Farsund Sedimentary Basin

Having worked in this area several years ago, in this notes, using few basic seismic lines, I'll summarize the major geologic events recognized in this offshore (Fig. 1 & Fig. 2) and, then, I'll advance some original hydrocarbon exploration hypotheses, particularly, for potential Paleozoic petroleum systems, since the Farsund geographic basin has a weak Mesozoic hydrocarbon potential, in spite of the presence of potential Jurassic Generating Petroleum Subsystem (GPSS).

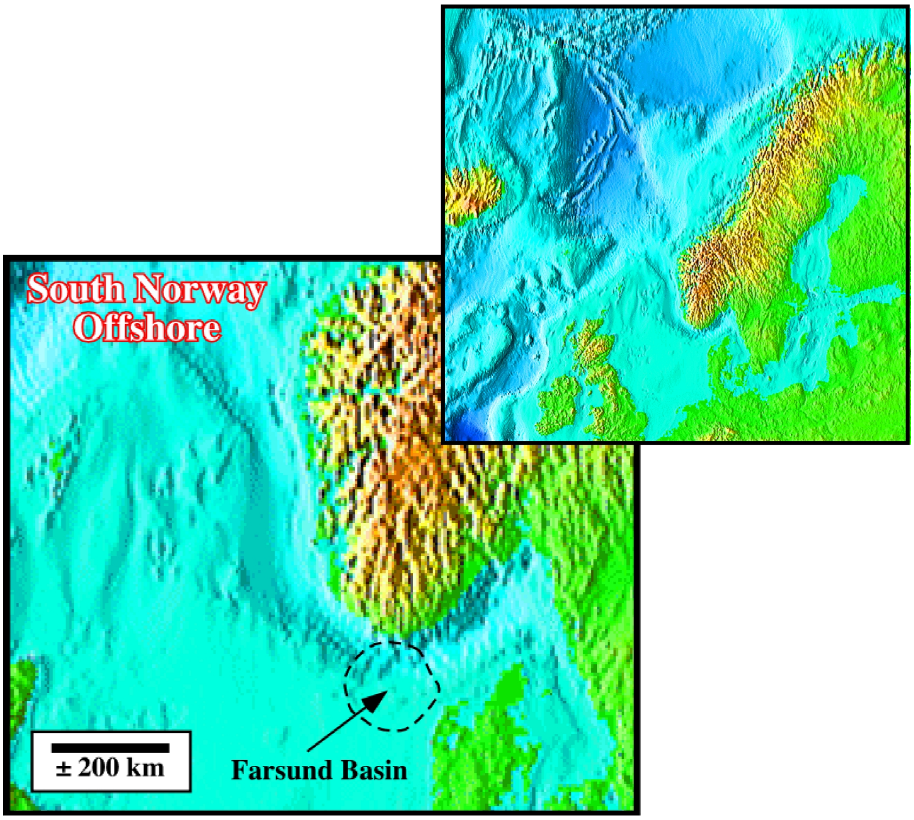

Fig.1 - Farsund geographic basin is located in the South Norway Offshore, near the limit with the Danish waters. The name of this basin comes from Norwegian Farsund formation, which correspond to a local appellation of the Late Jurassic Kimmeridgian. However, in this area, the equivalent of the organic facies of the Kimmeridgian clay is not so rich in organic matter as in the other areas of the North Sea.

Regional Geological Setting

1) Generating Petroleum Subsystem

In this area, the principal petroleum generating subsystem is Late Jurassic Kimmeridgian / Volgian in age. It is thermally mature and actively generating expelling oil at formation temperatures higher than 93° C (200° F).

A maturation map of the Kimmeridgian shale (fig. 2) permits one to delineate both immature areas, where temperatures are lower than about 93°C and no significant oil generation has taken place, and mature oil generative depression (where present-day earth subsurface temperature exceeds 93°C. This corresponds approximately to a R_o =0.6 (vitrinite reflectance level).

South Norway Offshore

(Farsund Geographic Basin

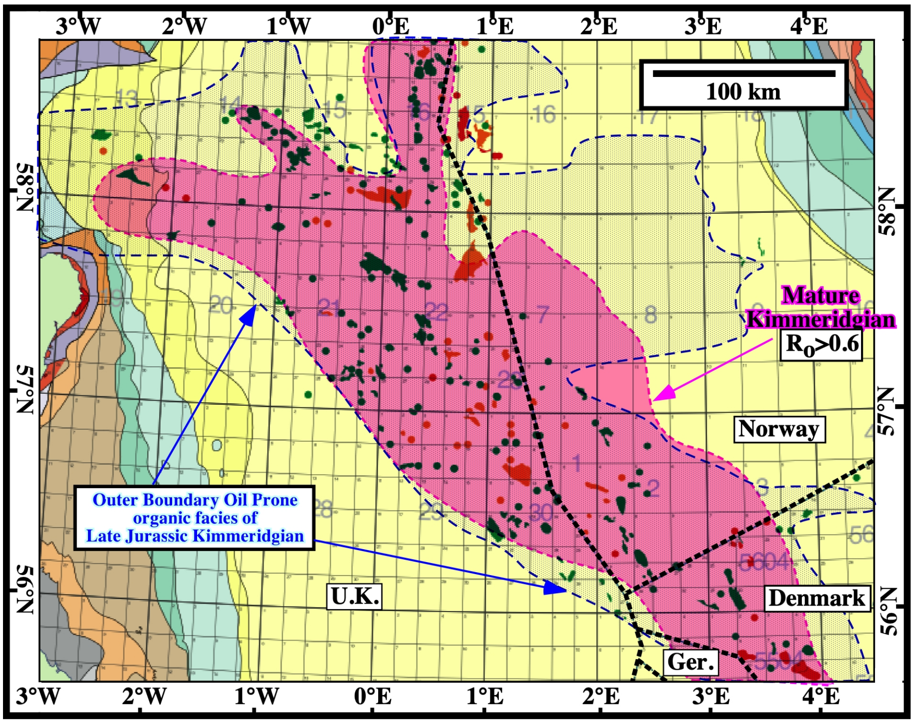

Fig. 2 - The area and the seismic lines discussed in this notes are located in South Norway offshore, between the UK and Danish offshores. The major depicted oil and gas fields depicted enlighten the hydrocarbon potential of the central area. Landward, the hydrocarbon potential decreases, strongly, as the conventional potential generating petroleum subsystem disappears. This is, clearly, indicated in the cartography of the oil prone to mixed organic facies of Late Jurassic Kimmeridgian and the maturation zone (R_o>0.6) proposed by G. Demaison (1980).

In the discussed area, using Demaison's studies (1980), one can say, a statistical count of all dry holes and successful wells suggests that:

A) Virtually all the oil and gas fields lie within, or very near, a petroleum generative depression containing mature Kimmeridgian source-rocks.

B) The historical success ratio in the mature fairway, or generative basin, was in the order of 1 in 3. At the present-time, the success ration is much lower.

C) The obvious hydrocarbon traps have already been drilled. Only subtle and high-risk traps (stratigraphic), which identification and mapping is quite difficult, are undrilled.

D) Outside the Kimmeridgian generative depression the historical success ration was in the order of 1 in 30.

E) The oil fields found so far, in this higher risk area (e.g., Beatrice, Briesling and Bream), which crude oils are different in composition, are probably sourced from Middle or Lower Jurassic beds.

F) At present-time, the historical success ration is probably in the order of 1 in 50.

G) Migration distances are commonly short and limited by drainage areas of individual structures.

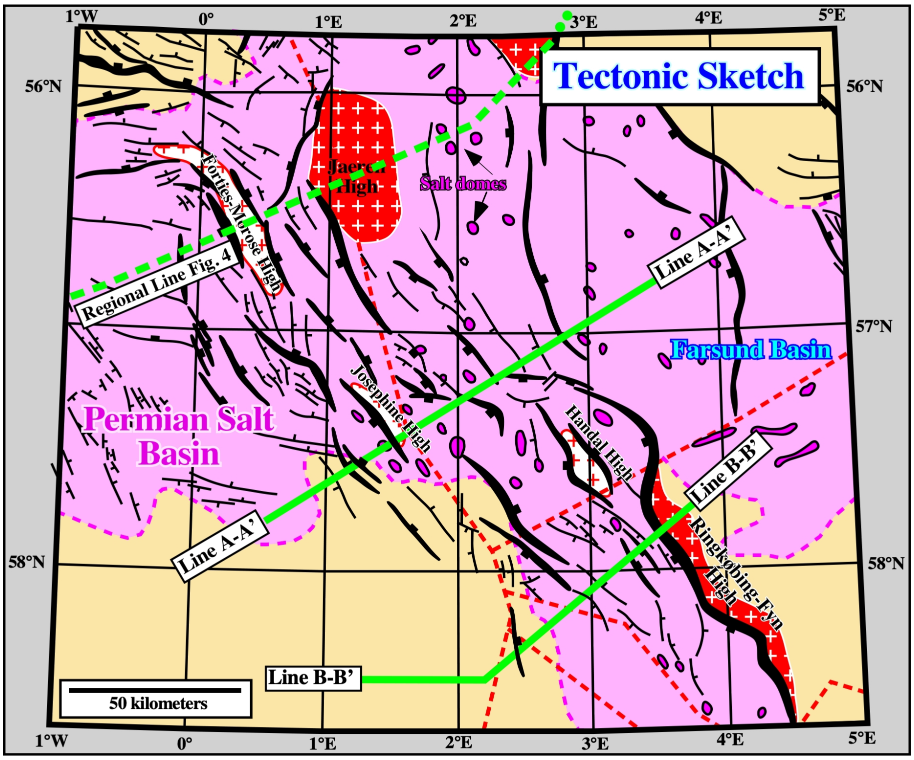

Fig. 3 - In this tectonic sketch are indicated the regional seismic line (Fig. 4), in which the major geologic events affecting the area can be easily recognized and two other lines (A-A' & B-B') to review the stratigraphic signatures and petroleum systems.

H) Vertical migration along the fault planes was preponderant.

I) The fields with the largest reserves seem to be located at the centre of the generative depression in close proximity to the most thermally mature and thickest Kimmeridgian clay depocenters (e.g., Statfjord, Piper, Forties, Ekofisk fields, etc.).

To increase the chances of a successful and profitable oil exploration, in this area, geoscientists, in a first step of exploration must recognize the petroleum generative depressions, which can be, easily, found overlaying two maps:

(i) Areal extension of Jurassic potential generating subsystems (GPSSs)

The main GPSS is associated with the organic–rich Kimmeridgian clay interval. It can be easily picked on the seismic lines.

However, it must be pointed out that in the proximal areas of the South Norway offshore, their organic matter content can be quite low, i.e., their HC potential can be insignificant.

Lower and Middle Jurassic clays can be alternative GPSSs. Their stratigraphic signatures are not so typically as the Kimmeridgian clays, i.e. they are difficult to predict and to map.

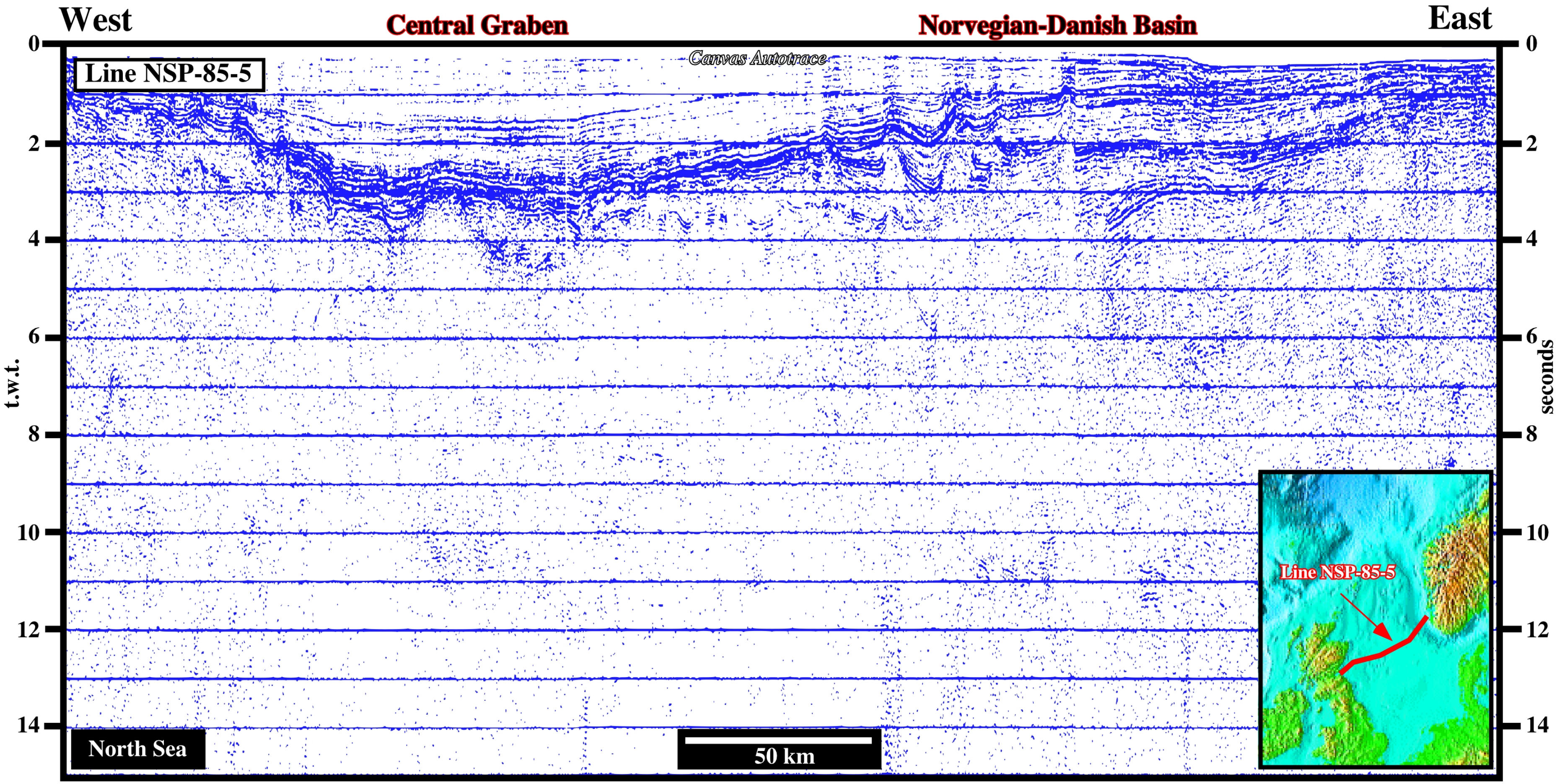

Fig. 4- This Canvas autotrace of the reginal seismic line NSP-85-5 (for detailed location see the Tectonic Sketch, fig.3), was tentatively interpreted in geological events. Such tentative interpretation is proposed on following plate (figure. 5). Obvious, the interpretation lower part of the autotrace is quite speculative, while the proposed interpretation of the upper part (fig. 5) is much more difficult to falsify (refute)

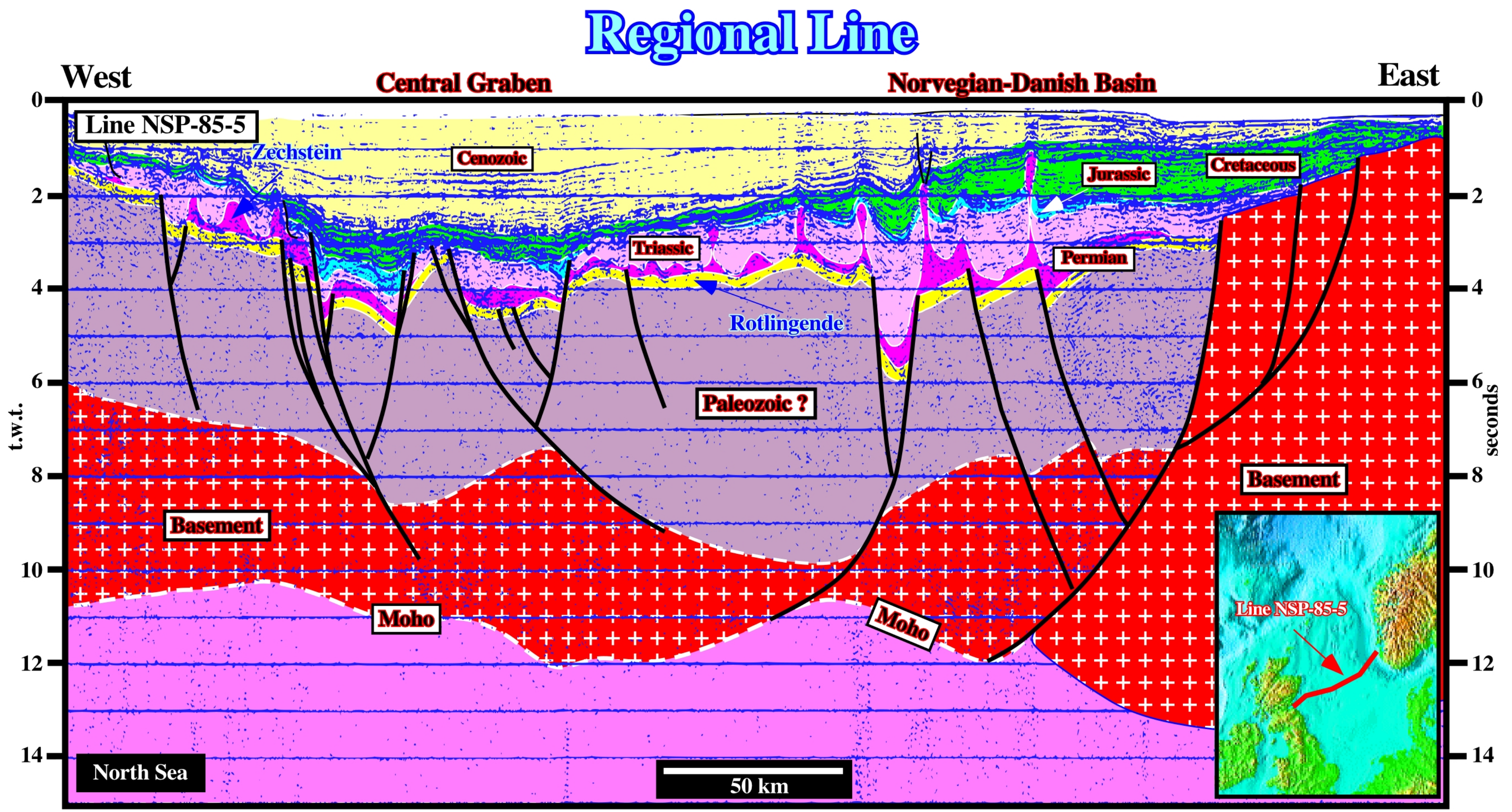

Fig. 5- This tentative interpretation of a Canvas autotrace of a regional seismic line depicts the major geologic events characterizing the South Norway Offshore. The Moho discontinuity can be hypothesised at the the bottom of the continental crust. A Paleozoic interval, with a gas generating petroleum subsystem, is visible below the Rotlingende formation, above which were deposited the Permo-Triassic evaporites. An important rifting, characterized by a differential subsidence, took place since Triassic until Upper Jurassic, in which several paroxysm can be recognizing (isopach variations). It is during this period that the organic-rich Kimmeridgian clays were deposited. Since the lengthening of the lithosphere stopped at Upper Jurassic a Cretaceous-Tertiary cratonic basin (North Sea geographic basin) started to develop with an important eastward terrigeneous influx.

(ii) Maturation map of each potential source-rock.

The maturation maps are compiled from seismic depth maps, near the potential source horizons, and from maturation gradients derived from well data and calibrated time-temperature models (Waples, 1983).

Seismic Line A-A'

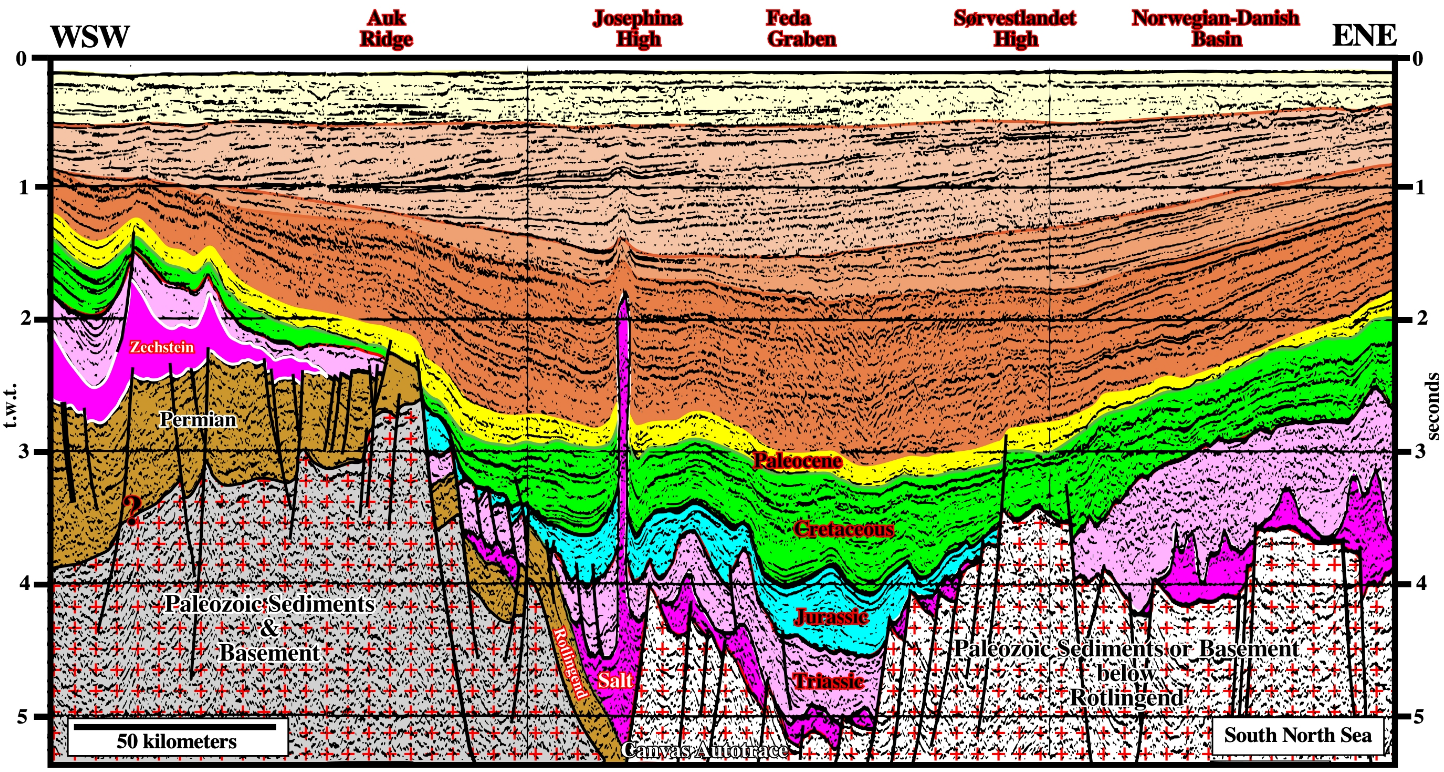

Fig. 6 - This tentative interpretation of a Canvas auto trace of seismic line A-A' (see location on fig. 3),strongly, suggests that in the Norwegian-Danish basin, eastward of the Sørvestlandet high, the Jurassic sediments are absent. Therefore, the conventional generating petroleum subsystem is unlikely. However, southward of this line, at the level of the Ringkøbing-Fyn high (Denmark Offshore), as shown in fig. 7, the Jurassic sediments are present. A Paleozoic gas generating petroleum system, as well as a Paleozoic-Rotlingend petroleum system is likely in the Norwegian offshore. Such an alternative petroleum system requires pre-Cretaceous traps (pre-migration) below the evaporites and a continuous salt layer (no salt welds).

These two maps combined with the map of the more likely migration-paths (vertical and lateral), strongly, increase the changes of success. Their superimposing suggests the areas where the chances of find hydrocarbons are higher. Just after having build-up some maps, the explorationist should start to look for the more likely entrapment-migration petroleum subsystems, i.e., the areas where a potential reservoir could trap hydrocarbons.

2) Entrapment-Migration Petroleum Subsystem

The entrapment-migration petroleum subsystems are linked to the stratigraphic and tectonic evolution of the basin. They are composed by sealed reservoir-rocks (tectonically or stratigraphically), which, theoretically, can trap hydrocarbons in their pores.

The major geological events responsible for the principal hydrocarbon parameters of this area are well visible on the regional seismic line illustrated in figs 4 & 5 (see fig. 3 for location of the regional line), and they can be summarized as follows:

A) Gathering of Eurasia Continent

The closure of the Palaeozoic seas, induced by B-type subduction zones, originate successive tectonic collisions between Paleozoic sedimentary prisms and old cratons.

At the end of the Palaeozoic, almost all continental crust was gathered in one or two lithospheric plates forming the supercontinent Pangaea, which was composed by two major small supercontinents: (i) Gondawa, in the southern hemisphere and (ii) Eurasia, in the northern.

On the seismic line illustrated in figs. 4-5, the substratum of the Permo-Triassic sediments (orange and violet) is part of the old Eurasia continent.

B) Emergence and Peneplanation of Paleozoic Sediments

The subduction of the lithospheric plates and the continental collisions increased the volume of the oceanic basins inducing a significant eustatic fall producing the emergence (a) and the peneplanation of the Paleozoic sediments (b). On seismic lines, it is quite frequent to recognize a tectonically enhanced unconformity individualizing the Pangea sediments from the cratonic Permian sediments (Rotlingend formation).

C) Cratonic deposition

Overlying the upper enhanced unconformity (or angular unconformity) bounding the Pangea, a non-marine clastic interval was deposited during the Lower and Middle Permian. These sediments (yellow interval on the regional seismic line of figs. 5) form the Rotligend formation, in which several reservoirs levels were recognized. Actually, as we will see later, gas accumulations are associated with a Palaeozoic petroleum system characterized by a gas prone Paleozoic source-rock and the Rotlingend sandstones as reservoir. The remnant HC potential of this area seems to be, mainly, associated with this Paleozoic petroleum system.

D) Evaporitic Basin

At the Upper Permian-Lower Triassic, a thick salt interval was deposited. This interval is, easily, recognized in all seismic lines (dark pink in fig. 6), whether by its deformation (halokinesis) or by the depocenters overlying salt welds. The limits of the Permo-Triassic salt basin are schematized in the « Tectonic Sketch » (fig. 3). Continental lowstand Triassic sediments, deposited in association with the Triassic-Jurassic rifting, surmounted the evaporites.

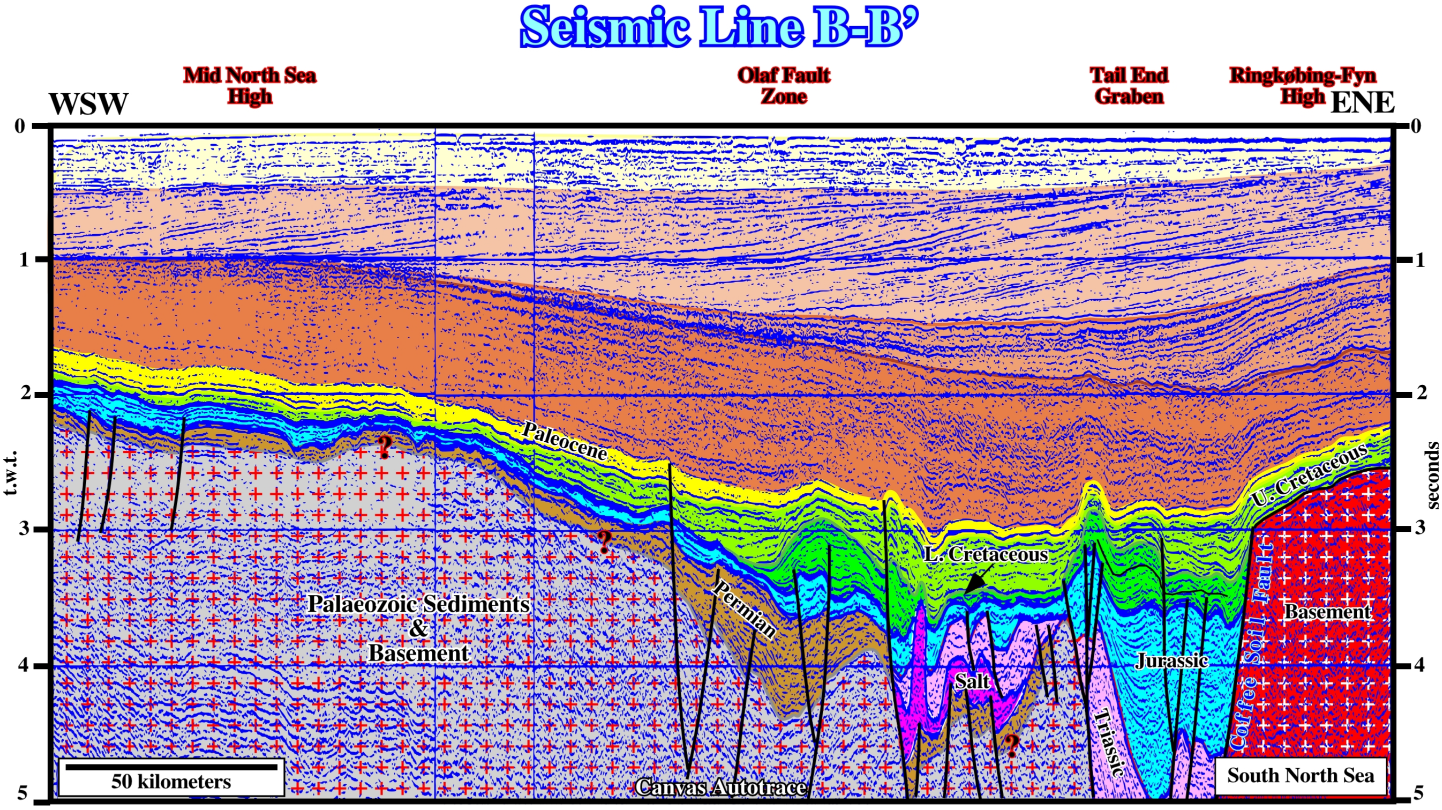

Fig. 7 - This tentative interpretation of a Canvas auto trace of the seismic line B-B' (see location in fig. 3) shows the Triassic-Jurassic rift-type basin and the cratonic basin as well. The Rotlingend sediments can be recognized in the west part of this tentative, but not in the Ringøbing-Fyn high, which seems be, mainly, be composed by Precambrian supracrustal rocks. The rifting Coffee-Soil fault limits the Jurassic sediments. Landward of this fault, assuming that migration was, mainly, vertical, the hydrocarbon potential very poor, see inexistent. However, in Farsund basin (fig. 8), Jurassic sediments seem to be present.

E) Lengthening of the Eurasia

Probably due to thermal anomalies, Pangea and, particularly, its northern continent, i.e., the small Eurasia supercontinent was fractured.

Their continental crusts were obliged to length and Permo-Triassic-Jurassic complex rift-type basins were created and filled, mainly, by non-marine sediments, at least in their lower sections.

On the regional line (fig. 5), one of these rift-type basins is clearly recognized below the cratonic Tertiary and Cretaceous sediments.

F) Triassic-Jurassic Rifting

An extensional tectonic regime, with a medium effective stress (σ_2) striking, more or less, N 150°, took place since Triassic. It lasted till Upper Jurassic.

The regional lengthening associated with this tectonic regime, stretched the substratum and the already deposited sediments (Rotlingend and Zechstein). Eventually, evaporites flowed donward filling the opened reactivated fracture zones.

Often, the salt flowed *per descendum* giving structures that very often are erroneously interpreted i.e., suggesting that the Permian evaporites were deposited in small rift-type basins.

During this tectonic regime, Triassic and Jurassic sediments were deposited with an internal configuration, generally, divergent.

The sediments thicken toward the fault with higher vertical throw (higher differential subsidence).

The depositional water-depth increased upward due to the global Jurassic eustatic rising.

During the Upper Jurassic, organic-rich Kimmeridgian clays were deposited and preserved in association with a secondary downlap surface.

G) Cratonic Basin

End Jurassic-beginning Cretaceous, the lengthening of the lithosphere stopped.

The balancing of the isotherms induced a thermal subsidence creating a post-Jurassic deep cratonic basin.

As illustrated on the tentative interpretation of the Canvas autotrace of the regional line (fig. 5), the sediments filling the cratonic basin are, mainly, deep-water sediments.

In the borders of the basin, near the Precambrian shields, shallow-water sediments can be recognized.

On the seismic data, particular in the Norwegian offshore, it is possible to pick and map the seaward progradation of the successive shelf-breaks.

The forestepping geometry of the cratonic sediments is particularly sharp after major Middle Turonian downlap surface. The sea level, after reaching the Mesozoic eustatic high, in Cenomanian-Turonian, started to fall.

H) Isostatic Rebound

During the Plio-Pleistocene, in answer to the shrinkage of the polar icecap, the proximal Norwegian offshore was uplift (isostatic rebound). On the tentative interpretation illustrated in fig. 7, the isostatic rebound is well visible eastward of the Tail End graben. The Rinkøring-Fyn High was partly induced by the rebound. Similarly, on the tentative interpretations of the Farsund seismic line SKAG-86-05 (fig. 8) and on the basin the isostatic rebound is well visible.

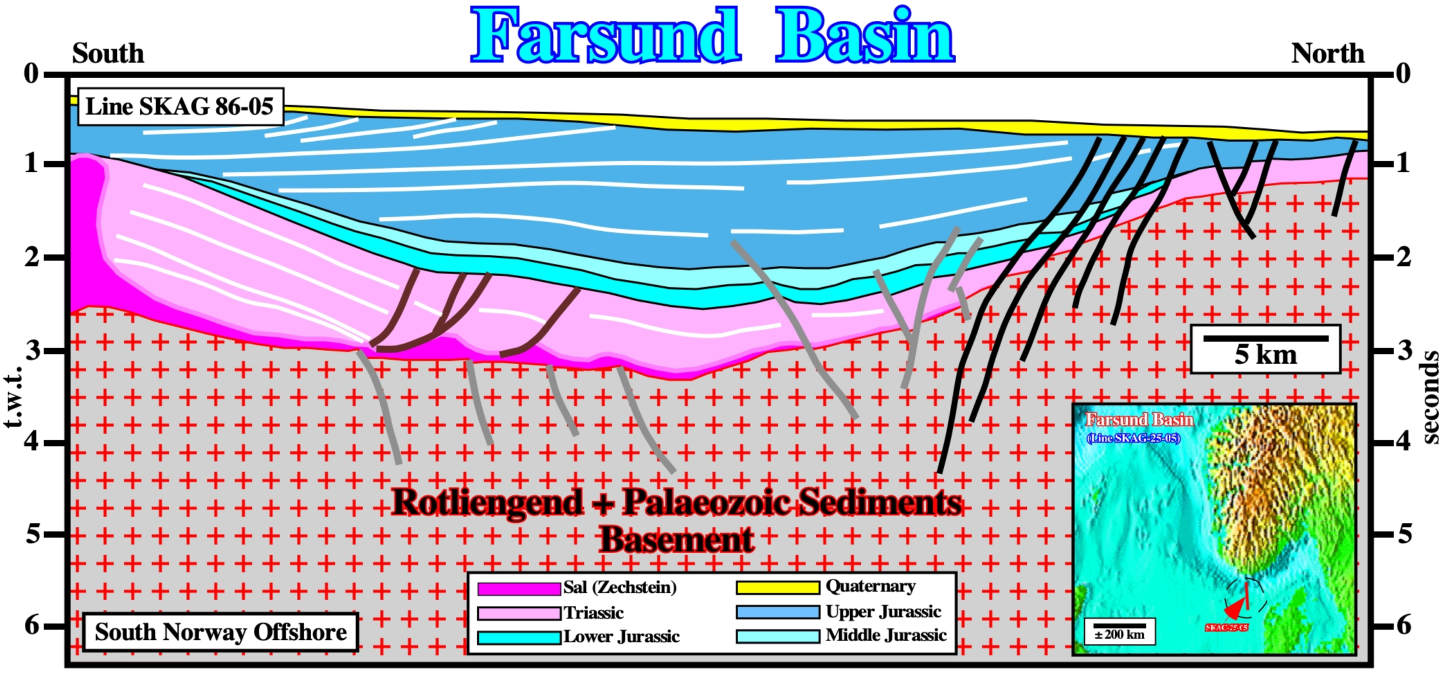

Fig. 8 - Geological speaking, the offshore Farsund geographic basin corresponds to an Upper Jurassic depocenter induced by salt flowage and a northward uplifted during the Plio-Pleistocene due to the isostatic rebound. i.e, an elevation of the continent in response to the discharge induced by the removal (melting) of the ice from the ice caps.

The enhanced unconformity between the Quaternary and Upper Jurassic sediments is easily explained by the isostatic rebound (see also fig. 9) . The uplifted induced an important relative sea level fall, which was responsible by the erosion of the Cenozoic and Upper Mesozoic sediments (Cretaceous and Uppermost Jurassic). The uplifted was also responsible for the normal faulting, with westward vergence (faults in black), recognized on the norther part of this line.

In fact, do not forget, during the last glacial period, most of northern Europe, Asia, North America, Greenland and Antarctica were covered with ice sheets and ice caps, as well as by ice seas. The thickness of the ice reached about 3,000 meters at the Last Glacial Maximum, about 21,000 years ago (calibrated age) or 19,000 B.C.

The enormous weight of this layer of ice forced the crust to deform in an inverted bell shape (synform, extensional structure, the rocks are lengthened), which forced the material of the terrestrial mantle to flow away from the overloaded area. Since the temperature had increased and the ice began to melt, the removal of the overload from the sunken region caused an uplift of the area and a return of the material from the Earth's mantle to its original position, that is, to that which it had before glaciation. Taking into account, the viscosity of the mantle material, it will probably take several thousand years for the Earth's surface to reach an isostatic equilibrium. For an ice thickness of about 2,000 m (as there is today in Greenland), the terrain sank about 700 meters (the ice density is about 1/3 of the density of the mantle).

Isostatic Rebound

(Post-Glacial or Isostatic Adjustement)

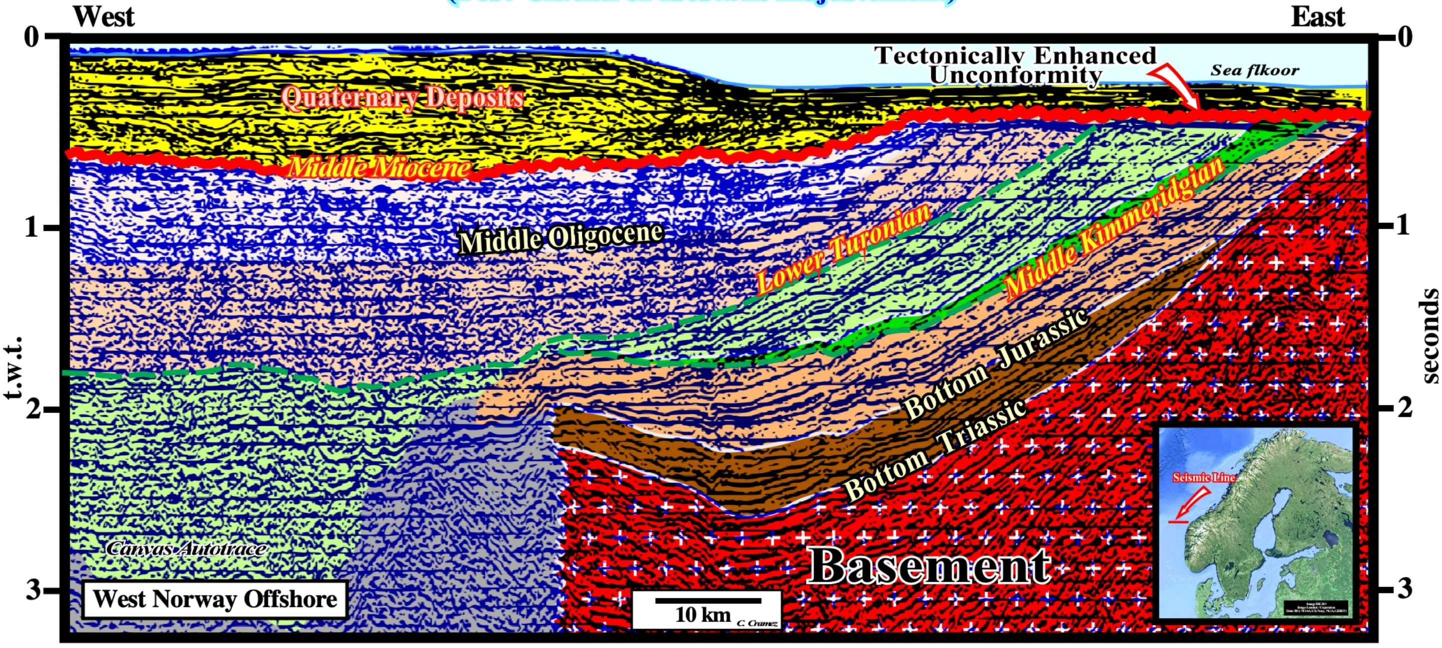

Fig. 9 - On this tentative geological interpretation of a Canvas auto-trace of a seismic line from the West Norway offshore , the isostatic uplift (rebound or readjustment) induced by the discharge (melting) of the glacial ice, that covered the North Europe and, particularly, Norway during the beginning of the Quaternary, is perfectly visible. In the European coast, the fjords of Norway, the Baltic Sea and North Sea, as well as the separation of Britain and Ireland from the continent, are the result of glacio-isostasy. Central Scandinavia continues to rise at the rate of 9 mm/year. in the American side, the Great Lakes, Hudson Bay and morphology of Canada's Arctic coast are the direct result of the sinking and uplift of the crust in that vast region. On the other hand, old coast lines and raised beaches are quit well visible. This phenomenon, which theoretically corresponds to an absolute sea level fall, is observed in several parts of the world, as in New Zealand, where the old coastlines and raised beaches are well known of the geoscientists.

Hydrocarbon Potential

Admittedly, all evident traps located on the vertical, or nearby, of the mature Kimmeridgian clays have been drilled. On the other hand, it is not gloomy to say the probabilities of find economical accumulations (stand alone), associated with the conventional generating petroleum subsystem (Kymmeridgian clays), are very small.

Even in the Farsund basin (fig. 8), the more likely is that the Kimmeridgian clays have been eroded. Some explorationists had invoked potential Lower and Middle Jurassic source-rocks. However, as illustrated (tentative interpretation of seismic line SKAG 86-05, in fig. 8) the chances of find significant traps (four way dips or morphological by juxtaposition) are small.

In my opinion, but I may be wrong, the remnant hydrocarbon potential of this area (South Norway offshore) is, mainly, associated with a gas Paleozoic generating petroleum system, with the Rotlingend sandstones as main reservoir. The exploration of such a Petroleum systems requires three steps:

a - An exhaustive interpretation of the substratum Triassic-Jurassic rifting in order to identify and map, the Palaeozoic basin (potential source rocks) and the Permian Rotlingend formation (potential reservoir).

Let's assume that on the tentative interpretation of a Canvas autotrace of a North Sea seismic line, illustrated on fig.10, below the salt layer (in pink), there is a petroleum system:

(i) The source-rocks are Palaeozoic ;

(ii) Their organic matter reached maturation when the upper light green interval was deposited ;

(iii) The potential reservoirs are the infra-salt Rothlingend sandstones located at the top of the interval colored in brown ;

(iv) Several infra-salt potential morphological traps by juxtaposition are identified below the salt large ;

(v) The large infra-salt structural high, in the middle of the tentative interpretation, is excluded since its upper limit is a salt weld, so there is no seal and therefore no closure.

The exploration game is to decide the age of the potential traps, i.e. to decide if they predate the migration or if the age of the faults (in white), which induce the morphological traps by juxtaposition, is anterior or posterior to the deposition of the light green marker (supposed to date the age of the migration).

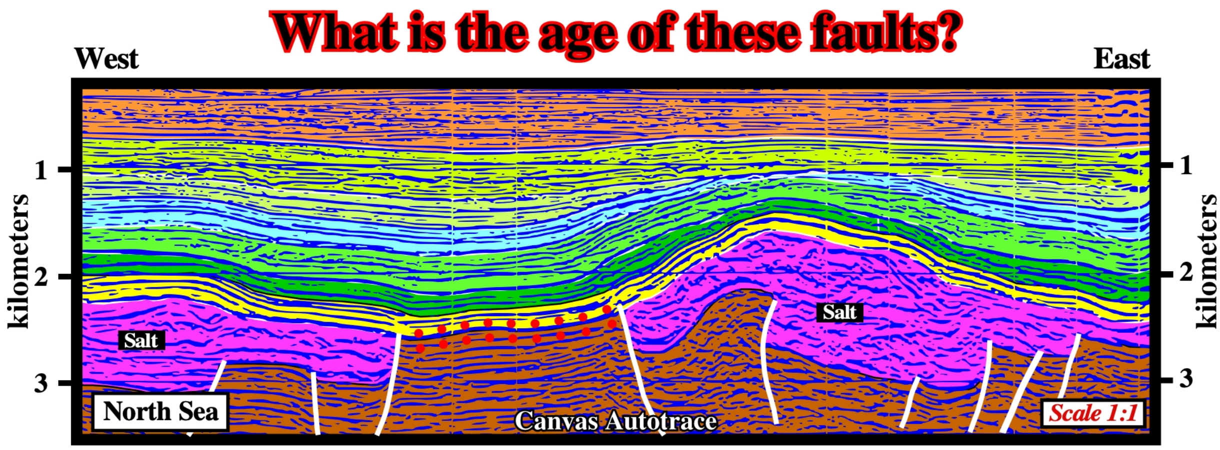

Fig. 10 - Before take a decision the geoscientist must notice the interpreter proposed a salt weld above the large structural high. Such an interpretation is logical: there is a depocenter at the vertical of the salt weld. The seismic intervals colored in light green (above the light blue) show a clear convergent thickening, which can only be explained by a compensatory subsidence (salt flowage). However, the salt did not flowed laterally (there is no salt mounds or domes). The salt flowed downward filling the space created by reactivation of the pre-existent faults, which gives the illusion that the evaporites were deposited in small grabens. In fact, the salt was deposited over an initially unbroken and subhorizontal surface as illustrated in figures below.

b - A detailed picking of the evaporitic layer (salt welds included), which were deposited, roughly, horizontally between the substratum and the overburden (see depositional model in fig.11), to identify the potential infrasalt traps (morphological by juxtaposition and structural, i.e., four-way-dips).

The evaporites (massive salt and interbedded salt) ensure the lateral and vertical closure of the potential reservoir-rocks.

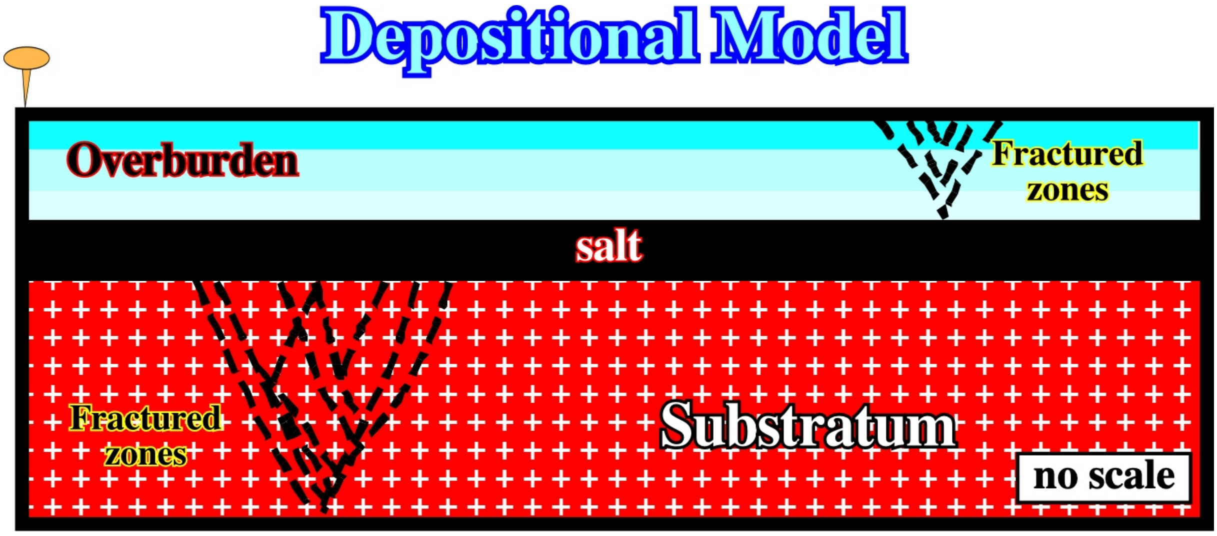

Fig. 11 - This sketch illustrates the more likely depositional model of the evaporites. They were deposited over an unbroken and subhorizontal substratum. However, within the substratum, which is composed mainly by Palaeozoic rocks with the Permian Rotlingend sandstones in the top, there were weak fracture zones (faults in black). Similar fracture zones were also present in the overburden. During the Triassic-Jurassic rifting and, episodically, during the cratonic basin, all these sediments were lengthened and later on, in the Tertiary, shortened. The results of the extensional tectonic regime is illustrated in flex figure (Fig. 12).

3 - Localization and mapping of the depocenters induced by salt flowage to differentiate the fault predating and postdating the salt deposition (fig 10).

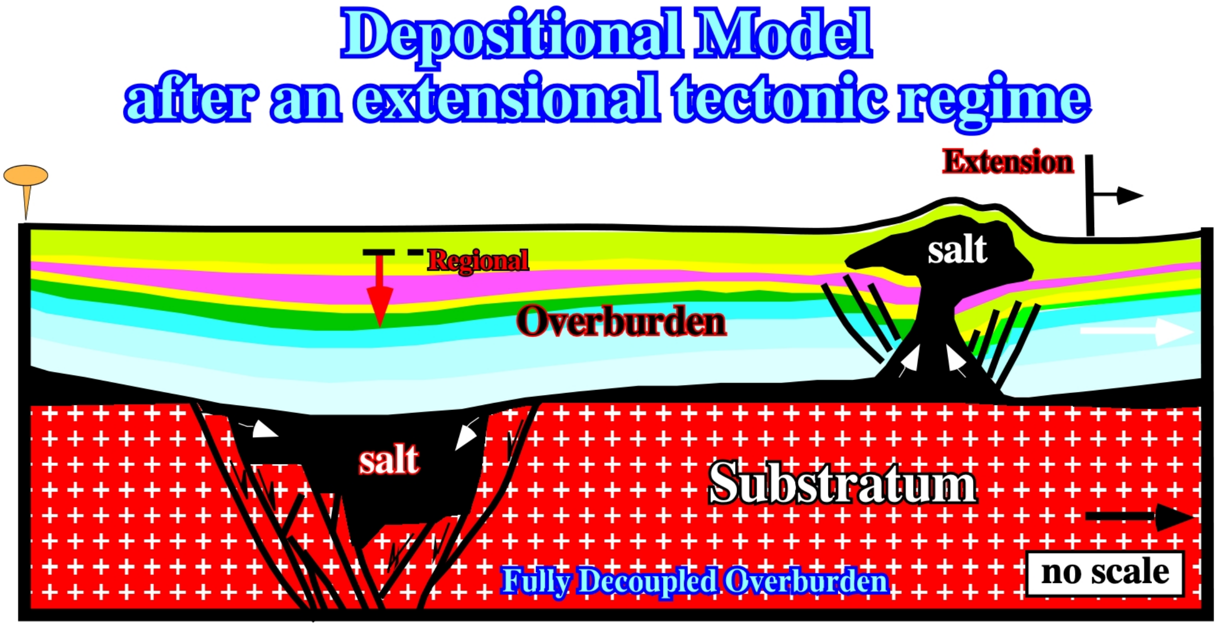

Fig. 12 - This sketch shows the more likely results when the depositional model, illustrated in fig. 9, is submitted to an extensional tectonic regime (Triassic-Jurassic rifting). All sediments are lengthened. The pre-existent pre-salt, as well as, post-salt fractures zones (in black) are reactivated as normal faults. Such a fault-reactivations creates potential voids. However, as Nature hates emptiness, the evaporites flowed downward in order to fill the space induced by the sedimentary lengthening. The downward flowing of the salt created a compensatory subsidence, in the contemporaneous overburden sediments, developing a depocenter. The age of the depocenter dates the ages of the extension, therefore, the ages of the fault reactivation, i.e., the age of the associated morphological by juxtaposition traps. So, one can said that in fig. 10, the more likely age of the potential morphological by juxtaposition traps are probably posterior to the migration of the generated hydrocarbon and they do not have any hydrocarbon potential.

This is an imperative step because it allows to individualize the post-migration traps from the pre-migration traps. The majority of the unsuccessful wells tested post-migration traps. The fig. 10, 11 and 12 illustrate how to date the potential infra-salt traps and how to avoid dry wells in this area.