this period, the lithosphere underwent stretching perpendicular to the structural trends of the Paleozoic.

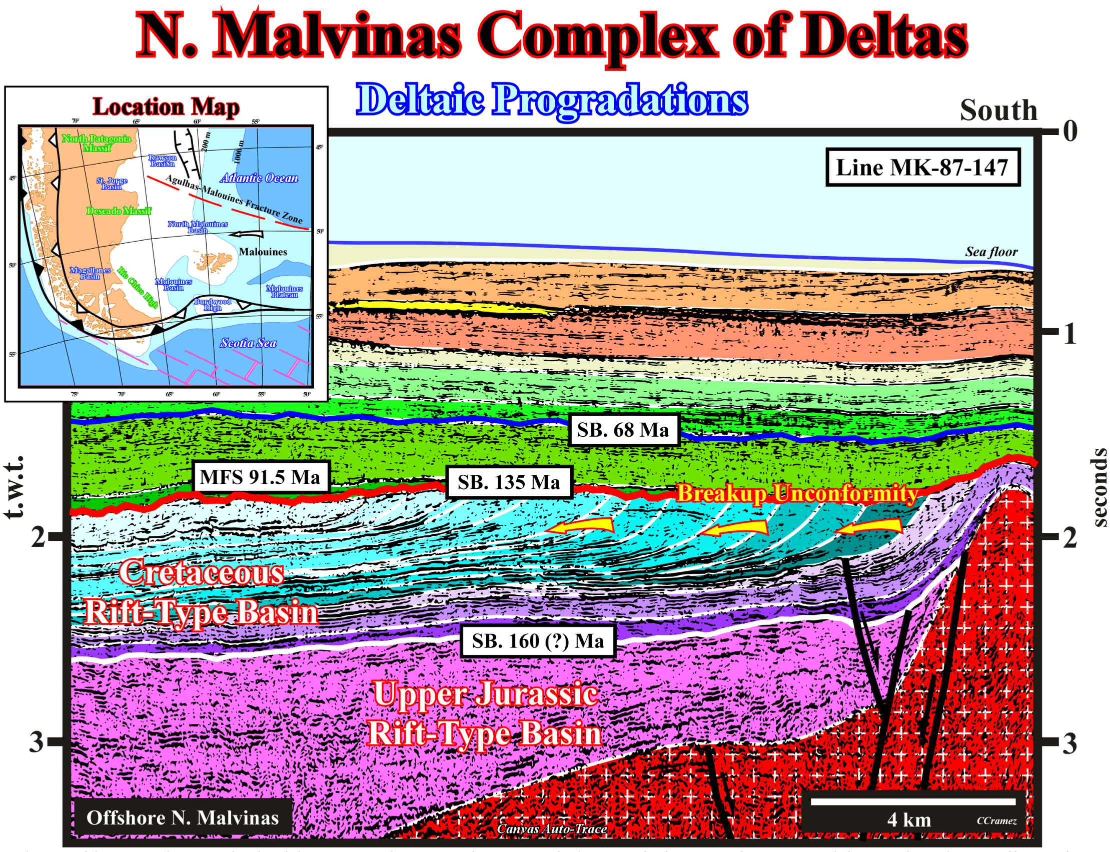

Figure 14 – This tentative geological interpretation remains speculative, as it has not been tested by exploration well results. The geological calibration is primarily based on the overall geological setting, meaning that significant changes are possible. Despite this uncertainty, the following geological intervals can be recognized from bottom to top: (i) A Paleozoic basement; (ii) A rift-type basin with two distinct phases, separated by an unconformity (SB. 160 Ma?); (iii) The lower phase is probably Upper Jurassic, while the upper phase is Lower Cretaceous; (iv) A break-up unconformity, here enhanced by tectonic deformation (angular unconformity), marking the breakup of the continental crust; (v) A Meso-Cenozoic divergent margin, where it is possible to distinguish the transgressive phase of the continental encroachment cycle, bounded at the top by the Lower Turonian downlap surface (MFS 91.5 Ma), and the regressive phase, mainly composed of Late Cretaceous and Tertiary sediments. A well-developed delta complex is visible within the Cretaceous rift-type basin. The erosional surface associated with the break-up unconformity (SB. 135 Ma) appears to have partially eroded the top-sets of the deltaic systems (delta plain). The bottom-sets (pro-delta) are well developed and vertically stacked. Potential petroleum systems are likely associated with this delta complex. The generating petroleum subsystem is probably linked to organic-rich pro-delta shales, while the reservoir-entrapment subsystem is related to delta front sandstones. The most probable trapping mechanism is stratigraphic or morphological by juxtaposition, where potential reservoir rocks are juxtaposed against sealing rocks—specifically, the Cenomanian-Turonian marine transgressive shales associated with the major downlap surface (MFS 91.5 Ma).

3- In response to this stretching, half-grabens and grabens striking 150–160° N were formed. These structures were largely filled with volcano-clastic deposits, with the amount of volcanic material decreasing upwards in the stratigraphic succession.

4- During the Jurassic, what is now the western and southern margins of South America was bordered by an extensive volcanic arc, behind which back-arc basins developed. These features were induced by the subduction of the Panthalassa oceanic crust. Most of these basins trend NNW-SSE, suggesting that the extension of the continental crust behind the volcanic arc was facilitated by the reactivation of pre-existing normal faults from the Jurassic-Triassic rift systems.

5- Approximately 25 million years before the separation of South America and Africa (Upper Jurassic), a new phase of lithospheric extension occurred, leading to the emplacement of volcanic crust (both subaerial and oceanic). This stretching event was marked by fault systems that controlled the formation of geographic basins such as Orange, Salado, Pelotas, Walvis, and Santos. Another set of basins associated with this extension includes Rawson, Western Colorado, Macachín, Laboulaye, and North

Malvinas. Several geoscientists suggest that these basins were strongly influenced by the Rio de la Plata and Agulhas-Malvinas fault zones.

6- At the onset of the Cretaceous, before the beginning of seafloor spreading between South America and Africa, significant crustal extension and fracturing took place along the Atlantic margin of Argentina, Uruguay, and southeastern Brazil. Fracturing was particularly pronounced along the Agulhas/Malvinas and Rio Grande/Walvis alignments. Although the associated rift-type basins sometimes exhibit orientations locally perpendicular to the opening of the Atlantic, they serve as direct geological indicators of continental separation.

The progradations visible within the Cretaceous rift-type basin (figure 14) are clearly associated with deltaic systems. Their dimensions, and particularly the height of the inclined segment, are not those of a continental slope. They lie within 200-300 milliseconds (two way time). The recognition on the seismic lines of such a deltaic progradations and especially of the complexes of deltas fundamental to well evaluate, in the petroleum mature basins, the remanent petroleum potential.

Indeed, potential source rocks can be found in the pro-delta and in the delta plain (e.g., oxbow shales), while potential reservoir rocks are typically present in the delta front and the delta plain (e.g., point bar sandstones). In other words, the proximity between the petroleum-generating subsystem and reservoir rocks favors the development of non-structural traps, which are key to remnant petroleum discoveries, particularly in petroleum basins that are mature from a structural perspective.

b) Geographic Neuquén Basin

Before analyzing the tentative geological interpretation of seismic lines shot in the geographic Neuquén Basin, it is essential for a geoscientist to understand the geological setting to determine what to look for (Theory precedes Observation) and, more specifically, where delta complexes are most likely to be found. Additionally, assessing the remnant petroleum potential of the geographic Neuquén Basin primarily requires an understanding of the temporal and spatial evolution of tectonic regimes and subsidence that have affected the region, particularly since the breakup of Gondwana, i.e., from the Permian-Triassic onward.

1) Above the Paleozoic mega-suture (whose petroleum potential must also be evaluated), a back-arc basin developed during the Triassic-Jurassic in association with an extensional tectonic regime. Since the Berriasian-Valanginian, this back-arc basin has been overlain by a foredeep basin.

2) The lower sub-basins (rifting phase) of the back-arc basin, formed due to differential subsidence, resemble rift-type basins and are Triassic–Lower Jurassic in age.

3) These rift-like sub-basins are easily recognized on seismic lines but do not appear to have significant petroleum potential, although some geoscientists have locally identified thin intervals of lacustrine shales within the volcano-clastic sediments.

4) The upper sub-basin (sag or cratonic phase) of the back-arc basin is associated with regional thermal subsidence, likely caused by isothermal rebalancing.

5) This subsidence triggered a regional marine transgression, reaching its maximum extent near the end of the Portlandian (Lower Quintuco Formation). At the base of this transgression (Middle Jurassic), sediments exhibit a progradational geometry (Cuyano and Los Molles Formations), while towards the top (Upper Jurassic), their geometry becomes retrogradational.

6) Sediment thickness increases towards the basin margins, as seen in Vaca Muerta and Lower Quintuco deposits. In the central part of the basin, where low sedimentation rates prevailed, only condensed stratigraphic sections were deposited. These condensed sections accumulated in deep-water conditions, locally exceeding 600–800 meters in depth.

7) During the sag or cratonic phase of the back-arc basin, extensional tectonic regimes, eustatic variations, and terrigenous influx (originating from the east, i.e., from the Paleozoic mega-suture) were the primary controls on stratigraphic architecture. These factors influenced the deposition of the Kimmeridgian sandy reservoir rocks (Tordillo Formation) and the Vaca Muerta source rocks (mainly Portlandian in age), which have generated most of the hydrocarbons discovered in the basin to date.

8) The western edge of the back-arc basin, corresponding to the eastern flank of the volcanic arc, was likely located near the present-day position of the first thrust structures. Some exploration wells (Bridas) in this area appear to have encountered thick alluvial deposits originating from the west. These deposits, which are synchronous with the Tordillo Formation sandstones, were directly transported into deep-water settings, forming Neptunian sands or delta fans.

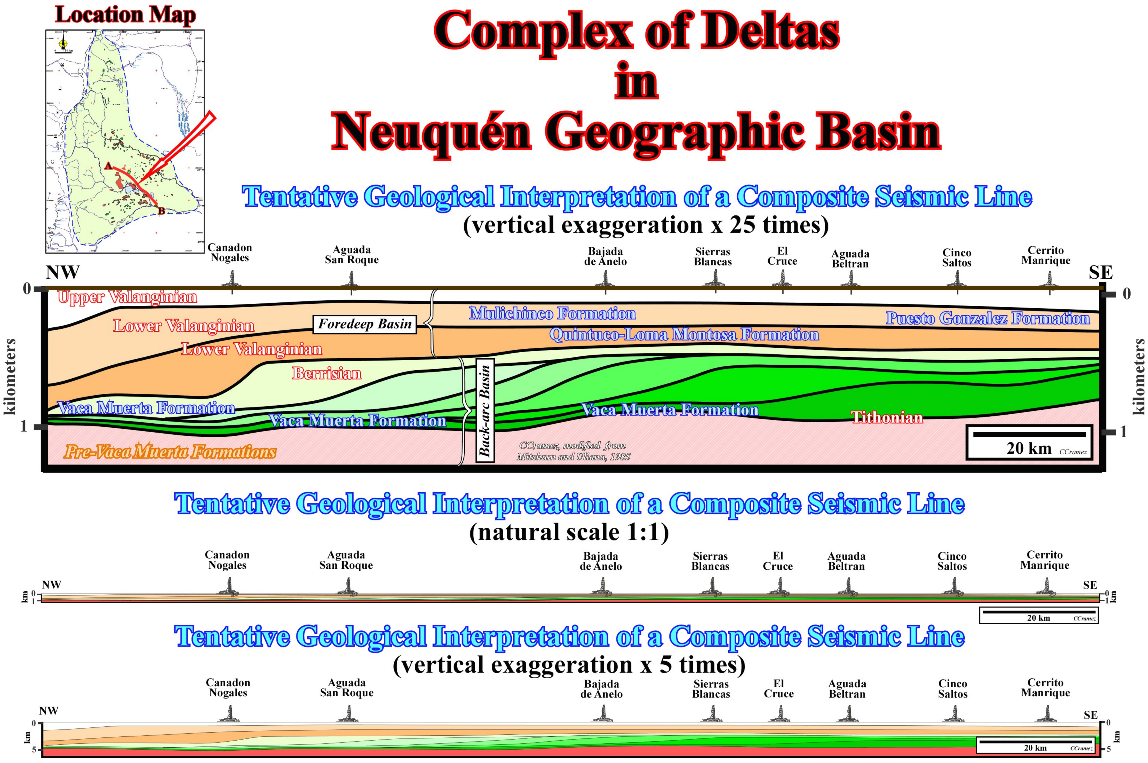

Figure 15 – The uppermost cross-section corresponds to a tentative geological interpretation of a composite seismic line from the geographic Neuquén Basin. The progradations are primarily sigmoidal (up-building and out-building). Their heights exclude the possibility of continental slopes, instead falling within the typical height range of delta slopes. An Upper Jurassic–Lower Cretaceous delta complex is proposed, with the ages of individual deltas ranging from Tithonian (150.7–144.2 Ma) to Berriasian (144.2–137.0 Ma). Two relative sea level falls (or two lateral depocenter shifts due to the pendulum effect) can be recognized during the westward progradation of the deltas. These relative sea level falls caused a seaward displacement of the shoreline and associated coastal deposits. The deposition of proximal turbidites and the potential development of stratigraphic traps are possible down-dip of such unconformities.This delta complex appears to terminate or change significantly with the onset of flexural subsidence, marking the beginning of the foredeep basin during the Late Berriasian–Early Valanginian. As illustrated, it is evident that attempting to calibrate this tentative interpretation in terms of geological formations such as Vaca Muerta or Quintuco lacks stratigraphic validity.It is important to note that the original composite seismic line is vertically exaggerated by a factor of 20. When displayed at a natural scale (1:1), the progradations of the delta complex are not visible. Even with a 5× vertical exaggeration (as seen in the lower tentative interpretation), which approximates the standard exaggeration of conventional seismic lines, the deltaic progradations remain barely visible. Geoscientists working in this area should analyze seismic lines at multiple scales—using highly vertically exaggerated seismic sections to discern detailed geological features, while also working with low-exaggeration sections to maintain perspective on regional structures.

9) From the Berriasian (Upper Quintuco Formation) onward, geological conditions changed catastrophically due to the emplacement of a foredeep basin (see Fig.12). This abrupt shift affected tectonic regimes, subsidence patterns, terrigenous influx, eustatic variations, and depositional systems, marking a fundamental transformation in the basin's geological evolution:

(i) From the end of the Portlandian, compressional tectonic regimes became predominant, leading to sedimentary shortening. This shortening primarily resulted from the reactivation of pre-existing normal faults from the rifting phase of the back-arc basin, now inverted into reverse faults (tectonic inversions).

(ii) These tectonic inversions are particularly evident near the Paleozoic craton, while in the western area, near the volcanic arc, they are still recognizable but largely masked by successive shortening events. During the Cretaceous and Cenozoic, continued shortening progressively transformed parts of the foredeep basin into a fold-and-thrust belt.

(iii) The overloading caused by thrusting, associated with tectonic inversions, induced flexural subsidence, marking the onset of the foredeep basin. The transition from thermal subsidence (characteristic of the sag or cratonic phase of the back-arc basin) to flexural subsidence (characteristic of the foredeep basin) is defined by a major unconformity, clearly visible on regional seismic lines (see Fig. 5).

(iv) Sedimentary shortening caused uplift in the western part of the back-arc basin, leading to the formation of a mountain range and fold belt, which became the primary source of terrigenous influx during the foredeep phase (since the Berriasian-Valanginian). In contrast, the Paleozoic mega-suture in the east was already heavily eroded, limiting its role as a sediment source to foreland river mouths. The entire sedimentary interval of the foredeep basin thickens westward toward the Cordillera, while it pinches out eastward in the foreland by downlapping, indicating that most of the terrigenous influx originated from the west.

(v) During the foredeep phase, terrigenous influx remained continuous but was strongly influenced by tectonic convulsions, which are clearly identifiable through their distinct stratigraphic signature, a pattern that sequential stratigraphy alone does not fully explain. The frequency of these tectonic upheavals (sedimentary uplifts) exceeded the rate of eustatic sea level changes.

(vi) As a result, the stratigraphic signature and cyclicity of deposits were more tectonically controlled than eustatically driven. Additionally, successive uplifts and subsequent denudation phases rapidly altered drainage surfaces and sediment supply, in contrast to the assumptions of sequential stratigraphy, which typically considers sediment input to be relatively constant over longer periods.

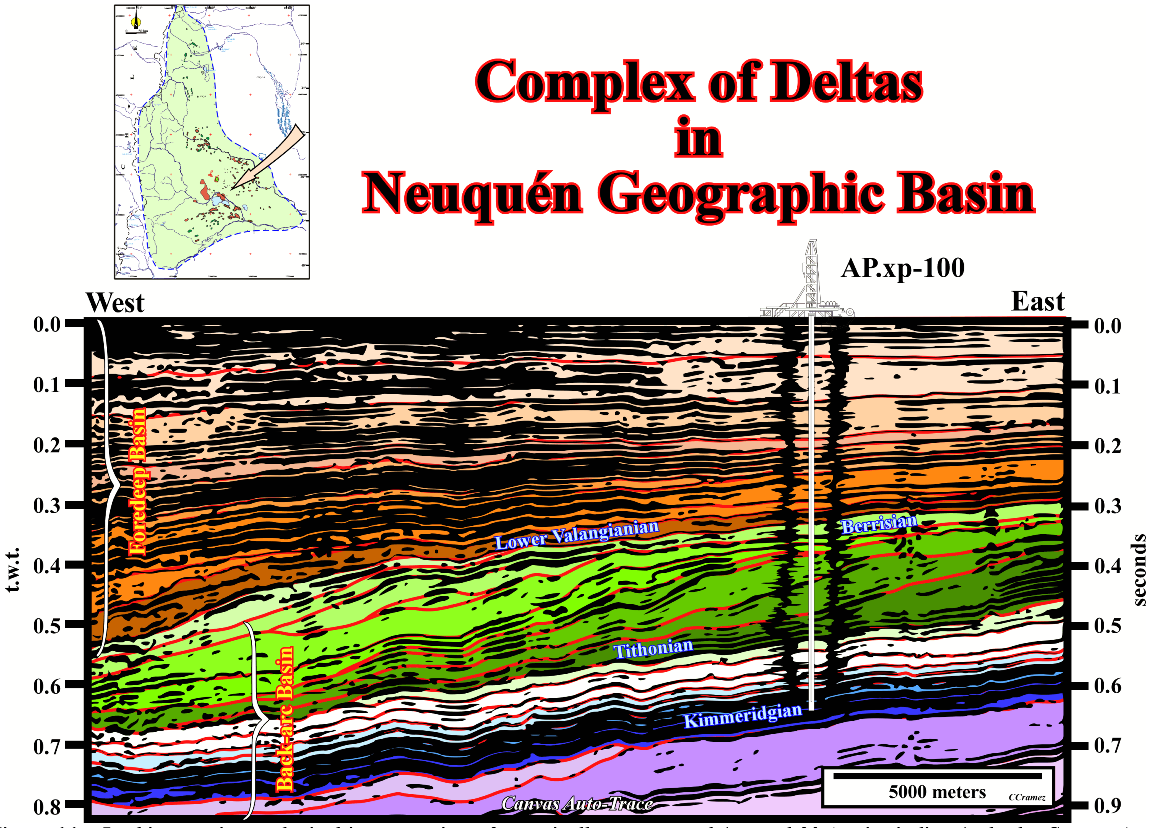

Figure 16 – In this tentative geological interpretation of a vertically exaggerated (around 20×) seismic line (only the Canvas Auto-Trace is illustrated here) from the geographic Neuquén Basin, the Upper Jurassic–Lower Cretaceous delta complex is easily recognized. Several negative aggradations (relative sea level falls) can be inferred from the geometric relationships between seismic reflectors. The upper boundary of the delta complex (representing the lateral accretion of deltaic systems) appears to correspond to the basal unconformity of the foredeep basin, marking the onset of flexural subsidence. In the foredeep basin, additional delta complexes are possible, such as those formed during the Valanginian (Tordillo Formation). However, the mechanisms of accommodation space creation and the provenance of terrigenous influx appear to be significantly different from those of the back-arc basin.

(vii) Admittedly, under such geological conditions, the depositional systems of the Neuquén foredeep basin do not correspond precisely to those predicted by the P. Vail sedimentary model (1977, 1991). The progradational and retrogradational geometries, stratigraphy, and the predominance of terrigenous influx from the Cordillera are likely better explained by short-duration erosion cycles (E. Mutti, 1996), meaning a succession of uplift-denudation eventssimilar to those proposed in the late 19th century by W. M. Davis (1899).

(viii) The sedimentological model that best explains the lithologies observed in field geology, drilling, and seismic data is one characterized by non-confined flood events alternating with delta fans and confined flood events forming river deltas.

The proposed tectonic-sedimentary evolution, particularly the depositional model of the foredeep basin since the Portlandian, is, so far, corroborated by the observational data available. The sedimentary structures such as HCS (Hummocky Cross-Stratification), which have been cited to challenge the significance of river floods, are not considered, according to some sedimentologists (Southard, 1990; Allen and Underhill, 1989; Arnott and Southard, 1990; E. Mutti et al., 1996), as diagnostic of any specific depositional process or sedimentary environment.

3) Seismic Lines are Time Profiles

When examining a tentative geological interpretation of a seismic line, one is not simply viewing the actual geological interpretation. Observing a seismic line—whether interpreted or not—is not a passive process of receiving sensory data but rather a complex cognitive process that involves receiving, selecting, and categorizing information.

In fact, when looking at the clean seismic line illustrated in the upper part of Fig. 17, as previously mentioned, electromagnetic waves in the form of white light illuminate the image. Part of the light is absorbed, while another part is reflected. Specific wavelengths enter the eyes, stimulating retinal cells and triggering complex chemical and electrical changes in the brain, ultimately reaching the visual center at the rear of the brain. As a result, what is perceived is not the real seismic line, but rather an internal representation constructed by the brain. Moreover, the clean seismic line itself is not a direct representation of reality, but rather a processed copy derived from a reflection seismic survey[8].

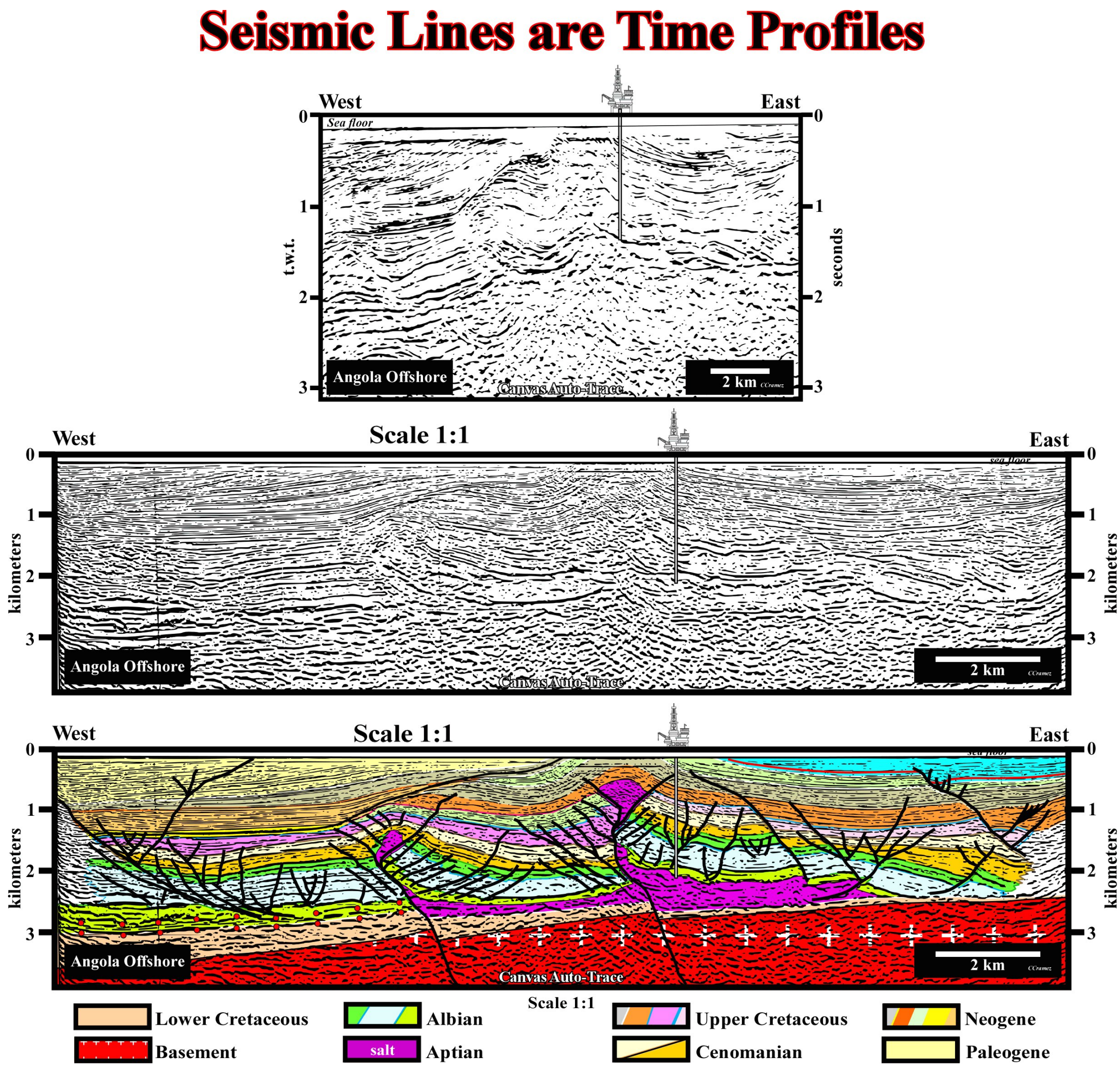

Figure 17 – The automatic Canvas Auto-Trace of a conventional seismic line from offshore Angola, illustrated in the upper part of this figure, is clearly displayed in time. The vertical scale is in time (seconds two-way time, TWT), while the horizontal scale is in metric units (kilometres). Consequently, what your brain perceives is an internal representation of a seismic line that does not correspond to a direct copy of geological reality, as it is measured in time and vertically exaggerated (likely by a factor of 2–3 times). When observing the automatic Canvas Auto-Trace in the middle of the figure, your brain perceives an internal representation of a seismic line that more accurately represents geological reality, as it is in depth (vertical scale in kilometres) and at a natural scale (1:1). A tentative geological interpretation of the depth-converted seismic line is proposed in the bottom part of the figure.

As the majority of seismic lines used in petroleum exploration are in time, the visual cortex[9] of geoscientists interpreting these lines perceives an internal representation that does not correspond to a direct copy of geological

[8] Reflected waves from interfaces between materials with significantly different elastic properties (density and seismic velocity) are used in this type of survey. More specifically, a specialized acquisition and processing technique known as the CDP (Common-Depth-Point) method is applied, producing a final seismic section that represents a cross-sectional image of the subsurface beneath the surveyed line.This type of seismic survey is based on the theory of elasticity, aiming to deduce the elastic properties of subsurface materials by measuring their response to elastic disturbances, commonly referred to as seismic (or elastic) waves. A seismic source, such as a sledgehammer, is used to generate these seismic waves, which are detected by receivers arranged along a preset geometry (receiver array) and recorded by a digital seismograph. Seismic surveys primarily use compressional waves (P-waves), which are the fastest seismic waves, arriving first at the recording instruments. P-waves, also known as pressure waves, consist of alternating compression and extension phases within each cycle. The recorded signals (measured in time) are later processed into subsurface images, which can be interpreted for oil and gas exploration, development, and production purposes.

[9] The part of the cerebral cortex responsible for processing visual information is a key component of the central nervous system, enabling organisms to interpret visual detail and supporting several non-image photoresponse functions. It detects and processes visible light, constructing an internal representation of the surrounding environment.The visual system performs a range of complex tasks, including: receiving light, forming monocular representations, integrating two-dimensional projections into a binocular perception, identifying and categorizing visual objects, assessing distances between objects, and guiding body movements in response to the visual stimuli.

reality[10]. Consequently, when a geoscientist "sees" a seismic interval with a constant thickness on a conventional time-domain seismic line, they cannot be certain that the actual geological interval maintains a constant thickness in depth. While they can and must formulate a hypothesis, they must also rigorously test it—that is, attempt to refute it - as illustrated in Figure 18.

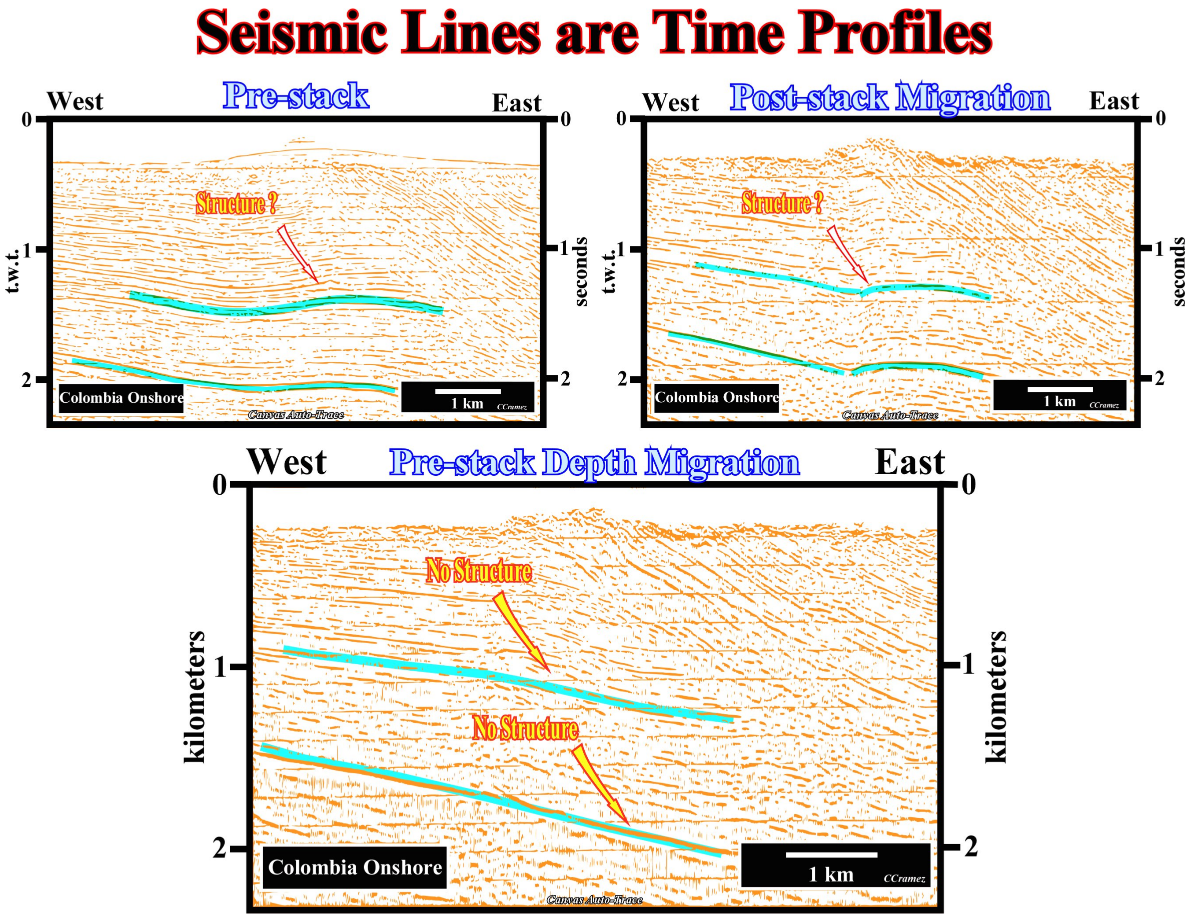

Figure 18 – In the internal representation of a pre-stack version of a seismic line from onshore Colombia (Canvas Auto-Trace), the brain of a geoscientist recognized—after identification and categorization of internal representations—a seismic interval between two green horizons (not all geoscientists perceive green the same way; some may see what we call "green" as their "red") that appeared to be slightly thickening eastward. Additionally, the boundaries of this seismic interval exhibited undulations, forming a potential antiform structure.Knowing that the seismic section was in time, the geoscientist had to test the validity of what they perceived. The first step in this falsification process was to generate a post-stack migration version of the seismic line. In this version, the geoscientist still "saw" a similar internal representation, but with some differences: (i) The antiform structure appeared sharper but was located directly beneath the reverse fault plane. (ii) The eastward thickening of the seismic interval was less evident than in the pre-stack version, as illustrated above.However, since the post-stack migration version was also in time, it could not be considered a true geological representation. To verify the interpretation, the geoscientist requested a pre-stack depth migration version. Astonishingly, the antiform structure in the lower faulted block (footwall), beneath the reverse fault plane, disappeared. Despite the fact that the pre-stack depth migration version was not at a natural scale (1:1), as illustrated above, it was considered an approximate copy of geological reality. As a result, the geoscientist abandoned the initial interpretation of the internal representation and instead adopted the most likely interpretation—a reverse fault with an undeformed, thinning-upward seismic interval in the footwall.

In conclusion : Geoscientists must never forget that conventional seismic lines are time sections, meaning they must always attempt to falsify their tentative geological interpretations. Such falsification tests do not always require depth conversion, not only because depth conversion is costly, but also because it depends on an accurate understanding of velocity intervals, which typically requires drilling data. In many cases, a solid understanding of the geological settingcombined with a simple, approximate mental depth conversion is sufficient to refute naive interpretations, such as in offshore seismic lines that exhibit abrupt changes in water depth, as will be discussed later.

4) Geometrical Relations & Seismic Surfaces

Three major geometrical relationships between stratal surfaces or associated seismic reflections can be reco-gnized (Fig. 19): (i) Onlap, (ii) Toplap, and (iii) Downlap.

Onlap can be defined as a base-discordant relationship, where initially horizontal strata (at the time of deposition) terminate progressively against an initially inclined surface, or where initially inclined strata terminate progressively up-dip against a surface of greater initial inclination. Onlap can be:

[10] The geological reality (scale 1:1) can never be accurately represented by a time-domain seismic line, as it contains two different scale categories: time and length.

a) Proximal onlap – when it corresponds to a landward onlap.
b) Coastal onlap – when it involves coastal plain sediments.
c) Marine onlap – when it involves marine sediments.
d) Apparent onlap – when it is induced by tectonics (e.g., tilted downlap).

Sedimentary onlapping is characterized by: (i) Aggradation – the vertical component between two consecutive onlaps and (ii) Encroachment – the horizontal component between two consecutive onlaps.

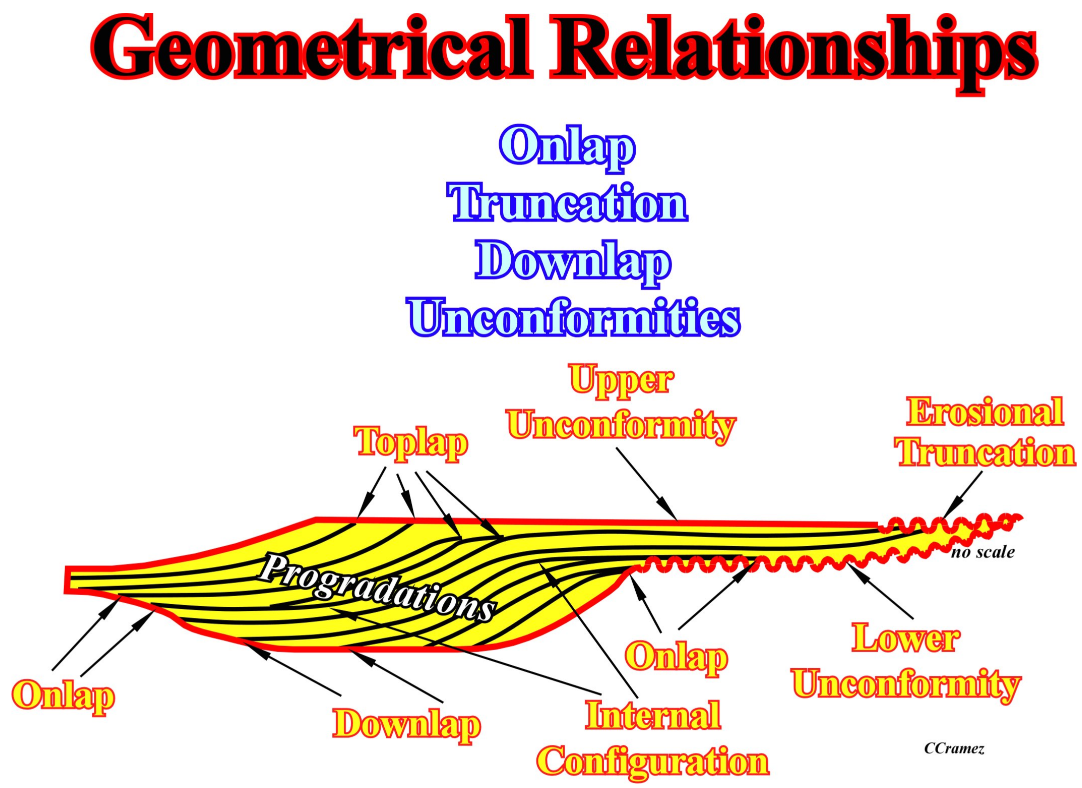

Figure 19 – This theoretical geological sketch represents a continental encroachment sub-cycle bounded by two unconformities, meaning it is framed by two erosional surfaces induced by two relative sea level falls. All geometrical relationships between stratal sets or associated seismic horizons at the time of deposition are illustrated. Onlaps, which can be proximal or distal, are clearly visible on the lower boundary of the stratigraphic cycle, along with downlaps, whereas toplaps are associated with the upper boundary. The seismic surface defined by successive onlaps is referred to as an onlap surface, and similarly, downlap and toplap surfaces can also be identified. Truncations are exclusively associated with the unconformities bounding the stratigraphic interval, as these are erosional surfaces. The internal configuration—the geometry of the sedimentary infill—can be parallel, sigmoidal, or oblique. In this case, the infilling is a combination of sigmoidal (up-building and out-building) and oblique (out-building without up-building) geometries.

Toplap is the termination of strata against an overlying surface and occurs along the upper boundary of a stratigraphic interval. The term toplap is used when this termination results from non-deposition (sedimentary bypass) with only minor erosion. Down-dip of a toplap, there is always a downlap or an apparent downlap. Toplaps are mainly associated with coastal deposits (coastal toplaps). When a toplap is caused by erosion, it is referred to as a truncation.

Truncation corresponds to the termination of strata or seismic reflections (interpreted as strata) along an unconformity surface, resulting from post-depositional erosion. Like toplap, truncation occurs along the upper boundary of a stratigraphic interval. However, unlike toplap, truncation implies the deposition of strata followed by their removal, forming an unconformity surface.

Downlap is a base-discordant relationship, in which initially inclined strata terminate down-dip against an initially horizontal or inclined surface. A downlap geometry indicates deposition away from the sediment source.

A seismic downlap is a downlap observed on a seismic section, meaning it is a relationship where a seismic reflection, interpreted as initially inclined strata, terminates down-dip against a reflection discontinuity, which may correspond to:

(i) A flooding surface,
(ii) A complex transgressive back-stepping surface,
(iii) An unconformity, or
(iv) A paraconformity (a conformity with a significant hiatus).

There are two types of apparent downlaps:

(i) Tectonically induced downlaps, often caused by halokinesis or shalokinesis, correspond to tilted onlaps due to salt or shale flowage.

(ii) Resolution-induced downlaps, where seismic reflections representing inclined or tangential strata appear to terminate down-dip, but in reality, the strata flatten and continue as units that are too thin to be resolved by seismic data.

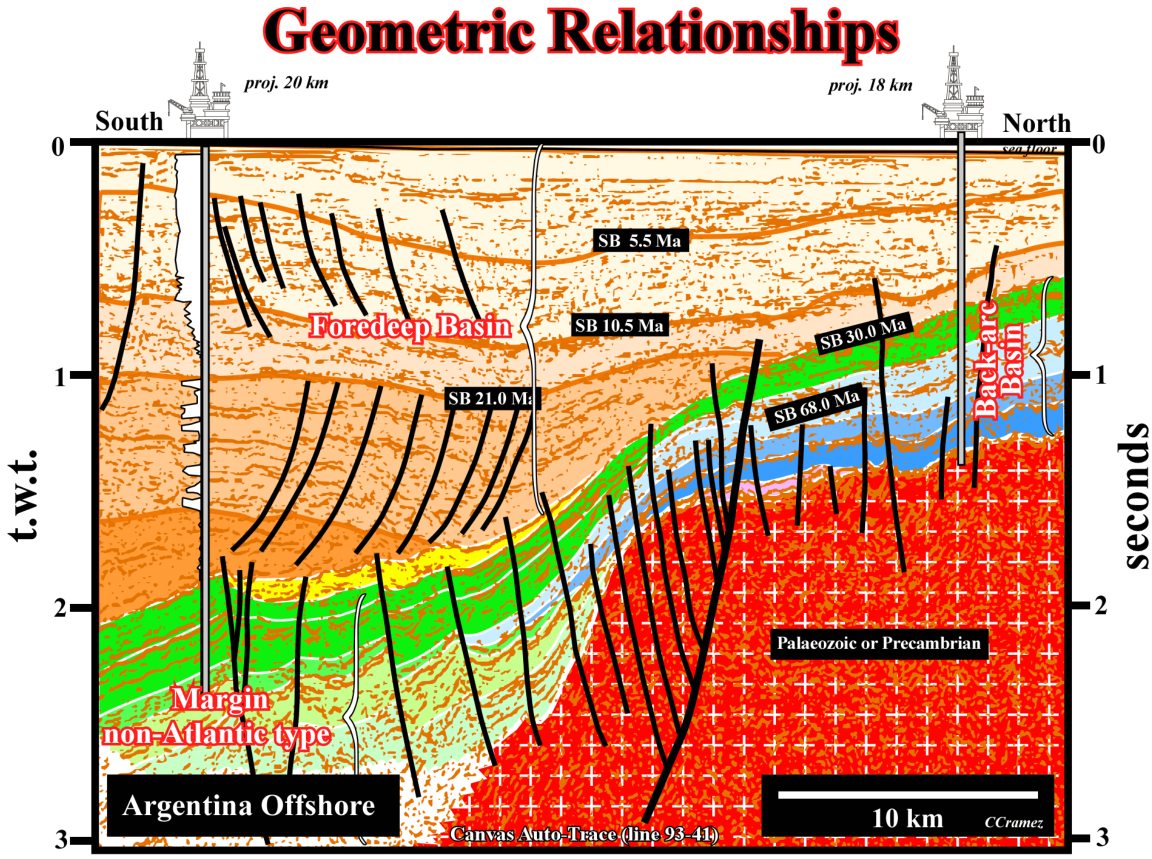

Figure 20 – This tentative geological interpretation of a seismic line from offshore South Argentina clearly distinguishes the different sedimentary basins forming this offshore region. From bottom to top, these include: (i) a Paleozoic or Precambrian folded belt, (ii) a back-arc basin, (iii) a divergent margin of a non-Atlantic type associated with the oceanization of a marginal sea, and (iv) a foredeep basin. All geometrical relationships between the seismic reflectors are considered accurate, as the sedimentary layers are mostly undeformed, meaning they retain roughly the same geometry as at the time of deposition. Consequently, in this tentative interpretation, successive onlaps indicate positive aggradation, while a seaward displacement of coastal onlaps suggests negative aggradation—or in other words, an unconformity induced by a relative sea level fall. Similarly, downlaps generally indicate the direction and provenance of terrigenous influx, while toplaps—and especially erosional truncations—typically define the boundaries of stratigraphic cycles.

A **stratigraphic surface** can be considered a **continuous physical boundary**. At least **three major groups of stratigraphic surfaces** can be observed in the **field or on seismic data**:

(i) Stratal Surfaces – These include bedding planes and chronostratigraphic seismic reflectors, representing primary depositional boundaries that separate successive layers of sediment or rock.[11];

(ii) Discontinuity Surfaces – These are physical surfaces formed by erosion or non-deposition. Discontinuity surfaces include:

a) Unconformities – Surfaces caused by erosion, representing a significant gap in the geological record.
b) Paraconformities – Surfaces that separate parallel layers, indicating a hiatus of non-deposition without significant erosion.
c) Depositional Hiatuses, which can be defined by:

- **Toplap / Downlap indicating, respectively, sub-aerial / sub-aqueous deposi-tional environments ;**
- **Downlap / Apparent Truncation indicating, respectively, Sub-aqueous / Sub-aqueous depositional environments and**
- **Onlap / Conformable indicating, respectively, Sub-aqueous / Sub-aqueous**

[11]A seismic reflector represents a sedimentary interval of variable thickness, depending on seismic resolution. The thickness of this interval typically ranges between 10 and 100 meters, as determined by the wavelength of the seismic signal and the limits of vertical resolution.

(iii) Diachronous Surface, in which are included in the retrogradational transgressive (back-stepping) surfaces and, on seismic data, the reflectors associated with gas/oil-water plane contact ("bright-spots).

A stratigraphic boundary which separate rocks of significantly different environments or lithology, can be:

a) Synchronous, i.e. parallel to stratal surfaces and
b) Diachronous,i.e. step across stratal surfaces.

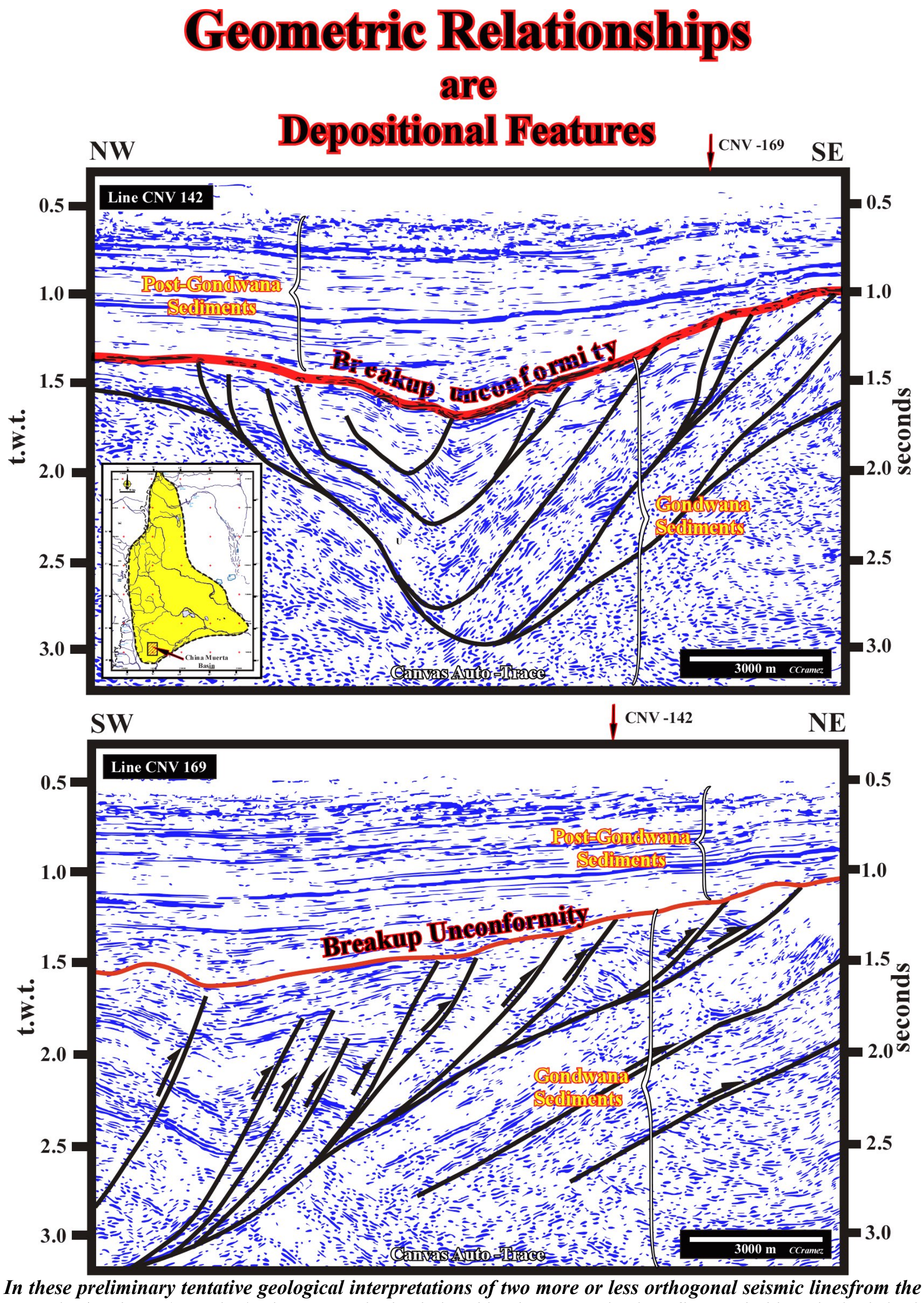

Figure 21 – In these preliminary tentative geological interpretations of two more or less orthogonal seismic linesfrom the geographic China Muerta Basin (onshore Argentina), the geometrical relationships between seismic reflectors hold geological significance only within the post-Gondwana sediments, i.e., above the break-up unconformity. Below the break-up unconformity, the shortening of Gondwana sediments has completely deformed the original geometrical relationships, making their application in seismic sequential stratigraphy particularly difficult, especially for the identification and picking of unconformities.A similar effect occurs when sediments are extended by halokinesis or shalokinesis, where original high structural points become low structural points. As a result, onlaps become tilted, adopting a geometry similar to downlaps, which means they transform into apparent downlaps. Therefore, only pristine or undeformed geometrical relationships retain a valid geological meaning.

The recognition of different geometrical relationships on seismic lines is fundamental in sequential stratigraphyand, consequently, in petroleum exploration. All potential clastic reservoir rocks—such as sand-prone basin-floor fans, sand-prone slope fans, transgressive sandstones, and coastal plain sandstones—terminate by onlappingagainst unconformities, which are highlighted by onlap and toplap surfaces. Similarly, downlap surfaces, as we will see later, mark the peak of transgressive episodes, indicating the most likely locations for potential marine source rocks.

Accordingly, it is difficult to understand why certain geoscientists consistently use workstation-flattened seismic linesfor sequential interpretation and remnant petroleum potential evaluation, given that the automatic flattening process significantly destroys or strongly masks critical onlap and downlap seismic surfaces, as illustrated in Fig, 22.

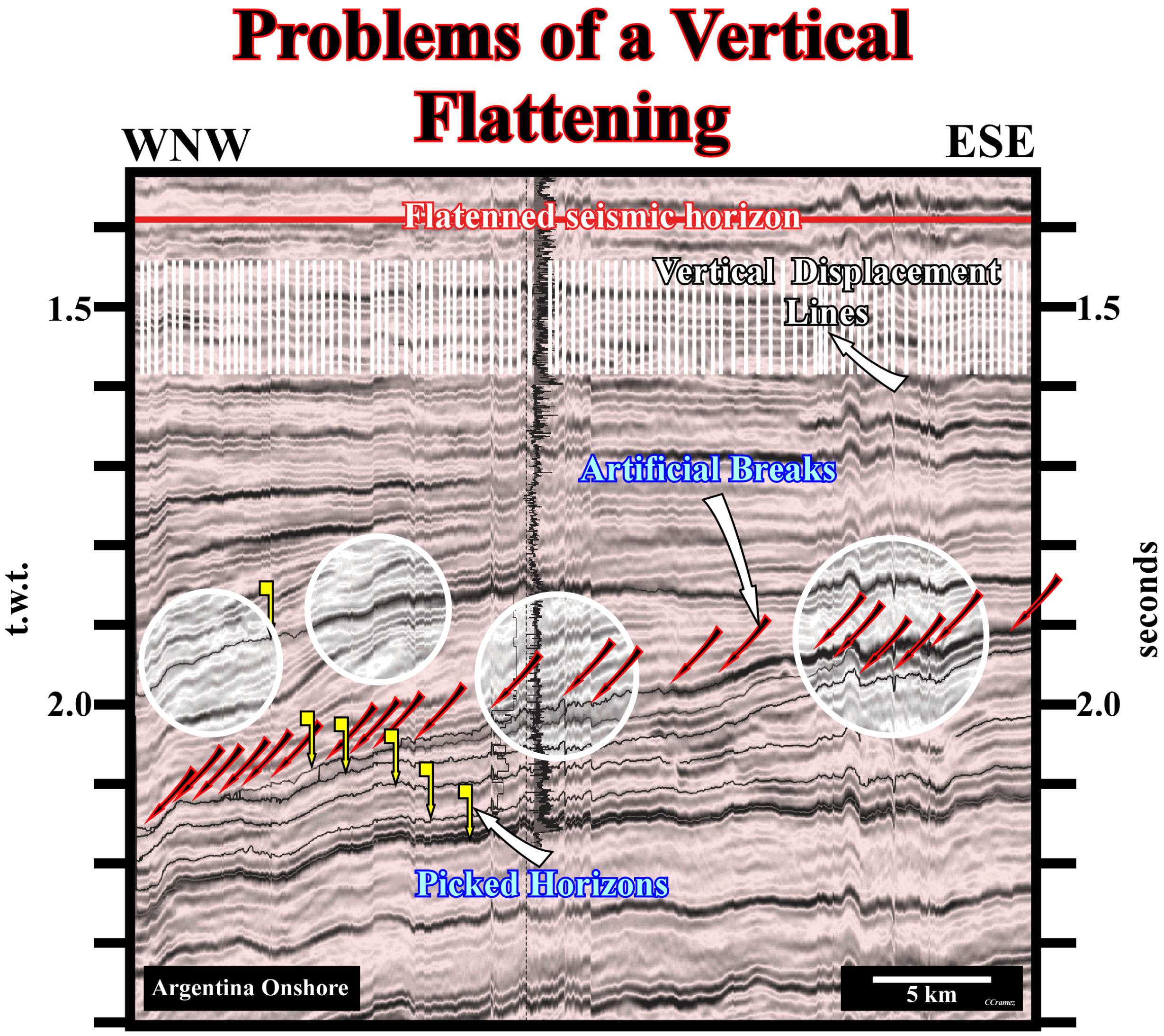

Figure 22 – A simple glance at this flattened seismic line from the Neuquén geographic basin is enough to understand why certain geoscientists become frustrated when, in an exploration meeting, a speaker attempts to explain the remaining petroleum potential of a given area using flattened seismic lines—particularly when the area has undergone shortening due to a regional tectonic regime. In fact, in these flattened seismic lines, all syndepositional geometrical relationships (those occurring at the time of deposition) are disturbed by vertical displacements. These displacements not only partially destroy the original relationships but also create new ones without any geological significance, as illustrated above. Similarly, these vertical displacements lead to erratic, semi-automatic seismic horizon picks. On this seismic line, six horizons were picked automatically, generating false antiform and synform structures. These artificial structures can be easily recognized, as they extend from the top to the bottom of the seismic line (see the white circles). The white vertical lines at the top of the seismic section highlight the most prominent gliding planes used in the flattening process. Additionally, the amount of vertical displacement required to horizontally align the seismic horizon taken as a datum is variable, as it depends on the degree of extension (lengthening) or compression (shortening) that the strata responsible for the seismic reflection have undergone. On the other hand, as illustrated in Figure 24, a seismic line flattened in this manner (solely through vertical displacement) lacks any true geometrical significance.

It is important to keep in mind that in a compressional tectonic regime (σ_1 horizontal), as is the case in the Neuquén geographic basin, sediments are shortened by folding and/or reverse faulting. Apart from a few exceptions (such as compaction, dissolution, etc.), the volume of sediments remains more or less constant during deformation (see later: Volume Problems, Goguel's Law).

Similarly, in an extensional tectonic regime (σ_1 vertical), sediments are lengthened by normal faulting while maintaining volume preservation. Based on these geological principles, it is evident that a compressional regime always postdates an extensional tectonic regime. After all, it is impossible to shorten sediments before they have been deposited.[12] The geological events that follow compression and extension are completely different.

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12 In the geographic Neuquén basin, one can say that the back-arc basin (rifting phase + cratonic phase) was deposited during an extension tectonic regime (lengthening), while the overlying foredeep basin is associated with a regional compressional tectonic regime (shortening), which shortened also the back-arc basin sediments. When the maximum effective stress σ_1 is horizontal, the sediments are shortened, which implies uplift and subsequently : (i) a relative sea level fall ; (ii) erosion and (iii) an unconformity. Contrariwise, when σ_1 is vertical, sediments are lengthened, which implies subsidence and subsequently : (a) a relative sea level rise and (b) sedimentation.

Therefore, geologists must be careful not to mistake shortening for lengthening or vice versa.

Additionally, it is important to note that both sequences of geological events—Compression → Shortening → Uplift → Relative Sea Level Fall → Erosion → UnconformityExtension → Lengthening → Subsidence → Relative Sea Level Rise → Sedimentation → Transgression or Regression—are fundamental in testing and falsifying tentative geological interpretations (see later).

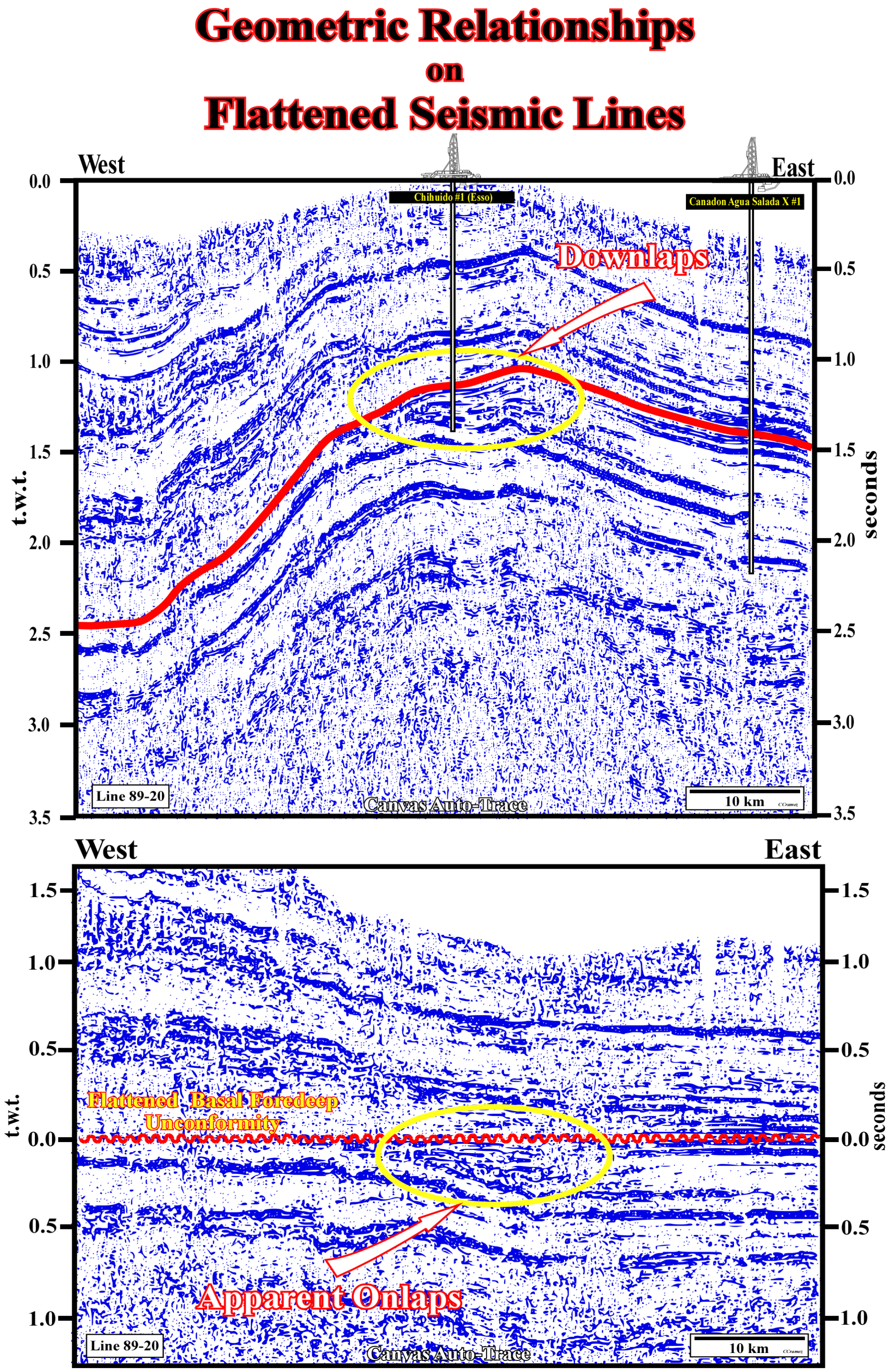

Figure 23 – The seismic line from the Neuquén geographic basin, shown in the upper part of this figure, was flattened (via vertical displacement) using as a horizontal datum the most probable basal unconformity of the foredeep basin.In the original seismic line, significant shortening and uplift of the sediments are clearly visible. Additionally, the downlap geometrical relationships below the unconformity (marked in red) at the apex of the Chihuido Anticlinoriumare quite evident.In the flattened seismic line, shown in the lower part of the figure, it is interesting to note that the original downlaps have been transformed into apparent onlaps, solely as a result of the flattening process.As mentioned previously, an automatically flattened seismic line is created by shifting samples in the original line either up or down. This means that certain parts of the original image are stretched in some areas and compressed (squeezed)in others to achieve the flattened appearance. Specifically, the flanks of the anticlinorium were squeezed (shifted upward), while the crest area was stretched (shifted downward).

Let's consider an example. Suppose a geoscientist working in hydrocarbon exploration is tasked with solving the following problem: In the given Argentine basin, particularly in an area covered by seismic data, what types of traps can be expected?The geoscientist, after formulating the most likely tentative solutions based on the global and regional geological setting of the area and his past experience, will proceed to falsify them using seismic data. Understanding the problem, he must systematically work toward a solution.The first step is crucial—he must examine the seismic data to eliminate the tentative solutions that can be easily refuted. However, the key decision in this observation phase is determining whether the sediments (represented by seismic reflectors) have undergone lengthening (extension) or shortening (compression). If he misinterprets this first step, the entire sequence of geological events he investigates will be incorrect, leading to a wrong conclusion. In fact, it is quite common to see: Antiforms (extensional structures) mistakenly interpreted as anticlines (compressional structures), and Morphological traps by juxtaposition misidentified as structural traps.The inevitable result of such an initial mistake is the same—dry wells, except in cases where oil is found by serendipity(which, incidentally, happens more often than one might think).

It is evident that the geoscientist must base his tentative geological interpretations on normal seismic lines rather than flattened seismic lines. This is because he knows—or must know—that a flattened seismic line (generated in a workstation) is not a palinspastic section, as illustrated in Figure 24.

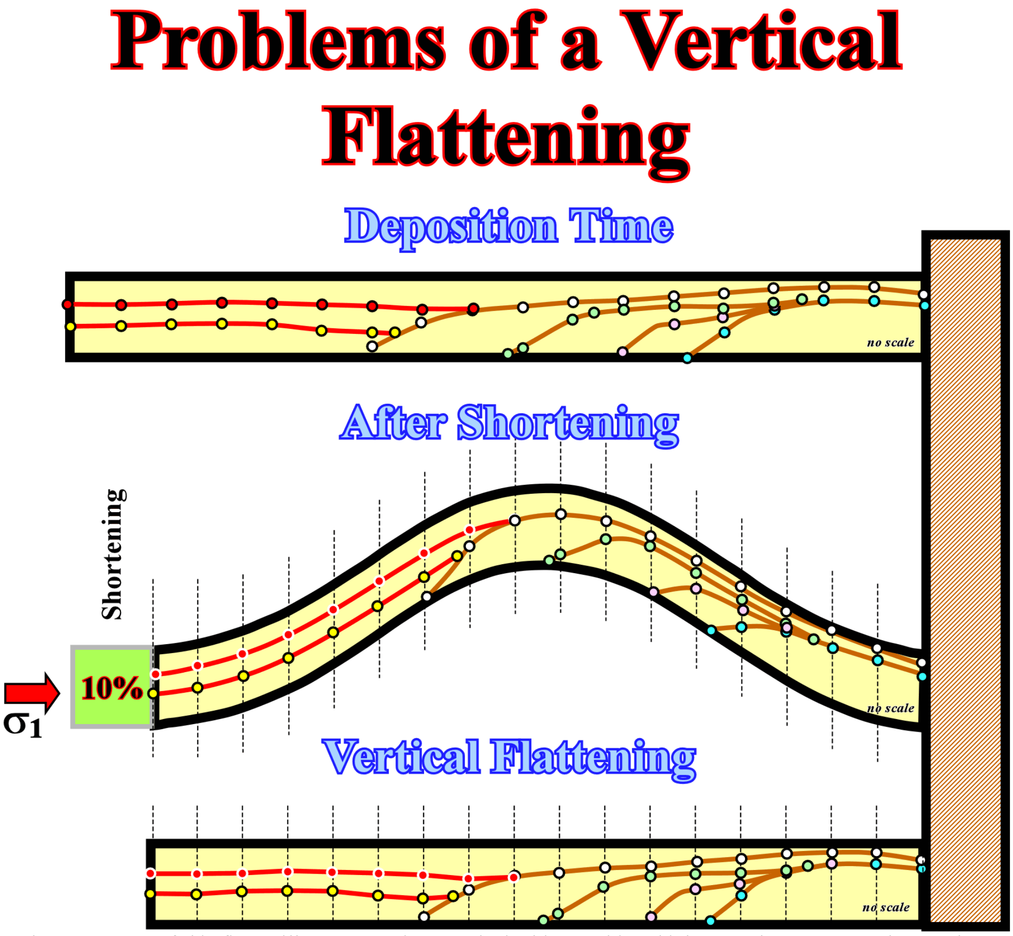

Figure 24 – The upper part of this figure illustrates a given geological interval in which several sequence cycles can be recognized. Both onlaps and downlaps are easily identifiable.Under the influence of a compressional tectonic regime, the sediments were shortened by folding, leading to the formation of anticline and syncline structures. Relative to their original deposition, the sediments experienced a 10% shortening.A seismic reflection survey was conducted over one of the anticline structures. A tentative geological interpretation of the seismic line crossing the anticline - i.e., the seismic line shot perpendicular to the axial direction of the fold - is illustrated in the middle section of the figure. Considering the horizontal scale of this seismic line, it is evident that its total length is 10% shorter than that of the original, undeformed section. Consequently, the original geometrical relationships were altered: (i) Some of the original downlaps now appear as apparent onlaps, and (ii)nSome of the original onlaps now appear as apparent downlaps.However, despite these distortions, many of the original geometrical relationships can still be recognized. The flattened version of the seismic line is shown in the lower part of the figure. While the original geometrical relationships remain visible, the total length of the section does not correspond to that of the original, undeformed state. In this flattened version, the sediments exhibit a 10% shortening without uplift. The central part of the seismic line was squeezed upward, while the flanks were stretched downward, a direct consequence of the flattening process.

Seismic image flattening aims to reverse the effects of geological processes by removing all structural deformation present in the image, thereby transforming it into a representation of layers as they were originally deposited in geologic time. In other words, flattening modifies a seismic image to make structural features appear horizontally aligned.This process enhances the visibility of stratigraphic features, such as channels, making them easier to recognize because the interpreter can view an entire geologic interface at once. Typically, a flattened seismic image is generated by shifting samples in the original image up or down. As a result, certain parts of the original image are stretched in some areas and compressed (squeezed) in others to achieve the flattened appearance.

Summing up : Avoid making tentative geological interpretations based on flattened seismic lines (especially those produced through conventional automatic workstation flattening). In areas where sediments have undergone shortening or lengthening, most geometrical relationships and seismic surfaces become distorted, making geological interpretation highly unreliable.

5) Geometry of Depositional Surfaces

In the sand-shale depositional model illustrated below (Figure 25), P. Vail and coauthors (1977) introduced the concept of sedimentary building blocks, which they termed sequences—later referred to as sequence-cycles:

"Succession of genetically related strata (or associated seismic reflections) bounded by unconformities or their correlative conformities, deposited during a third-order cycle of sea level change between two relative falls of sea level" (Mitchum et al., 1977).

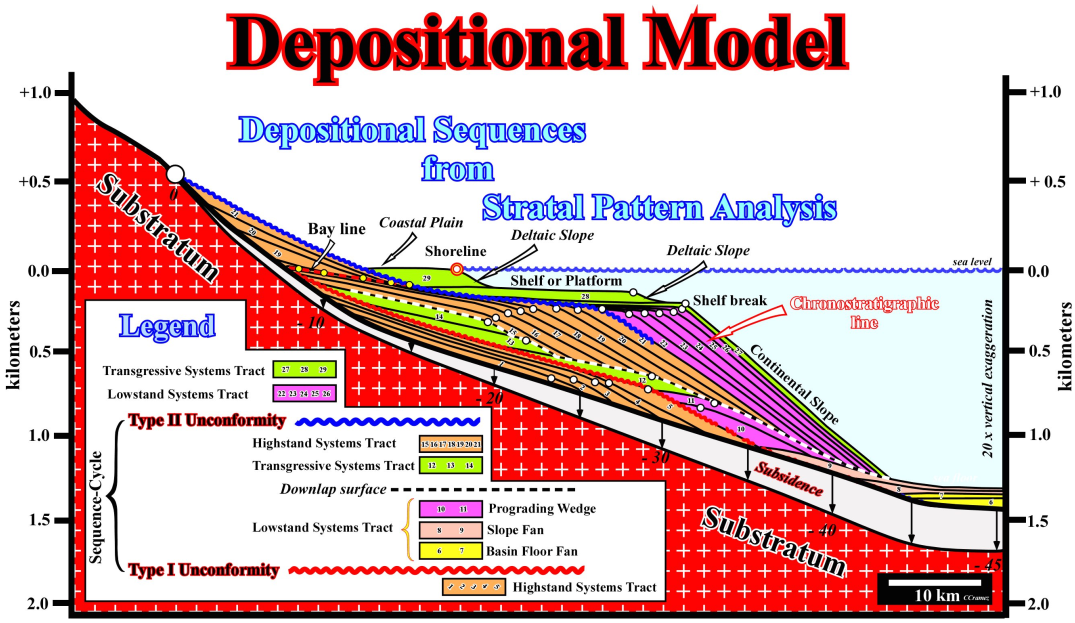

Figure 25 – This depositional model was proposed by P. Vail and co-authors for sand-shale facies. Three sedimentary intervals bounded by unconformities are easily recognized. They are called sequence-cycles, i.e., stratigraphic cyclesdeposited during third-order eustatic cycles. The intermediate interval (6 to 21) comprises all intervening strata of a complete sequence-cycle. The other two intervals are incomplete: In the lower interval (1 to 5), only the regressive highstand deposits (Highstand Systems Tracts – HST) are present. In contrast, in the upper interval (22 to 29), the regressive lowstand deposits (Lowstand Prograding Wedges – LPW) of the Lowstand Systems Tracts (LST) and the transgressive deposits of the Transgressive Systems Tracts (TST) are present. It is interesting to note that during a complete sequence-cycle, the basin has no shelf (platform) during the deposition of the Lowstand Systems Tracts (LST), which is composed of three elements: (i) Basin Floor Fans, (ii) (BFF) Slope Fans, (iii) (SF) Lowstand Prograding Wedges (LPW). The basin begins to develop a platform during the Transgressive Systems Tracts (TST). The platform reaches its maximum extent at the onset of the Highstand Systems Tracts (HST), when relative sea level rise begins to decelerate. However, as the shoreline progrades seaward, the continental platform progressively shrinks until it disappears. When the basin has a platform, the shoreline (more or less corresponding to the depositional coastal break) is located landward of the shelf break, which marks the edge of the basin. However, when the basin has no shelf, the depositional coastal break is more or less coincident with the edge of the basin. On the other hand, this model clearly illustrates the difference between deltaic and continental slopes. Apart from differences in height amplitude: (a) Deltaic slopes are located landward of the shelf break, (b) Continental slopes are located seaward of the shelf break (when the basin has a shelf) and (c) seaward of the edge of the basin (when the basin has no shelf). Put differently: - When the basin has a shelf, the deltaic slope is disconnected from the continental slope.- When the basin has no shelf, the deltaic slope is connected to the upper part of the continental slope.

In this model, Exxon's explorationists assumed :

1 - Eustasy is the main factor driving the cyclicity of sedimentary deposits ;
2 - Subsidence and Terrigeneous Influx rates are smaller than sea level changes, i.e., than Eustasy ;
3 - Eustasy, Subsidence, Accommodation, Terrigeneous Influx and Climate are the major geological parameter affecting the stratal patterns ;
4 - Terrigeneous Influx is constant in Time and Space ;
5 - Subsidence increases gradually and linearly basinward ;
6 - Sedimentary intervals have high completeness[13] ;
7 - There is no erosion during relative sea level falls ;
8 - The time interval between each chronostratigraphic line is 100 k years ;
9 - Each chronostratigraphic line corresponds to a depositional line.

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[13] **The completeness of a given sedimentary interval is the relationship between the real deposition time and the total geological time. For example, if the time between two successive unconformities is 10 My and real time of deposition deposit is 1 My, the completeness is 0.1. In turbidite systems, the completeness of the deposits is very low, but the preservation is great. The deposition time of a basin floor fan is practically instantaneous (in geological terms), while the time between two consecutive lobes, in which almost nothing happens (at the deposition point of view) may be thousands of years or more.**

Taking into account geological time, the sedimentary building blocks—that is, the sequence-cycles, which range in duration between 0.5 Ma and 3.0–5.0 Ma—are considered instantaneous and catastrophic depositional events.In fact, during the Phanerozoic (600 million years), an instantaneous geological event, in mathematical terms, represents a time change of 1/100 of the total time. This equates to 1/100 of 600 Ma, or approximately 6 million years.

For many geologists, this stratigraphic model is not only too general and theoretical but also built upon too many geological assumptions. Nevertheless, as suggested by P. Bak, geoscientists might find looking at details fascinating and, at times, interesting, but ultimately, they learn the most from generalities.

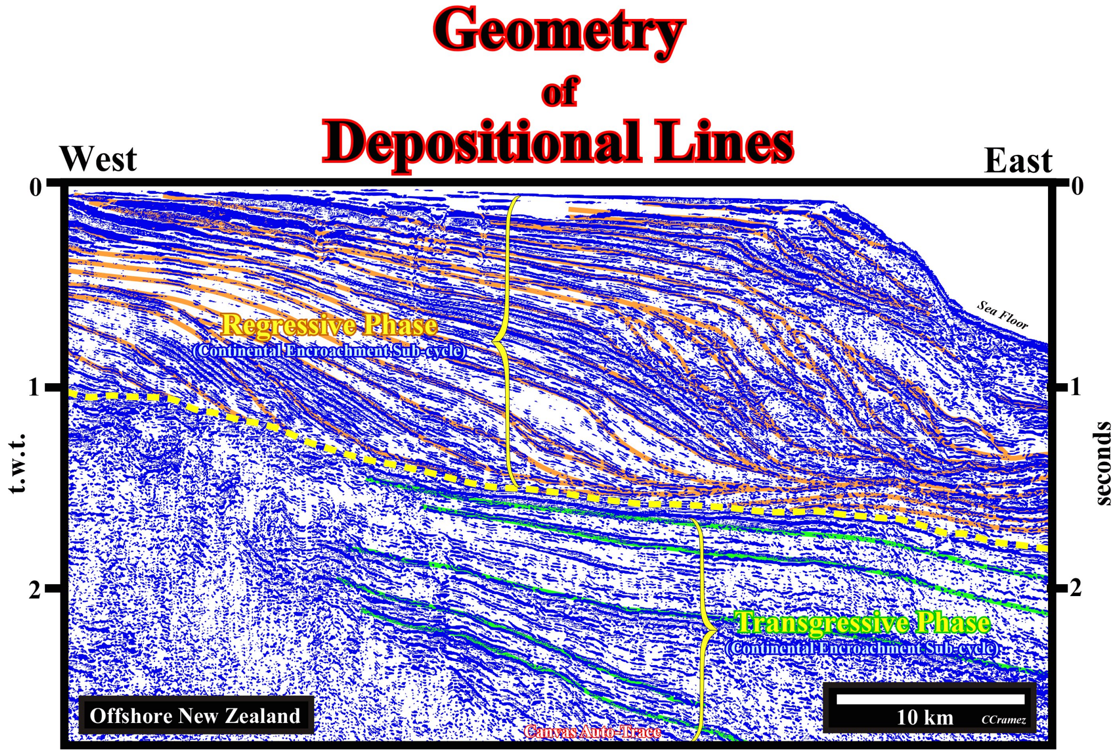

Figure 26 – Considering that deltaic deposits are often below seismic resolution, one can schematically describe a depositional line (more accurately referred to as depositional surfaces) as being composed of three coeval segments: an inclined horizon (Segment 1), which corresponds to the continental slope; up-dip of Segment 1, a sub-horizontal segment (Segment 0), which corresponds to the coastal plain or a combination of the coastal plain and continental platform (if the basin has a shelf); and down-dip of Segment 1, another sub-horizontal segment (Segment 2), which corresponds to the abyssal plain. In a concise manner, and applying Walther's Law, a depositional line can be considered a lateral succession of Segments 0-1-2, with Segment 1 being the most important. Identifying the location of Segment 1 allows for the prediction of Segment 0 landward, Segment 2 seaward, Segment 2 upward, and Segment 0 downward, assuming continuous sedimentation. In the transgressive phase, the sub-horizontal reflectors can only correspond to Segment 0 or Segment 2; however, since the most probable location of the coeval Segment 1 is eastward of the seismic line, these sub-horizontal reflectors should tentatively be interpreted as Segment 0, meaning they represent coastal plains. In the regressive phase, the geometry of the depositional lines is much more apparent, making the identification of the three segments easier. It is important to note that only Segments 0 and 2 can be flattened, whereas Segment 1 can never be flattened because it was originally deposited with an inclined geometry.

Notice that along each depositional surface (represented in the above depositional model by a chronostratigraphic line), several breaks or changes in inclination can be observed: (i) Bay-line (in the Highstand Systems Tracts – HST); (ii) Depositional coastal break, which corresponds, more or less, to the shoreline or delta front; (iii) Bottom of the deltaic slope; (iv) Shelf break (top of the continental slope); and (v) Abyssal plain break (bottom of the continental slope). Contrary to the principle of Original Horizontality[14], along a depositional surface, between these inclination breaks, both horizontal and oblique realms of deposition are possible. Coastal plain, platform, and abyssal plain sediments are deposited more or less horizontally, whereas alluvial fan, pro-delta, continental slope, and slope fan sediments are deposited at an oblique angle. The depositional angle is primarily de-

[14] This geological principle states that sedimentary layers were deposited in lateral continuity and that they thin out and disappear either by downlap or onlap against the edges of the deposition zones. However, this principle has recently been updated. Today, we understand that bedding planes are chronostratigraphic surfaces composed of different geological environments with varying depositional inclinations. For example, alluvial deposits (upstream of the bay line) and pro-deltas—particularly in Gilbert-type deltas—are not deposited horizontally. There are several other fundamental geological principles that geoscientists must always keep in mind: (i) Principle of Composition – A rock represented by fragments within another rock is older than the rock that contains it; (ii) Principle of Intersection – The latest veins displace the older veins; (iii) Principle of Intrusion – An intrusive igneous rock is younger than the rock it penetrates; (iv) Principle of Superposition – In an undeformed or slightly deformed stratigraphic column, the oldest layers are at the bottom, with progressively younger layers above; (v) Principle of Fossil Succession – The distribution of fossils in rocks is not random; rather, they follow a defined vertical succession; (vi) Principle of Goguel – During deformation, the volume of sediment remains more or less constant; (vii) Principle of Walther – The facies (lithology) observed in a vertical succession within conformable strata can also be observed laterally in adjacent environments; (viii) Principle of Dextrogyre – If a reference system rotates in a clockwise direction, an object within it (due to the Coriolis effect) will be deflected to the left; (ix) Principle of the Carbonate Bucket – The growth of a rimmed carbonate platform is controlled by the growth of its aureole (outer margin); (x) Principle of Uniformitarianism – Geological changes occur mainly through the same processes and continuous changes that can be observed in the present; (xi) Principle of Ockham (Occam's Razor) – Plurality should not be invoked without necessity ("Non sunt multiplicanda entia sine necessitate"), meaning that the simplest explanation is usually the most likely.

pendent on the stability of the associated slope, which, in turn, is influenced by factors such as terrigenous influx, water depth, and climate.

Consequently, to conclude this chapter, we can state that, at a macroscopic scale, and particularly at the scale of seismic lines, considering seismic resolution, three sub-areas can be distinguished within a depositional surface:

(i) A dipping subsurface (surface 1) ;
(ii) A sub-horizontal surface down-dip of the dipping surface (surface 2) and
(iii) A sub-horizontal surface up-dip of the dipping surface (surface 0)[15].

6) Unconformities (Type, Recognition, Age)

The origin, meaning, and spatial/temporal extent of unconformities are critical aspects to consider in all tectonic and stratigraphic studies. Over time, and particularly after the advent of Sequence Stratigraphy, the term unconformityhas often been misused. Goguel (1952) noted that, from a structural perspective, it is common to distinguish between tabular and folded areas. This distinction depends on the age of the observed strata relative to the age of deformation. Strata that postdate deformation rest upon pre-deformation strata, separated by a tectonically enhanced unconformity (angular unconformity), which is of fundamental importance in structural interpretation. Grabau used the term unconformity to refer to a stratigraphic hiatus (gap) associated with a transgression. He distinguished two types of unconformities and assigned them specific terms: (i) "Nonconformity" to denote an angular unconformity, and (ii) "Disconformity" to describe an interruption in the sedimentary chronological sequence where no apparent angular unconformity is present.

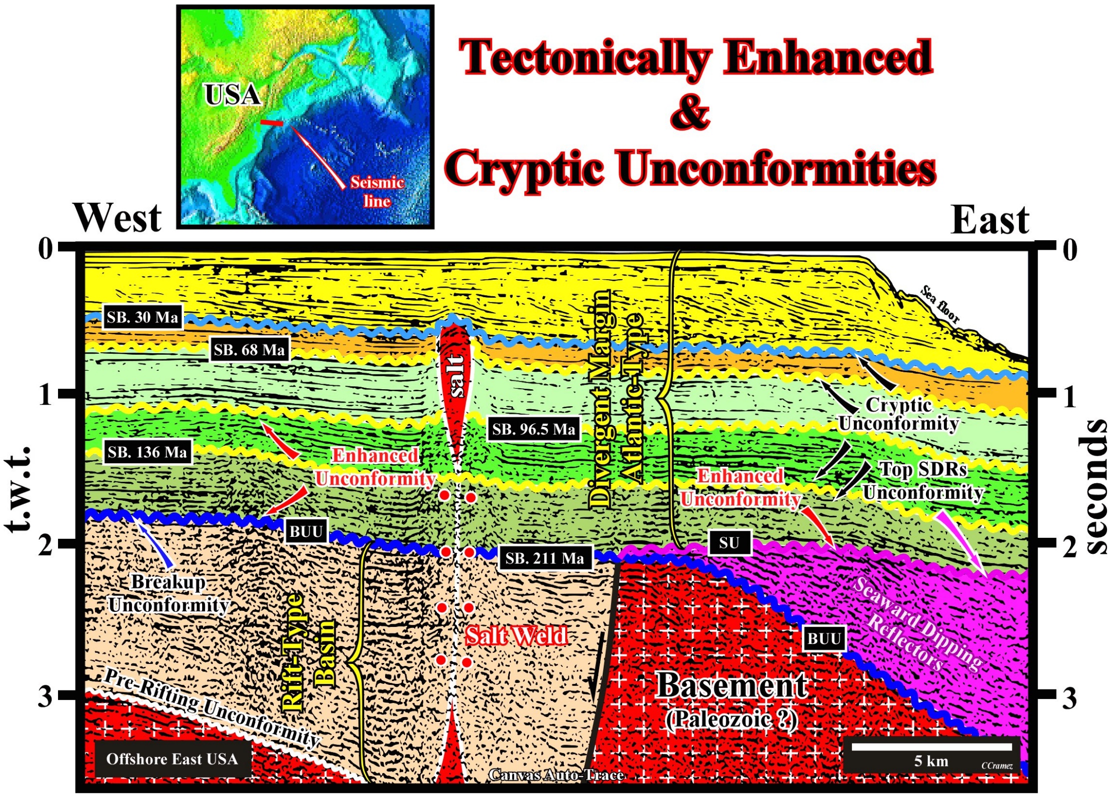

Figure 27 – As illustrated in this tentative geological interpretation of a seismic line from Baltimore Canyon (New Jersey offshore), several unconformities have been identified. All of these unconformities were induced by relative sea level falls, which lowered sea level below the edge of the basin (typically the shelf break, when the basin has a platform). Certain unconformities, such as the pre-rifting unconformity, the break-up unconformity (BUU), and the unconformity associated with the top of the seaward-dipping reflectors (subaerial lava flows), were locally tectonically enhanced and, therefore, correspond to seismic surfaces characterized by distinct geometrical relationships. Similarly, the SB. 96.5 Ma unconformity, located west of the Triassic salt dome, was locally tectonically enhanced due to the emplacement of a volcanic plug, whose presence was confirmed by magnetism and drilling. The remaining unconformities are cryptic, meaning there is apparent conformity between the underlying and overlying reflectors. These unconformities were identified in specific locations where erosion associated with relative sea level fall is evident, such as in incised valley fills and submarine canyon fills, and were then traced laterally in continuous seismic reflections.

A. Orbigny introduced the terms: (a) "True Unconformity" to describe an angular unconformity and (b) "Unconformity of Isolation" to refer to a stratigraphic hiatus. However, these terms have largely been forgotten.

Bally (1989), in discussing the importance and significance of unconformities in sequence stratigraphy, noted that unconformities can have very different origins. In some cases, such as those mentioned below, the eustatic componentappears insignificant, meaning that eustasy does not seem to be the primary geological cause of these unconformities:

[15] Only the surfaces (0) and (2) can be flattened.

- Unconformities characterized by erosion and truncation of tilted fault blocks
- Unconformities induced by deepwater currents on the slope
- Unconformities associated with canyons on divergent margins
- Unconformities observed in shallow-water environments, induced by geostrophic currents
- Unconformities associated with starved geological conditions
- Unconformities underlying the onset of seafloor spreading
- Break-up unconformities
- Basal foredeep unconformities
- Unconformities associated with the relaxation of foredeep basins
- Unconformities associated with salt flowage, etc.

These unconformities require detailed characterization and differentiation because they are often interpreted in a generalized manner, frequently attributed solely to eustatic changes, as proposed by P. Vail. His model assumes that the rate of tectonic events (subsidence, folding, fault movements) is much slower than the rate of eustatic sea level variations, while neglecting other factors such as subsidence induced by sediment load or sudden variations in sediment influx.

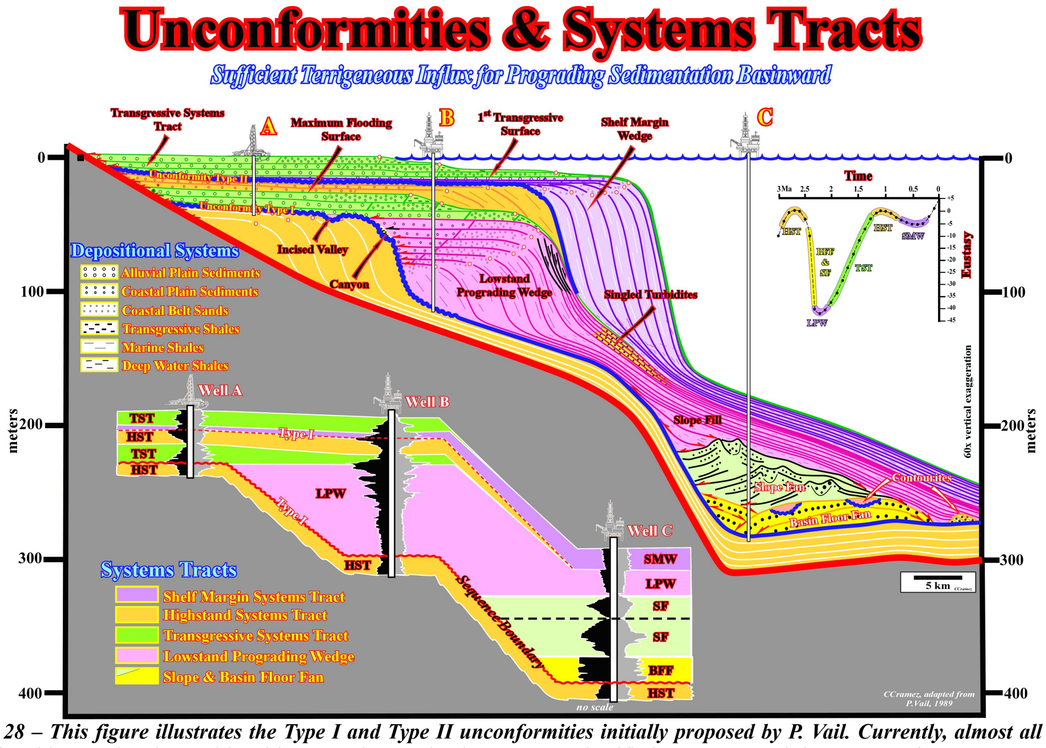

Figure 28 – This figure illustrates the Type I and Type II unconformities initially proposed by P. Vail. Currently, almost all Type II unconformities previously considered by Exxon's geoscientists are now classified as Type I, and the concept of Type II unconformity has largely disappeared from the scientific literature. Type I unconformities represent the boundaries of stratigraphic cycles, and their age corresponds to the age of the associated relative sea level fall (see Figure 29). This age can be determined based on the age of the basin floor fan of the overlying sequence-cycle. Consequently, only an exploration well that penetrates the basin floor fan associated with a given relative sea level fall can provide an accurate dating of the corresponding unconformity. In this figure, the paleontological results from wells A and B do not allow for the dating of the basal unconformity of the middle sequence-cycle (the complete sequence-cycle). Only the paleontological results from exploration well Ccan date the basal unconformity, as this well drilled into the associated basin floor fan. When a core drilling is performed in a basin floor fan, a geoscientist can date it if the pelagic layer of the Bouma sequence is identified. This is because only this specific stratigraphic level contains fauna contemporaneous with the relative sea level fall. In contrast, all other layers within the Bouma sequence contain transported fauna.

In a strict sense (sensu stricto), particularly in Sequence Stratigraphy, an unconformity is an erosional surface caused by a relative sea level fall significant enough to lower sea level below the edge of the basin. In some geological settings, this edge corresponds to the shelf break, while in others, it corresponds to the continental break, while in others, it corresponds to the continental break (when the basin lacks a shelf). In a broader sense (sensu lato), unconformities are discontinuous stratigraphic surfaces, where the associated time gap may represent:

a) Prolonged periods of subaerial exposures with minimal erosion, possibly with local valley or channel downcutting ;

b) Periods of uplift and major subaerial erosion of strata ;

c) Submarine erosion[16] by turbidites, slump or submarine currents.

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[16] Submarine erosion induced by gravity-driven processes or turbiditic currents is generally localized. The unconformities associated with this type of erosion are primarily found in deep-water environments, such as the slopeand abyssal plain. These unconformities do not have equivalents in shallow-water environments and, therefore, do not serve as boundaries for stratigraphic cycles. However, when sequence-cycles are incomplete, meaning they consist only of deep-water strata, these unconformities may still play a role in stratigraphic interpretation.

Uplift and Erosion are characterized by:

(i) Onlap, above the unconformity.
(ii) Truncation, below the unconformity.

Infilled Valleys or Channels are also characterized by:

(a) Onlap above the unconformity and
(b) Truncation below the unconformity.

Note that very often, geoscientists confound valley with valley fill and channel with channel fill:

- **A valley is a morphologic feature which characterised by low-lying land bordered by higher ground ;**
- **A valley fill or valley infilling is the name given to the, more or less, unconsolidated sediment deposited by any agent that totally or partially fill a valley ;**
- **A channel is the bed where a natural body of water flows or may flow ;**
- **A channel fill or channel infilling names the sediments deposited in a stream channel, especially, in an abandoned cutoff channel or where the transporting capacity of the stream is insufficient to remove material supplied to it.**

For P. Vail, within the framework of Sequence Stratigraphy, all unconformities are associated with erosion induced by eustatic changes in sea level, which contrasts significantly with earlier hypotheses proposed by E. Beaumont, E. Argand, Wegmann, and others. These earlier theories attributed the formation of erosional surfaces primarily to transgressions (relative sea level rises). However, Vail acknowledged that unconformities can be locally enhanced by tectonics, referring to them as "tectonically enhanced unconformities."

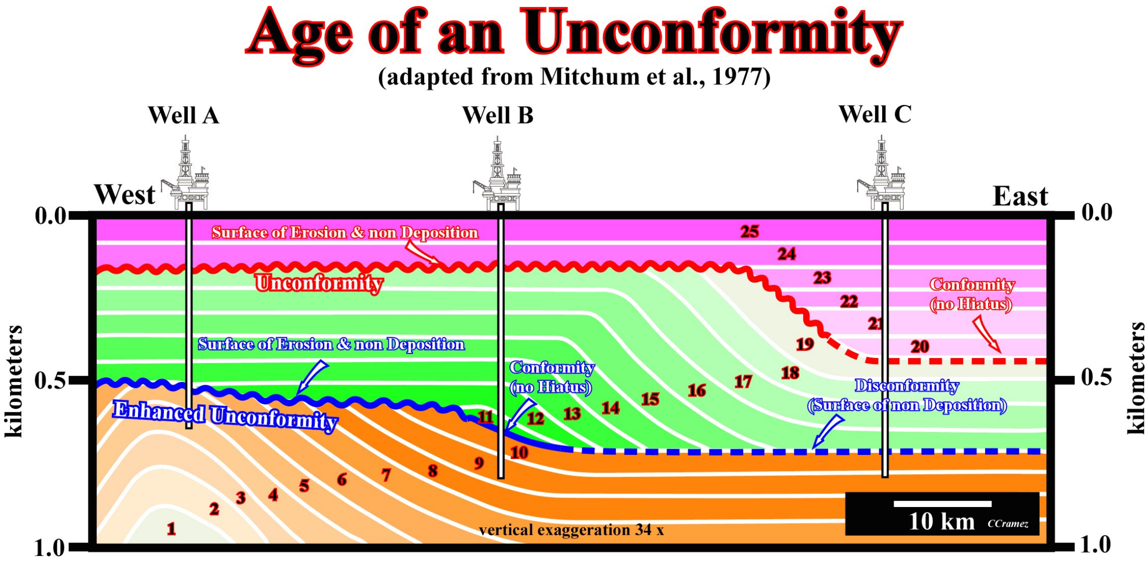

Figure 29 – As previously stated, the age of an unconformity corresponds to the age of the relative sea level fall that induced it. In this geological sketch, Well A can never provide the exact age of the unconformities it identifies. The micro-paleontological results from Well A can only indicate that the upper unconformity (which is not tectonically enhanced) is younger than time interval 17 and older than time interval 24, while the lower unconformity is youngerthan time interval 5 and older than time interval 12. This is because Well A crosses both unconformities in a sector where they correspond to a high-depositional surface. Well B also cannot date the upper unconformity (the red one) but can date the lower unconformity (the blue one) because it intersects a section of the unconformity where there is conformity between the underlying and overlying intervals, meaning there is no hiatus. Conversely, the micro-paleontological results from Well C can date the upper unconformity since it intersects the unconformity in a sector where there is conformity between overlying and underlying intervals with no hiatus. However, Well C cannot date the lower unconformity because it intersects it in a distal sector where there is a disconformity with a large depositional hiatus. It is important to note that downlapping can characterize a sequence boundary but not an unconformity (erosional surface).

The concept of tectonically enhanced unconformity ("angular unconformity") inherently implies the simultaneous development of regional and local structures. Unconformities can serve as highly sensitive time markers, recording the evolution of structural deformations. This is particularly relevant in perisutural sedimentary basins associated with the formation of mega-sutures, a factor that is often overlooked by many geoscientists.The recognition of abrupt tectonic transitions allows geoscientists to understand the progression of continuous structural deformations and, consequently, to determine the age of structural traps. These traps have a higher probability of retaining hydrocarbons when the timing of hydrocarbon migration is known. By closely examining the next geological sketch (Figure 29), one can easily understand how the age of an unconformity can be determined, particularly when it is locally tectonically enhanced. The hypothesis of tecto-nically enhanced unconformities can be tested easily. Geoscientists need only perform a detailed stratigraphic and biostratigraphic analysis of observed data to verify whether subsidence and/or the tectonic regime continued after the unconformity.

7) Volume Problems (Goguel's law)

Geology is systemic, and volume problems cannot be understood in isolation. Their interpretation should progress from the general (whole) to the particular (part). A geologist correctly understands an individual structure (compressionalor extensional) only when he comprehends the entire system. This is especially true when interpreting seismic lines in fold belts or shortened back-arc basins, such as in the Neuquén Basin. A geoscientist (or seismic interpreter) working in such basins cannot simply begin picking seismic markers or fault planes, whether in continuity or not, while expecting a coherent geological model to emerge at the end. Instead, a systematic approach is required, integrating regional tectonics, structural evolution, and stratigraphic relationshipsto ensure accurate interpretation.

- Naive inductive seismic interpretations do not exist.

- The theoretical framework within which a geoascientist works is critical to observation and picking.

- There is no legend on seismic line that tells the interpreter what to see.

- To identify reflections and seismic surfaces, the interpreter must already know what to look for.

- If this seems somewhat circular, and it is, it explain why scientific exploration progress is challenging.

In Geology, and particularly in Petroleum Exploration, ground rules concerning volume preservation during deformation have been used for a very longtime, including :

(i) Incompressibility of rocks ;
(ii) Dissolution ;
(iii) Erosion ;
(iv) Salt and shale tectonics ;
(v) Folding and Faulting ;
(vi) Facies ;
(vii) Subsidence ;
(viii) Compaction

Incompressibility of Rocks

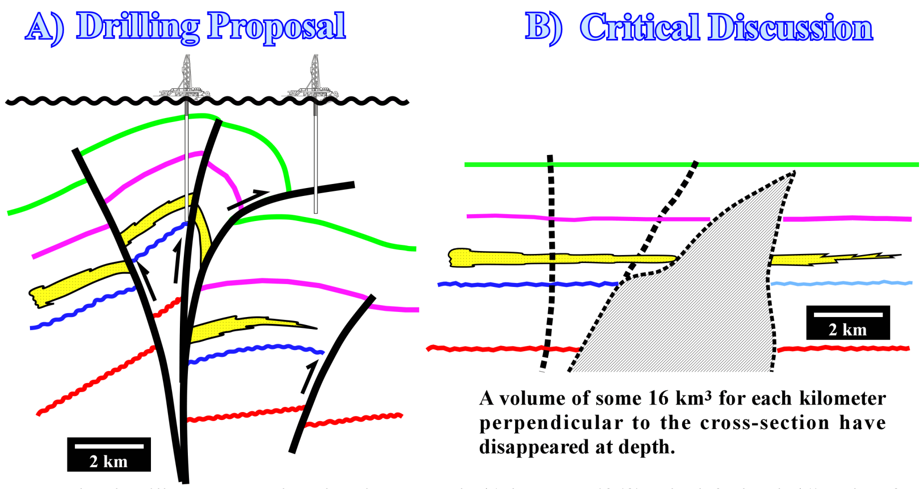

***Figure 30** – These two sketches illustrate a real exploration example (Arbenz, B., 1968). The left sketch (A), taken from the drilling proposal, represents a tentative geological interpretation of a seismic line, in which the interpreter proposed two exploration wells. The seismic line is perpendicular to the structural trends, which are primarily associated with cylindrical folds and thrust faults. The tectonic regime responsible for the shortening was characterized by σ_1 horizontal and σ_3 vertical, meaning that, theoretically, no significant lateral displacements should be expected. The proposed tentative interpretation (A) appears plausible, but it does not withstand critical analysis. A simple restoration test (see the sketch on the right) refutes the initial interpretation. The geoscientist did not respect volume preservation during deformation (Goguel's Law). In fact, for each kilometer perpendicular to the profile, a volume of approximately 16 km³ disappeared at depth. As a result, the geoscientist is forced to propose another tentative solution, meaning a new geological interpretation of the seismic line - one that, at the very least, must honor volume constraints. At this point, it is crucial to emphasize once again that interpretation progresses through iterative tentative solutions (trial and error). Seismic interpreters cannot complete their work by performing only one tentative interpretation of the seismic data. In many cases, they are surprised to find that, by the second or third iteration, they begin to recognize many more geological events in the data. Once again, it is important to remember: observations are theory-laden, i.e. that what we observe is always influenced by our underlying theoretical framework.*

The idea that the better or more preferable tentative geological interpretation is more likely to be correct than the less probable one may seem evident, but it is not necessarily true. On this subject, philosophers of science introduced the concept of corroboration or degree of corroboration, aiming to demonstrate that any probabilistic theory of preference is fundamentally flawed. At any given time (t), the degree of corroboration of a geological hypothesis is simply an assessment of how well it has withstood critical tests. Corroboration is essentially a report evaluating past performance, and it provides no indication of future performance or the reliability of the hypothesis.Instead of trying to corroborate a tentative interpretation, geoscientists should focus on refuting it. Only through systematic falsification—by testing, questioning, and challenging interpretations—can one improve geological models and achieve more robust and reliable conclusions.

Volume Problems & Fault Picking

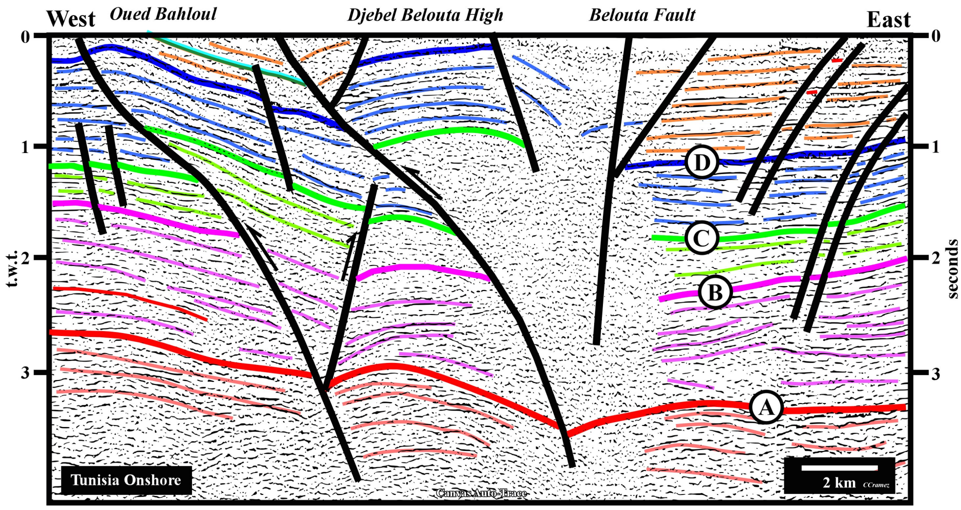

Figure 31 – This picking of the main seismic reflectors is based on a seismic line where no significant lateral displacements are present. The proposed picking interpretation clearly shows that the interpreter overlooked a fundamental principle: during deformation, the volume of sediments must be preserved (taking into account porosity reduction and stylolite formation). This interpretation fails a simple geometrical critical test.In particular, the shortening of the seismic markers is inconsistent. For example, the green marker (C) is much more shortened than the red marker (A). This discrepancy suggests the presence of a detachment plane or a tectonic disharmony.The geometrical relationships between the seismic markers can only be explained by one of the following: Tectonic inversion, where old normal faults were reactivated by a compressional tectonic regime.Tectonic disharmony, indicating different styles of tectonic deformation affecting separate stratigraphic levels.A proper restoration test and a volume-balancing analysis would be necessary to validate the structural interpretationand identify the correct deformation mechanism.

In these notes, only the incompressibility of rocks will be considered, as this is the key factor in which most tentative geological interpretations of seismic lines - particularly those I reviewed during my last trip to Argentina - are easily falsified, especially due to fault picking errors. The examples illustrated in Fig. 30 and 31, taken from other exploration areas, are included to avoid any "Argument ad Hominem". The captions of these figures emphasize the following fundamental principle: From a structural standpoint, geoscientists must be able to restore every tentative geological interpretation to its original state without violating volume preservation (Goguel's Law). This rule must be respected, considering the most likely exceptions, such as: (i) Dissolution, (ii) Erosion, (iii) Salt basins, etc.

Fault Curvature with Depth

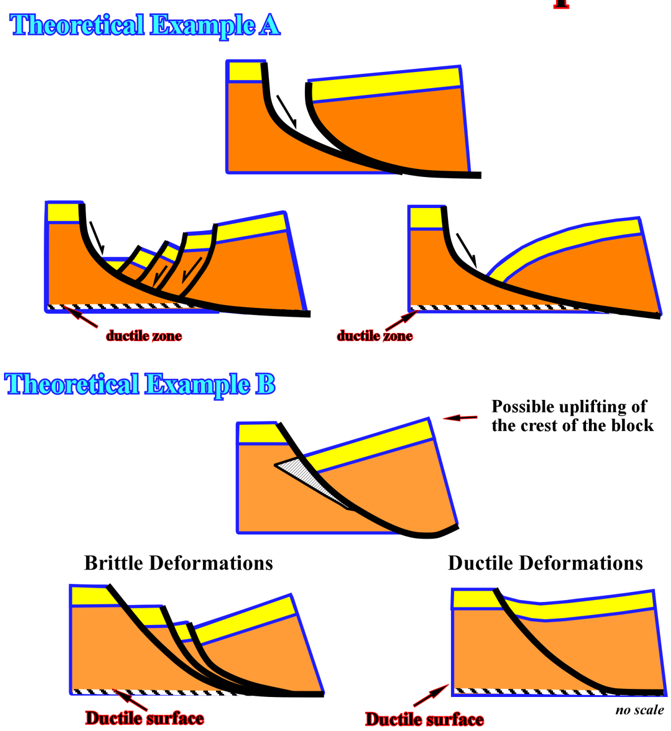

Figure 32 – When the geometry of a fault plane is curved, avoiding a potential void requires that the sediments be lengthened. This is achieved through the formation of antithetic normal faults, which terminate within a major synthetic curved fault that limits the hanging wall in the down-dip direction (in brittle materials).In contrast, when sediments are ductile, faulting is minimal or even absent. Instead, a rollover structure in the hanging wall accommodates the volume problem. In this geological model, the volume issue of curvilinear faults (both at the surface and at depth) is resolved in two ways: (i) By synthetic listric faults, forming multiple drag-faulted blocks (riders) when sediments are brittle. (ii) By a synform, when sediments are ductile, allowing for plastic deformation rather than faulting.

For that, geoscientists should not forget that volume problems created by extension, such as in normal faulting, can be resolved in two different ways, as illustrated below (Figure 32).

In the theoretical example A, the geometry of the fault plane creates a potential void when the hanging wall is displaced forward. To fill the space created, the sediments undergo lengthening. The specific lengthening mechanismdepends on the rheology of the sediments: a) If the sediments are brittle, accommodation occurs through antithetic normal faulting, b) If the sediments are ductile, accommodation occurs through ductile deformation (e.g., rollover folding). In the theoretical example B, the geometry of the fault plane is such that when the hanging wall displaces, theoretically, an overlap occurs between the faulted blocks. This overlap problem can be solved in two different ways, which are illustrated below.

8) Velocity Lateral Changes

Since modern data processing and interpretation produce seismic sections that resemble geologic cross-sections, inexperienced geoscientists are often tempted to interpret geology directly from seismic data. However, this approach can lead to serious errors, especially in areas with irregular surfaces, complex weathering, complex tectonics (high dips), rapid lithological changes (density and velocity variations), or sharp changes in water depth.

In onshore environments, the recorded reflection times on seismic traces must be corrected for time differences introduced by near-surface irregularities, which can shift reflection events on adjacent traces out of their true time relationships. The two major sources of irregularity are:

(i) Elevation differences between individual shots and detectors.

(ii) Weathered layers, which are heterogeneous surface layers (ranging from a few meters to several tens of meters thick) with abnormally low seismic velocities.

To correct for these effects, static corrections (a bulk shift of seismic traces in time during seismic processing) account for both topography and the weathered zone. In areas with sharp topographic variations, since the velocity of subsurface sediments is higher than the velocity of seismic waves in the air, seismic waves spend more time at the vertical of topographic highs than in topographic lows when referenced to a horizontal datum.

As weathered zones generally have low seismic velocities, the weathered/non-weathered sediment interface is pulled down in areas where the weathered zone is thicker. The same effect occurs in the presence of salt domes or organic build-ups, where high-velocity seismic waves induce significant pull-ups of horizons at their base and below.

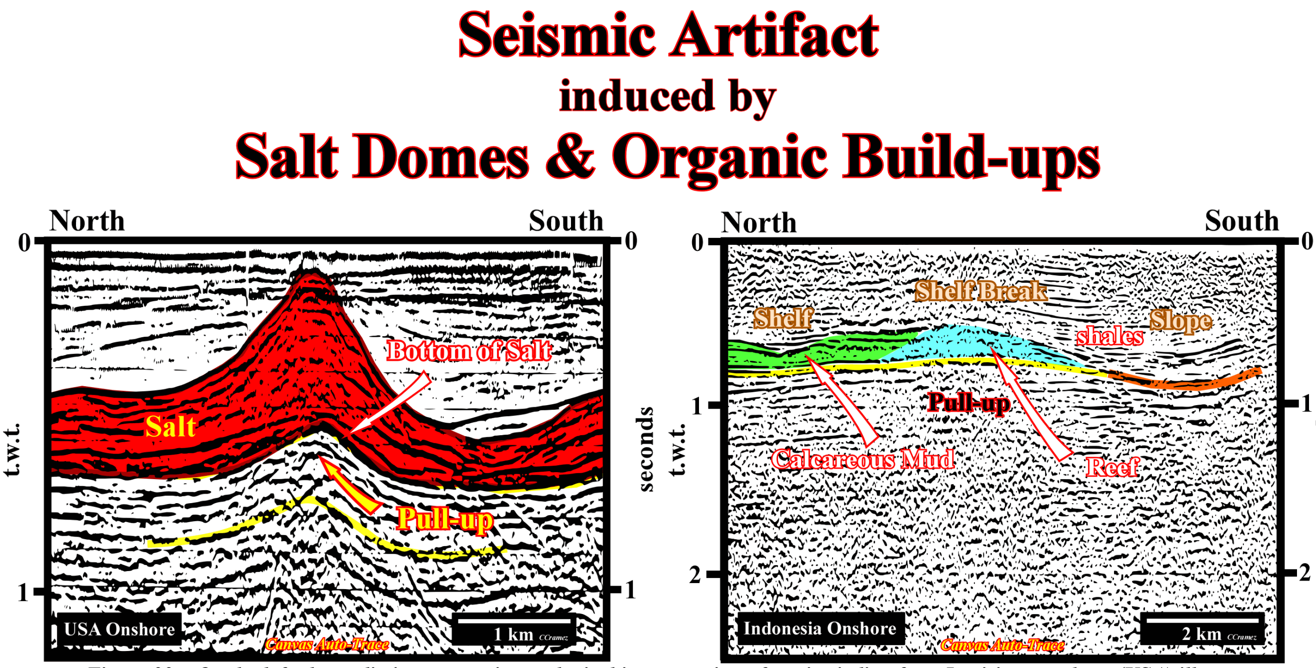

Figure 33 – On the left, the preliminary tentative geological interpretation of a seismic line from Louisiana onshore (USA) illustrates a seismic artefact induced by a non-isopachous evaporitic interval; the bottom of the salt layer is pulled up where the salt interval is thicker. Seismic waves traveling through a thicker high-velocity interval (approximately 5000 m/s) spend less time, causing the base of the salt to be pulled up (i.e., appear higher). Without a corrected time–depth conversion, it is sometimes dangerous to assume a flat salt bottom a priori. In Angola and Brazil offshore, salt steps are often observed in association with major fracture zones and pre-salt carbonate buildups, which are fossilized by the onlapping of salt. On the seismic line illustrated on the right, which comes from onshore Indonesia, the shelf break of the upper colored interval appears to emphasize the development of a reef; in fact, the bottom of the shelf limestone is pulled up, and this pull-up is enhanced by the pull-down of the reflectors associated with the slope shales to the south. In certain basins, such as the Michigan Basin (USA), the recognition of reefal anomalies is mainly based on the absence of reflectors; in other words, when a continuous, high-amplitude marker representing a limestone interval experiences an abrupt interruption over a few kilometers, it may indicate the presence of a local porous reef.

In offshore settings, changes in water depth induce typical seismic artifacts, particularly in the distal parts of seismic lines covering continental platforms and the upper continental slope. These artifacts are especially common in areas where submarine canyons have been carved by turbiditic currents, often triggered by relative sea level falls.

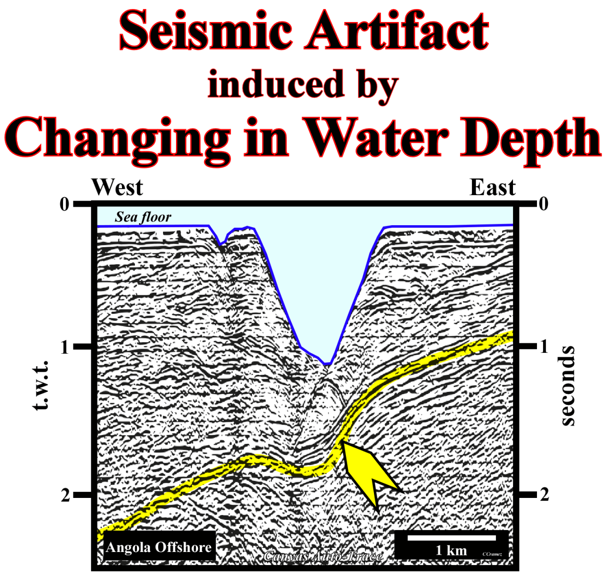

Figure 34 – This seismic line from northern offshore Angola, near the mouth of the Congo River, clearly illustrates a seismic artifact caused by water-depth variation. Since seismic waves travel slower through water than through sediments, the result is a local pull-down of reflectors, particularly beneath the Congo submarine canyon, which is obvious in this section. It is important to note that pull-downs have no geological significance in terms of true subsurface geometry. In a depth-converted section, the yellow reflectors maintain their regional seaward dip, which is consistent across the entire profile. This seaward dip is primarily attributed to the Late Tertiary uplift of the eastern part of the margin.

A sharp change in water depth, as illustrated in Figure 35, induces lateral variations in velocity between the sediments and water column. Consequently, seismic waves traveling through deeper water are progressively retarded, resulting in a longer travel time. As a result, the associated reflections are gradually pulled down, creating a seismic artifact that must be corrected for accurate interpretation..

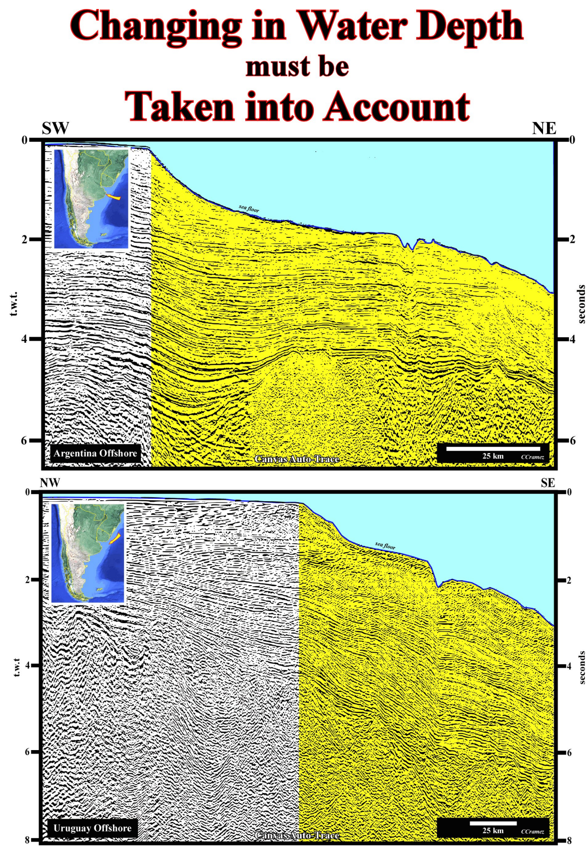

Figure 35 – These seismic lines from the southeastern offshore of South America highlight the critical need for geoscientists to consider multiple factors when making a tentative geological interpretation. Beyond the abrupt change in water depth caused by the transition from the shelf to the continental slope, interpreters must also account for the continuous seaward dipping of the continental slope.Additionally, local variations in water depth induced by submarine valleys and canyons, which are visible on both seismic lines, must be incorporated into the interpretation. The seismic artifacts associated with submarine valleys and canyons—which extend from the seafloor to the bottom of the seismic section—are generally easier to recognize than those caused by the progressive dip increase of the continental slope. On these seismic lines, seaward of the shelf break, geoscientists should, at a minimum, mentally estimate the depth of the seafloor, knowing that the velocity of seismic waves in water is approximately 1,4–1,5 km/s, while in: Sandstone: 1,4–4,3 km/s, Granite: 5,5–6,0 km/sA useful approach is to take half the water depth at the eastern end of the seismic line and trace a regional depth trendback to the shelf break. Even with these underestimations, it is evident that in depth-converted sections, the dip of the seismic reflectors in the yellow area will be significantly smaller, or even inverted, which fundamentally alters the geometry of potential traps and the migration pathways of generated hydrocarbons.
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Among all categories of seismic pitfalls, the most elementary yet crucial is the one related to velocities. This is because the majority of seismic lines are still presented in double travel time, and constructing accurate depth sections requires a precise and detailed understanding of interval velocities. Geoscientists play a critical role in estimating an accurate velocity field for converting seismic time to depth. Even a small depth estimation error as minor as 10 meters in the reservoir rock- can have a tremendous financial impact, potentially costing millions of dollars in exploration and development. Now, consider the consequences when geoscientists overlook water depth variations, as illustrated in the example below (Figure 36). The impact of incorrect velocity assumptions can lead to significant misinterpretations, affecting the geometry of traps, hydrocarbon migration pathways, and overall economic viability of a prospect.

This example comes from the western Palawan offshore (Philippines), where, in the 70's, several oil companies explored the conventional offshore (water depth less than 200 m). It can be summarised as follows :

(i) An exploration well was supposed to test the hydrocarbon potential of a structural high ;

(ii) The structural high was identified on un-migrated seismic lines ;

(iii) The original seismic line, where the well was located, is illustrated in the upper part of figure 35 ;

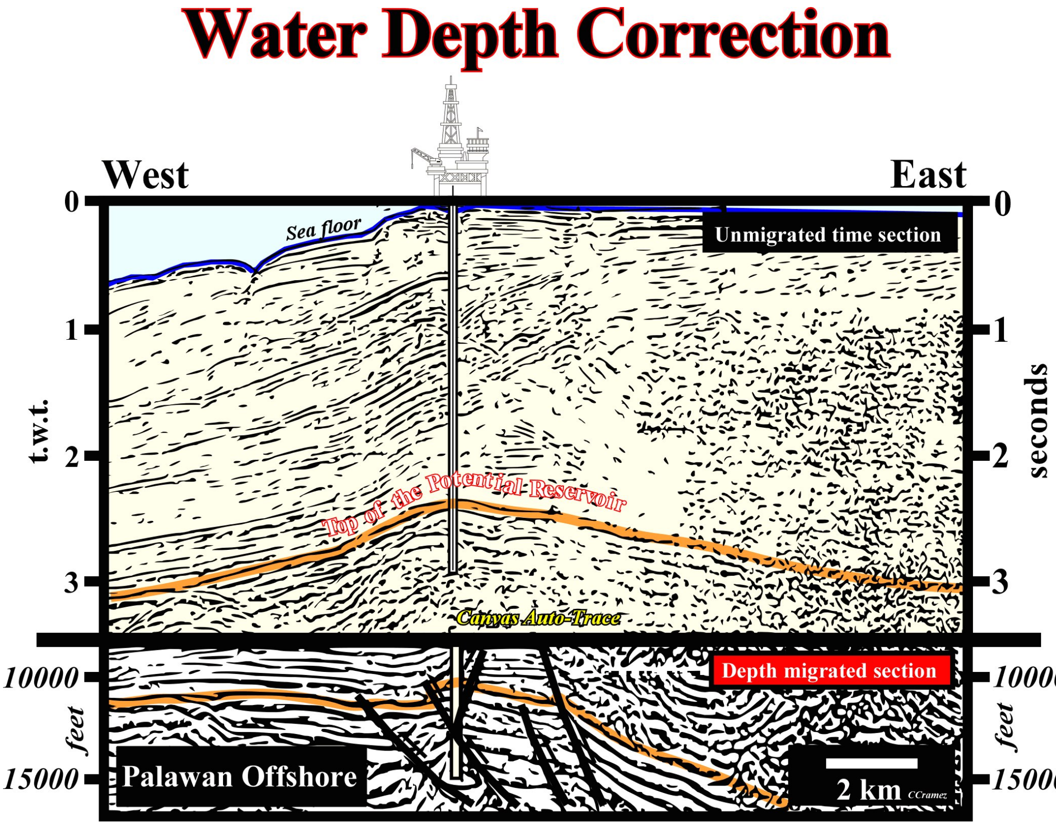

Figure 36 – The upper part of this figure illustrates the unmigrated time version of a seismic line, where an exploration well was drilled. The lower part presents the post-drilling depth-migrated version at the level of the potential reservoir interval.The depth-migrated version strongly suggests that the time-structural high was actually a seismic artifact, rather than a real antiform structure. Instead of representing a compressional structure created by shortening, the feature corresponds to an extensional structure formed by sedimentary lengthening. In other words, the drilled prospect was not a structural trap, but rather a morphological trap by juxtaposition.The geoscientists responsible for evaluating this lead (a trap with potential hydrocarbon accumulation) made two critical errors: (i) They overlooked the fact that western Palawan offshore is located within the Meso-Cenozoic mega-suture, meaning it is part of a compressional geological setting. (ii) They failed to account for the significant pull-down effect caused by the abrupt increase in water depth below the present shelf break (the boundary between the continental platform and the continental slope).These oversights led to the misinterpretation of a seismic artifact as a valid structural trap, ultimately resulting in an unsuccessful well.

(iv) On the seismic line (in time), the structural high was located directly above the present boundary between the continental shelf (<200 m water depth) and the upper slope environment, meaning it was positioned above an abrupt change in water depth (bathymetry).

(v) The structural high was interpreted as a potential reef anomaly located near a shelf break. At that time - as today - the basin had a well-developed continental platform (ranging from 0 to 200 meters water depth), meaning the depositional coastal break was positioned far landward of the shelf break.

(vi) The exploration well was drilled and suspended approximately 200 meters below the apex of the structural highat the level of the potential reservoir rock (upper part of Plate 36).

(vii) The well results were negative: No hydrocarbon indications and no reservoir rocks were identified.

(viii) After the negative well results, a depth migration of several seismic lines was performed. A depth-time conversion of the line where the wildcat well was located is illustrated in the lower part of the figure (vertical scale in feet, not two-way time (TWT)).

(ix) By comparing the two seismic versions, geoscientists immediately recognized that the time-structural high was actually a seismic artifact, caused by the abrupt water-depth variation and facies changes in the sediments overlying the potential reservoir rock.

In conclusion : When tentatively interpreting a seismic line in geological terms, geoscientists must always consider the following: (i) They are generally working with time sections, not depth sections, (ii) Seismic artifacts may persist even after seismic processing or, in some cases, may be generated by seismic processing itself. If horizontal and vertical subsurface velocities were constant everywhere, a seismic line would provide an exact geological cross-section. However, under such conditions, seismic profiles would not display reflections at all. Fortunately, the real geological world behaves differently:

- Firstly, natural compaction of stratigraphic layers under their own weight causes velocities to increase with depth. The deeper a geological level, the higher the velocity of acoustic wave propagation through it. As a result, seismic time sections become progressively squashed from top to bottom.

- Secondly, seismic velocities also vary due to lateral and vertical lithological changes. These velocity variationsare superimposed on the normal vertical distortion caused by compaction. The only way to approximate a true geological cross-section is by converting time sections into depth sections at a natural scale (1:1). Achieving this requires: A good understanding of the local velocity field. The use of an iterative velocity model, as applied in depth migration processing.

9) Downlap Surfaces & Source Rocks

Ulmisheck and Klemme (1991) demonstrated that the majority of the world's oil and gas reserves were generated from specific organic-rich stratigraphic intervals. Considering the hydrocarbons lost during the Hercynian Orogeny, approximately 60% of the world's hydrocarbon reserves originate from Upper Jurassic (25%) and Aptian–Turonian (29%) organic-rich intervals (Fig. 37).

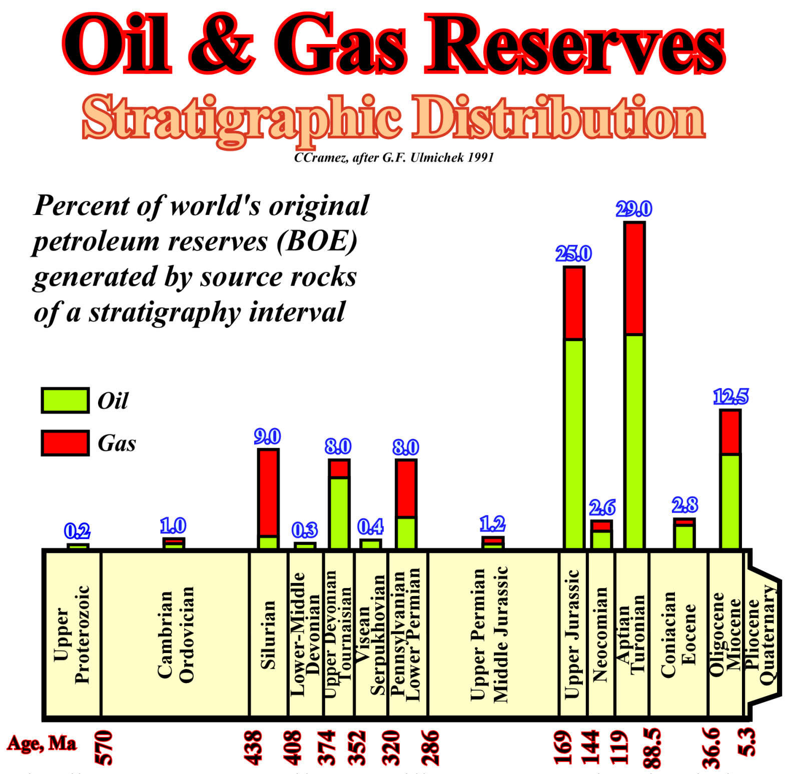

Figure 37 – In this cross-plot, oil reserves are represented in green, while gas reserves are shown in red. The numbers at the bottom of the diagram (red-black) indicate the geological age in million years, while the numbers above each column (blue) represent the percentage of the world's original petroleum reserves (BOE) generated by source rocksfrom a given stratigraphic interval.Since there is no reason to assume that pre-Pangaea source rocks were inherently inferior to post-Pangaea source rocks, it is believed that a significant amount of hydrocarbons was lost during the Hercynian Orogeny.Based on the known global oil and gas reserves, it is estimated that Paleozoic source-rock intervals contributed roughly 30% of the world's original petroleum reserves. In contrast, the Upper Jurassic and Aptian–Turonian source rocks generated approximately 60% of the world's hydrocarbons. The remaining 10% appears to be associated with Upper Tertiary source rocks, which are predominantly lacustrine.

Assuming that the hydrocarbon loss during the Hercynian Orogeny affected all Paleozoic potential source rocksequally, Ulmisheck's diagram (Figure 37) suggests that the majority of the world's reserves were generated during periods of high sea level, specifically during the Cambrian–Silurian and Jurassic–Cretaceous transgressions. This statement holds particularly true for the post-Pangaea stratigraphic interval, where Upper Jurassic and Middle Cretaceous marine source rocks account for approximately 60% of the world's reserves.In contrast, the values for Paleozoic source rocks are significantly impacted by erosion during the Hercynian Orogeny, making them less reliable for direct comparison.

To understand how potential source rocks can be identified on seismic data, it is useful to review some of the geological characteristics of continental encroachment stratigraphic cycles and sub-cycles:

- There are two major continental encroachment cycles in the Phanerozoic.

- Continental encroachment cycles (Figure 38) are associated with first-order eustatic cycles, driven by changes in ocean basin volume. These changes resulted from the break-up of the proto-Pangaea and Pangaea supercontinentsand the subsequent reassembly of individual continents.

- The older cycle began in the uppermost Proterozoic and extended until the end of the Permian.

- The Proterozoic was characterized by slow encroachment with regression, whereas the Cambrian was a period of extensive encroachment with transgression.

- A eustatic high was reached during the Ordovician–Silurian, followed by a gradual restriction of the marine domain from the Silurian to the Permian.

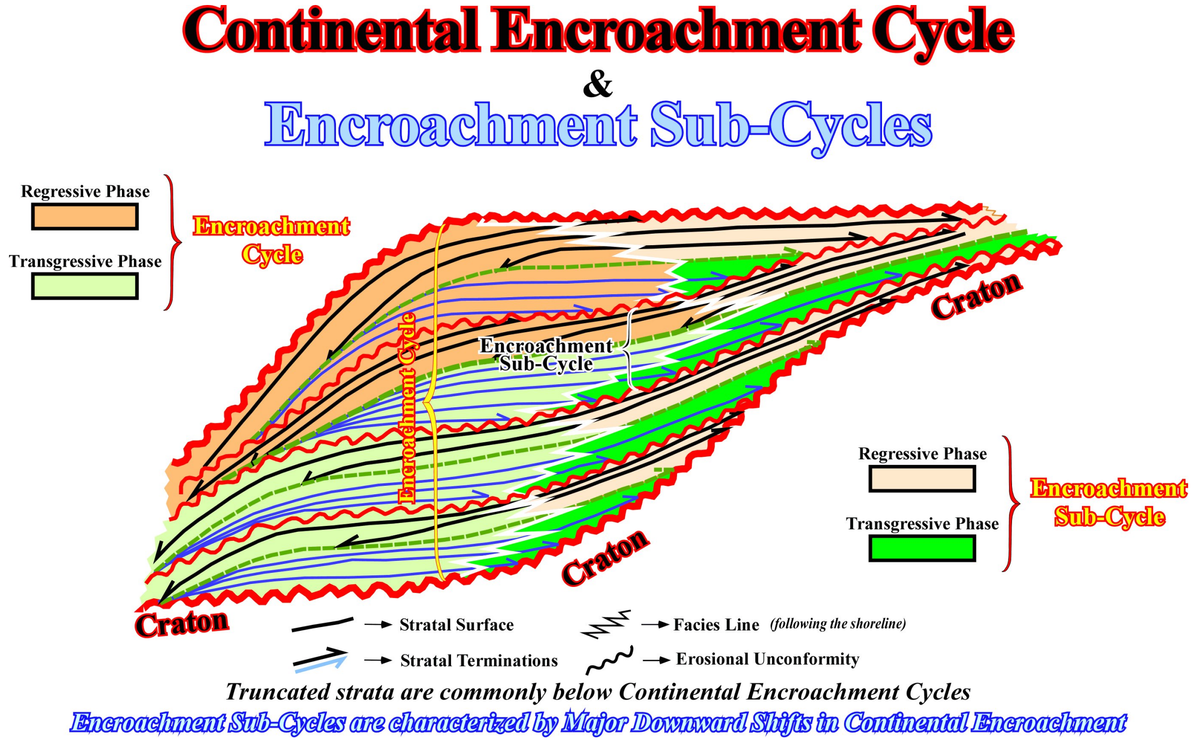

***Figure 38** – Continental encroachment sub-cycles collectively form a continental encroachment cycle. While they share the same characteristics, they differ in hierarchical scale. The transgressive phase of a continental encroachment cycle or sub-cycle exhibits a back-stepping geometry, whereas the regressive phase is characterized by a progradational or fore-stepping geometry. When sea level rises, the depositional coastal break becomes separate from the shelf break and is displaced landwardduring the transgression. This landward migration of the shoreline results in the formation of a continental platform, which widens and deepens as long as sea level continues to rise at an accelerating rate.*

- The younger cycle started in the Triassic and extents to the Present time ;

- Triassic Period was a time of slow encroachment of sediments onto the craton, while the Jurassic and the Early Cretaceous Periods were times of extensive encroachment ;

- The younger continental encroachment cycle began in the Triassic and extends to the Present.

-The Triassic Period was a time of slow sediment encroachment onto the craton, whereas the Jurassic and Early Cretaceous Periods were marked by extensive encroachment.

- Early Turonian time is believed to represent the maximum eustatic high, while the Late Cretaceous and Cenozoicperiods were characterized by a gradual restriction of sediments to continental margins and basinal areas.

- The maximum marine transgression within the continental encroachment cycles occurred at the Ordovician - Silurian boundary in the older cycle and near the Cenomanian - Turonian boundary in the younger cycle.

-Each continental encroachment cycle follows a pattern of smooth, long-term landward displacement of the shoreline, followed by a seaward displacement.

- Sedimentary packages deposited during the landward displacement of the shoreline exhibit parallel and retrogradational geometries, forming what is known as the transgressive phase.

- Sedimentary packages deposited during the seaward displacement of the shoreline exhibit fore-stepping progradational geometries, making up the regressive phase.

- The transgressive phase thickens landward to a maximum, then pinches out against the craton.

- The regressive phase reaches its maximum thickness seaward and becomes condensed in the more distal parts of the basin.

- The surface between the transgressive and regressive phases is marked by a downlap surface, which represents the eustatic highstand and a period of starved sedimentation.

- The boundaries between the transgressive and regressive phases of the Phanerozoic stratigraphic cyclescorrespond to the Cenomanian–Turonian and Cambrian–Ordovician maximum eustatic highs. On seismic lines, these are identified by major downlap surfaces and maximum encroachment of coastal onlaps (Figure 40).

- On regional seismic lines, these geological features correspond to the interfaces between retrogradational and progradational geometries of seismic markers.

The above geological conditions, combined with coeval upwelling currents and anoxic environments, create ideal conditions for the development and preservation of major source rocks. By identifying the major downlap surfaces of continental encroachment cycles, geoscientists can locate the most likely marine source rocks, as illustrated in Fig. 39.

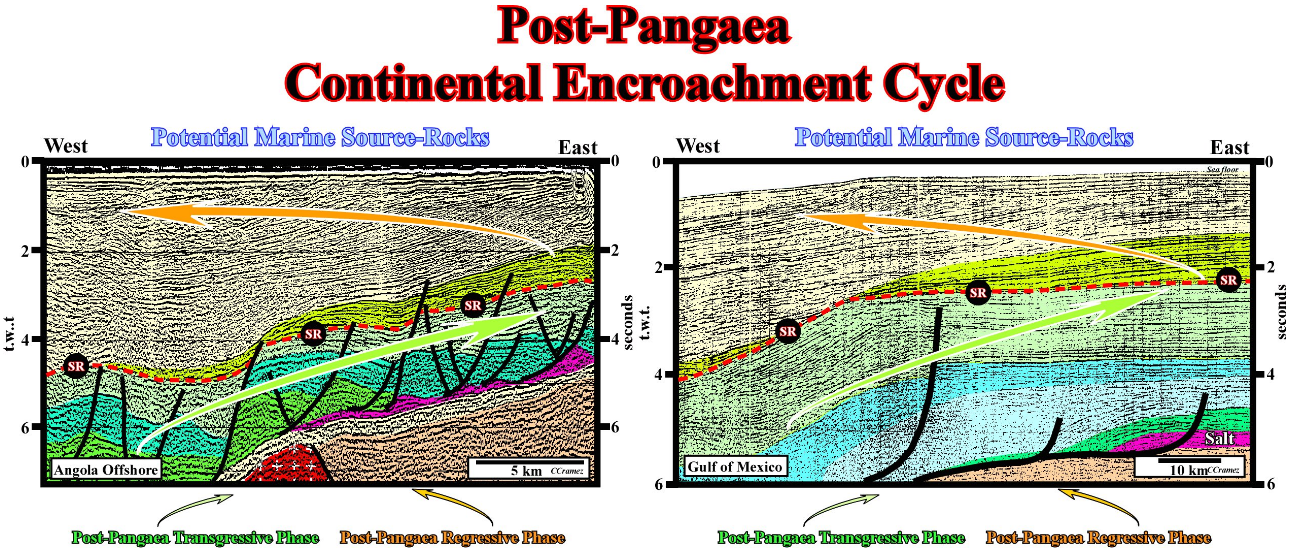

Figure 39 – On the left, a tentative geological interpretation of a seismic line from offshore Angola is illustrated. A vertical stacking of two sedimentary basins is recognized: (i) At the bottom, landward of a buried hill, a rift-type basin (colored in brown) is present , (ii) Above the break-up unconformity, the continental margin is well developed ; (iii) Despite intensive salt flow (salt is colored in violet), the transgressive (retrogradational) phase is easily identifiable below the Cenomanian–Turonian downlap surface. This phase is highlighted by a green arrowpointing landward, indicating that the depositional coastal break migrated landward as sea level rose; (iv) The regressive (progradational) phase is also well defined by the fore-stepping geometry of the seismic markers above the major downlap surface. The major marine source rocks on this margin are concentrated between the two phases, along the Cenomanian–Turonian downlap surface (underlined in red). However, these potential source rocks have not generated hydrocarbons because they have not been buried deep enough for their organic matter to reach maturation. Instead, in this area, the generating petroleum sub-system consists of lacustrine source rocks deposited in the rift-type basinand within the continental margin below the salt layer. On the right, a tentative geological interpretation of a seismic line from the Gulf of Mexico is shown, where the post-Pangaea continental encroachment cycle is represented by the superposition of a Pannonian basin and a divergent continental margin. As in the Angola seismic line, the transgressive and regressive phases of this stratigraphic cycle are clearly identifiable by their retrogradational and progradational geometries, respectively. The interface between these phases is the Cenomanian–Turonian downlap surface, which is associated with potential marine source rocks.

During a continental encroachment cycle, onlapping against cratons does not always exhibit a continuous landward and upward movement (positive aggradation). Occasionally, onlapping patterns shift seaward and downward(negative aggradation). During these large downward shifts of coastal onlaps, the coastal plain and upper slope are exposed due to major eustatic sea level falls, forming a pronounced erosional surface that results in unconformities.

Like a continental encroachment cycle, a continental encroachment sub-cycle is defined as the interval between two consecutive downward shifts of onlap, meaning it is bounded by two significant erosional unconformities within a continental encroachment cycle. Each sub-cycle develops in association with a second-order eustatic cycle, with a duration ranging between 3–5 My and 50 My. Within each encroachment sub-cycle, the most significant downlap surface separates a retrogradational sub-phasefrom an overlying progradational sub-phase (Fig. 38). The basinward extent of this downlap surface varies between sub-cycles and depends on the construction of each sub-cycle. The major downlap surface of the continental encroachment cycle coincides with the downlap surface of only one sub-cycle, while the downlap surfaces of the other sub-cycles are considered secondary downlap surfaces, as illustrated in Fig. 40.

In petroleum basins worldwide, tentative geological interpretations using stratigraphic cycles and geochemical studies reveal a strong correlation between marine source rocks and the downlap surfaces of continental encroachment cycles and sub-cycles.

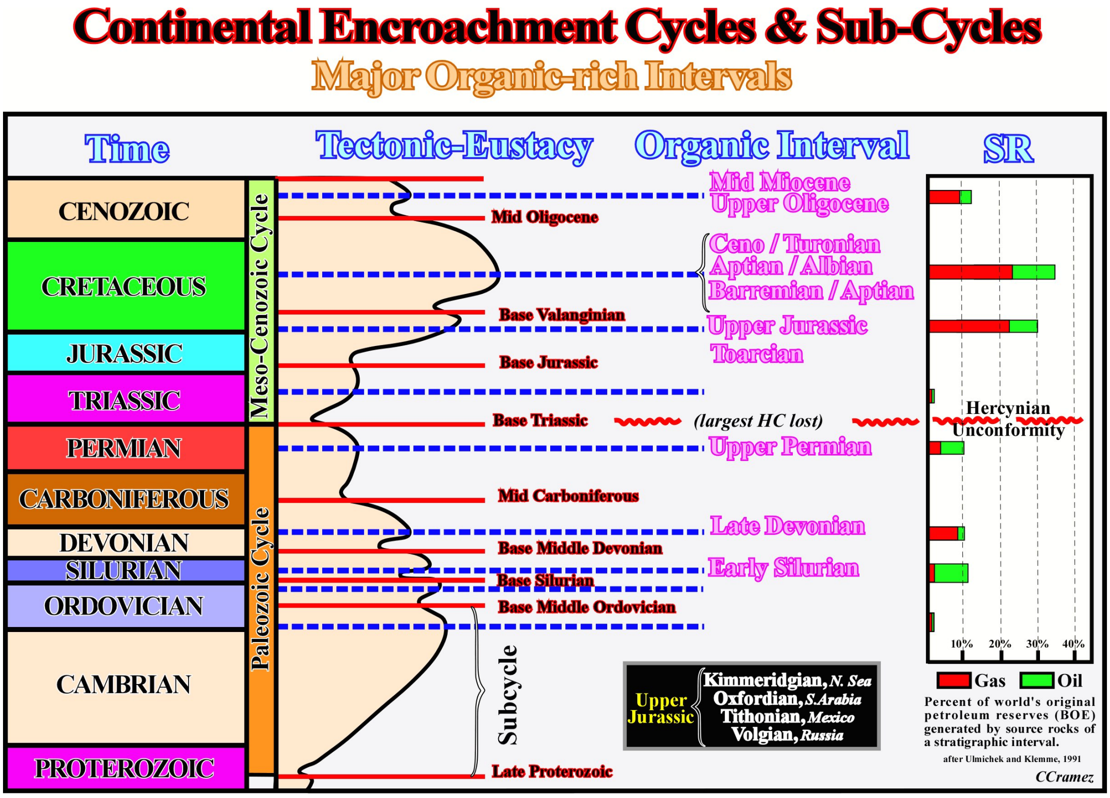

Figure 40 – The major organic-rich intervals of the Phanerozoic are closely associated with the downlap surfaces of continental encroachment sub-cycles. The correlation between these downlap surfaces and the percentage of the world's original petroleum reserves generated by source rocks of different stratigraphic intervals, as proposed by Ulmisheck and Klemme (1990), is remarkably strong, despite hydrocarbon loss during the aggregation of the supercontinent Pangaea. The highest percentage of petroleum reserves is associated with the major downlap surfaces of the continental encroachment cycles, particularly during the Ordovician–Silurian and Middle–Upper Cretaceous periods. (i) In the Upper Jurassic, Kimmeridgian source rocks are well known in the North Sea; (ii) In South Arabia, Oxfordian source rocks are significant; (iii) In Mexico, the main source rocks are associated with organic-rich Tithonian source rocks. These findings emphasize the global significance of downlap surfaces in identifying potential source-rock intervalsand their role in hydrocarbon generation and accumulation.

During the Phanerozoic, two major downlap surfaces are associated with the most significant organic-rich marine source rocks: (i) Cambrian–Ordovician, linked to proto-Pangaea continental encroachment cycles ; (ii) Early–Late Cretaceous, associated with Pangaea continental encroachment cycles.

Secondary downlap surfaces within encroachment sub-cycles are related to the other important marine source rocks. The age of potential marine source rocks, from oldest to youngest, can be summarized as follows:

1) Early Silurian, within the continental encroachment sub-cycle bounded by the Base Middle Ordovician and Base Silurian unconformities.
2) Late Devonian, within the continental encroachment sub-cycle bounded by the Base Silurian and Base Middle Devonian unconformities.
3) Upper Permian, within the continental encroachment sub-cycle bounded by the Mid-Carboniferous and Base Triassic unconformities.
4) Toarcian–Upper Jurassic, within the continental encroachment sub-cycle bounded by the Base Jurassic and Base Valanginian unconformities.
5) Barremian–Aptian / Aptian–Albian / Cenomanian–Turonian, within the continental encroachment sub-cyclebounded by the Base Valanginian and Mid-Oligocene unconformities.
6) Upper Oligocene–Mid Miocene, within the continental encroachment sub-cycle bounded by the Mid-Oligocene unconformity and the present day.

Diachronic Potential Marine Source-Rocks

(Progradational Intervals)

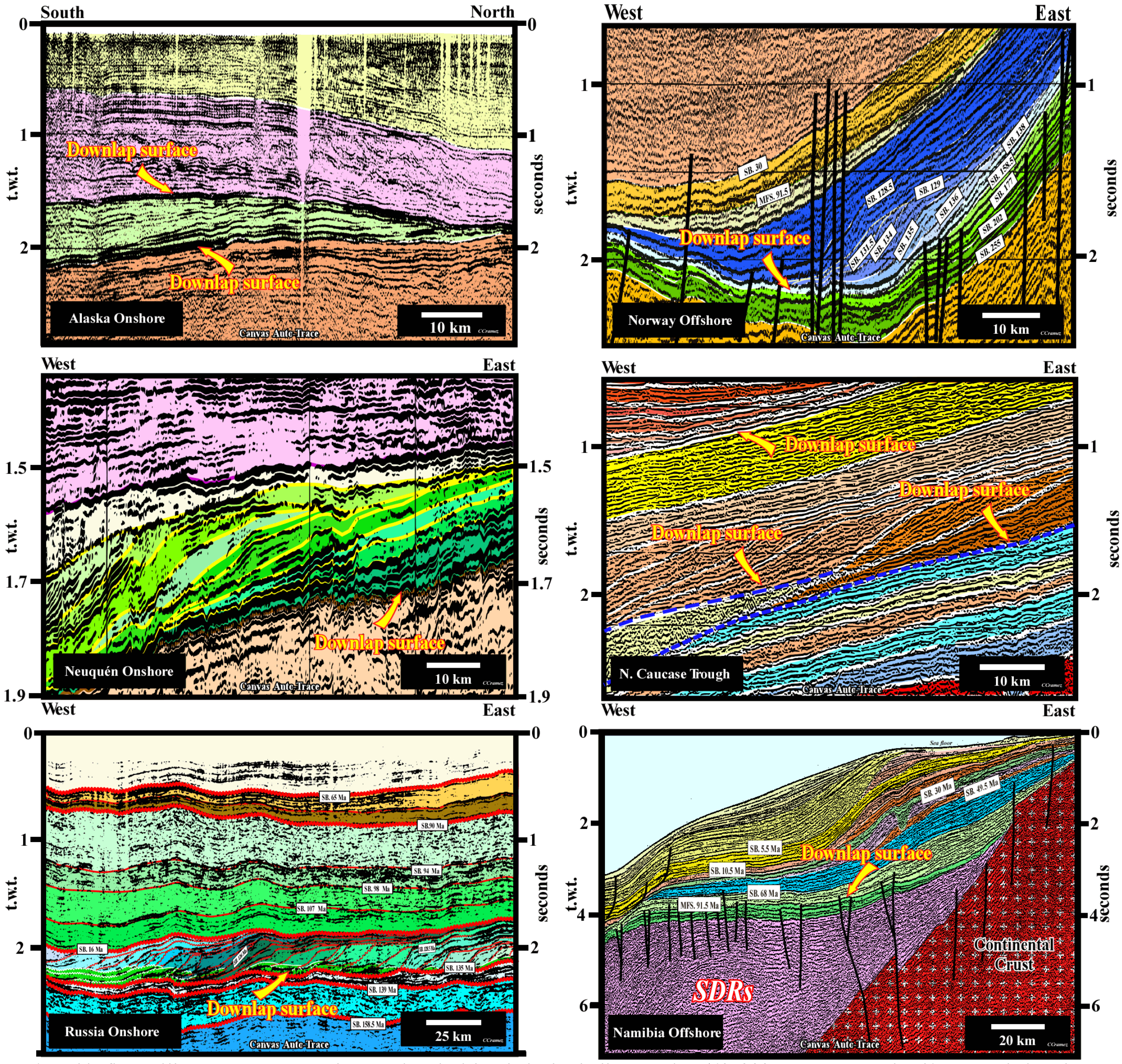

Figure 41 – This figure illustrates source rocks associated with relatively shallow marine (60–300 meters water depth) progradational intervals. Alaska Onshore: The marine potential source rocks associated with the lower downlap surface were deposited in the continental margin basin, while those linked to the upper downlap surface formed in the foredeep basin. Norway Offshore: The source rocks associated with the downlap surface likely belong to the top of the North Sea rift-type basin, specifically the Kimmeridgian shales. Geographic Neuquén Basin: The diachronic source rocks associated with the illustrated downlap surface (Vaca Muerta source rocks) were deposited during the upper phase of the back-arc basin evolution. North Caucasus Trough: The lower downlap surface highlights the source rocks of the margin basin, which are likely equivalent to the Tithonian–Early Berriasian Bazhenov shales. The upper downlap surface may correspond to the organic-rich Oligocene–Miocene source rocks of the Maykop Formation. West Siberia (Russia Onshore): The tentative geological interpretation of a seismic line illustrates a progradational interval that characterizes the organic-rich Bazhenov shales, considered the world's largest oil source rocks.Namibia Offshore: The downlap surface separates the transgressive and regressive phases of the post-Pangaea continental encroachment cycle. It highlights the stratigraphic location of the main marine source rocks, particularly in Angola and Brazil offshore, where they were deposited above the salt interval. However, in Namibia offshore, the organic matter in these source rocks is still immature.

Summarising : For conventional marine source rocks, the recognition and mapping of continental encroachment cycles and sub-cycles significantly enhance the probability of locating the main petroleum-generating subsystems. Without a functioning source rock, all other essential elements of a petroleum play - such as reservoir rocks, traps, and seals - become irrelevant. The primary focus, therefore, is on 1st and 2nd order stratigraphic cycles, specifically through: 1) Identification of encroachment cycles and sub-cycles using geometrical relationships. 2) Recognition and mapping of major downlap surfaces, which serve as key indicators of potential source rock intervals. 3) Whereas seismic stratigraphy is traditionally more focused on finding reservoirs, this methodology also aids in identifying regional seals, which are another critical factor in petroleum systems. 4) Additionally, it helps define new exploration areas with poor stratigraphic control, where traditional exploration approaches may be limited. 5) This approach is par-

ticularly valuable for the long-term strategic planning of the oil and gas industry, especially as mature petroleum provinces become increasingly depleted, necessitating the exploration of new, less understood basins.

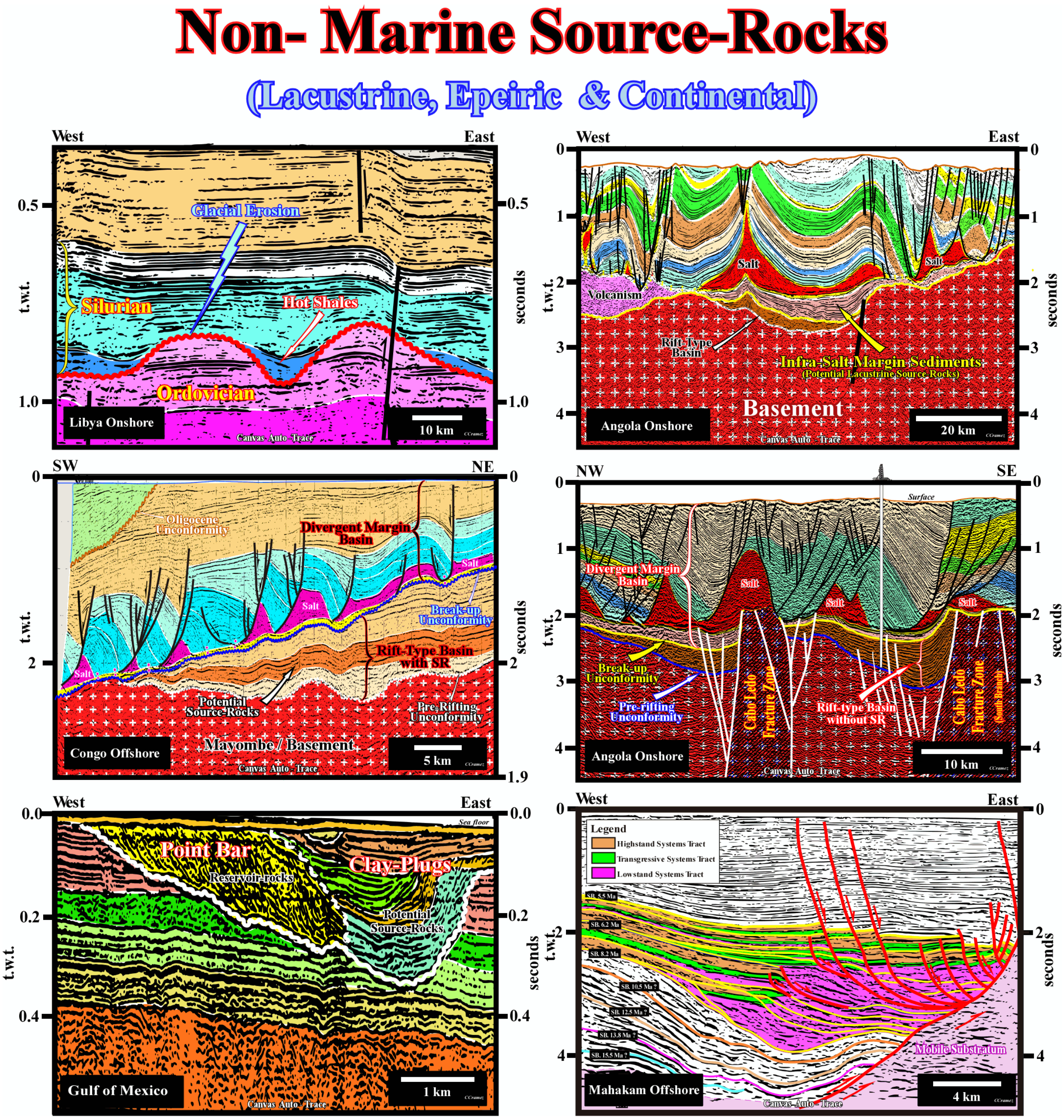

Figure 42 – This figure illustrates tentative geological interpretations of seismic lines where non-marine potential source rocks—including lacustrine, epeiric, and continental source rocks—have been corroborated by drilling (e.g., Libya, Angola, Congo, Indonesia) or are highly probable, as in the Gulf of Mexico seismic line. The Silurian "Hot Shales" are primarily epeiric source rocks, having been deposited in an inland extension of the sea that flooded the Ordovician glacial valleys. In onshore Angola, the infra-salt margin source rocks are lacustrine, deposited in large lakes that formed after the break-up of the lithosphere, immediately following the deposition of subaerial lava flows. On the offshore Congo seismic line, the source rocks were deposited in rift-type basins that predate the Gondwana break-up. These lacustrine source rocks roughly correspond to the Bucomazi Formation. In offshore Mahakam, the source rocks are continental, represented by coal layers deposited in the deltaic plain, landward of the depositional coastal break. The seismic line from the Gulf of Mexico illustrates the infilling of a meander, where potential reservoir rocks correspond to the sandstones of point bars, which migrate eastward, and speculative potential source rocks are linked to clay plugs, though they remain immature due to insufficient burial. The clay plugs correspond to the aggradational infilling of oxbow lakes, where organic matter can be preserved under anoxic conditions, a common feature in these depositional systems. The stacking of multiple clay plugs strongly suggests that the river reoccupied its former path multiple times following its abandonment. Each clay plug represents an abandonment period, marking the formation of an oxbow lake. The proximity of reservoir and source rocks in these settings favors the formation of non-structural traps, enhancing the potential for hydrocarbon accumulation.

In many petroleum systems worldwide, including some Argentinian petroleum basins, the generating petroleum sub-system is composed of non-marine source rocks, particularly lacustrine and epeiric source rocks. Therefore, a brief review of these source rocks is necessary (Fig. 42).

(i) The Silurian "Hot Shales" of the Murzuk Basin in Libya (Figure 42) provide an excellent example of epeiric source rocks. The Late Ordovician Glaciation, which is observed in many regions such as Morocco,

Libya, Algeria, Wyoming, Bolivia, Peru, and Argentina[17] played a crucial role in shaping these source rocks. This glaciation, particularly the Late Ashgillian, was not only a major factor in the Ordovician–Silurian extinction event but was also responsible for the glacial topography that characterized the end of the Ordovician period.

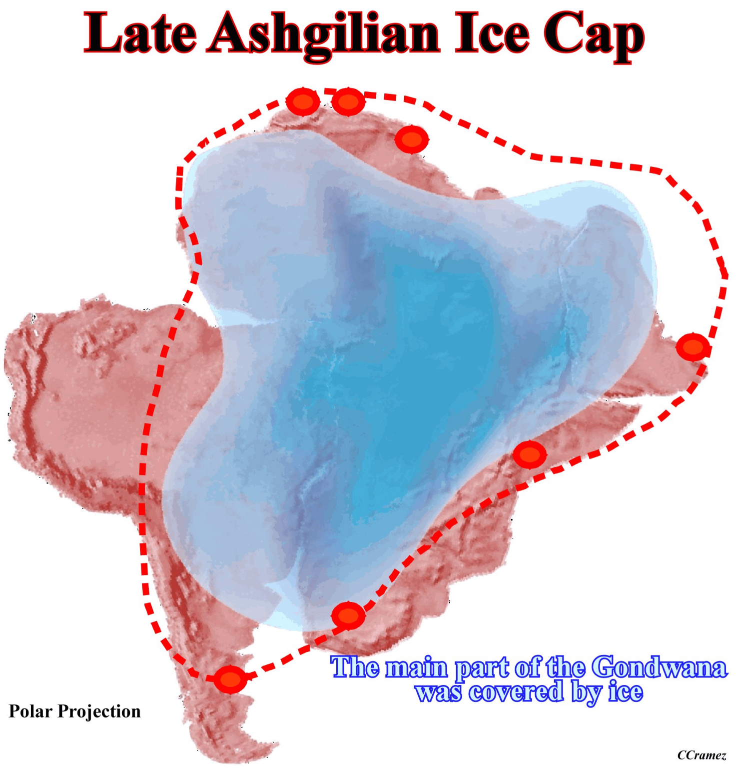

Figure 43 – This figure illustrates the extent of the Late Ashgillian ice cap, which covered most of Gondwana. During this time, the northern part of Argentina was covered by ice, and southwestward-flowing glaciers carved deep valleys, similar to what occurred in Algeria and Morocco. Later, these glacial valleys were flooded by the Silurian sea, creating favorable conditions for the deposition of organic-rich shales, which, when sufficiently buried, became potential source rocks.

All around the Late Ashgillian ice cap (Figure 43), glaciers carved deep glacial valleys. Just before the Silurian marine ingression, during lowstand geological conditions, these incised glacial valleys were flooded, creating anoxic depositional environments that were progressively filled with organic-rich shales ("hot shales"), coeval with the upper lowstand prograding wedge (lowstand systems tract). As the Silurian relative sea level rose, the Ordovician glacial sediments were submerged, displacing the shoreline landward, far from the shelf break, and forming a large continental platform seaward of the Ordovician continental slope. With the progressive deposition of thick Silurian progradational sediments, the continental platform gradually shrank, until the shoreline became coincident with the former Ordovician shelf break, which then became the new Silurian continental break. From that point onward, the basin had no shelf, and the continental slope was progressively accreted by Silurian slope sediments, marking a significant transformation in the basin's stratigraphic evolution.

(ii) In the geographic Kwanza Basin (Angola), after the break-up of the Gondwana lithosphere and immediately following the deposition of subaerial lava flows, large lakes or an epeiric sea[18] developed at the onset of the Cretaceous transgression.

Such depositional environments, particularly the larger ones, were partially filled with organic-rich sediments(organic matter Type I), which today form the most likely infra-salt petroleum-generating sub-system in onshore and offshore Angola (southward of the Ambriz structural arch) (Figure 42). In this region, the majority of rift-type basins, formed before the break-up of the Gondwana lithosphere, have little to no hydrocarbon potential. These half-grabens are too small, with a typical divergent internal configuration, and are primarily filled with lateral terrigenous influx, reducing their effectiveness as source-rock depocenters. The most promising generating petroleum sub-system in this

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[17] These concepts can be applied to the Chaco-Paraná Basin in Argentina (Paleozoic), which has so far been explored using an old, noisy, and sparse 2D seismic coverage. Potential Late Ordovician and Early Silurian post-glacial source rocks are likely present, though their viability depends on whether they are over-mature. Additionally, Early Permian post-glacial coaly and bituminous shales may also serve as source rocks. Late Carboniferous interglacial deposits, characterized by channel stacking, represent potential reservoirs. However, due to the strong Early Hercynian unconformity, which eroded the Silurian–Devonian sequences, sub-crop maps are required to better assess the hydrocarbon system parameters, as illustrated later.

[18] Inland seas are shallow seas that cover central continental areas during periods of high sea level, typically at the onset of marine transgressions. At present, as continents stand high and eustatic sea level is relatively low, there are few epeiric seas, with the largest example being the Caspian Sea.

area is associated with margin infra-salt lacustrine or shallow-water source rocks, which are highly similar to those developed along the western South Atlantic margins. These source rocks were responsible for generating most of the hydrocarbons discovered in the deep-water Santos Basin (offshore Brazil). However, margin infra-salt depocenters appear to be absent southward of Santos Basin. They are not present in the geographic Pelotas Basin (offshore Brazil and Uruguay). Additionally, regional seismic lines from offshore Argentina corroborate the absence of such lower-margin depocenters, further limiting the potential for similar infra-salt petroleum systems in those areas.

(iii) In the Congo onshore and offshore, as well as, in the Cabinda onshore and offshore [19], the rift-type basins, developed before the break-up of the lithosphere, were filled, partially, by organic-rich lacustrine sediments, which form, probably, the most important generating petroleum sub-systems.

Contrary to the rift-type basins of the geographic Kwanza Basin, the Congo rift-type basins are characterized by large dimensions and a parallel internal configuration. Some geoscientists have proposed the conjecture that the development of potential lacustrine source rocks in rift-type basins requires a divergent internal configuration of the sedimentary infill. However, the formation of organic-rich lacustrine shales depends on the presence of a lake, meaning the creation of a water column within the rift basin.Such a water column is more likely to develop when the rate of extension (lengthening) is not balanced by terrigenous influx. If the rate of extension is balanced by terrigenous influx, the water depth remains close to zero, and the basin fills with sand-prone sediments that thicken toward the bordering fault, where differential subsidenceis higher. In Fig. 41 (tentative geological interpretations in the middle of the figure), two rift-type basins with different internal configurations are illustrated: (a) The Congo offshore basin, which has a parallel internal configuration, is rich in lacustrine source rocks, with the Bucomazi organic interval (colored in brown) acting as the main petroleum-generating unit, (ib) The Kwanza onshore basin, which has a divergent internal configuration, is almost entirely filled with sandstones, as confirmed by exploration wells drilled in the area. This contrast highlights the importance of basin configuration in controlling the distribution of lacustrine source rocks, influencing hydrocarbon generation potential.

(iv) Potential non-marine source rocks are likely to develop in oxbow lakes, even when the abandonment of the stream bed[20] s intermittent, as appears to be the case in the meander illustrated in Fig. 42 (Gulf of Mexico seismic line). Clay plugs, which are rich in organic matter, are found not only in modern meander belts but also in ancient meander belts, where they may serve as potential source rocks if burial conditions allow for organic matter maturation.

Such potential source rocks appear to generate sufficient hydrocarbons to support small but economically viable accumulations, particularly in onshore structurally mature petroleum basins, as seems to be the case in onshore Argentina basins.[21].

(v) The Mahakam Delta complex, illustrated by the tentative geological interpretation in Fig. 42 (Mahakam offshore, southeast Kalimantan, Indonesia), serves as an excellent example demonstrating that non-marine source rockscontaining Type III organic matter can be predicted using seismic data..

Geologically, Mahakam offshore is a back-arc basin that developed within the Meso-Cenozoic megasuture. The tentative geological interpretation illustrated in Fig. 42 was conducted using sequence-cycles, which were deposited during third-order eustatic cycles, lasting between 0,5 and 3–5 million years. The widespread fore-stepping geometryof these sequence-cycles indicates an overall regressive pattern, characterized by a general seaward displacement of the depositional coastal break.

Each time the relative sea level rose, the seaward shift of the shoreline was interrupted by a landward shift (some of which are below seismic resolution). However, the magnitude of these landward displacements decreased upward, indicating an overall regressive shoreline trend. The calibration of multiple tentative geological interpretations, using sliding averages of exploration wells, reveals that the encroachment of transgressive intervals decreased upward, along with a reduction in the time displacement of boundaries between different sedimentary environments (alluvial plain, delta plain, delta front, and upper slope).

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[19] Cabinda, also spelled Kabinda and formerly known as Portuguese Congo, is an enclave and province of Angola. It is separated from mainland Angola by a narrow strip of territory belonging to the Democratic Republic of the Congo (DRC), which borders Cabinda to the south and east. Locally, it is known as Tchiowa.

[20] The channel bottom of a stream, river, or creek is the part that confines the normal water flow. The lateral confinesor channel margins, which contain the water during all but flood stages, are known as the stream banks or river banks.

[21] The geographic Cuyo Basin (Triassic) appears to be a strong candidate for further exploration. After more than 70 years of structural exploration, new non-structural traps are likely. Potential reservoir rocks, mainly point barsfrom the Carnian Potrerillos Formation, could be charged by local source rocks deposited in nearby oxbow lakes (abandoned meanders) and paleo-valleys of the Norian Cacheuta Formation.

The combination of sliding averages with chronostratigraphic lines from seismic reflectors highlights an important Upper Miocene depocenter on the delta plain, with abundant coal beds and organic-rich marine shales in the delta front. These coal beds and marine organic-rich delta-front shales serve as the primary source rocks for the Mahakam oil and gas fields. The Middle–Upper Miocene delta plain and delta front depocenters are so thick that the potential source rocks are located within the oil window in landward areas.

However, most hydrocarbons were generated by the coals, rather than the delta-front marine organic shales. The Total Organic Carbon (TOC) and Hydrogen Index (HI) are highly significant. The productivity of delta-front organic shales is approximately 30 - 40 kg of hydrocarbons per tonne, whereas that of coals is around 200 kg per tonne. In contrast, the productivity of slope shales is only about 2 kg per tonne, highlighting the dominant role of coals in the Mahakam petroleum system.

In conclusion : The best way to identify Type III non-marine source rocks, particularly coal, is by targeting thick delta-plain depocenters within progradational regressive intervals.

10) Angular Unconformities, Sub-crop & Paleo-geographic Maps

Angular unconformities are erosional surfaces caused by significant relative sea level falls, which were locally enhanced by tectonics. In sequential stratigraphy, geoscientists refer to them as tectonically enhanced unconformities to emphasize the role of relative sea level changes in their formation.

Laterally, all tectonically enhanced unconformities transition into cryptic unconformities. These unconformities are most easily recognized in the distal parts of the continental platform or near the shelf break, where erosional evidence—such as submarine canyons and incised valleys - is often observed.

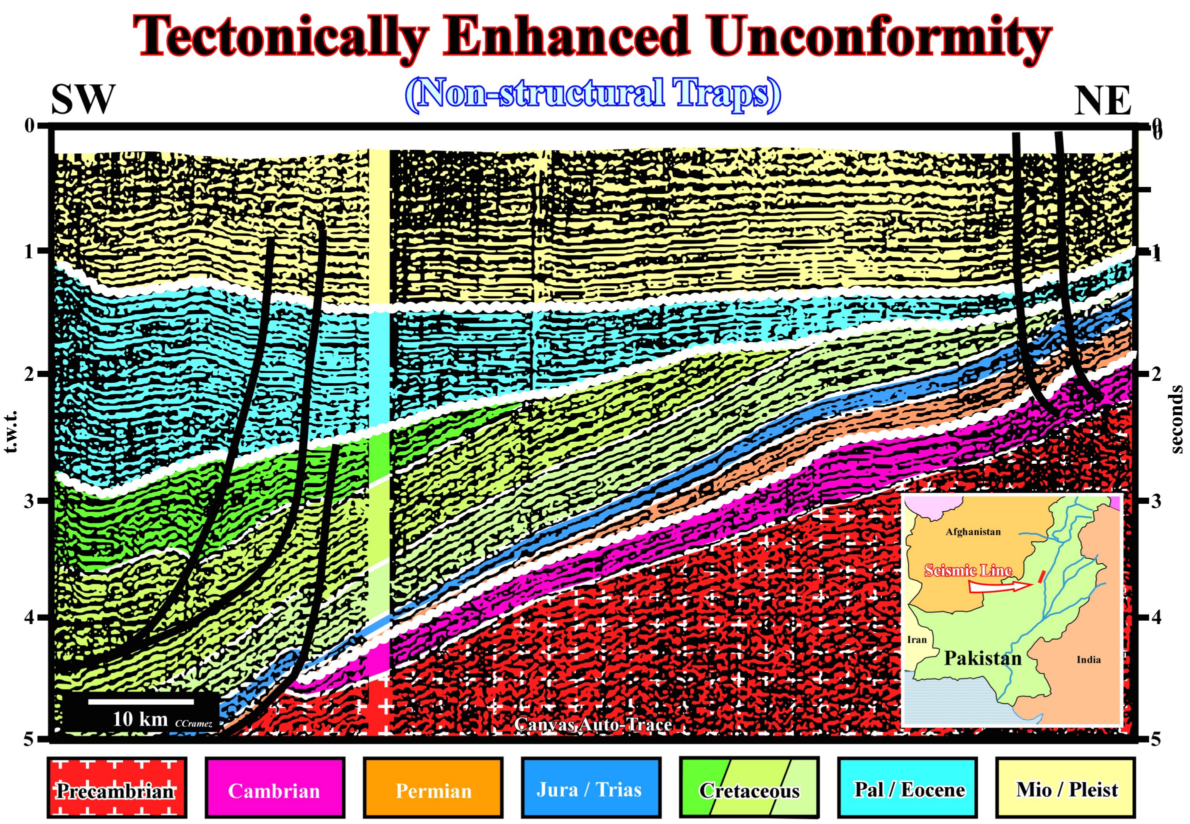

Figure 44 – This tentative geological interpretation of a seismic line from onshore Pakistan clearly identifies two tectonically enhanced unconformities. The most evident is the unconformity between the Cretaceous and Paleocene–Eocene sediments, while the tectonic enhancement of the Cambrian–Permian unconformity is also highly pronounced. Both enhanced unconformities are characterized by truncation (erosional toplaps) of the underlying sediments and onlapping of the overlying sediments, which strongly contrast with the geometrical relationships of the unconformity between the Paleocene/Eocene and Miocene/Pleistocene sediments. Along a tectonically enhanced unconformity (angular unconformity), the sedimentary interface between the overlying and underlying sediments varies laterally, causing changes in the acoustic impedance profile. As a result, geoscientists often need to switch from picking a peak to a trough (or vice versa) when identifying an unconformityon seismic data. Such lateral changes in acoustic impedance prohibit continuous or automatic picking, making manual interpretation necessary. It is in this context that some American geoscientists humorously remarked: "Picking unconformities is for men, not for ladies."

Potential non-structural traps are often associated with tectonically enhanced unconformities, either within the underlying sediments or in the overlying onlapping sediments. Morphological traps (see later) related to specific geological bodies such as reefs, turbiditic fans, and incised valley infills are predominantly found in sediments overlying a tectonically enhanced unconformity. In contrast, morphological traps by juxtaposition, induced by faulting or truncation, are more common in the underlying sediments (Fig. 45). In a structural trap, the map of the

sealing rock is not as critical. However, in a non-structural trap, the sealing rock map is just as important as the reservoir rock map, since it is the sealing rock that encloses the reservoir rock.

For non-structural traps, particularly those located below tectonically enhanced unconformities, geo-scientists must always keep in mind that:

A) The structural map of the unconformity is not significative of the trap.

B) The crucial maps are :

(i) The map of the top of the reservoir rock ;

(ii) The map of the sealing rock and

(iii) The map of the hydrocarbon migration paths.

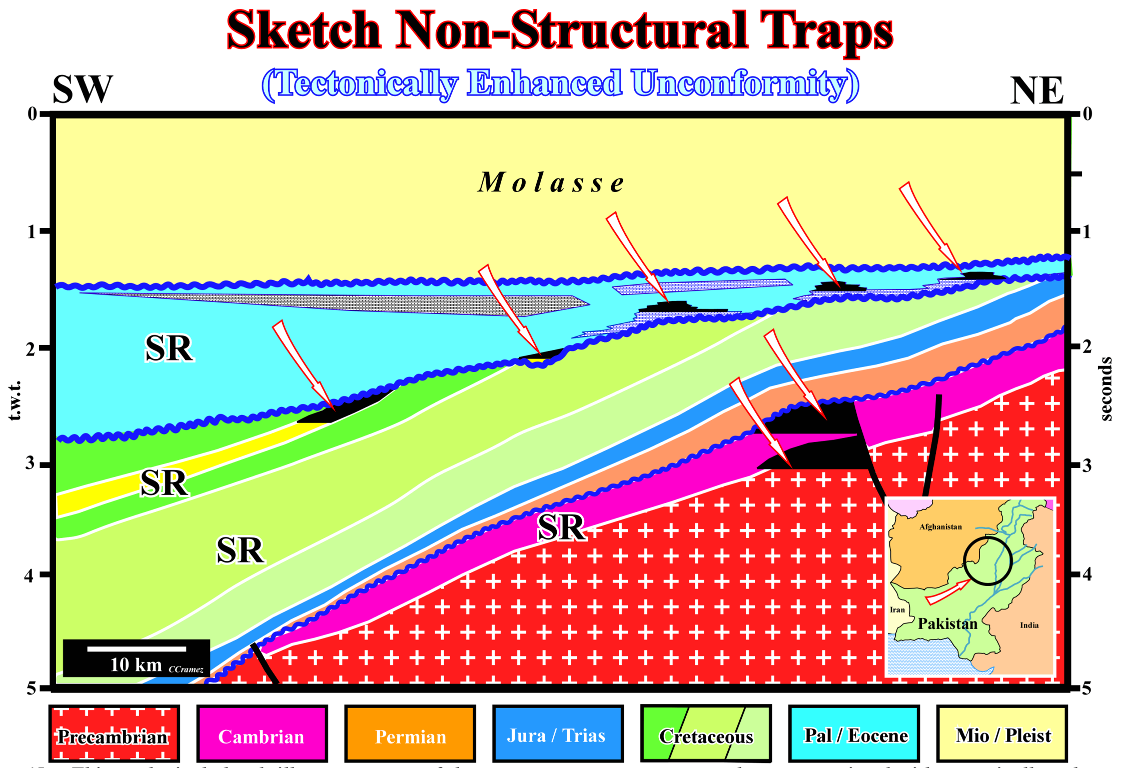

Figure 45 – This geological sketch illustrates some of the most common non-structural traps associated with tectonically enhanced unconformities. Assuming the presence of a generating petroleum sub-system down-dip, hydrocarbon accumulations are possible in morphological traps both below and above the enhanced unconformities. Below the unconformity, in the Cambrian sediments, morphological traps by juxtaposition are likely, particularly in association with normal faulting. It is important to note that a fault plane itself does not seal the reservoir rock. The term "fault trap" is often considered a misnomer by many geoscientists, as there are no true "fault traps." Instead, the relative movement of faulted blocks may place the reservoir rock in juxtaposition with a rock that has a higher displacement pressure, which can then laterally seal the reservoir rock. Just below a tectonically enhanced unconformity, a trapping mechanism can exist only if a sealing rock onlaps the unconformity, ensuring lateral closure. Above a tectonically enhanced unconformity, morphological traps associated with reefs, incised valley infills, or turbiditic mounds can develop. However, for these traps to be effective, a sealing rock must be present to prevent hydrocarbons from escaping.

C) A sub-crop map (paleogeologic map) for each tectonically enhanced unconformity is essential to accurately identify true high structural points and migration paths [22]. A sub-crop or paleogeologic map represents the outcrop pattern of rocks immediately beneath the unconformity on the surface of the unconformity. It illustrates how the geological map would appear if the overlying rocks above the unconformity were removed. Such a map must be constructed using available data on the nature of the rock that directly underlies the unconformity surface.

D) The most favorable time for hydrocarbon migration within an aquifer is during periods when sediments are either tilted upward (lengthened by an extensional tectonic regime) or uplifted by a compressional tectonic regime, leading to shortening followed by erosion. These events disturb equilibrium conditions, creating migration pathways. In uplifted areas, fluid pressures decline as erosion progresses, eventually exposing the reservoir rock. This pressure decline causes differential fluid expansion, with gas expanding many times its original volume as it nearsatmospheric pressure.

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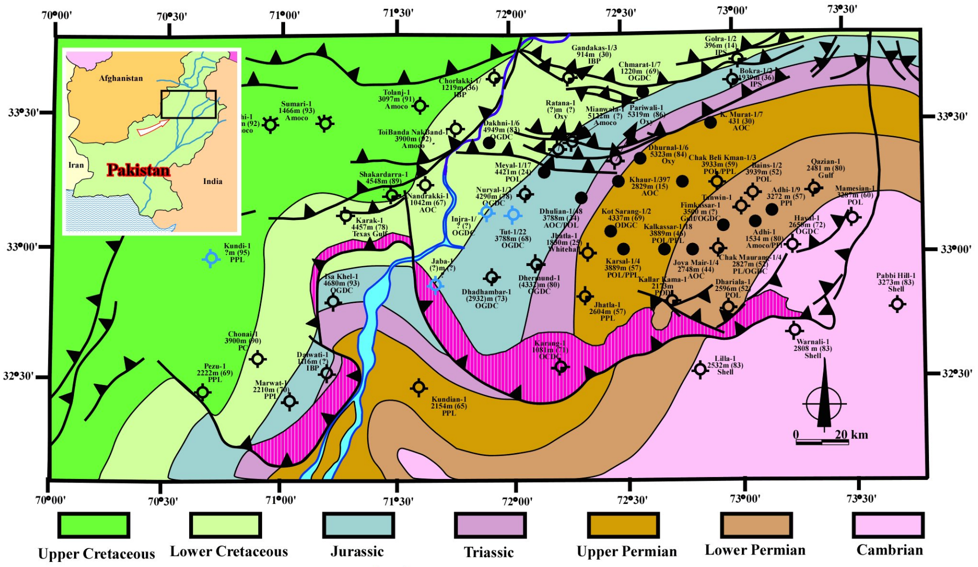
[22]A crucial exploration map for understanding the potential petroleum systems of the geographic Chaco-Paraná Basin in Argentina is, undoubtedly, a sub-crop map at the level of the tectonically enhanced unconformity, along with paleogeographic maps. In fact, some high structural points identified on seismic lines and tested by drilling may not correspond to the highest structural points when analyzed on a sub-crop map.

The expanding fluids (water, oil, and gas) are forced out toward areas of lower pressure, typically in the direction of the eroding surface. As hydrocarbons migrate up-dip, or toward lower pressure zones, any encountered barriers may trap portions of the oil or gas, leading to the formation of accumulations. This process is particularly significant when two or more tectonically enhanced unconformities are present, as seen in onshore Pakistan (Fig. 44 and 45). The existence of multiple unconformities allows for the charging of multiple reservoir rocks, including Cambrian, Cretaceous, and Paleocene–Eocene reservoirs.

Sub-crop Map

Pre-Paleocene Unconformity



HC Migration Paths

(Source rocks within Mesozoic and Paleozoic sediments)

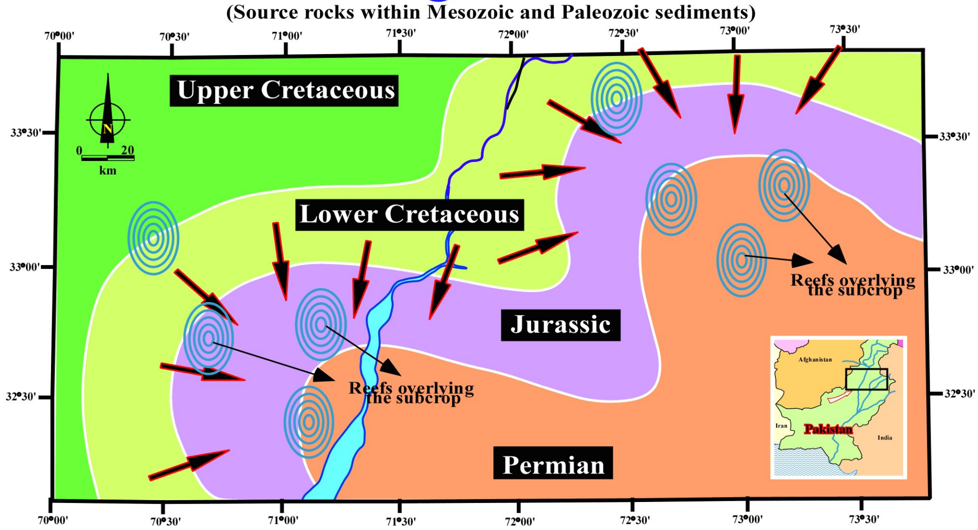


Figure 46 – The sub-crop map above represents the Palaeocene-Cretaceous tectonically enhanced unconformity, based on a tentative geological interpretation of the seismic line from the Pakistan onshore. This interpretation incorporates stratigraphic data from exploration wells. The structural trends generally strike NW–SW, with two anticline axes clearly identifiable. These structural axes appear to control the distribution of Palaeocene reefs, which form excellent morphological traps. The sub-crop map strongly suggests the timing of oil and gas migration, as well as the most probable migration pathways.

E) Paleogeographic maps, i.e., geological maps representing the stratigraphic units immediately below an erosional surface (unconformity), with formations restored to their original positions before deformation and erosion, can provide valuable insights into key exploration challenges, such as:

1 - Pre-unconformity structures ;
2 - Truncation or shoreline as the cause of sedimentary wedge-out;
3 - Time of deformation ;
4 - Location of sedimentary wedge belts ;
5 - Source of post-unconformity sediments ;
6 - Timing of oil and gas migration and the most probable migration pathways ;
7 - Paleo-hydrodynamic gradients ;
8 - Major tectonic disruptions, such as thrust faulting or continental drift.

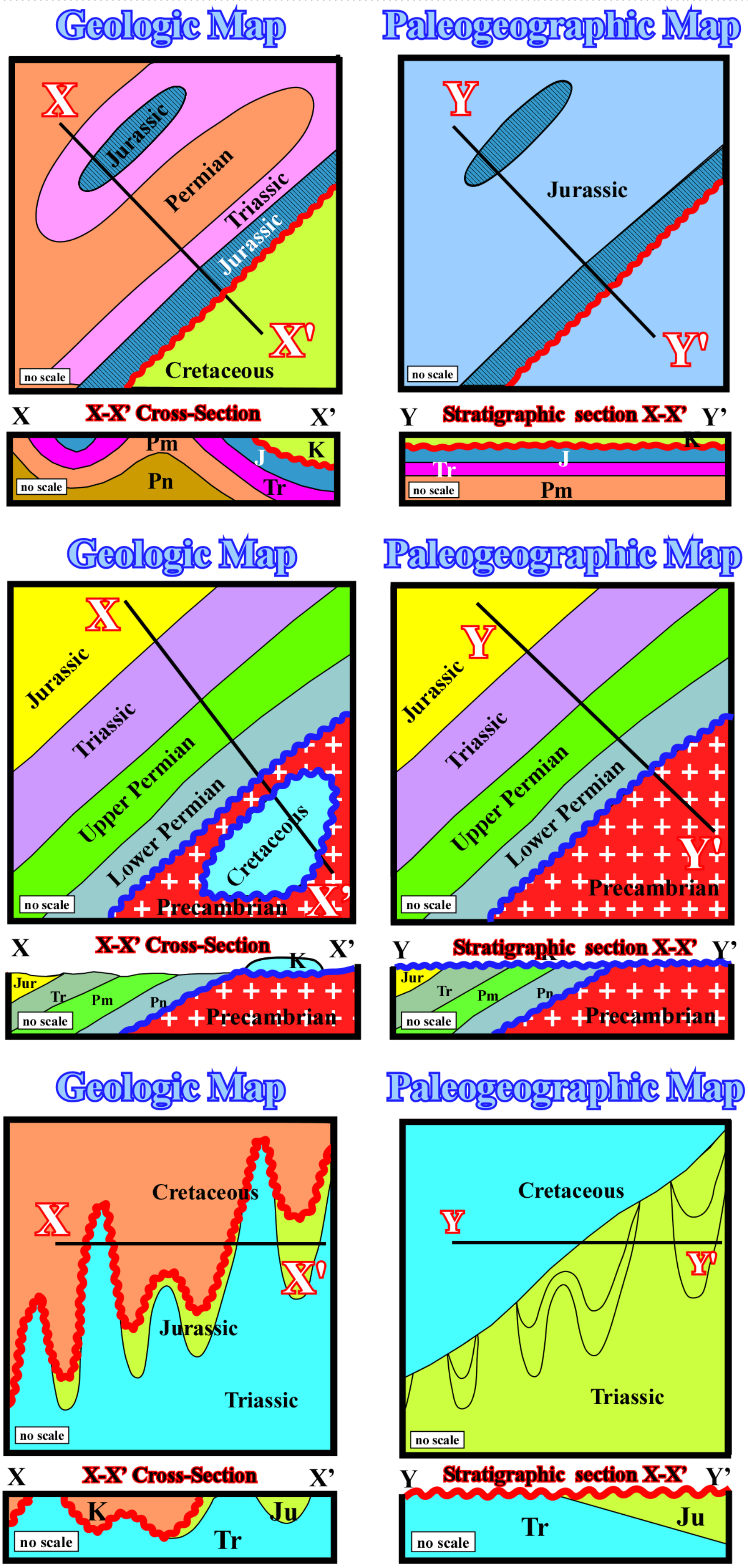


Figure 47 – On the left side of this figure, three areal geological maps are illustrated along with their corresponding structural cross-sections (X–X'), referenced to sea level as the datum. On the right side, the respective paleogeographic maps depict conditions as they existed in the pre-Cretaceous period. These reconstructions are based on geological map data and stratigraphic sections (Y–Y'), illustrating the structural and stratigraphic relationships at the onset of the Cretaceous. The unconformity at the base of the Cretaceous serves as the reference plane. The stratigraphic sections Y–Y' can be interpreted as paleogeographic structural sections, representing the structural framework at the time of Cretaceous deposition.

At this point, a quickly review of some typical examples of paleogeographic maps (Levorsen, A. I., 1960 - Paleogeologic Mapsis more than necessary. In fact, such maps are no longer widely taught in most universities and cannot be automatically generated using standard workstation software.

In the first geological map (upper part of Fig. 47), two areas provide control for the paleogeographic reconstruction (hatched areas): (i) The Jurassic sediments within the western syncline, which were likely present when the Cretaceous overlapped the region, even though no Cretaceous deposits remain there today. (ii) The contact between the Cretaceous and the Jurassic along the unconformity. Since the Cretaceous was folded together with the Jurassic and older rock units, it can be inferred that folding within the syncline and along the unconformity is post-Cretaceous. Consequently, only the Jurassic (hatched area) is interpreted as having been exposed at the surface when the Cretaceous was deposited.

A slightly different situation is depicted in the geological map in the middle of Fig. 47. Here, the control for the paleogeographic reconstruction is based on: a)The extent of Jurassic rocks, as they are the stratigraphic unit immediately underlying the Cretaceous and must have been present when the Cretaceous overlapped the area.b)The contact between the Cretaceous and the Precambrian rocks. Additionally, the Triassic and both the Upper and Lower Permian units must have been present in the pre-Cretaceous period, approximately as they appear in the geological map. Since the formation boundaries are parallel, it is likely that the entire pre-Cretaceous sequence was tilted upward toward the southeast before being truncated by erosion. Following this tilting and erosion, the Cretaceous was presumably deposited across the truncated edges. The current absence of Cretaceous deposits over much of the area could be attributed to either post-Cretaceous erosion or non-deposition. If the absence is due to non-deposition, then the pre-Cretaceous geology would have been essentially the same as it is now, implying that the tilting and erosion occurred before Cretaceous time.

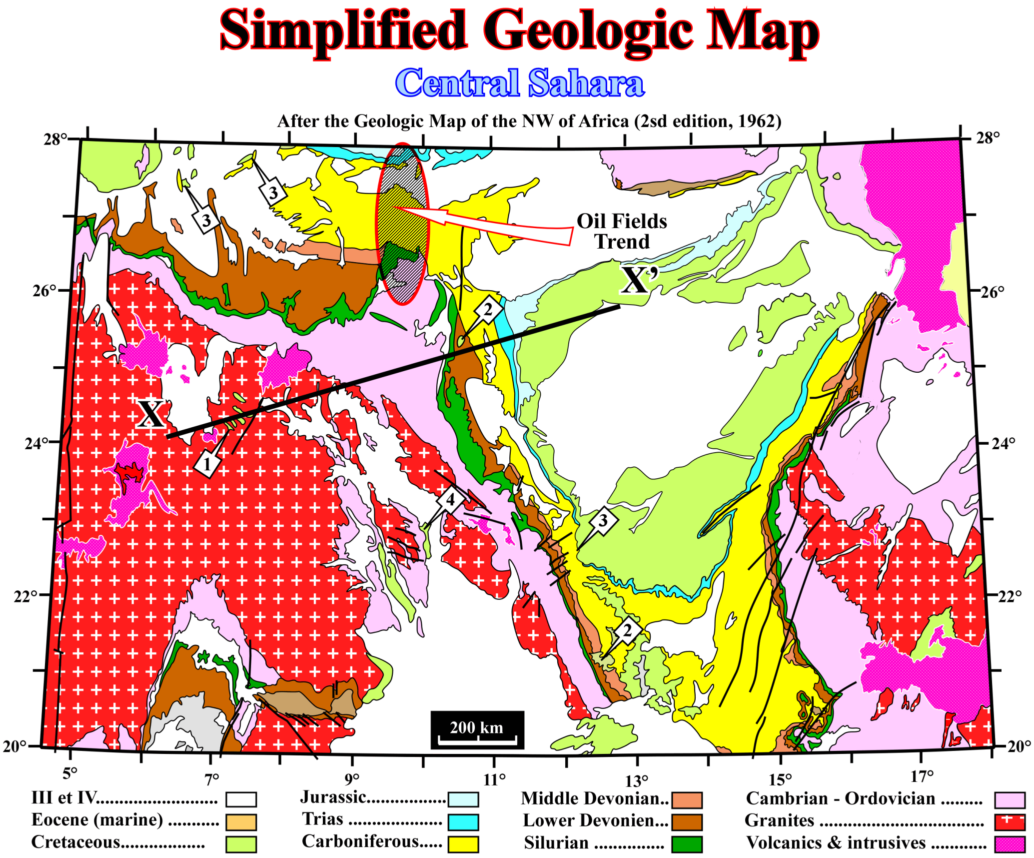


Figure 48 – This simplified geological map of the Central Sahara illustrates that the Cretaceous sediments (light green) rest upon various older rock units, including Precambrian rocks (1) and Devonian sediments (2). Similarly, they overlie Carboniferous sediments (3) and Cambrian-Ordovician sediments (4). This stratigraphic relationship suggests that the current pre-Cretaceous geological framework was established during pre-Cretaceous and post-Carboniferous times.Notably, the locations of several oil fields, including Edjele, Tiguentourine, and Zarzaïtine, are situated roughly along a distinct, colored elliptical trend. For a petroleum geoscientist, the key question is: Why do these oil fields align approximately along a North-South trend?

A wedge-out outcrop or a distinctive distribution pattern on an areal geological map often marks the point where a formation is truncated at the surface of an unconformity. This is illustrated in the lower part of Fig. 47. The map indicates four northward-plunging anticlines, identified based on the distribution of formations. A line connecting the wedge-out points represents the northernmost extent of Jurassic rocks. North of this line, Cretaceous rocks rest directly on Triassic strata, whereas south of it, Cretaceous rocks overlie Jurassic formations. From the present areal geological maps, it can be inferred that folding in this region occurred after the Cretaceous, as the contact between the Cretaceous and Jurassic rocks is folded together with the Jurassic-Triassic contact. Additionally, the erosion responsible for shaping the current geological pattern must have occurred after the folding event.

These maps often provide key insights into the most probable locations of hydrocarbon accumulations, as appears to be the case in the Central Sahara. A simplified geological map of the region is shown in Fig.48. From this map, it is evident that the present surface boundaries of the pre-Cretaceous formations were established before the deposition of the Cretaceous, as they extend beyond the Cretaceous cover without any significant change in direction. Consequently, the present areal geological map of the pre-Cretaceous formations in this area corresponds directly to the paleogeographic map of the pre-Cretaceous period. The basal Carboniferous rests on a stratigraphic succession of Devonian, Silurian, Ordovician, and Cambrian formations from west to east. This same sequence then repeats in reverse from near the center of the map toward the southeast corner. The regular transition from younger to older formations, symmetrically distributed on either side of the center, suggests the presence of a pre-Carboniferous arch along the unconformity (Fig. 49).

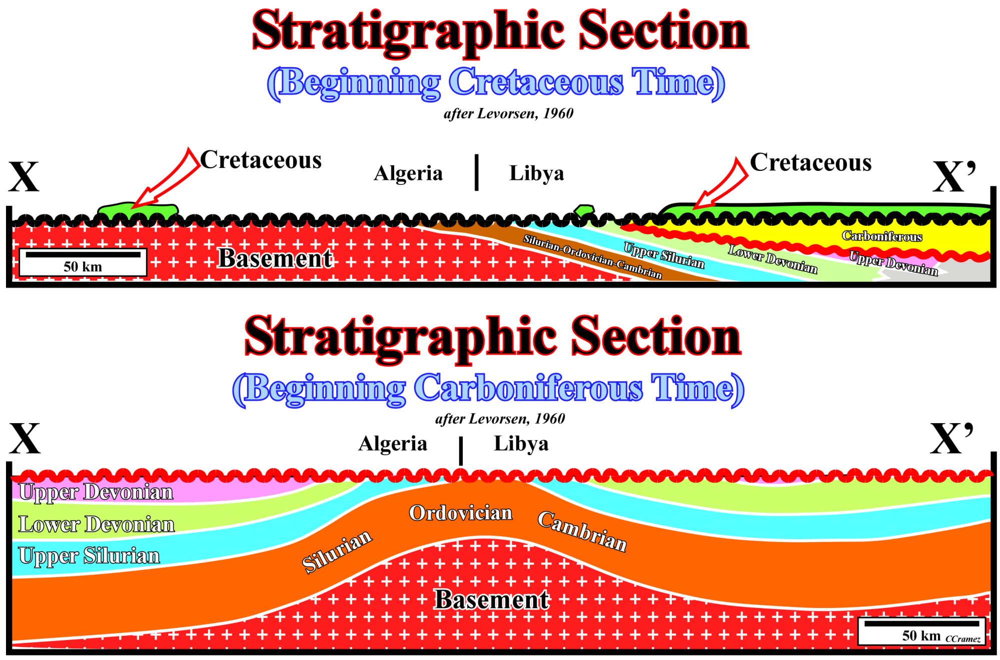


Figure 49 – The idealized stratigraphic sections X–X' (see location in Figure 48) illustrate the structural configuration at two key geological moments: the beginning of the Cretaceous and the beginning of the Carboniferous (Mississippian). The Hercynian orogeny resulted in significant erosion of the western flank of the anticlinorium, shaping the pre-Cretaceous geological framework.

Presumably, the pre-Carboniferous contacts extend northward beneath the Carboniferous, and the Carboniferous itself was eroded from the arched area toward the south, where older formations are now exposed. The oil fields are located along this projected arch, suggesting a structural control on hydrocarbon accumulation.It is evident from the geological map and stratigraphic sections that the underlying arch existed in pre-Carboniferous time, predating the formation of the local folds that later deformed the Carboniferous strata. These local folds, which developed after the initial arching, now coincide with the locations of the oil fields.

11) Trapping (structural and non-structural)

For hydrocarbons to be trapped in economically viable quantities, the subsurface must simultaneously meet two key conditions: (i) An isolated area of reservoir rock with relatively low potential, (ii) A barrier (or seal) with sufficient displacement pressure to retain the hydrocarbons

Hydrocarbon migration, whether primary (expulsion from kerogen and source rock) or secondary (movement of hydrocarbons toward lower pressure and temperature zones), follows the path of decreasing pressure gradients. As a result, hydrocarbons tend to accumulate preferentially in low-potential areas. Geoscientists classify hydrocarbon traps based on the predominant geological factor responsible for isolating a lower-potential sector within the reservoir rock. These traps fall into three broad categories:

A) Structural Traps – Formed by tectonic deformation, such as folds and faults.

B) Non-structural Traps, which include:

B.1) Stratigraphic Traps – Resulting from variations in rock facies or depositional patterns.

B.2) Unconformity-Related Traps – Where hydrocarbons accumulate due to truncation or onlapping relationships at an unconformity surface.

B.3) Morphologic Traps, which can be:

B.3.1- Morphologic by Juxtaposition – Created by lateral changes in rock properties due to faulting or depositional variations.

B.3.2- Purely Morphologic – Resulting from depositional geometry, as reef buildups or channel fills.

C) Hydrodynamic Traps – Formed when water movement alters the hydrocarbon migration pathways, leading to accumulations controlled by hydrodynamic forces rather than structural or stratigraphic barriers.

However, structural traps are, in every point of view, a very special and very different type from the other two categories of traps. Their closure, that is to say, the barrier that forces the flow of hydrocarbons to accumulate upstream, is fundamentally different from the closure of non-structural and hydrodynamic traps. This difference is very significant not only geometrically, but also at the dynamic point of view.

At geometrical point of view, the closure of structural traps is formed by a chronostratigraphic concave downward geometry of the layer forming the cover. This characterises all traps associated with anticlines. Obviously, such a definition does not apply to the traps associated with non-synchronous warped surfaces of the sand-prone sedimentary anomalies that are very recognisable on seismic lines. Also, it cannot be applied to the reef structures, which are typical morphological traps.

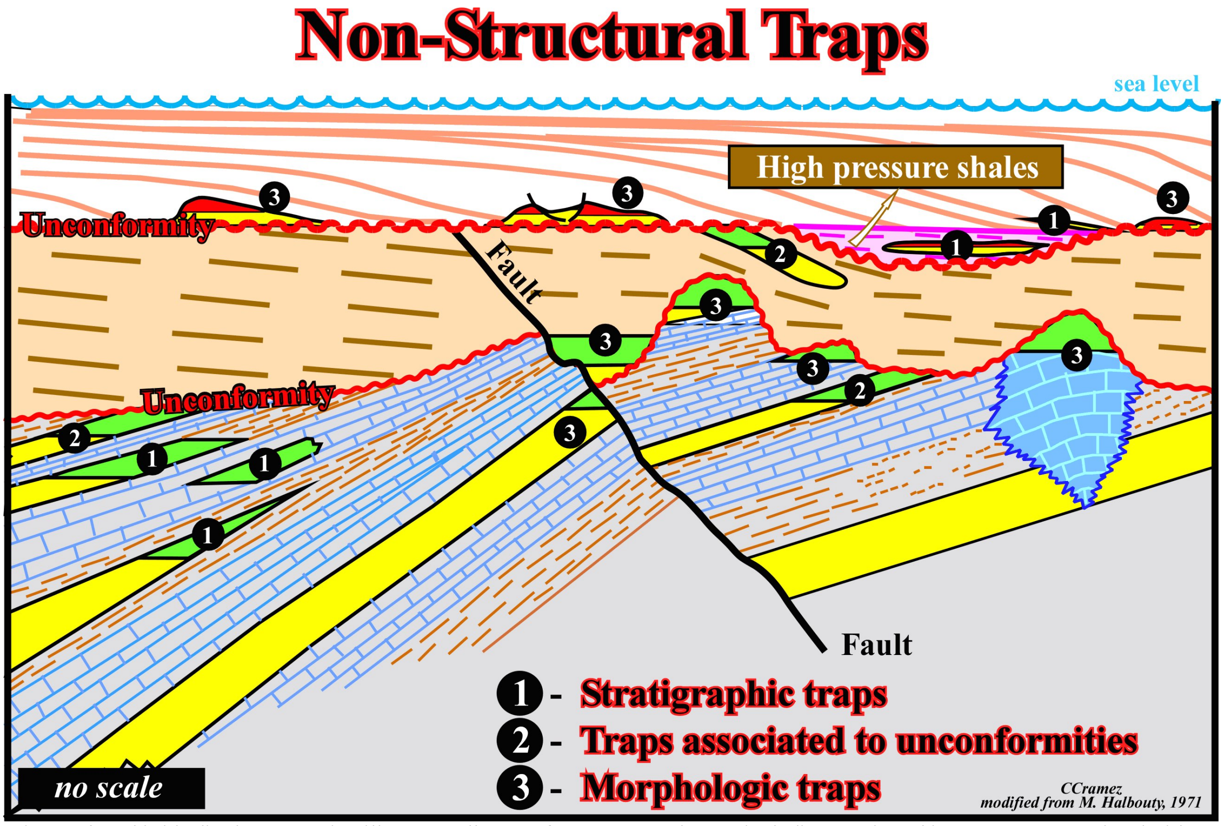


Figure 50 – This idealized cross-section illustrates all types of non-structural traps, including stratigraphic traps, traps associated with unconformities, and morphologic traps. Notably, these traps are formed due to the contiguous presence of a reservoir rock and an overlying sealing rock, which together create the necessary conditions for hydrocarbon accumulation.

From a dynamic perspective, the difference between structural trap closures and other types of trapping mechanismsbecomes even more pronounced. A closure serves as a barrier to hydrocarbon migration, marking the transition from a porous and permeable facies (reservoir rock) to a fine-grained sediment with a pore or displacement pressure greater than the pressure exerted by surrounding fluids. If capillary pressure is sufficient to force the oil-water interface through the pores of the upstream sediments, those sediments will not form an effective migration barrier.In structural traps, hydrocarbon flow is perpendicular to bedding, whereas in non-structural traps, flow is generally parallel to stratification. Fault-related trapping presents a distinct case: when a fault plays a direct or indirect role in trapping hydrocarbons, migration is not perpendicular to the layers, making fault-related traps fundamentally different from conventional structural traps.

In other words, structural traps are relatively easy to identify due to their geometry, and their closures tend to be more effective. Even if the first sealing layer above the reservoir rock lacks sufficient displacement pressure to trap hydrocarbons, higher stratigraphic levels may provide an effective seal. Conversely, non-structural traps are often more difficult to recognize. Their identification on seismic lines is often subtle, making them more obscure. Their closures depend primarily on the displacement pressure of stratigraphic layers or fractures extending from the reservoir rock. However, even one thin detrital bed with a lower displacement pressure may be enough to allow hydrocarbon migration, compromising the trap's effectiveness. Aquifers and hydrodynamic forces play a significant role in determining trap efficiency. This is particularly true for non-structural traps, where the hydrodynamic gradient is parallel to bedding or fractures. As a result, the preferred leakage pathways for hydrocarbons are also parallel to these structures, making the closure of such traps more susceptible to hydrodynamic influences.

Closures, as well as seals, can be effective barriers for certain fluids under specific pressure and temperature conditions, while allowing the migration of others. They form a delicate and complex system of hydrocarbon inputs and outputs. Some geoscientists argue that, in most cases, a trap remains filled only as long as it is supplied upstream at a rate roughly equal to its downstream losses. Consequently, traps located in the more subsiding sectors of a sedimentary basin have a higher likelihood of reaching full capacity compared to those in stable or uplifted regions.

Before proceeding, we will summarize the fundamental principles that all geoscientists learn on this subject during their education:

1) Almost all hydrocarbon (HC) accumulations are associated with an aquifer environment, where water plays a key role in hydrocarbon migration, trapping, and pressure maintenance.

1.1 – The interstitial water contained within reservoir rocks is generally in motion.

1.2 – Interstitial water migrates toward areas of lower potential. The velocity of this movement depends on the difference in potential and the transmissibility of the aquifer.

1.3 – The velocity of displacement is generally low, typically on the order of a few centimeters per year. However, hydrodynamic forces play a crucial role in both hydrocarbon migration and trapping mechanisms-

2) Gas and oil are immiscible in water and have a lower density, causing them to migrate upward through perme-able formations until trapped by a suitable seal.

3) The age, origin, composition and petrophysical characteristics of the reservoir-rocks are highly variable.

4) Potential traps are formed by tectonic or depositional processes, or a combination of both.

A water potential gradient within a reservoir rock can act as a barrier to hydrocarbon migration and contri-bute to trapping. This effect is particularly significant when combined with tectonic and stratigraphic factors.

5) The shape and size of porosity, permeability pathways, and chemical composition of reservoir rocks vary greatly. These factors define the migration and trapping environments where hydrocarbons accumulate.

6) The minimum time required for hydrocarbons to be generated, migrate, and become trapped is estimated to be less than 1 million years under favorable geological conditions.

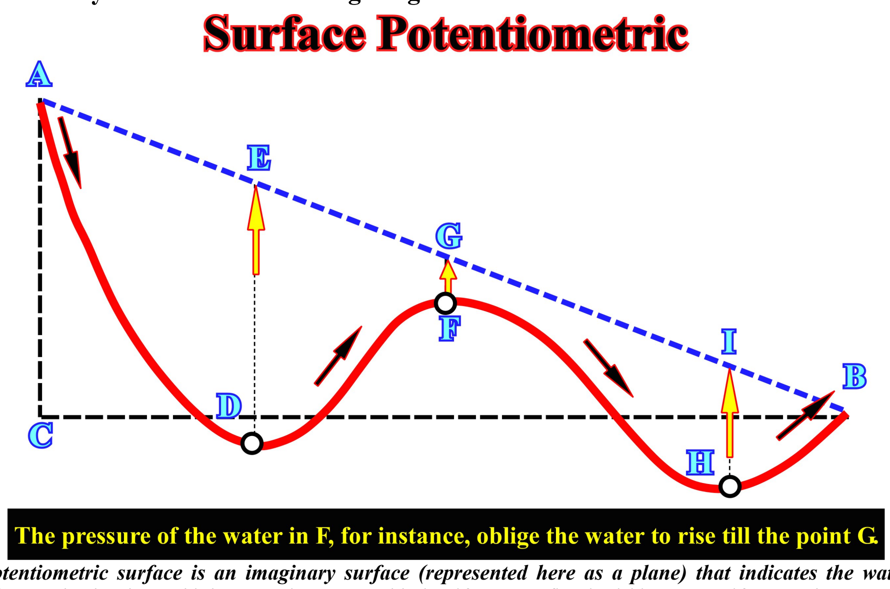


Figure 51 – A potentiometric surface is an imaginary surface (represented here as a plane) that indicates the water table in an unconfined aquifer or the level to which groundwater would rise if not confined within an aquifer.In other words, it functions similarly to two interconnected water storage tanks, where one is full and the other is empty. Over time, water will naturally flow from the full tank to the empty one, balancing the levels, since the potentiometric surface of the full tank provides the necessary hydraulic gradient to drive the flow.Groundwater level measurements offer valuable insights into local groundwater resources. Because differences in water-level elevation create a potential for flow, spatial mapping of water levels can help identify regional groundwater flow directions. Generally, the potentiometric surface in a water table map follows the overlying land-surface topography and intersects the land surface at major streams, lakes, or wetlands, indicating areas of groundwater discharge.

7) The upper and lateral boundaries of a trap—whether structural, stratigraphic, or a combination of both, with or without a hydrodynamic component—form a relatively impermeable surface that is concave downward, effectively sealing hydrocarbons within the trap.

8) The temperature range of reservoir rocks typically falls between 50°C and 160°C, depending on burial depth, geothermal gradient, and basin history.

9) Fluid pressures within reservoir rocks can fluctuate over time, increasing or decreasing depending on geological events, such as sediment loading, faulting, uplift, or fluid migration.

10) The history of hydrocarbon traps varies significantly. A trap may form due to a single geological episode or result from a combination of events spanning extensive geological time scales.

11) During primary migration, when oil or gas is expelled from shales into reservoir rocks, it must displace the water already present in the reservoir. This displacement induces a water movement toward potential escape pathways.

12) Hydrocarbon particles carried by moving water along reservoir rocks tend to flocculate, forming small droplets. These droplets are transported with the water until they reach a critical size, at which point their buoyancy enables them to move independently of the water flow.

13) When considering water movement within a reservoir rock, geoscientists must account for two pressure gradients: (i)The hydraulic gradient, which governs water flow within the rock, (ii) B) The buoyancy-driven gradient, which influences hydrocarbon migration relative to water movement:

(i) The hydrostatic pressure gradient[23] and
(ii) The hydrodynamic pressure gradient[24].

If the potentiometric surface of an aquifer is horizontal, the system is in a state of hydrostatic equilibrium, meaning the water remains stationary. Conversely, if the potentiometric surface is inclined, the system is in hydrodynamic equilibrium, indicating that the water is in motion.

14) The movement of the water in the reservoir-rocks changes, continuously, according to the variation of pressure gradients.

15) The altitude of the potentiometric surface in a given point (x) can be calculated from the density of water and the pressure of the reservoir

$$h = z + p / \varphi g$$

Where,
"h" is water potential,
"z" is the altitude of x,
"p" is the hydrostatic pressure,
"φ" is the density of water and
"g" tis he gravity.

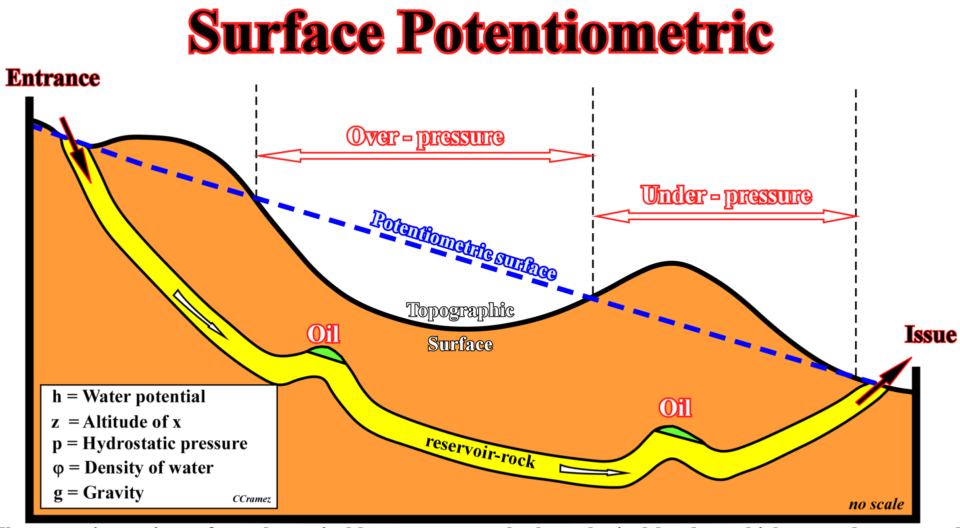


Figure 52 – The potentiometric surface, shown in blue, represents the hypothetical level to which groundwater would rise if it were not confined by an impermeable layer. In an unconfined aquifer, this surface is equivalent to the water table. However, in a confined aquifer, where water is under pressure due to an overlying impermeable layer, the potentiometric surface indicates the potential elevation to which water would rise in a well. In areas of overpressure, artesian wells are likely to occur. These wells penetrate impermeable strata and tap into water-bearing formations that receive recharge from a higher-altitude area. The resulting hydraulic pressure forces water to flow upwards without the need for pumping. Conversely, in underpressured sectors, such artesian flow does not occur. Due to sediment shortening, the reservoir rock (shown in yellow) has been locally uplifted, inducing a global down-dip flow of the aquifer from the recharge zone to the discharge area. This regional flow has tilted the oil-water contact, a phenomenon commonly observed in most oil accumulations within sedimentary basins associated with megasutures, such as back-arc basins. The Neuquén Basin, a well-documented hydrocarbon province, provides geographic evidence that supports this interpretation.

[23] The hydrostatic pressure gradient is increased pressure water with depth due to the weight of the overlying water column.

[24] The hydrodynamic pressure gradient is the gradient of the potential that exists in the aquifer wherein the water moves.

16) When the potentiometric surface intersects a trap, the pressure in the reservoir rock is at atmospheric level, as illustrated in Figure. 53. In this situation, hydrocarbons are lost to the water, meaning they fail to accumulate in significant quantities due to the absence of sufficient pressure to retain them within the trap.

Returning to the issue of closure effectiveness, aquifers and hydrodynamism play a crucial role. Their influence is particularly significant in non-structural traps, where the hydrodynamic gradient—as previously mentioned—is parallel to bedding or faults. This orientation aligns with the preferential escape pathways for hydrocarbons, making the effectiveness of such closures highly dependent on fluid movement.

When evaluating a trap, it is essential—and often decisive—to determine whether hydrodynamic forces are presentand whether they act in the direction of oil migration or opposite to it. The implications differ significantly depending on the direction of fluid movement. In young, subsiding sedimentary basins, such as the cratonic basin of the North Sea or Atlantic-type divergent margins, most of the sedimentary sequences are still undergoing compaction. As a result, the highest hydraulic potential is found in the central, deeper parts of the basin, creating centrifugal hydrodynamic gradients that drive fluid flow outward from the basin center.

Conversely, in sedimentary basins associated with the Mesozoic–Cenozoic megasuture, such as the episutural basins (back-arc basins) of Southeast Asia and South America or the perisutural basins (foredeeps), the geological setting is generally compressional. Here, structural deformation uplifts and folds the sediments, influencing fluid movement and trap effectiveness:

- These deformations are generally most pronounced along ancient normal faults that border basement highs and near the basin margins.

- In many cases, the deepest parts of these basins, which initially had very high hydraulic potential, become structurally inverted due to sedimentary shortening. As a result, they evolve into high structural areas rather than remaining low areas of subsidence.

- Consequently, the hydrodynamic gradients in these settings are typically centripetal, meaning that fluid flow is directed down-dip, toward the structurally lower areas that have become the new hydrodynamic sinks.

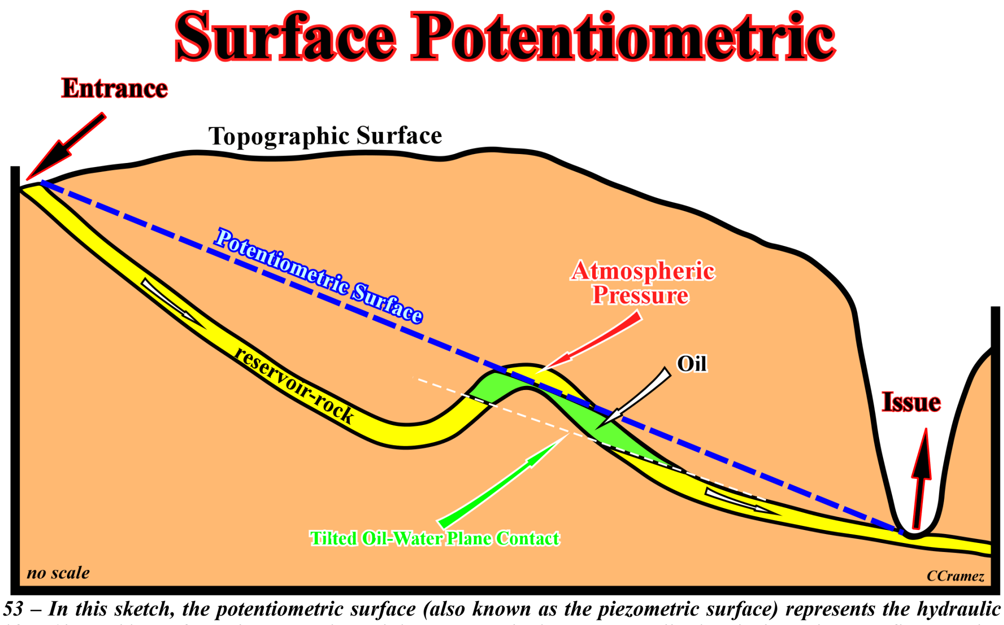


Figure 53 – In this sketch, the potentiometric surface (also known as the piezometric surface) represents the hydraulic head within the aquifer. Above this surface, the reservoir rock is at atmospheric pressure, allowing hydrocarbons to float on the aquifer. The aquifer flows from the recharge area (entrance) toward the discharge area (issue), which results in the tilting of the oil-water contact within the structural trap. Since hydrocarbons are generally lighter than water, they tend to migrate upward through adjacent rock layers until they either reach the surface or become trapped beneath impermeable seals. However, underground water flow dynamics can significantly influence hydrocarbon migration, sometimes causing oil to travel horizontally for hundreds of kilometers or even move short distances downwardbefore finally accumulating in a reservoir. The reservoir pore-fluid pressure is a fraction of the overburden pressure and is supported by the fluid system within the rock pores. The remaining portion of the overburden pressure is borne by the rock matrix, generating the in-situ rock stress. The overburden pressure itself results from the weight of the overlying rock layers at a given point. Consequently, the difference between the overburden pressure and the vertical rock stress provides an approximation of the pore pressure within the reservoir. It is important to note that the potentiometric surface of a confined aquifer is not a perfectly flat plane. Instead, it exhibits highs and lows, similar to the hills and valleys found on land. Just as surface water flows downhill, groundwater moves down-gradient, migrating from higher-elevation potentiometric regions toward lower-elevation regions, shaping subsurface fluid movement patterns.

In the evaluation of the non-structural traps, geoscientists must not forget :

"If the flow of the aquifer is in the same direction as that of the hydrocarbons, it will decrease the efficiency of the closure, and eventually, there will be no trapping (Fig. 54)."

To trap hydrocarbons under such conditions, specific geological factors must be present. Since migration follows decreasing pressure gradients, it is highly likely that most hydrocarbons have migrated along the unconformity (Fig. 54) toward areas of lower potential, either accumulating in a larger oil accumulation or escaping to the surface.

However, if the reservoir rock is protected by an overlying layer with very high pressure, this layer may act as an effective seal, potentially trapping hydrocarbons within the reservoir. Nevertheless, the accumulation will be economically viable only if:

(i) Hydrodynamism is not too active, ensuring that fluid movement does not disrupt the hydrocarbon accumulation.
(ii) The structural configuration of the reservoir rock is relatively horizontal, preventing hydrocarbons from migrating out of the trap due to significant tilting.

On this subject, it is interesting to note that certain oil fields, such as the Gabian oil field in southern France, exhibited the peculiar behavior of deflating rapidly. However, every spring, following winter rains, production resumed. This phenomenon is attributed to meteoric water infiltration, which caused a local increase in centripetal hydrodynamic flows, preventing the oil from dispersing. As hydrocarbons migrated toward the surface, they were trapped by hydrodynamic forces, temporarily enhancing production.

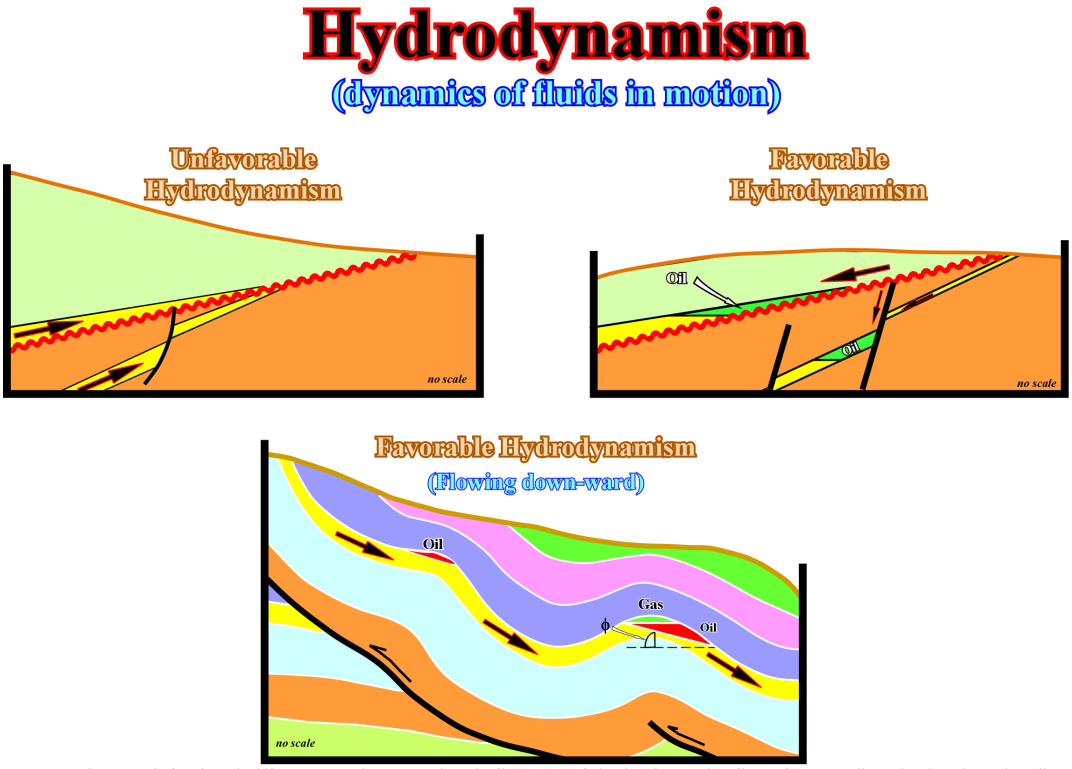


Figure 54 – The top-left sketch illustrates the negative influence of hydrodynamic flow (arrow direction) when it aligns with hydrocarbon migration. Under these conditions, no trapping occurs in the onlapping reservoir rock (yellow) or within the faulted blocks, as hydrocarbons continue migrating instead of accumulating.The top-right sketch demonstrates the favorable influence of a hydrodynamic flow moving in the opposite directionto hydrocarbon migration. In this scenario, hydrocarbons are often trapped at the onlapping termination of the reservoir rock and within the footwall of faulted blocks, where they are effectively retained by hydrodynamic forces.The lower sketch illustrates the influence of downward aquifer flow within a structural trap (anticline). The oil-water contact tilts in the direction of the flow, forming the hydrodynamic wall of the accumulation, in accordance with Hubbert's law: $t \cdot g \cdot \Phi = dxdh \times (dw - dh)dw$.This equation describes the relationship between hydrodynamic pressure gradients, fluid density contrasts, and the geometry of the oil-water contact within a tilted trap.

In structural traps, the influence of the hydrodynamic gradient is much less pronounced compared to non-structural traps. Since the aquifer flow is parallel to the bedding planes, it primarily causes a lateral displacement of the hydrocarbon accumulation rather than completely preventing trapping, as illustrated in Figure 54. The wall of the accumulation, defined by the oil-water contact, is tilted in the direction of aquifer flow, following Hubbert's law (1953):

$$t.g.\Phi = dh/dx \times dw/(dw-dh),$$ in which

"Φ" represents the angle of the oil-water plan contact with the horizontal,
"dh /dx," is the slope of the hydraulic tectonic nappe (see figure 53),
"dw" is the density of water and
"dh" is the density of the hydrocarbons.

According to Hubbert's equation, it is evident that the tilting of the oil-water contact increases as the hydrodynamic gradient strengthens and as the density contrast between oil and water decreases, especially when their densities approach 1 g/cm³.

When hydrodynamic flow is particularly strong, hydrocarbons can be entirely flushed out of the trap, preventing accumulation. In such conditions, within these types of traps, the hydrocarbon column may exceed the theoretical closure determined from structural maps. It is therefore crucial to distinguish between:

(i) The theoretical closure, and
(ii) The impregnated closure.

The theoretical closure is determined from geological data, primarily based on seismic surveys and field observations.The impregnated closure (or practical closure) corresponds to the actual height of the hydrocarbon column impregnated within the trap. In structural traps, for mono-layer accumulations (a single reservoir bed), the impregnated closure can be:

(i) Equal to the theoretical closure, in this case, geoscientists refer to the fill factor as 1 (i.e., the trap is fully charged),
(ii) Less than the theoretical closure, here, the fill factor is less than 1, meaning hydrocarbons have not filled the trap to its maximum potential.

For multi-layer accumulations (several reservoir beds), geoscientists must consider:

(a) A single, uniform oil-water contact, where the impregnated height equals the structural closure,
(b) Multiple oil-water contacts, where the total impregnated height exceeds the largest structural closure.

In evaluating a structural trap, geoscientists must assess these possibilities and adopt the most probable scenario. In some cases, the economic potential of the prospect may be limited, while in others, it may be economically viable.

In non-structural traps found in certain episutural and perisutural basins, where hydrodynamic gradients are often centripetal (opposing hydrocarbon migration), geoscientists have observed with satisfaction that the impregnated oil column can exceed the theoretical closure, sometimes significantly. This phenomenon has been quantified using Hobson's formula (1954):

Zc = 2y (rt /rp) / g (rw-rh), where

"Zc" is the right of the oil column ;
"y" is the interfacial tension (the necessary work necessary per unit area to expand the interface between two immiscible fluids, in this case the water and oil) ;
"rt" corresponds to the radius to the tubules between the pores ;
"rp" is the radius of the pores assumed equal to that of the oil drops ;
"g" is the gravity force ;
"rw" is the water pressure and
"rh" is the oil pressure.

All these observations have been corroborated by numerous oil fields, compelling geoscientists to acknowledge the critical role of hydrodynamic conditions in the exploration of non-structural traps. In fact, most economically viable non-structural traps only exist when hydrodynamic conditions are favorable. Otherwise, hydrocarbon accumulations rarely exceed mere geological success, meaning they may be detected but not commercially viable.

In onshore Argentina, particularly in back-arc basins, which have undergone shortening and are often overlain by foredeep basins, down-dip hydrodynamic flows are quite common. These flows, which move opposite to hydrocarbon migration, significantly enhance trapping efficiency. A notable example of this effect is the Aguada Pichana field, where hydrodynamics played a key role in the accumulation and preservation of gas reserves.
[25], illustrated inFig. 55.

Hydrodynamism can also significantly impact reservoir-rock characteristics. In the Aguada Pichana field, reservoir quality is directly influenced by necrosis induced by significant diagenesis, including the formation of clay minerals and silica. This diagenetic process appears to have occurred during both the burial and subsequent uplift of the reservoir rocks.Evidence suggests that approximately 30 million years ago, the potential reservoir sandstones of the Middle Mulinchico Formation were buried to depths of 3500 meters. Later, during the Andean orogeny, these horizons were uplifted and are now found at depths of approximately 1500 meters in the Aguada Pichana field. During both the burial phase and subsequent uplift, changes in the chemistry of hydrodynamic currents - initially centrifugal and later centripetal - along with variations in pressure and temperature, profoundly altered the petrophysical properties of the potential reservoirs. These diagenetic transformations significantly influenced reservoir porosity and permeability, impacting hydrocarbon accumulation and productivity.

[25] The Aguada Pichana field is a gas field located in the Neuquén Basin. Discovered in 1971 by YPF, the field was evaluated until 1980 through the drilling of 25 wells, but was not put into production.In 1993, YPF proposed the Aguada Pichana field to Total Austral as part of a compensation agreement related to gas pricing from the Cuenca Austral. Following a thorough assessment and acceptance of YPF's offer, Total Australbecame the operator of the field in 1994.Since then, more than twenty development wells have been drilled between the original appraisal wells, with the goal of initiating production in early 1996.

The trap classification proposed by M. Halbouty is one of the most applicable frameworks for hydrocarbon exploration. It is particularly useful for evaluating the petroleum potential of residual oil basins. This classification distinguishes two major families of traps:

A) Structural Traps – Formed primarily by tectonic forces, such as folding and faulting, which create closures that can retain hydrocarbons.

B) Non-Structural Traps – Resulting from stratigraphic, diagenetic, or hydrodynamic factors, rather than structural deformation (Figure. 50) , and often requiring detailed sedimentological and hydrodynamic analysis to identify:

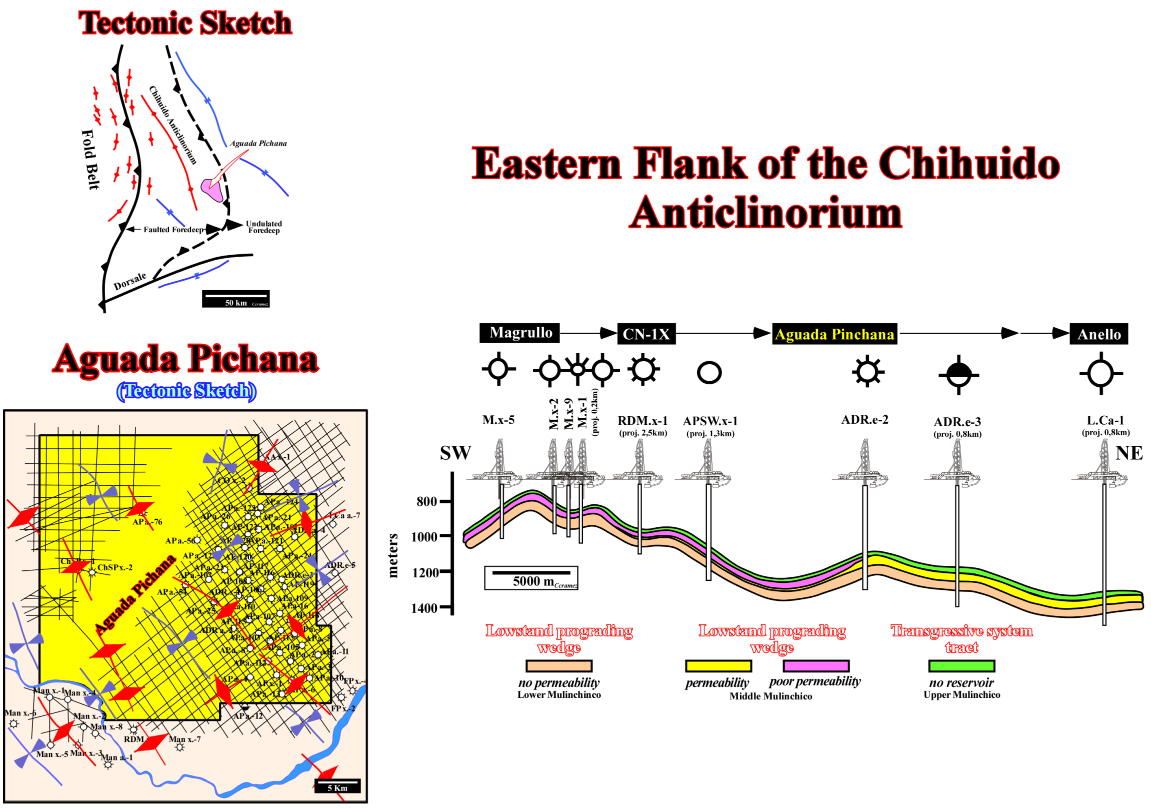


Figure 55 – Locally, the Aguada Pichana field is situated on the eastern flank of the Chihuido anticlinorium, south of an anticlinal structure. This schematic geological section highlights the eastern flank of the Chihuido anticlinoriumand provides insight into the structural complexity of the area. The final structuration of the Neocomian clastic sediments appears to be polyphasic, with a characteristic aleatory distribution of reservoir rocks. Structural mapping, derived from seismic data at the top of the Middle Mulinchico Formation, strongly suggests a polyphasic deformation history, with two distinct axial orientations: NW–SE and NE–SW. Establishing the chronology of these deformation phases remains a key challenge, as it is fundamental for understanding the trapping mechanisms and assessing the remaining hydrocarbon potential in the field. Additionally, the influence of hydrodynamic trapping is evident from the spatial distribution of hydrocarbons and dry wells. Notably, most dry wells are located at higher structural positions, whereas hydrocarbon accumulationsappear to have been displaced eastward, following the hydrodynamic flow of the aquifer. This pattern further supports the role of hydrodynamic forces in modifying the original trap configuration.

A - Structural Traps

- By definition, these traps form after the deposition of sediments.They are characterized by a concave downward geometry of the reservoir-seal rock pair.
- In most cases, the reservoir rock and the seal belong to a single depositional system; no significant geological events, such as a tectonically enhanced unconformity, separate them.
- These traps account for approximately 90% of the world's giant oil fields. A giant oil field must have at least 70 million tons of reserves (≈ 500 Mb), while a giant gas field must contain at least 70 billion cubic meters ($M.m^3$) ≈ 2,5 TCF).

Examples of These Traps:

a) Romashkino, in the Urals-Volga region, with a closed area of ~3,000 km².
b) Samotlor, in Western Siberia, with a closed area of ~2,000 km².
c) Ghawar, in Saudi Arabia, with a structural closure of ~2,300 km².
d) Kirkuk, in Iraq, located in the Zagros foothills, with reserves exceeding 2,000 Mt.
e) Kangan, in Iran, with gas reserves of several hundred TCF.
f) Gasharan, in Iran, with reserves exceeding 1,600 Mt.
g) El Furrial, in Venezuela's Maturín Basin, with reserves exceeding 4 billion barrels (Gbbl).
h) El Carito, in Venezuela, the western extension of the El Furrial field.
i) Cusiana, in Colombia, among other significant fields.

B - Non-Structural Traps

Non-structural traps (Figure 50) currently account for approximately 10% of the world's giant fields. This relatively low percentage should be interpreted in light of two factors: (i) The dominance of Middle Eastern fields, which are predominantly structural traps, (ii) The difficulty of recognizing non-structural traps, making them historically underexplored compared to structural traps. Today, non-structural traps are an integral part of petroleum exploration programs. Many geoscientists believe that the majority of undiscovered reserves are likely to be found in these types of traps.

Most economically viable non-structural accumulations result from the interaction of multiple trapping mechanisms. M. Halbouty classified them into three sub-families, based on the predominant geological trapping factor:

B.1 - Stratigraphic traps sensu stricto.
B.2 - Traps associated with unconformities, mainly tectonically enhanced unconformities.
B.3 - Morphologic traps.

B. 1 - Stratigraphic traps

- **Stratigraphic traps are fundamentally formed due to facies changes that occur during or after deposition. These variations in lithology, porosity, and permeability create natural barriers that prevent hydrocarbon migration, leading to accumulation.**

- **When the trap is synchronous with the deposition, it can be classified into two main types:**

  (i) The lateral facies change - A transition from permeable to impermeable lithologies, creating a stratigraphic seal.

  (ii) The pinch-out of reservoir-rocks - A gradual thinning and termination of a porous and permeable reservoir unit, leading to hydrocarbon entrapment against a sealing formation.

The lateral termination of a reservoir-rock can be done by proximal, distal, marine or coastal onlaps.

- **As examples of fields dominated by lateral facies changes (i):**

  - **Candeias, in the Reconcavo Basin, Brazil ;**
  - **Bell Creek, in the Powder River Basin, Montan, USA.**
  - **Jay, in the onshore Alabama-Florida (USA), etc,**

- **As example of tfields dominated by pinch-out traps (ii):**

  - **Bolivar, Venezuela (Lake Maracaibo and vicinity), with reserves exceed 15 G bl ;**
  - **Quiriquiri, Venezuela, with reserves of approximately 1 G bl ;**
  - **Pembina, Canada, with reserves of approximately 2 G bl), etc.**

B. 2 - Traps associated with Unconformities

- **The traps associated with unconformities (Figure. 50) form when an impermeable layer (clay, salt, etc.), which acts as the seal, fossilizes an erosional surface and comes into direct contact with a localized reservoir rock beneath the unconformity.**

- **The filling of these traps, meaning hydrocarbon migration, occurs primarily "per descensum", where hydrocarbons migrate directly downward from an overlying source rock, which also acts as a seal.**

- **"Per ascensum" migration (upward migration) is possible but much rarer.**

  These traps are preferentially associated with tectonically enhanced unconformities, which have been flattened (peneplains) by erosive agents, often forming angular unconformities.

- **These traps are the direct result of stratigraphic cycles, they are present in all petroleum basins.**

- **Their recognition requires fine stratigraphic analyses, in particular, sequential analysis. These analyses, either made using the seismic, land or subsurface data, must always start from stratigraphic cycles associated with eustatic cycles of the first order, to those of lower order.**

- **Their approach, like that of any exploration, is, generally, done from the general to the particular and not the opposite. When the hierarchy of stratigraphic cycles is not respected in a sequential analysis leads to failure, i.e., lithological predictions are false.**

- **The size of hydrocarbon accumulations associated with these traps varies from a few hundred thousand to several million recoverable barrels.**

- **Some examples include:**

  - **East Texas (> 5 Gbbl, USA);**
  - **Prudhoe Bay (> 10 Gbbl, Alaska, USA);**
  - **Hassi Messaoud (> 20 Gbbl, Algeria);**
  - **Meillon (Aquitaine Basin, France);**
  - **Boscan (> 5 Gbbl, Venezuela);**
  - **Kevin Sunburst (Montana, USA), etc.**

B.3 - Morphologic Traps

- **Geoscientists refer to morphological traps when topographic features or sedimentary anomalies are fossilized by overlying sediments, which are generally younger and impermeable (Fig. 50).**

- **Such anomalies are typically associated with unconformities or their down-dip correlable conformities and are formed by:**

  a) Geomorphic processes (e.g., cuestas) and

  b) Depositional processes (e.g., reefs, turbidite mounds, etc.).

- **The traps induced by the relative movements of faulted blocks are called morphological by juxtaposition.**

  (i) Although their genesis is different, their trapping mechanisms and recognition methods are very similar.

  (ii) The throw of faults (normal or reverse) can create false topographic anomalies, which, when closed by juxtaposition, form traps with geometries similar to morphological traps.

As example of morphological traps the following oil fields can be cited:

- **Poza Rica (reefs, in Mexico) ;**
- **Faja d'Oro (reefs, in Mexico) ;**
- **Redwater (reefs, in Canada) ;**
- **Scurry (atoll, in Texas) ;**
- **Frigg (basin floor fans, in North Sea) ;**
- **Balder (Basin floor fans, in North Sea) ;**
- **Marlin & Albacora (Basin floor fans, Campos offshore, in Brazil) ;**
- **President Aleman (filled canyon, Faja d'Oro, in Mexico).**

- **As examples of morphologic traps by juxtaposition, the following fields are often cited:**
  - **Jourdan (Texas) ;**
  - **Oklahoma City (USA) ;**
  - **Sari (Libya) ;**
  - **Bibi Eibat (Russia) ;**
  - **Faud (Oman), etc.**

A large number of geoscientists, particularly in South America, continue to classify antiform structures as structural traps, even when they have formed under an extensional tectonic regime (σ_1 horizontal). In other words, they consider them structural traps even when the sediments have been extended by normal faulting. However, traps associated with antiforms in these settings are typically morphological traps by juxtaposition. In such cases, the movement of normal fault blocks can result in a sealing rock being juxtaposed against a reservoir rock, creating an effective trap.

In reality, when a geoscientist fails to recognize normal faults at the apex of an extensional antiform structure[26], it is not because the faults are absent, but rather because their throw is below seismic resolution, making them too small to be detected on seismic lines. This misinterpretation of trapping mechanisms, where a

[26] The antiformes developed by compression are called anticlines. They shortened the sediments (as the reverse faults), and so they cannot have coeval normal faults associated. In geology, it is impossible to short and to length the sediments at same time in the same place.

morphological trap by juxtaposition is mistakenly classified as a structural trap, is undeniably responsible for a significant number of unsuccessful wildcats worldwide, particularly in South America.

In fact, when a geoscientist proposes a trap (structural or non-structural), they are referring to the trapping of a specific reservoir rock. It is possible for multiple reservoirs to form multiple traps within the same structure. However, from a geological and petroleum exploration perspective, proposing traps without specifying the reservoir rock is meaningless.This issue is particularly relevant—and frequently encountered—when a geoscientist identifies a large antiform structure on a map at the level of a tectonically enhanced unconformity (angular unconformity) and then assumes that the most probable reservoir rock lies beneath the unconformity.

Each time a geoscientist proposes a trap at a specific stratigraphic level (reservoir rock), the only map that is truly significant is the structural map at the top of that reservoir level. Additionally, it is crucial to remember that a trap cannot exist without a seal. The mapping of the seal (both laterally and vertically) is an essential part of the geological data required to define a trap.In the case of non-structural traps, the mapping of the seal is as important - if not more important - than the mapping of the reservoir rock. This is particularly true for morphological traps by juxtaposition, such as those illustrated in Fig. 56.

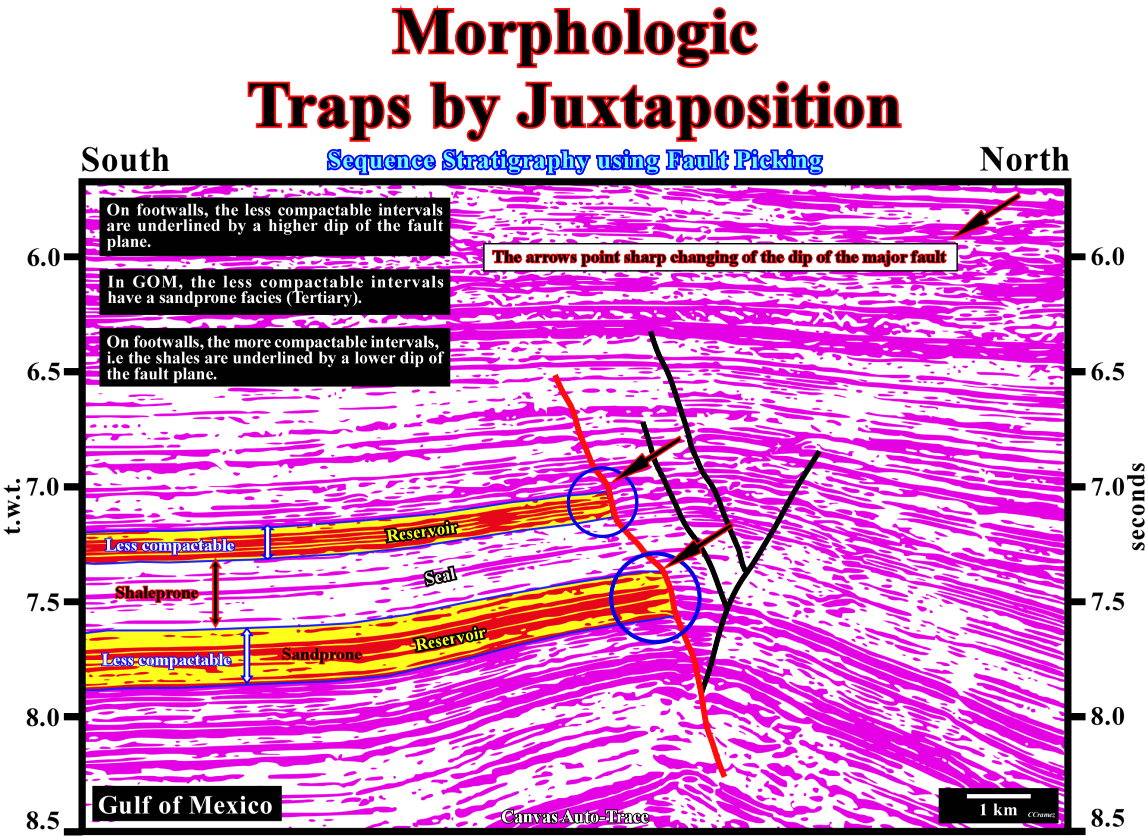


Figure 56 – The antiform structure recognised on this seismic line (Canvas Auto-Trace) is, obviously, the result of the lengthening of the sediments induced by an extensional tectonic regime (σ1 vertical). The normal faults, which allowed the lengthening, are clearly recognised at the apex of the structure. The fault planes (a mental construction of the geoscientist, since there are no seismic reflections associated) have a quite particular geometry. The dip of the fault plane changes with the lithologic changes within the faulted blocks, particularly the changes in the footwall. Indeed, the dip is much higher in the less compactable intervals, which often correspond to potential reservoir rocks. In the shale intervals, which are much more compactable, the dip of the fault planes is smaller (far from verticality).Every time the relative movement of the faulted blocks puts a less compactable interval (potential reservoir rock) in juxtaposition with a more compactable interval (potential sealing rock), a morphological trap by juxtaposition is formed. Consequently, in an antiform extensional structure, there are several potential morphological traps by juxtaposition. However, it is evident that if one of these potential traps contains hydrocarbons, it does not mean that the other traps are also filled with hydrocarbons. The opposite is also true.Admittedly, to define such a morphological trap, it is obvious that several geological maps are required: (i) The structural map of the top of the reservoir rock; (ii) Isopach map of the reservoir rock; (iii) Structural map of the top of the sealing rock;(iv) Isopach map of the sealing rock;(v) Map of the throw of the fault at each reservoir rock level.

Downay (1980) long ago insisted that the term "trap against fault," used by certain geoscientists, is a misnomer. A fault, which in the field or on a seismic line is merely a mental construction by the geoscientist (since, with very few exceptions, fault planes generally lack seismic reflections), never acts as a trap itself. In most cases, what actually creates the trap is:

(i) The sediment located on the other side of the fault, which is juxtaposed against the potential reservoir rock,

(ii) The sediments within the fault gouge zone, if present—though gouge zones are not always developed.

For trapping to occur, the capillary displacement pressure of the sediments juxtaposed against the reservoir rockmust be greater than that of the reservoir rock itself.

12) Sedimentary Shortening & Lengthening

Sediments can undergo either lengthening (extension) or shortening (compression). During a compressional tectonic regime ($\sigma1$ horizontal, meaning the maximum effective stress is horizontal), sediments are shortened and subsequently uplifted. This uplift induces a relative sea level fall, leading to the formation of an erosional surface (unconformity). Consequently, we can say:

σ_1 horizontal ☞ ☞ ☞ Shortening

Shortening ☞ ☞ ☞Uplift

Uplift ☞ ☞ ☞Relative Sea Level Fall

Relative Sea Level Fall ☞ ☞ ☞ Erosional Surface

Erosional Surface ☞ ☞ ☞ Unconformity

Unconformity ☞ ☞ ☞ New Sequence-Cycle

New Sequence-Cycle ☞ ☞ ☞ Basin Floor Fan ....

The shortening occurs along $\sigma1$ (perpendicular to the fold axes), but some lengthening can also be observed along σ_2. In fact, in the Jura Mountains, Wegmann (1954) recognized that anticlinal structures were elongated along their axes (σ_2) by relatively small strike-slip faults, which were absent in the synclines. Since then, these particular strike-slip faults have been identified in the majority of fold belts (Figure 57).

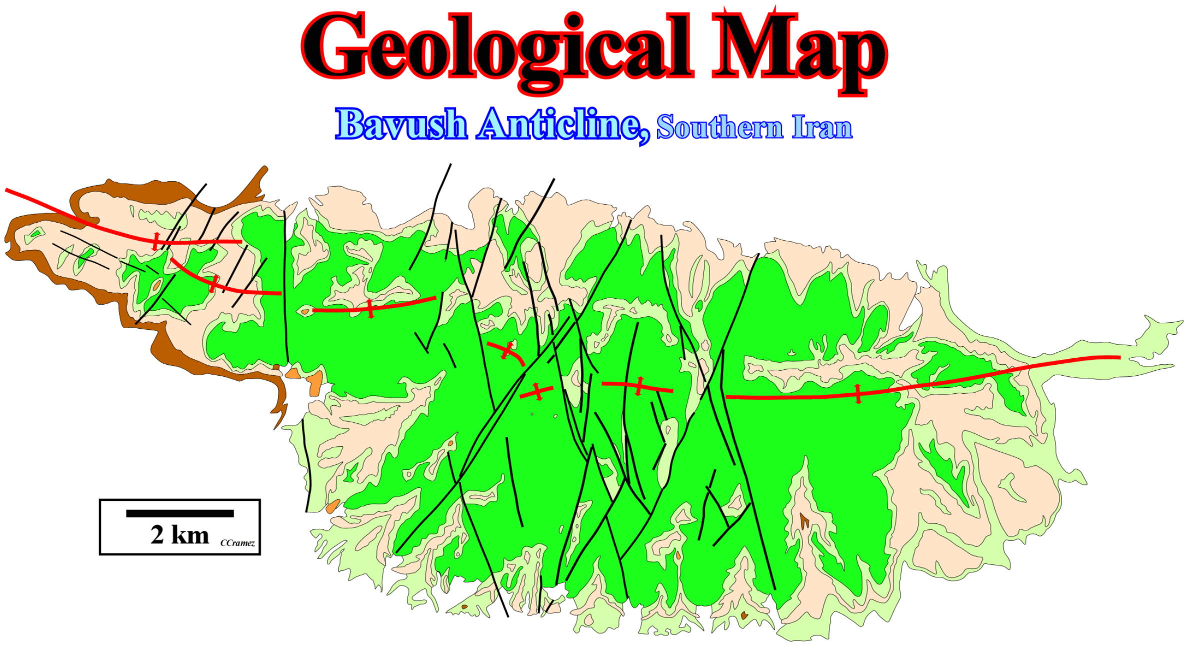


Figure 57 – The elongation of the Bavush Anticline along $\sigma2$ is clearly evident on this geological map. The vertical conjugate faults responsible for this elongation exhibit clear horizontal slickensides in the field, confirming that they are strike-slip faults rather than normal faults. In other words, as previously stated, during a compressional tectonic regime, it is impossible for normal faults to develop at the apex of an anticline, since sediments cannot be simultaneously shortened and lengthened at the same location. However, seismic interpreters frequently misinterpret such strike-slip faults as normal faults. It is important to emphasize that vertical normal faults do not exist—they are a physical impossibility.

During an extensional tectonic regime (σ_1 vertical), the sediments are lengthened. A lengthening implies subsidence, which creates a relative sea level rise, that is to say, an increasing in accommodation (space available for sediments) and so sedimentation. Consequently, we can say:

σ_1 vertical ☞ ☞ ☞ Lengthening

Lengthening ☞ ☞ ☞Subsidence[27]

Subsidence ☞ ☞ ☞Relative Sea Level Rise

Relative Sea Level Rise ☞ ☞ ☞ Increasing of Shelfal Accommodation

Increasing of Shelfal Accommodation☞ ☞ ☞ Deposition

Deposition☞ ☞ ☞ Transgression or Regression

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[27] However, certain geological features as isostatic factors, subduction of tectonic plates and others, can also produce subsidence and uplift. On the other hand, local crestal erosion is often associated to tilted blocks (extension).

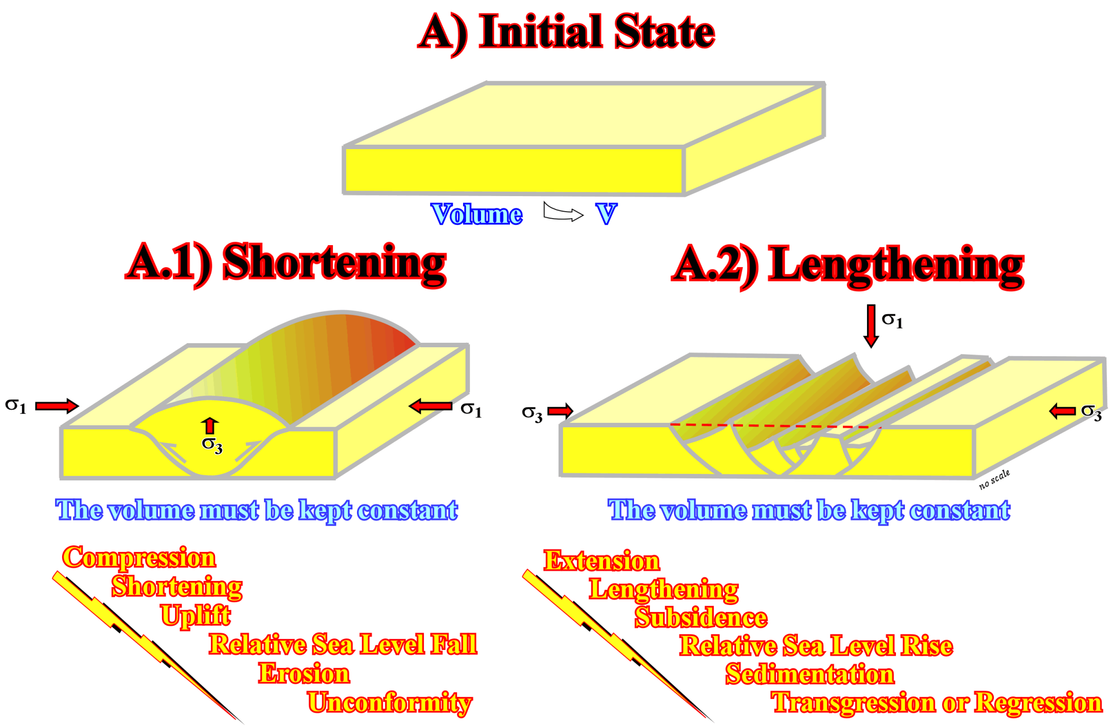

Figure 58 – In a compressional tectonic regime (σ1 horizontal), sediments are shortened by folding and/or reverse faulting. Apart from a few exceptions, discussed previously, during deformation, the volume of sediments remains more or less constant. Similarly, in an extensional tectonic regime (σ1 vertical), sediments are lengthened by normal faulting with volume preservation. From these geological conjectures, it is obvious that a compressional regime always postdates an extensional regime. Indeed, it is impossible to shorten sediments before depositing them. The ensuing geological events following shortening or lengthening are completely different, as indicated in the above sketches. Therefore, geoscientists must avoid mistaking shortening for lengthening or vice versa. On the other hand, it is important to note that both sequences of geological events are used to critique tentative interpretations. Let's see an example: Suppose that an explorationist, i.e., a geoscientist working in hydrocarbon (oil or gas) exploration, must solve the following problem: In onshore Argentina, and particularly in a given area covered by seismic, what are the most likely hydrocarbon traps? The explorationist, after advancing the most probable tentative geological interpretations of the available seismic lines, using the global and regional geological settings of the area and their past experience, will then critique the tentative interpretation using seismic data. Knowing the problem to be solved, they will begin analyzing seismic data to eliminate tentative solutions that are easily refuted. However, the first step of observation is crucial. The explorationist must first determine whether the sediments (in this case, seismic reflectors) were lengthened or shortened. If they make a mistake in this first step, the entire sequence of geological events that they must investigate will be completely different, and the final answer to the question will be incorrect. As a matter of fact, it is quite common to see: (i) Antiforms (extensional structures) misinterpreted as anticlines (compressional structures). and (ii) Morphological traps by juxtaposition misidentified as structural traps.The result of such an initial mistake is always the same: dry wells—except in cases where oil is found by serendipity, which, although quite common, is another story altogether.

In conclusion : Geoscientists, before starting their tentative geological interpretations of the seismic lines, for instance, must decide first, if the sediments were shortened or lengthened. A bad decision leads necessarily to a wrong tentative interpretation because they will be looking for features, on the seismic lines that they are not there. If a geoscientist assumes that the sediments were shortened, he will be looking for anticlines and syncline (figure 58). However, if he assumes that the sediments were lengthened, he will be looking for extensional antiforme structures. In the first hypothesis, he is going to find structural traps. On the contrary in the second one, he will find non-structural traps, what implies a completely different exploration approach.

13) Facies Prediction (Depositional Systems Tract)

Every time that a geoscientist, looking at a clean seismic line (uninterpreted line) or at a seismic line interpreted in continuity, that is to say, when the geoscientist just picks, in continuity, the high-amplitude chronostratigraphic lines, points to a given seismic reflector saying: "these sandstones are potential reservoir rocks" or "these limestones are the reservoir rocks," he is probably joking or, more frequently, he is not a geoscientist but just a petroleum exploration functionary.

In fact, as illustrated above (Fig. 59), there is just one way to prognosticate lithology on seismic lines. The seismic lines must be tentatively interpreted in terms of sequential stratigraphy. The tentative interpretation must be done in a decreasing hierarchical order of stratigraphic cycles:

A) Continental Encroachment Cycles;

B) Continental Encroachments Sub-cycles;

C) Sequence-Cycles;

D) Para-cycles of a sequence-cycle.

Arriving at the hierarchical level[28] of sequence cycles, the geoscientist can highlight the different depositional system tracts (lowstand systems tract, transgressive systems tract, and highstand systems tract) and, consequently, the different lithologies (Fig. 59) that compose each tract. Since each depositional system forming a tract is characterized by a typical lithology with a typical associated fauna, it corresponds to a typical facies, as defined in 1837 by Amanz Gressly.

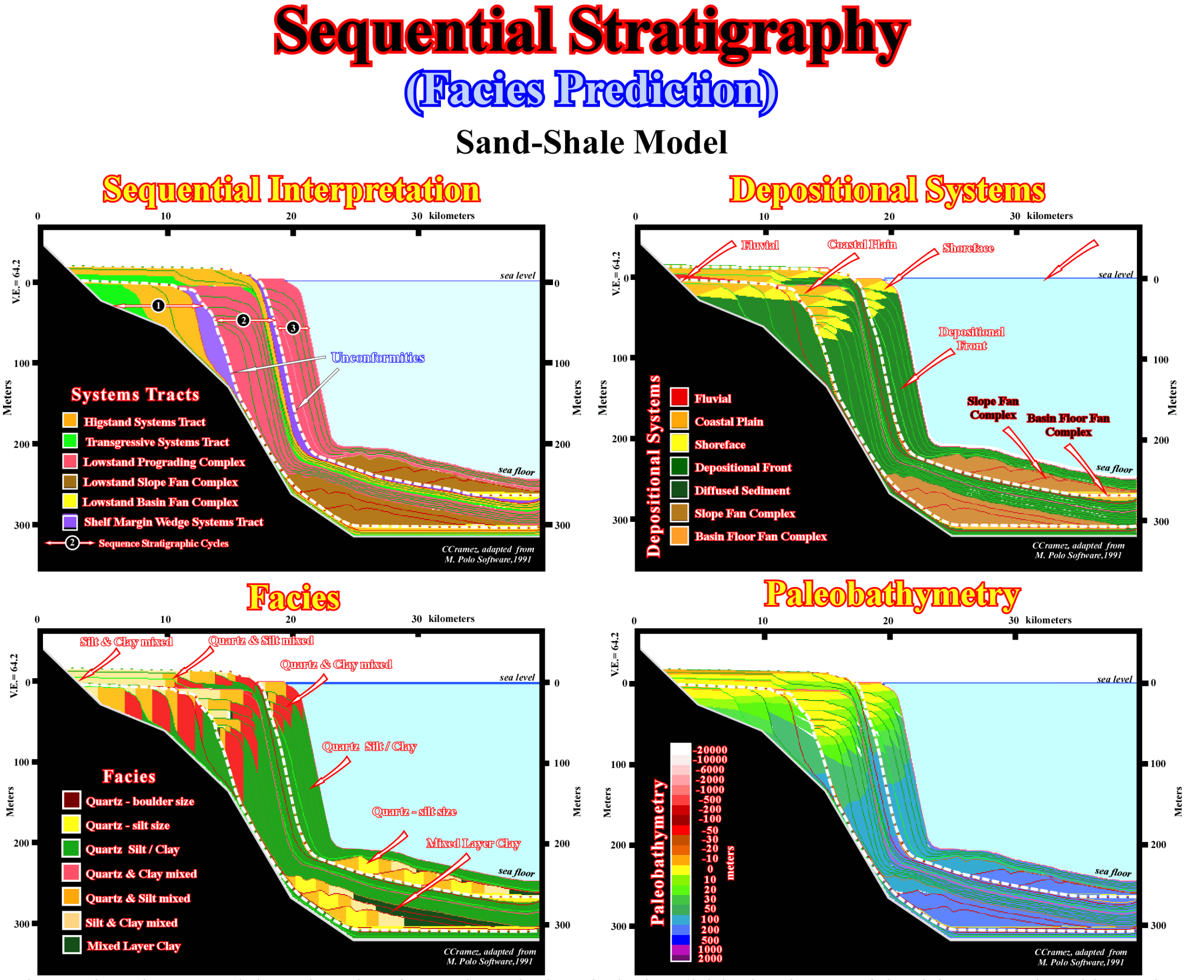

Figure 59 - The sequential stratigraphy of a mathematical geological model lasting between 3.0 - 0.0 Ma, put in evidence three stratigraphic sequence-cycles (upper sketch left). The oldest (chronostratigraphic intervals 1 to 4) is incomplete. From bottom to top, we recognise just the Transgressive Systems Tracts (TST, in green colour), the Highstand Systems Tracts HST (in brown) and a SMW (shelf margin wedge, in violet). The second sequence-cycle (chronostratigraphic intervals between 5 and 20) is complete. It is composed of a Lowstand Systems Tract (LST) composed by three members : (i) Basin Floor Fan (BFF) ; (ii) Slope fan (SF) and (iii) Lowstand Prograding Wedge (LPW) +SF+LPW), a Transgressive Systems Tract and Highstand Systems tracts (HST). The third sequence-cycle (chronostratigraphic lines between 21 and 30), which is not yet finished, is just represented by a LST (lowstand systems tract). As each systems tract corresponds to a lateral linkage of coeval depositional systems, i.e., coeval facies, environmental and lithological predictions can be advanced. As illustrated, in this sand-shale mathematical model, the following depositional environments can be predicted : (a) Fluvial (relating or occurring in a river, generally landward of the bay-line) ; (ii) Coastal Plain (extending along a coast) ; (iii) Shore-face (along the narrow, steeply sloping zone between the seaward limit of the shore at low water and the nearly horizontal offshore zone) ; (iv) Depositional Front (slope, seaward of the horizontal offshore zone) and (v) Deep water (turbiditic deposits). Systems tracts are composed of lateral assemblages of depositional systems, which are characterised by typical lithologies and depositional environments. On seismic data and particularly in absence of amplitude and sedimentary anomalies, the recognition of sequence-cycles and associated systems tracts, is the best way to hypothesise the most likely location of potential reservoir-rocks. The more likely potential marine source-rocks are associated to downlap surface separating transgressive systems tracts from the overlying highstand systems tracts. On the other hand, as depicted above the more likely sandy reservoir-rocks onlap against the basal unconformity bounding a sequence-cycle. The paleo-bathymetry, that is to say, the depositional water depth can be easily calculated, assuming that landward of the depositional coastal break, the paleo-water depth is more or less 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 datum plane depositional water depth in the platform ranges from zero to, more or less, 200 meters.

In a carbonate model, the methodological approach remains the same. By using the same geological parameters but replacing the terrigenous influx with a carbonate production curve (which varies as a function of water depth), the geometrical relationships between chronostratigraphic lines remain identical to those observed in a sand-shale model, as illustrated in Figure 60. Their recognition does not require more than five minutes of attention - it is simply a matter of habit and practice.

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[28] The relativity of hierarchies, known as Janus dualism, is an important feature in a sequential interpretation approach:(i) Geoscientists progress from the general to the particular. (ii) Geoscientists cannot study geological events in isolation. (iii) Geological structures, like biological structures, are multileveled. (iv) Each structure forms a whole in relation to its parts, while at the same time being part of a larger whole.(v) Geological structures, particularly stratigraphic intervals, have a hierarchical nature, which implies different levels of stratigraphic interpretations.

Sequential Stratigraphy

(Facies Prediction)

Carbonate Model

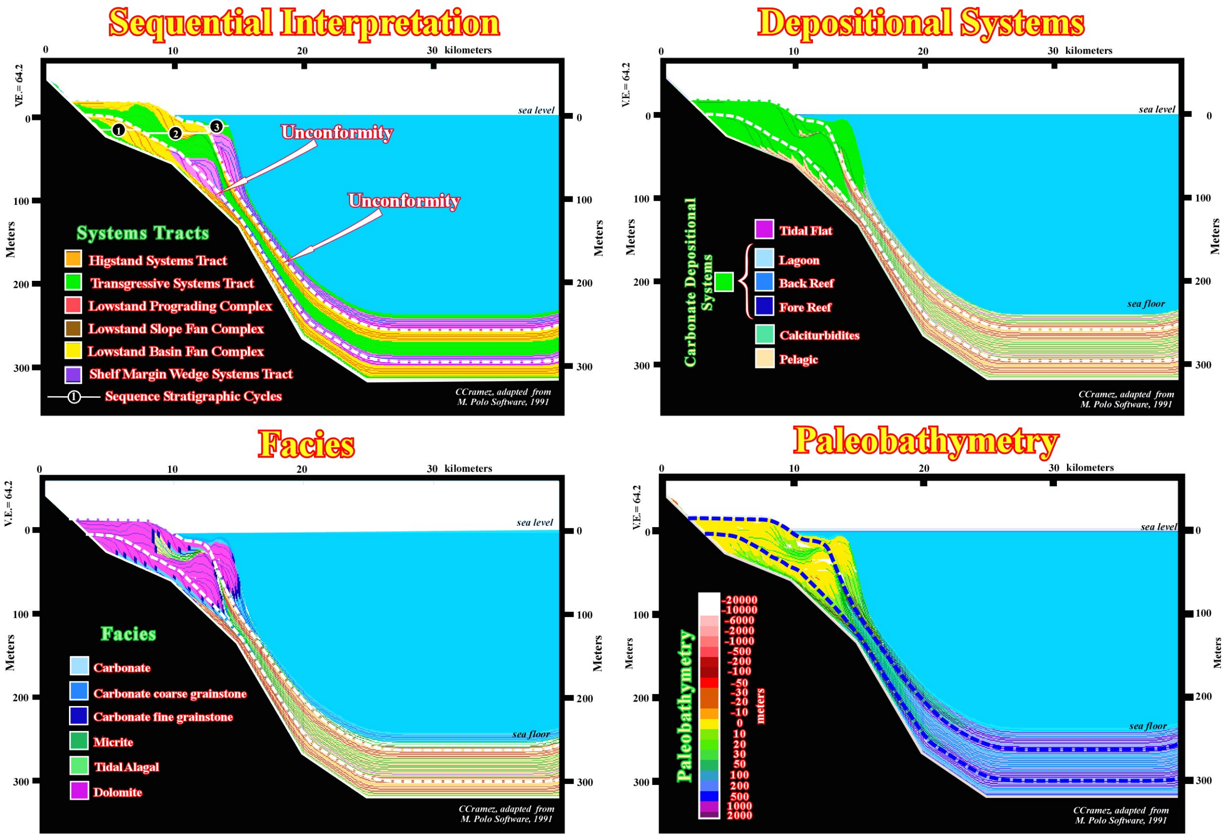

Figure 60 – The model response, when the terrigenous influx is replaced by a carbonate function, is quite different from the sand-shale response. Reef buildups develop near the shelf break, whereas in deep water, the geometry of the chronostratigraphic lines is more or less parallel (pelagic limestones). The sequential stratigraphy of the carbonate model strongly suggests that lowstand systems tracts (LPW, SF, and BFF) are often absent. On the contrary, the Shelf Margin Wedge (SMW) is more developed than in the sand-shale model, as well as the Transgressive Systems Tracts (TST). In a carbonate model, predicting depositional environments is much more challenging than in the sand-shale model. Instead of making precise predictions, we prefer to provide a rough indication of the limit between pelagic sedimentsand carbonate depositional systems, which includes: (i) Lagoon (ii) Back Reef(iii) Fore Reef. The software used in this study (Marco Polo) does not perform as effectively as it does in the sand-shale model. Similarly, facies prediction is highly speculative. The results of the model have been refuted multiple times. However, by analyzing the geometry of the chronostratigraphic lines and applying sequential stratigraphy, the above paleo-bathymetry can be predicted—though it remains highly dependent on the carbonate function used in the model.

Depositional systems such as (i) Tidal Flat, (ii) Lagoon, (iii) Back-Reef, (iv) Fore-Reef, (v) Calci-Turbidites, and (vi) Pelagic can be found in different systems tracts, but their individualization remains highly speculative. The same applies to facies, the most common of which are: (a) Carbonate, (b) Carbonate Coarse Grainstone, (c) Carbonate Fine Grainstone, (d) Micrite, (e) Tidal Algal, (f) Dolomite, etc.

In conclusion: Despite the fact that any lithological prediction requires a scientific approach rather than mere speculation, it must be acknowledged that in sand-shale depocenters, lithological predictions are relatively straightforward when using sequential stratigraphic analysis. This is because the depositional systems composing the systems tracts are relatively simple and easy to recognize. However, this is not the case for carbonate depocenters, where the depositional systems and facies are significantly more complex, making accurate predictions much more challenging.