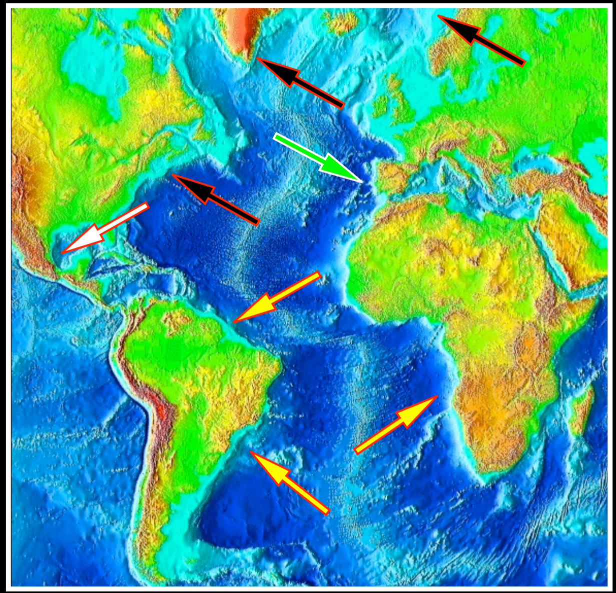
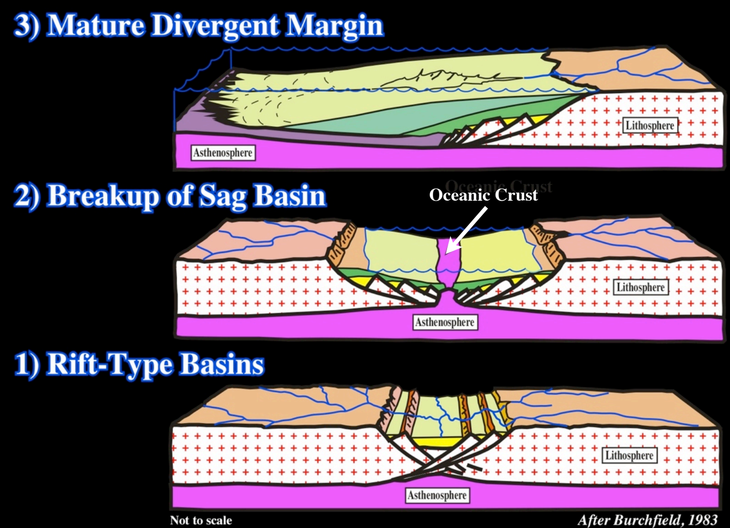

Semana Cultural
da
Universidade de Coimbra
1-11 Março 2006
Atlantic Ocean
Opening
Dos Mares Antigos ao Mar Actual
Os Saberes Geológicos e a Civilização
Carlos Cramez
Switzerland

# Areas of Interest



After a critic of the old conventional hypotheses proposed to explain the opening of Atlantic-Type Divergent Margins, we will propose a new hypothesis, testing it with regional seismic lines from South and North Atlantic and Gulf of Mexico. Then, we will briefly discuss the particularities of Iberia and Newfoundland Margins.

# Conventional Hypothesis
## Divergent Margins




**The Burchfield's hypothesis, which still is followed by a lot of geologists, have been, even before 1983, refuted by long regional marine seismic lines. In this hypothesis, three major stages a considered: (i) Rift-type basin formation, (ii) Break-up of a Sag basin and (iii) Mature Divergent Margin, The geological implications of such a hypothesis can be summarized as follows.**

# Conventional Hypothesis
## Geological Implications

**1-** Normal faulting, with faults opposite vergence, length the lithosphere, what creates by differential subsidence, a lot of rift-type basins, which were filled mainly by non-marine sediments, eventually withy potential source rocks.

**2-** After rifting, a sag phase (thermal subsidence) allows the deposition of a cratonic basin, in which sediments such as evaporites encroach the basement by onlapping fossilizing the rifting sediments.

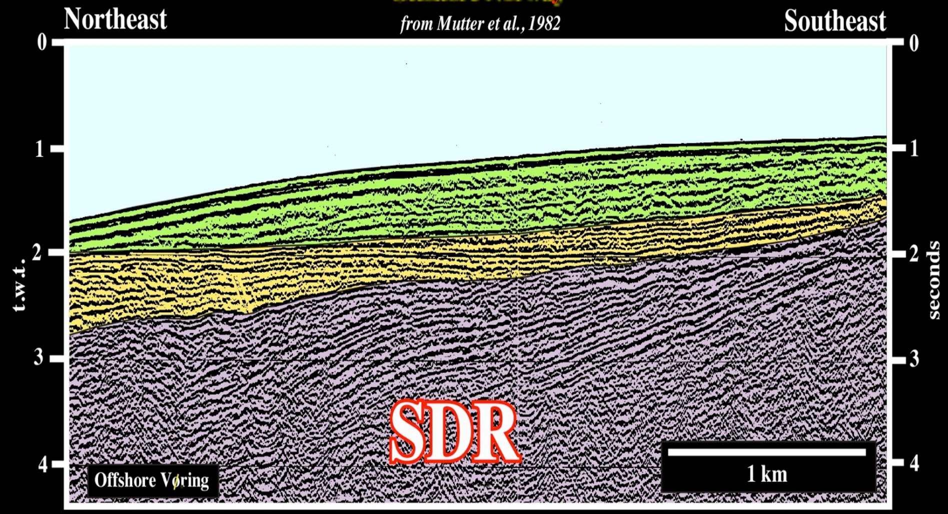
**3-** The break-up of the lithosphere takes place during or after the Sag Basin with the onset of sea-floor spreading and development of a margin with a progradational geometry.

This model implies:

- no sub-aerial vulcanism,
- break-up by thinning of the lithosphere,
- unique salt basins predating sea-floor spreading,
- salt brines not enriched hydrothermally,

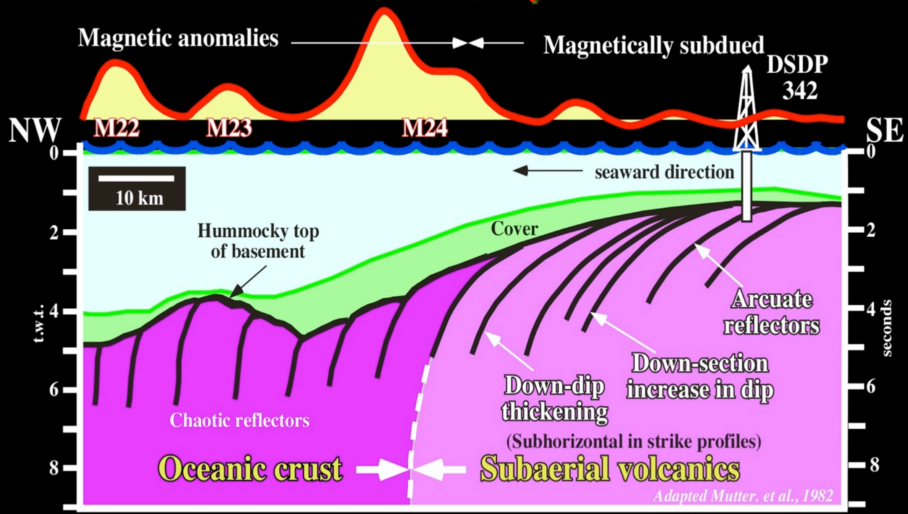
features that have been falsified since long time, as illustrated next.

# Seaward Dipping Reflectors
## Outer Voring Plateau
### Offshore Norway




When long regional marine seismic lines were shot on offshore Norway and South Atlantic, geologists recognised a consistent thick seismic interval composed by reflectors dipping and thickening seaward. As the lithology of such a typical deep-water reflectors was unknown, they labelled them SDR, i.e., seaward dipping reflectors and they suggest than a DSDP well should recognise their facies, since a lot of geologist interpret them as induced by rift-type basin sediments.

# Features of SDRs
## Outer Voring Plateau
### Offshore Norway




**The DSDP 342 recognised a subaerial volcanic facies for SDRs, i.e., lava flows spreading and thinning from a subaerial spreading) since spreading centres become immerse (volcanics cannot flow under water, they freeze). Subsequently, above SDRs, magnetic anomalies are subdued, while above oceanic crust they are well visible, on the other hand, seismically, oceanic crusts creates chaotic reflectors and SDRs arcuate continuous reflectors.**

# Features of SDRs
## Outer Voring Plateau
### Offshore Norway

* They are posterior to the break-up of the lithosphere and coeval of subaerial spreading.

* In longitudinal seismic lines, they dip and thick seaward, i.e, toward subaerial spreading centres.

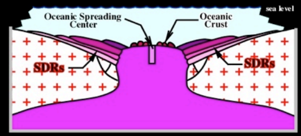
* In transversal lines, they are sub-horizontal and roughly parallel.

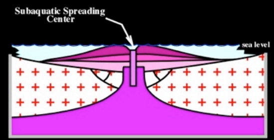
* They are magnetically quite. Their sub-horizontal geometry favours counterbalancing.

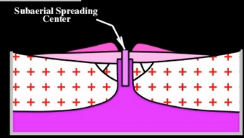
* When, due to the charge of lava flows, spreading centres immerse, volcanic material freezes. It cannot flow, so oceanic crust (sheeted dikes and pillow lavas) is created.

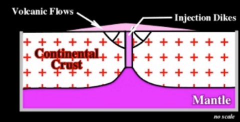
# Model of Development SDRs

**(modified from K. Hinz, 1981)**



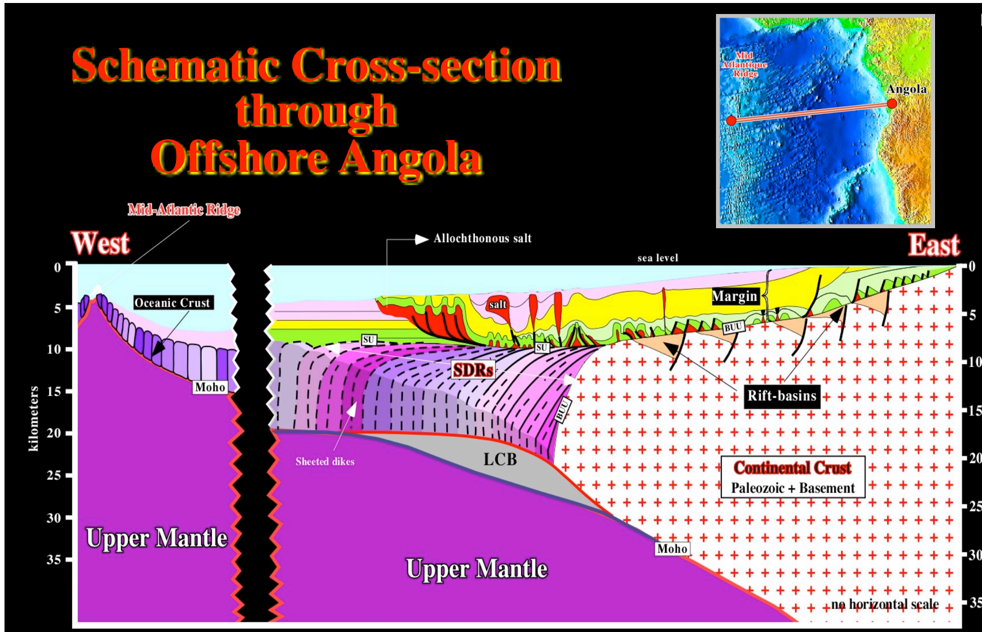

**In the 80's, several geologists explained the SDRs considering that crustal extension and thinning occurred during the processes of crustal rupture and it was followed by injection of dikes and basaltic flows developed in sub-aerial environments either creating structurally raised areas, or filling local lows forming thick deposits of volcanic rocks, volcanoclastics and siliclastic sediments.**

**This model explains the origin, age and evolution of the SDRs. It suggests a break-up induced by intense injection of mantle dikes rather than a thinning of the lithosphere. However, it does say anything about the evolution of the margins, how salt basins were developed and how the evaporite deposits of Atlantic margins are so rich in potash and so poor in MgS04. Let's see the hypothesis suggested by Total (2000).**

# Total's Model

C.Cramez, M.P.A. Jackson
&
P. Imbert

# Schematic Cross-section through Offshore Angola

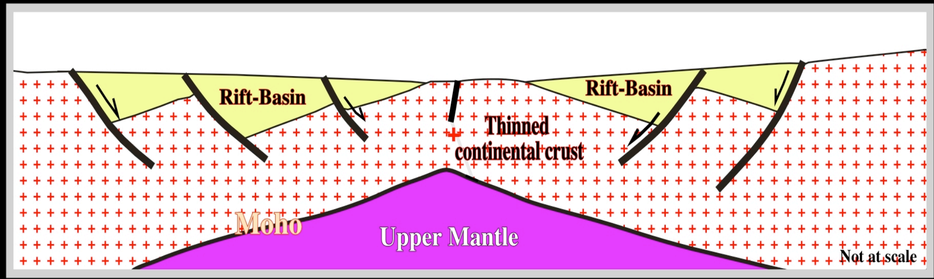



**Our model can be illustrated by the interpretation, in depth, of a long regional composite seismic line of the Northern Offshore Angola. The continental crust with their rift-type basins, the lava flows (SDRs) with the associated sheeted dikes and the oceanic crust are easily recognised. Overlying the break-up (BUU) and SDRs (SU) unconformities, the margin sediments, affected by a strong salt tectonics, form a transgressive and regressive phases of the post-Pangea continental encroachment cycle, as described next.**

# Total's Model
## Volcanic Divergent-type Margins

Opening of the
South Atlantic Ocean

# 1-Rifting



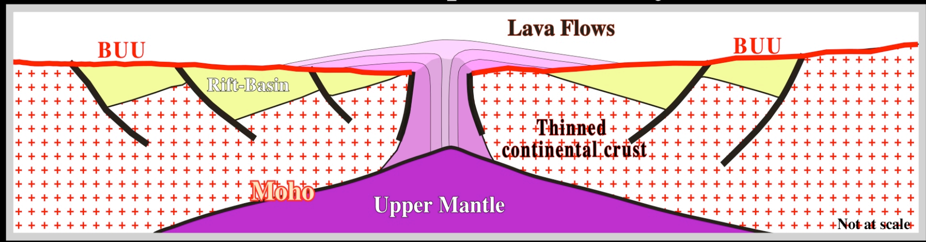

The continental crust of a supercontinent, Rodhinia or Pangea, is lengthened by normal faults, generally with an opposite vergence and the lithosphere is thinning (cause or effect). The lengthening creates rift-type basins, which are filled mainly by non-marine sediments. Three main sedimentary intervals are often recognised within rift-type basins: (i) alluvial , (ii) lacustrine and (iii) fluviatil or deltaic. Organic rich lacustrine sediments are often major potential source rocks. As the continental crust lengthens, it thins and so it is injected by matelic basaltic dikes and lava flows.

# Total's Model
## Volcanic Divergent-type Margins

Opening of the South Atlantic Ocean

## 2-Breakup

(lava flows, breakup unconformity BUU)



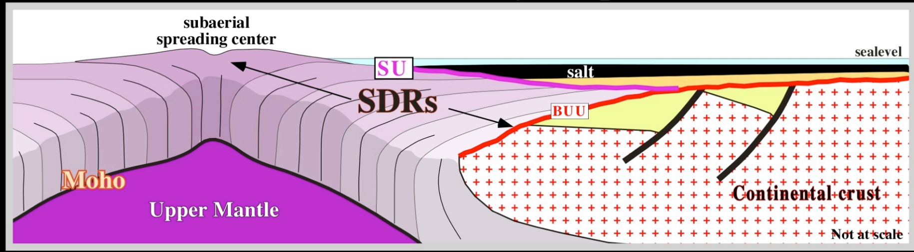

When the lengthening of the continental crust reaches a factor ß near 3.5-4 and its thickness is around 10-15 km, it becomes highly intruded by mantle material, and as it cannot anymore be lengthened by normal faults, it is split into two lithospheric plates (it is the break-up of the lithosphere). The injection of dikes and the associated basaltic lava flows (subaerial environment) fossilise the rift-type basins and so the break-up unconformity BUU creating structural raised areas, as illustrated above, or filling low or fractured areas. Symmetrically, the lava flows thin away of the associated sheeted dikes (sub-aerial spreading centers) toward the continent. At this stage, it is quite important differentiate the lava flows from the rift-type basin sediments.

# Total's Model
## Volcanic Divergent-type Margins

**Opening of the South Atlantic Ocean**

# 3.1- Early Drifting

**(SDRs, SDRs unconformity SU, proto-ocean)**



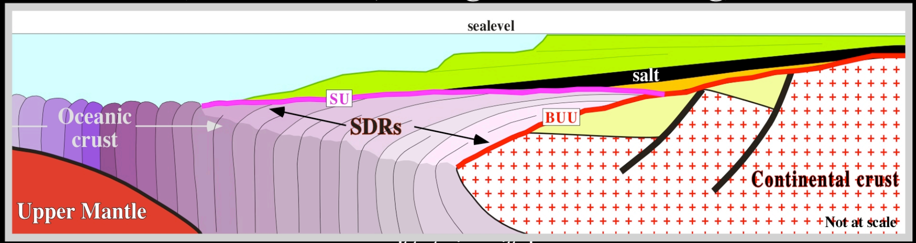

**The stacking of successive lava flows oblige the older to tilt seaward creating, gradually, seaward dipping time lines. Two twin symmetric shallow basins are formed, between the subaerial spreading centre and the continents. Progressively, the sea invades the new lithospheric plates and fluvio-shallow marine sandstones and evaporite are deposited in the basins. These evaporites are quite particular. They are rich in potash and poor in $MgSO_4$ (carnalite, tachyhydrite, bischofite, sylvite). Their brines were enriched by spilitisation. The basalt of the lavas was hydrothermally altered to spilite greenstone. At this stage, early subaerial drifting, the the lava flows and the rift-type sediments dip in opposite direction and two distinct major unconformities are recognized. The break-up unconformity (BUU) and that associated with the top of the SDRs (SU).**

# Total's Model
## Volcanic Divergent-type Margins

Opening of the
South Atlantic Ocean

# 3.2- Youthfull Drifting

(oceanic crust, transgressive drowning)



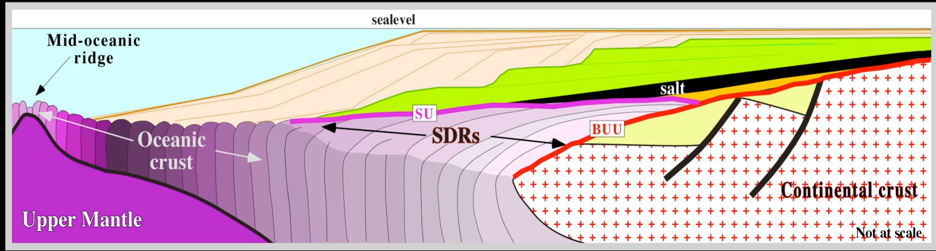

salt tectonics omitted

When the weight of the lava flows, in conjunction with the eustatic rise, submerge the spreading centre, the mantle material, arriving at sea floor, is frozen into pillow lavas. It is the begining of oceanic crust (volcanic material cannot flow under water) and a unique oceanic basin is born. The seaward subsidence of the margin enhances the eustatic rise and a transgressive sedimentary interval is deposited in the margins of the basin above the evaporites. The sediments are deformed by salt tectonics, but the backstepping geometry of the transgressive sediments is easily recognised. \This transgressive episode prevails till the Cenomanian-Turonian eustatic high when the encroachment of transgressive sediments is maximal (maximum flooding surface 91.5 Ma).

# Total's Model
## Volcanic Divergent-type Margins

Opening of the South Atlantic Ocean

# 3.3- Mature Drifting




salt tectonics omitted

**At the maximum flooding surface (MFS 91.5 Ma), the shoreline was faraway up-dip the shelf break (basin with platform). Then, the eustatic fall initiated a progradational interval. Progressively, the maximum flooding surface is fossilised by the forestepping creating a major downlap surface. As the depositional coastal break (roughly the shorelines) moved seaward, the size of the plataform decreased. Subsequently, at a given time, the basin has no more platform (depositional coastal break and shelf break become coincident) and the toe of the slope started to cover the pillow lavas, and seamounts, forming the oceanic crust. At this stage, it is quite important to say, SDRs dip toward the sea, while rift-type basin sediments dip, generally, toward the continent.**

# Total's Model
## Geological Implications

1- SDRs postdate Rifting (Rift-type basins). Observed.

2- Salt deposition postdate SDRs and so Rifting. Observed.

3- SDRs should underlie distal salt basin. Observed.

4- Conjugate salt basins were always separate and independent.

5- Oceanward, by thrusting, the evaporitic interval can be quite thick. Observed.

6- Oceanward edge of salt basin is pinch-out of thinnest salt, which creates a toe-thrust or allochthonous zone. Observed.

7- The basalt of lava flows is the most suitable host to explain potash evaporites poor in $MgSO_4$. (Observed in Lake Assal).

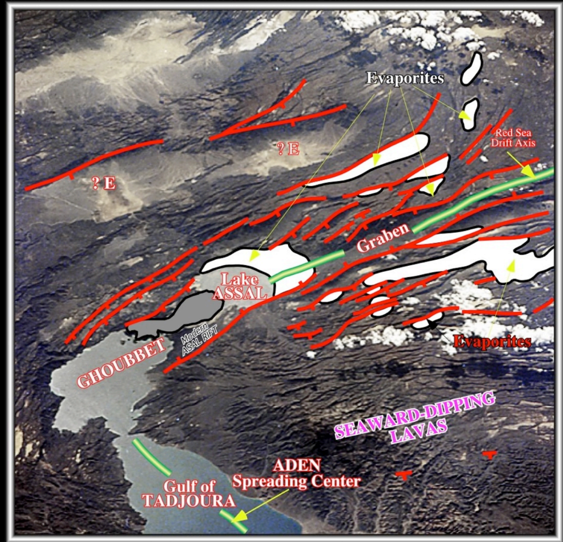
# SDRs & Hydrothermal Brines


Red Sea - Gulf of Aden

**One of the best present examples where MgSO4 poor potash evaporites are formed by spilitisation of the basalts of the lava flows is the Lake Assal, which is located at the junction of Aden Ridge, Ertaiale Red Sea rift axis and the East African rift axis.**

# SDRs & Hydrothermal Brines

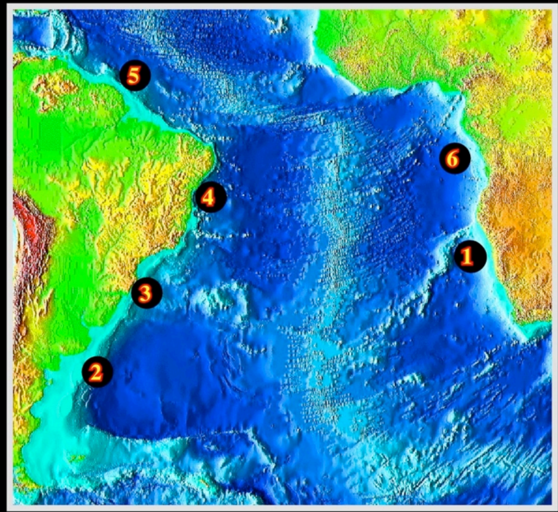
## Lake ASSAL - GHOUBBET - Gulf of TADJOURA




**The evaporites deposited in Lake Assal and associated grabens the same composition of the South and North Atlantic margins, as well as the Lohan salt of Gulf of Mexico. Admitdelly, their brines are hydrothermally by the rocks composing the SDRs, which are easily recognised on the field, Notice that Lakae Assal is around 250 meters below present sea level.**

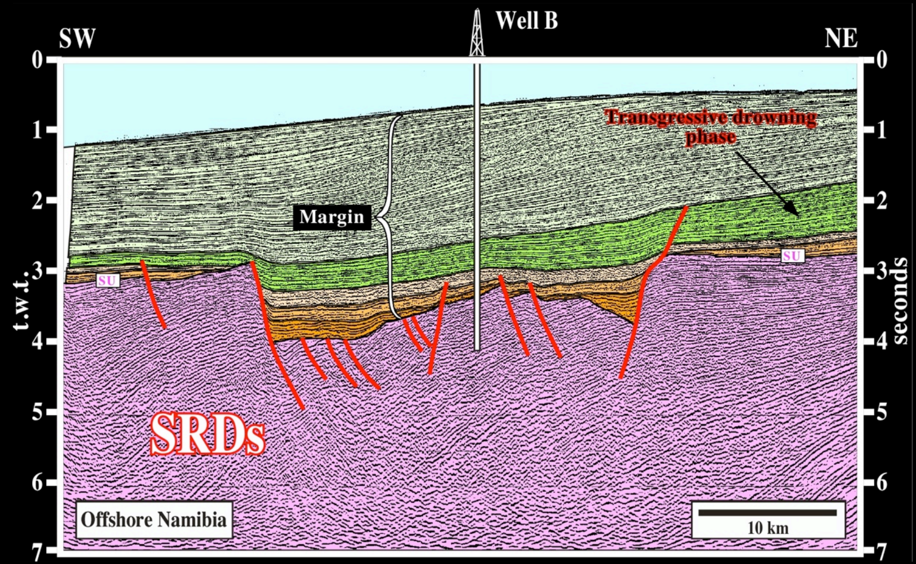
# Seismic Tests:

1. Namibia
2. Argentina
3. Brazil (Pelotas)
4. Brazil (Jacuipé)
5. Guyana
6. Angola



**The following regional seismic lines, and well results, from Namibia, Argentina, Brazil, Guyana and Angola corroborate, that is to say, they do not falsify the hypothesis advanced by Total's geologist to explained the Atlantic-type divergent margins of South Atlantic.**

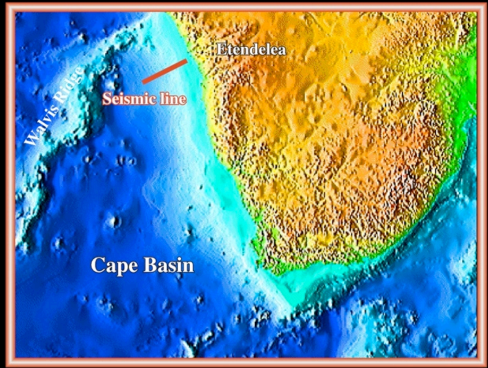
# Seismic Examples

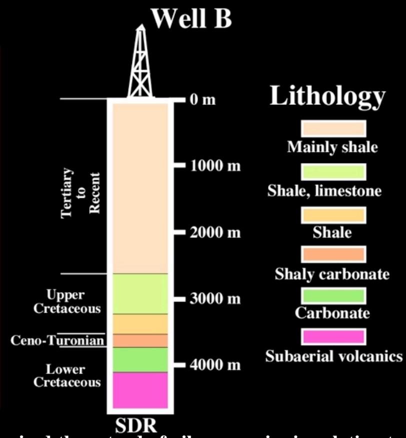



In the 90's, on this area, several major oil companies drilled wildcats looking for hydrocarbons generated by potential lacustrine source rocks deposited in rift-type basins developed in the continental crust. In other others, the reflectors in the lower part of the line, which are tilted and looking seaward, were interpreted as induced by sedimentary interfaces within Lower Cretaceous Rift-type basins.

# Seaward Dipping Reflectors

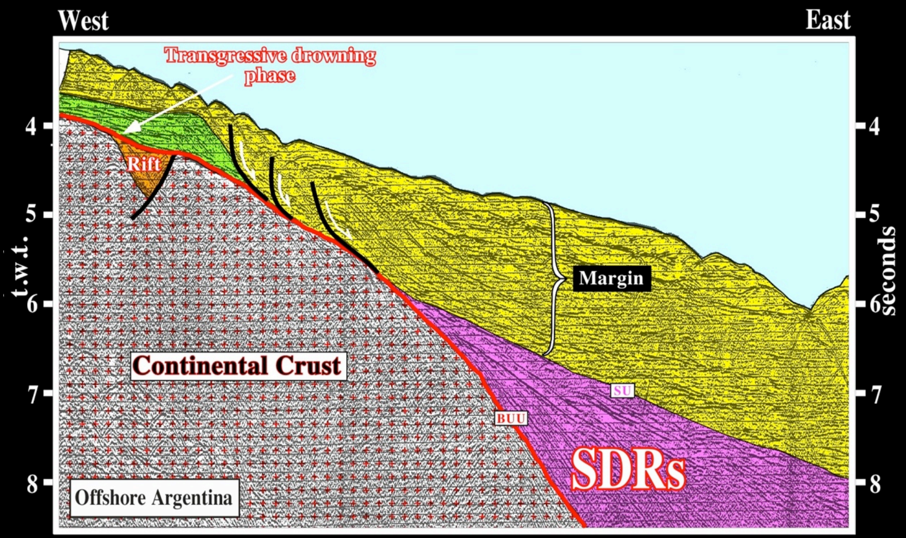
## (Offshore Namibia)



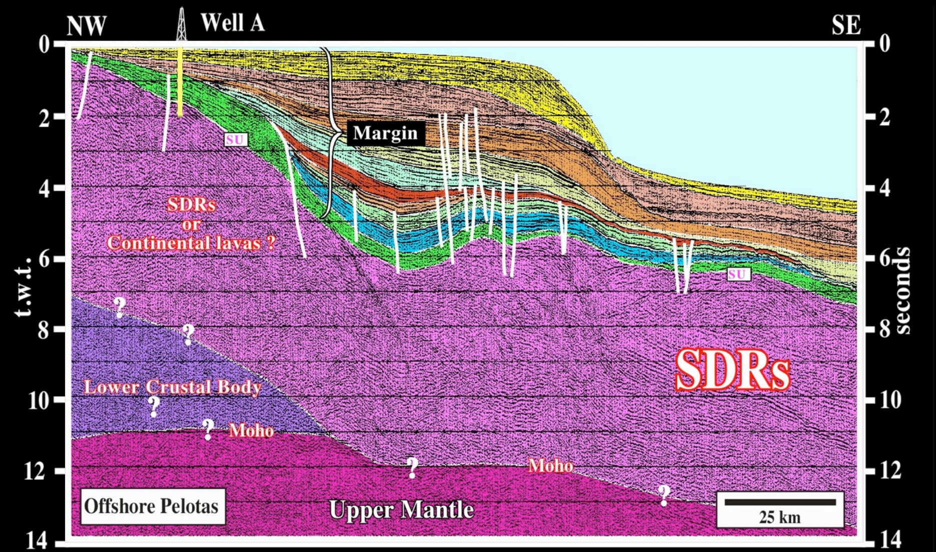

**The well's results, as illustrated in this sketch, strongly emphasised the retard of oil companies in relation to the the academia. The seismic reflectors interpreted as potential hydrocarbon source rocks were just post break-up lava flows with any generating hydrocarbon potential, i.e. SDRs. Astonishingly, even after the results of the first well, several oil companies continue drilling expecting to find, in Namibia, the Cabinda Eldorado, i.e. the Bucomazi formation of the rift-type basins. So far, they just find lava flows.**

# Seismic Examples



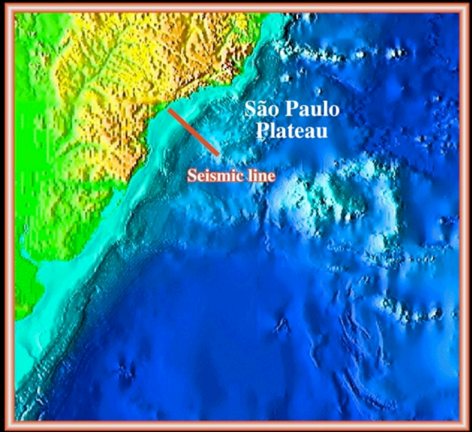

**This seismic line from the offshore Argentina, clearly illustrates the difference between rift-type basins (pre-dating the break-up) and SDRs (post-dating the break-up). Cleverly, argentine explorationists, following K. Hinz's works, considered this offshore as very poor, in terms of hydrocarbon potential. Indeed, as recognised on this line, the thickness of the margin sediments is to small to develop a generating petroleum sub-system.**

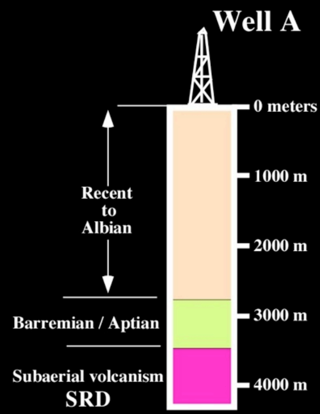
# Seismic Examples




This seismic line from the offshore Brazil (Pelotas basin), clearly illustrated that Petrobras explorationist drilled a lot of wildcat assuming that rift-type basins, with potential source rocks were always present in the offshore. Unfortunately, the results of the wells drilled southward Santos basin and particularly in Pelotas basins are more than noteworthy: total absence of source rocks.

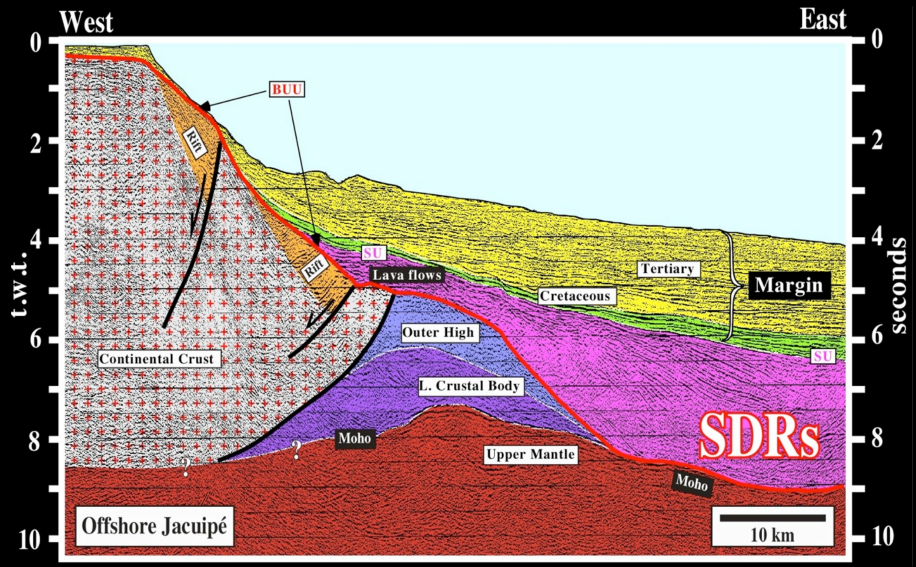
# Seaward Dipping Reflectors
## (Offshore Pelotas, Brazil)



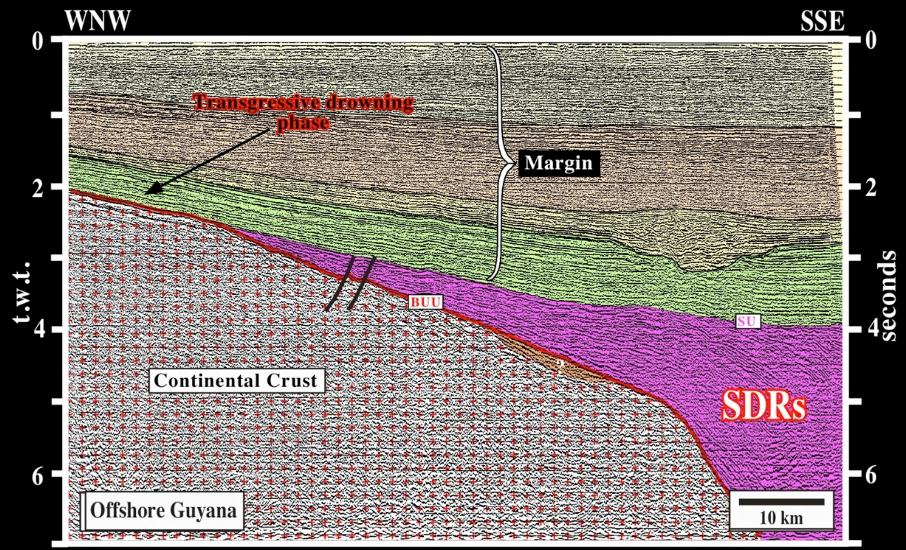

As said previously, the well's results of Pelotas basin, indicated the substratum of the basin was composed by volcanic material, which seismically speaking can be interpreted as SDRs, i.e. lava flows. In terms of petroleum exploration, these wells shows the absence of a rift-type basin generating petroleum subsystem.

# Seismic Examples



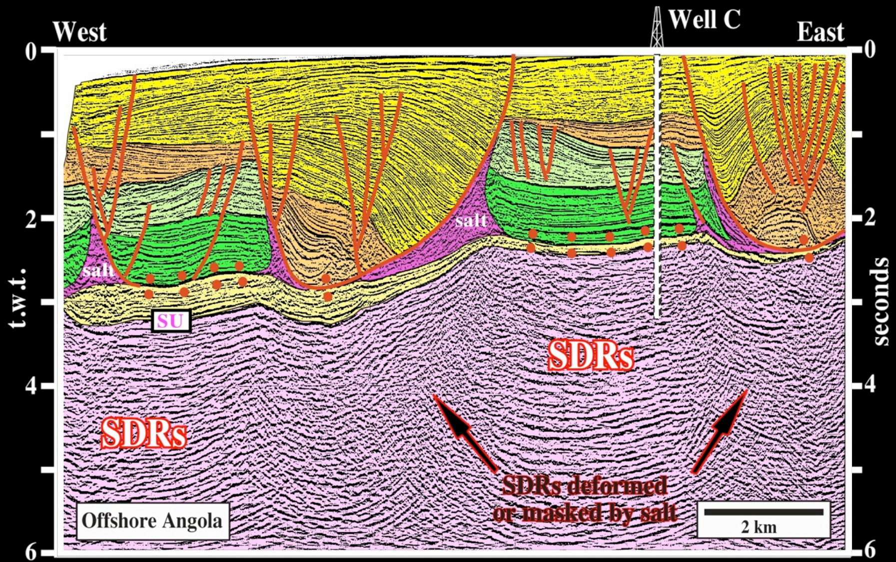

**In Brazil, the turnover took place in 1998, in São Paulo convention, when a Brazilian geologist (Webster Mohriak) showing this line (roughly interpreted as presented) said: "Before J.C., that is to say me, the pink interval was interpreted as rift-type basin with an huge hydrocarbon potential. After, J.C., this same interval is interpreted as lava flows post-dating the break-up (BUU) as so with a nil hydrocarbon potential".**

# Seismic Examples



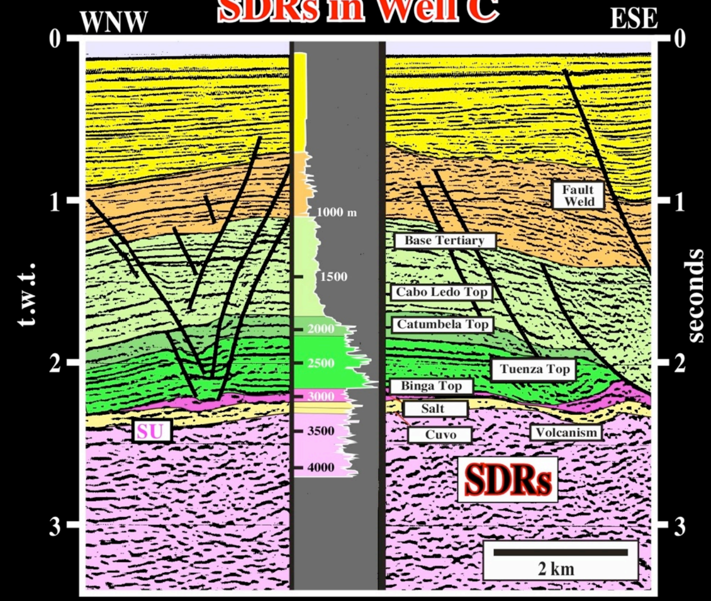

**Going northward, for instance to Guyana, major oil companies, after understanding the lower hydrocarbon potential of certain of their exploration blocks (taken to look for hydrocarbons generated by rift-type basin source rocks) try to farmout them. This line illustrates a typical example. Several geologists came to my office to sell the best, and thicker, potential source of the area (the pink interval). They forgot two thinks, firstly that I was closely tie with the academia and secondly the results of a neigborhood wildcat that was stopped in lava-flows.**

# Seismic Examples



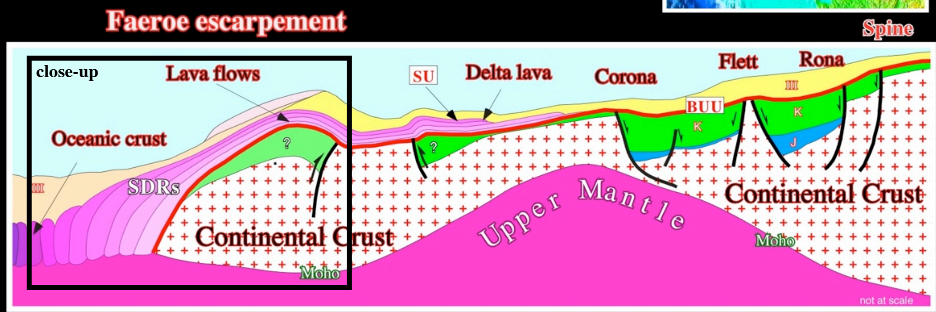

**Returning to the eastern Atlantic margin, I remembered that in the 80's, Total drilled a well, in the offshore Angola, that was stopped in vulcanics after drilled almost 1000 meters of lava flows. Admittedly, even now it is difficult to recognise SDRs on this line due to the lateral changes in velocity induce by the salt. However, the volcanic interval was cored and the cores indicate a ± 15 º seaward deep as illustrated in next plate.**

# SDRs in Well C



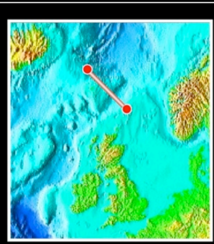

The well was located on this line, which is perpendicular to the previous one. The core studies indicated a vulcanic facies for pink interval. The ±15º seaward dip recognised on the cores was corroborated by dip of the associated seismic reflectors. Today, for the majority of explorationist working in the area, it is evident that such infra-saltvolcanic interval correspond to post break-up lava flows, but not at that time.

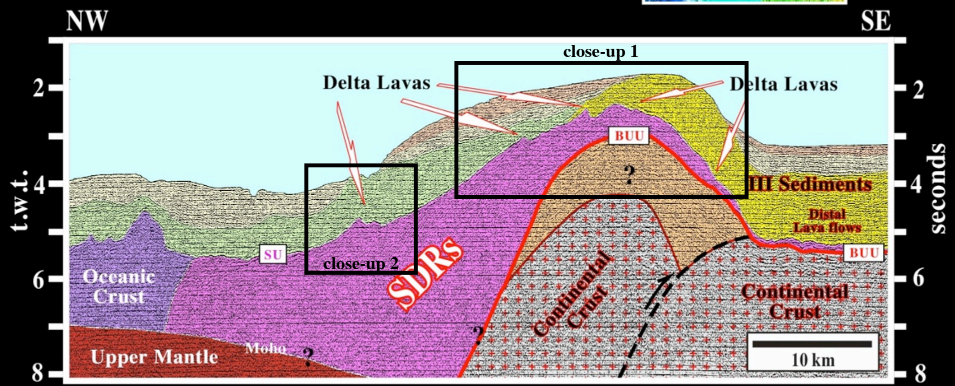
# Schematic Cross-section through Faeroe - Shetland




Let's jump to North Atlantic (offshore Faeroe-Shetland), the limit between the continental and sub-aerial crust is well visible, as well as the limit between the sub-aerial and oceanic crust. In addition, several rift type basins (some inverted) were recognized in the continental, below the break-up unconformity (BUU) and delta lavas are frequent along the SU unconformity (top of the lava-flows). Let's see a cross-section and a seismic line.

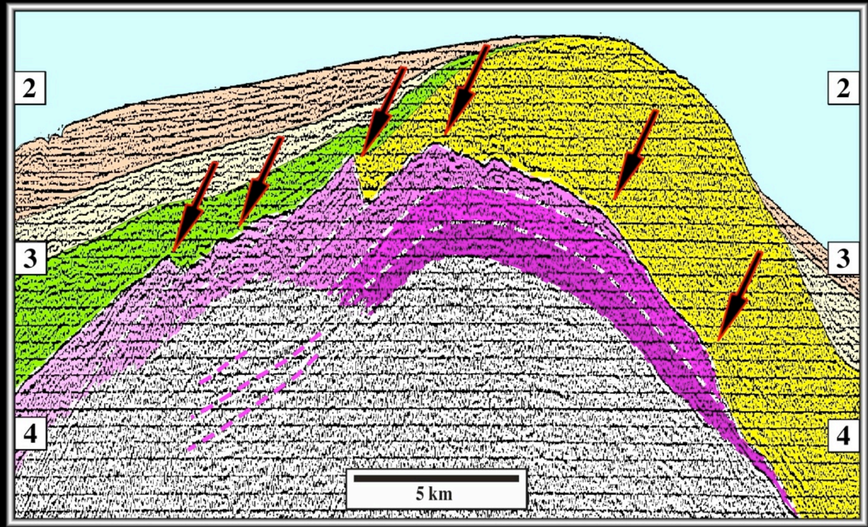
# SDRs & Delta Lavas on the Faeroes offshore





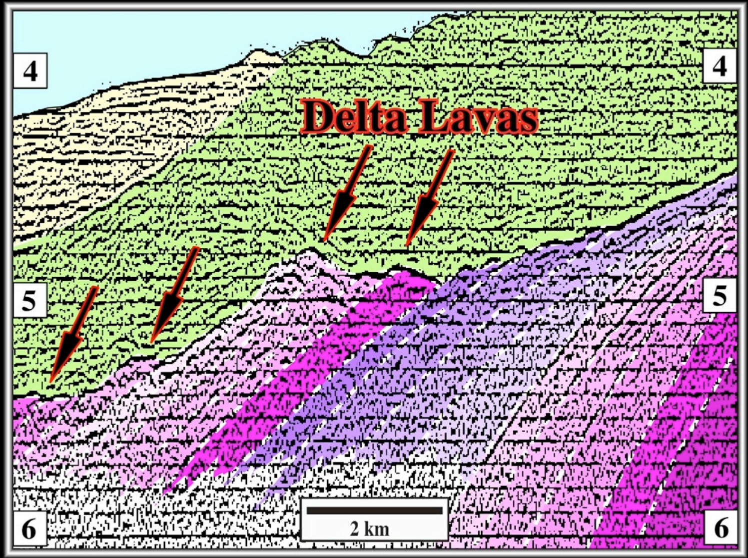

On this line, from East to West, it is easy to recognise under Tertiary deep-water sediments: (i) the continental crust, (ii) an inverted rift-type basin, (iii) the break-up (BUU) unconformity, (iv) the SDRs (folded in continentward end, (v) and the oceanic crust. Delta lavas, i.e., vulcanic structures (frozen lavas) created when the lava flows enter in an aquatic realm (lake, sea, etc.,) are also recognised along the SU unconformity, as illustrated in dedtail on the following close-ups.

# Close-up 1 — Delta Lavas



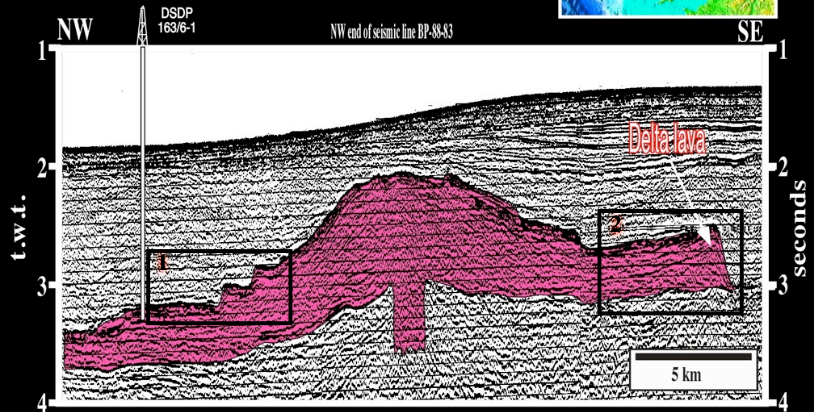

**Naive inductive seismic interpreters (those refuting that "Theory preceds Observation) never recognise on this seismic line SDRs and the delta lavas. However, those knowing the Theory, and particularly, that SDRs thick and dip seaward im direction of the spread centre (sheeted dikes) and that vulcanic material under water is frozen (cannot flow), easily interpret this line as illustrated.**

# Close-up 2




**This close-up is as convincing as the previous one. The volcanic material arriving in surface, via a sheeted dike, flowed to the craton. However, certain lava flows entered ian aquatic environment, and so, they froze forming a delta lavas. One can say, lake or sea was present in the right part of the line at the time of sub-aerial spreading.**

# Delta Lavas on the flanks of the Darwin seamount (North UK Rockall trough)

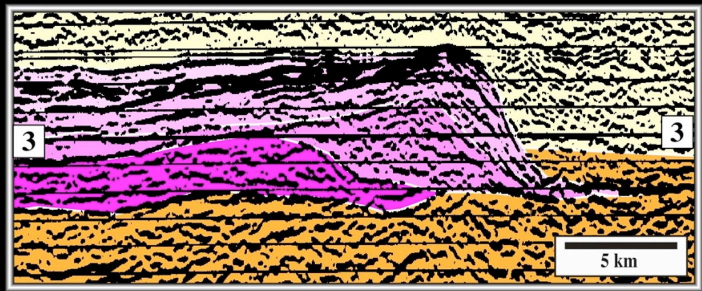




**For those still doubting, the seismic line through Darwin seamount (offshore North UK) and the DSDP 163/6-1 results, are going to give them a convincing geological model explaining how delta lavas are formed.**

## Close-up 1

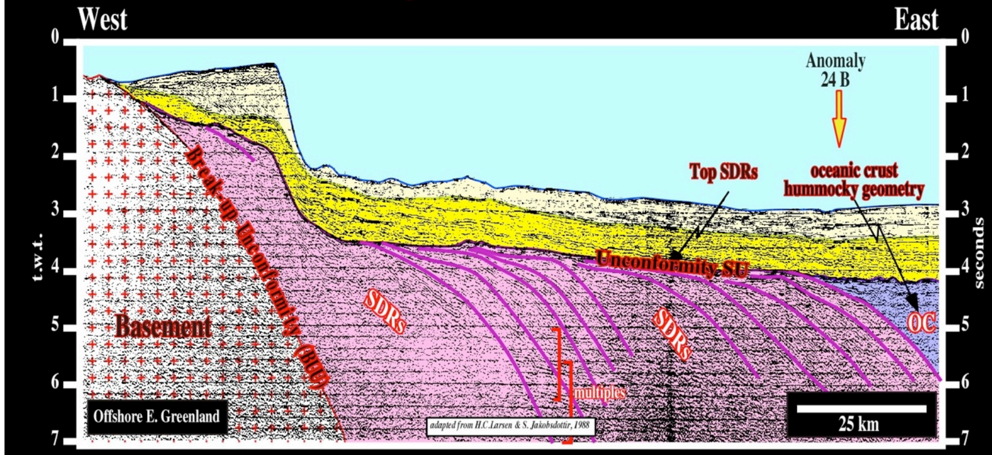

# Delta Lavas

## Close-up 2



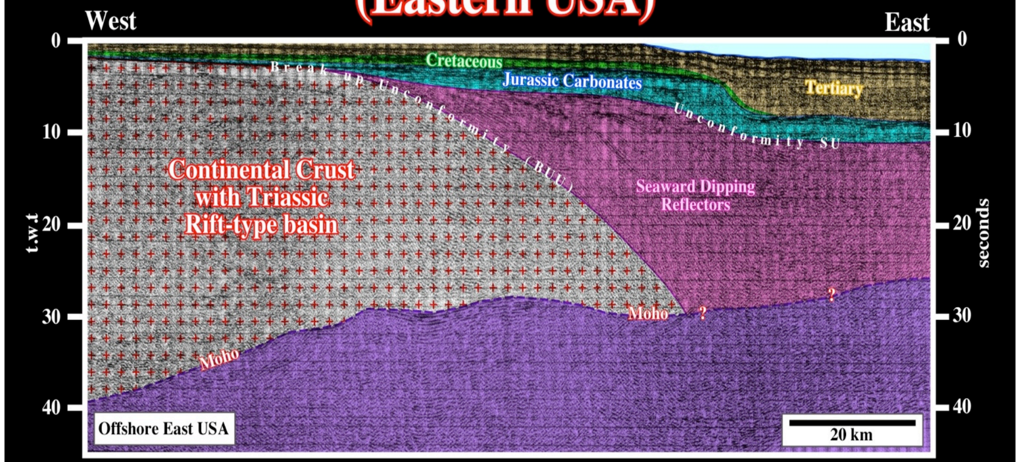

**These close-ups show of the geometry created by vulcanic material when becomes frozen under water. Such a geometry is similar to that of a delta, but the slope angle is much higher in a delta lava. The geometry, and particularly the backstepping geometry of the close-up 1, suggest successive relative sea or lake level rises as subaerial spreading goes on.**

# SDRs - Oceanic Crust Boundary in E. Greeland



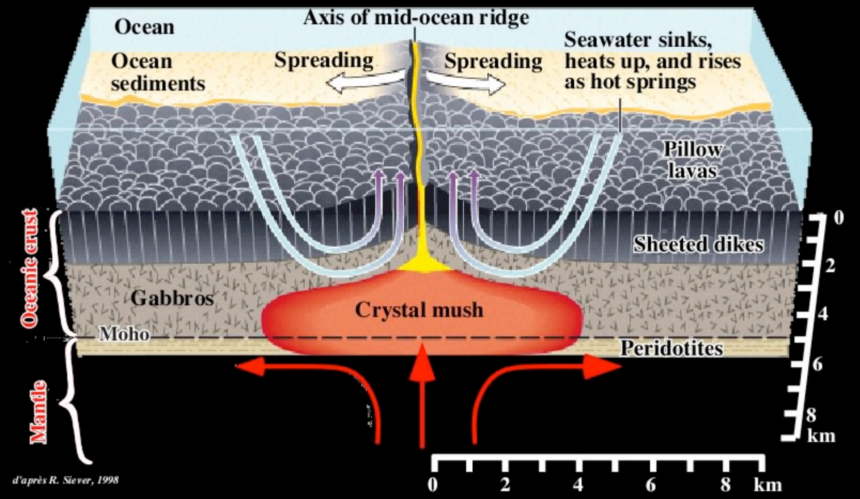

In eastern Greenland, the SDRs are known since long time. In 1988, Larsen and Jakoksdottir published this seismic line, in which sub-aerial lava flows are quite evident as well as the limit between their realm and the oceanic crust. The sedimentary interval posterior to the SU unconformity is too thin to develop a generating petroleum sub-system, that is to say, mature source rocks.

# Seaward Dipping Reflectors (Eastern USA)




We are going to jump over the Eastern Canada (Flemish Cap, North and South Terra Nova basin) because as we will see later, this area, which match with the offshore Iberia, seems to a particular opening history in terms of depth of the spreading centres. South of this area, as northward, the seaward dipping reflectors are recognised in all regional seismic lines, as in the one illustrate next.
Indeed, on the eastern part of the line, below the Jurassic carbonate bank, the lava flows thinning landward are easily recognised above the break-up unconformity. Their seaward terminations are highly speculative since the geometric relationships with the Moho discontinuity are not quite clear.

# Oceanic Crust



# Oceanic Crust

The mechanism explaining the creation of oceanic crust was proposed, in 1973, by Y. Bottinga, i.e.,

**Fusion-Percolation-Segregation.**

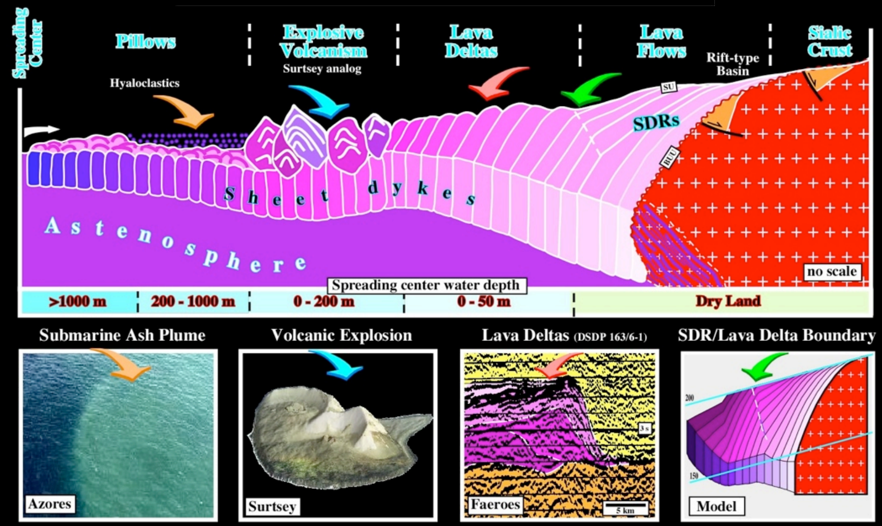
When mantle material (solid state) is pushed upward, it is transformed in a kind of "sponge" soaked of basaltic liquid (magma), which amount increases with the upward movement.

If this "sponge" is pressured, it ejects the liquid into surface forming the sheathed dikes and the pillow lavas, while the residual solid material stays on the bottom forming the peridotites that we find below the gabbros.

Geologically speaking, the rising of mantle material, their partial fusion (between 1-10%) and the expulsion of magma is continuous process. Each new portion of lithosphere migrates laterally, by the spreading, and it is immediately replaced, at the axis, by a new portion lithosphere and so on.

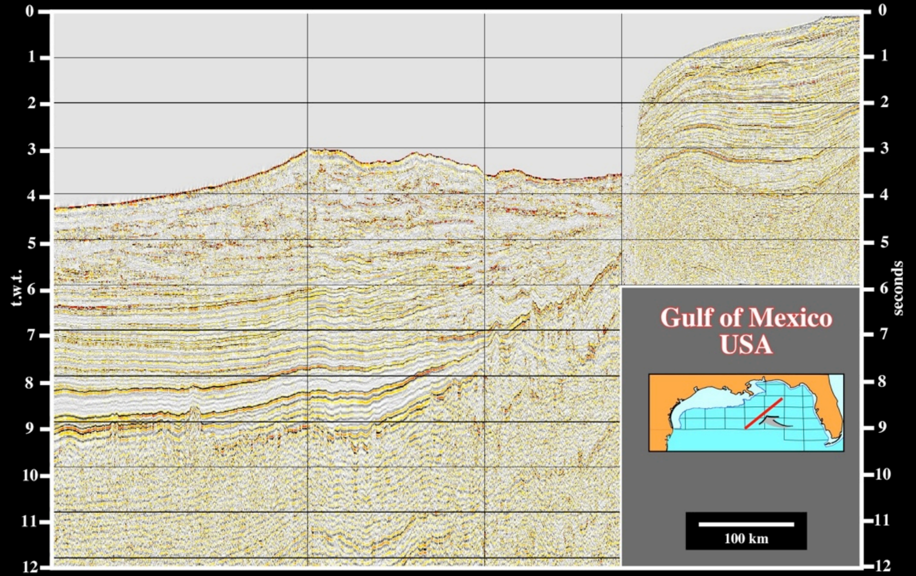
# Basement Evolution Model for Volcanic Margins

(Sediments omitted)



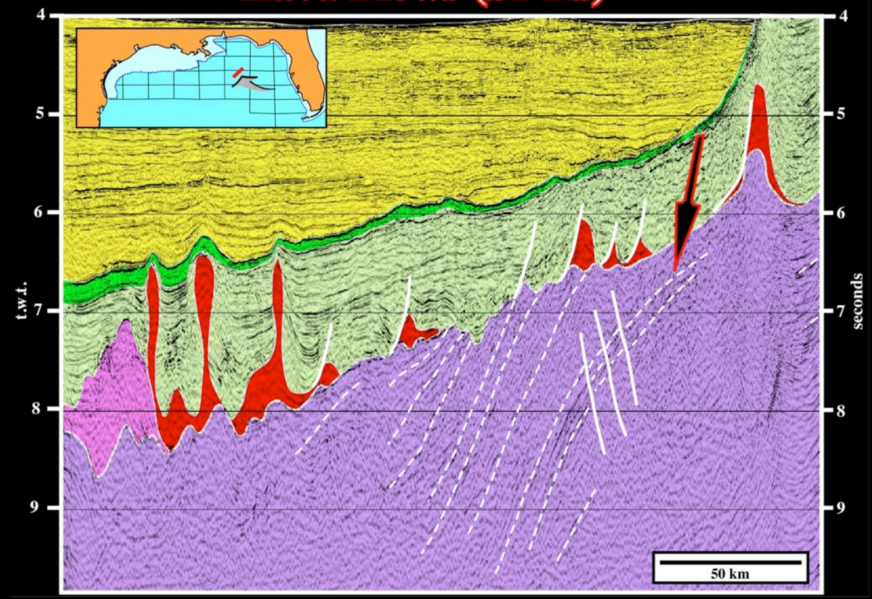

A GOM seismic line allowed us to see the changings of the volcanic opening structures with a progressive immersion of the spreading centre. When it is sub-aerial, (i) SDRs are predominant. However, with its progressive immersion, it is possible to recognise (ii) Lava deltas, (iii) Explosive volcanism with hyaloclastics associated and (iv) pillows lava. Let's start with geological sketch before showing you the line (Theory preceds Observation).

# Composite Regional Seismic Line



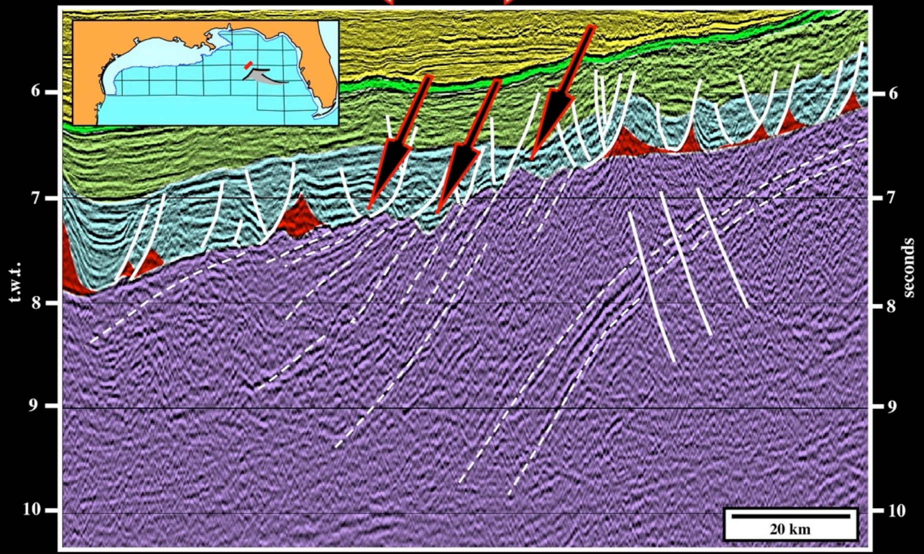

This is the regional line of GOM, in which all volcanic structure associated with the break-up of the lithosphere can be recognised. So, in the following close-ups, from NE to SW, we are going to see successively: (i) lava flows, (ii) delta lavas, (iii) explosive volcanism and (iv) pillow lavas.

# Lava Flows (SDRs)



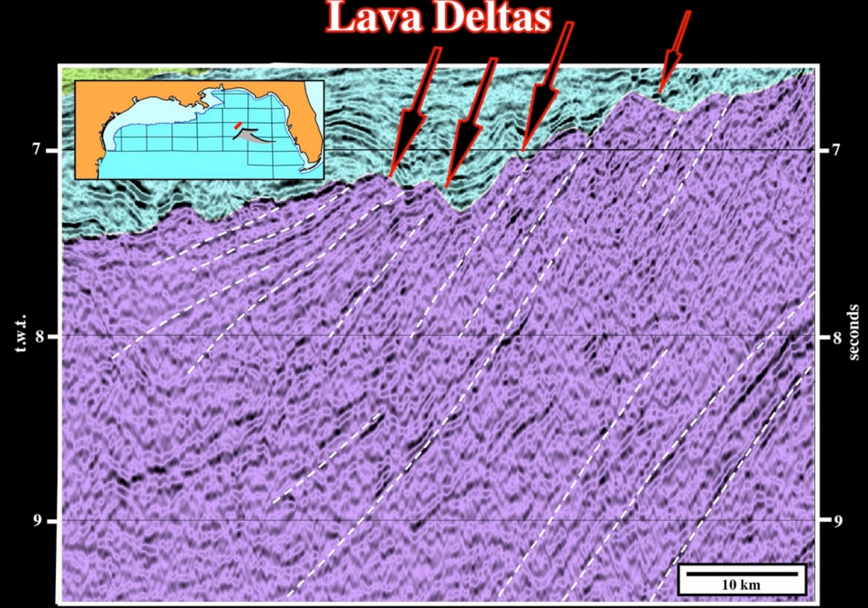

In the eastern close-up, seaward dipping reflections below the bottom of the salt reflector, or salt weld, are clearly recognised on the right part of the line. They suggest a sub-aerial spreading centre , that is to say above the water.

# Lava Flows (SDRs) / Lava Deltas



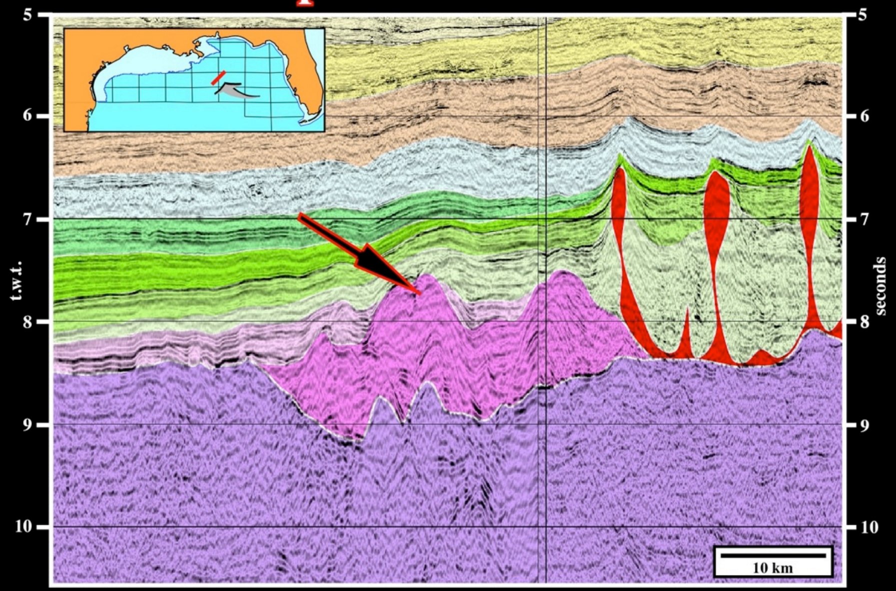

**As illustrated on this line, going seaward, with a water depth of the spreading centre ranging between 0 and 50 meters, the predominant volcanic structures are lava deltas.**

# Lava Deltas



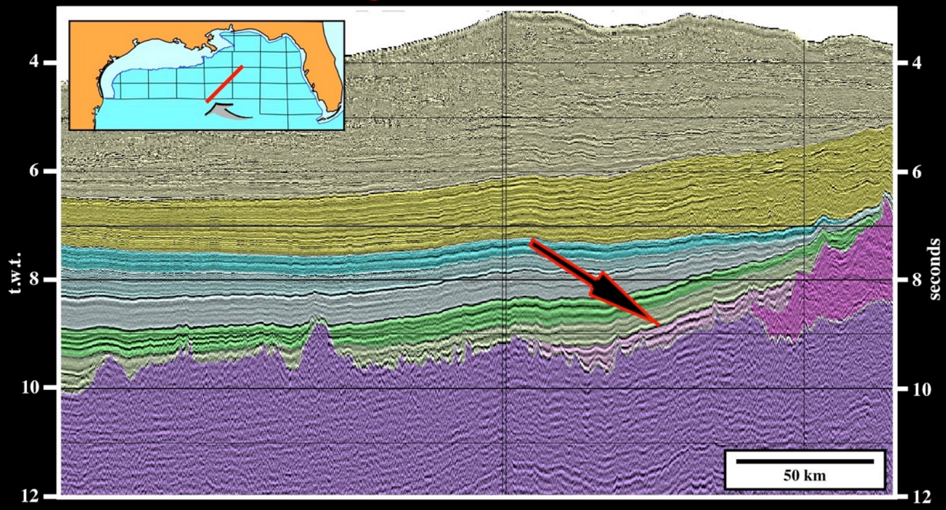

A detail of the previous close-up shows the morphology of the lava deltas particularly the slope of the frozen basaltic material, which in certain aspects is quite similar to erosional cuestas. Notice that between successive lava deltas, sedimentary troughs of the margin sediments should not be taken as rift-type basin. Do not forget rift-type basins are predate the break-up and so they anterior to the lava flows and lava deltas.

# Explosive Volcanism



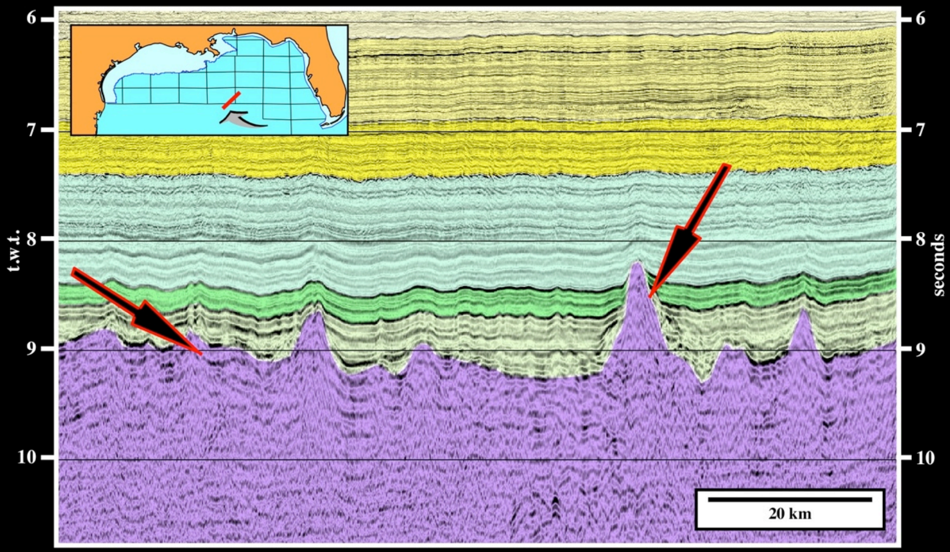

When the spreading center reaches a water depth ranging between 0 and 200 meters, explosive volcanism of Surtsey-type is often predominant. The V shape morphology is typical of these structures as their fill by volcanic debris. Hyaloclastic deposits are often onlapping on the seaward side of this kind of explosive volcanism.

# Hyaloclastites




On this close-up, the onlapping of the hyaloclastic interval on the seaward flank of the explosive volcanism is quit well visible, as well as the onlapping on the oceanic crust, On left part of the line, seamounts are recognized, but as we will see their are much  more evident on the next and last close-up.

# Oceanic Crust & Seamounts

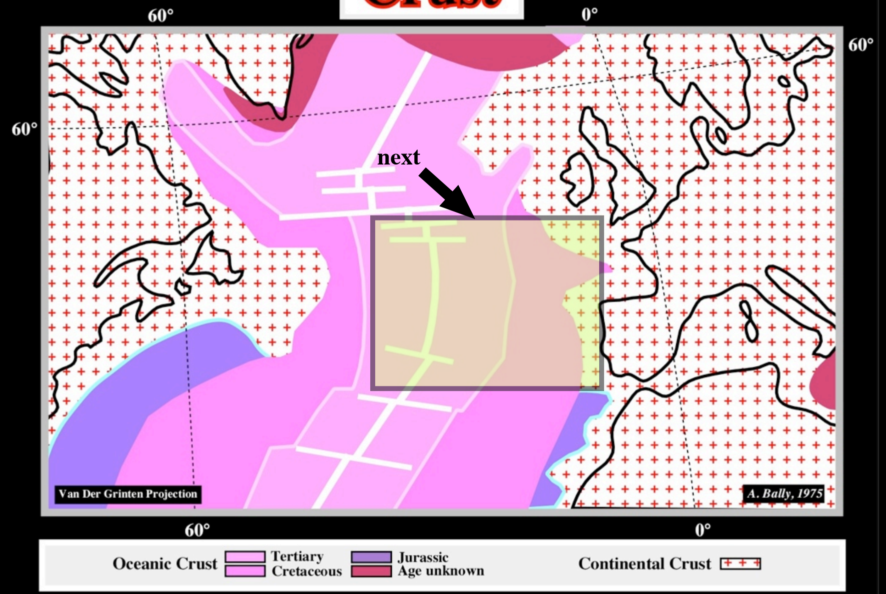



**On this close-up, seamounts in the oceanic crust are paramount. However, certain major oil companies still refuse to recognise the oceanic crust in Gulf of Mexico, and they unsuccessfully tried to farmout their "Jurassic reefs", actually the seamounts, as giant prospects. Indeed, often, in oil industry, geological monstruosities are hypothesised just for business reasons.**

# Finally, Are There SDRs Present in Offshore of Iberic Peninsula?

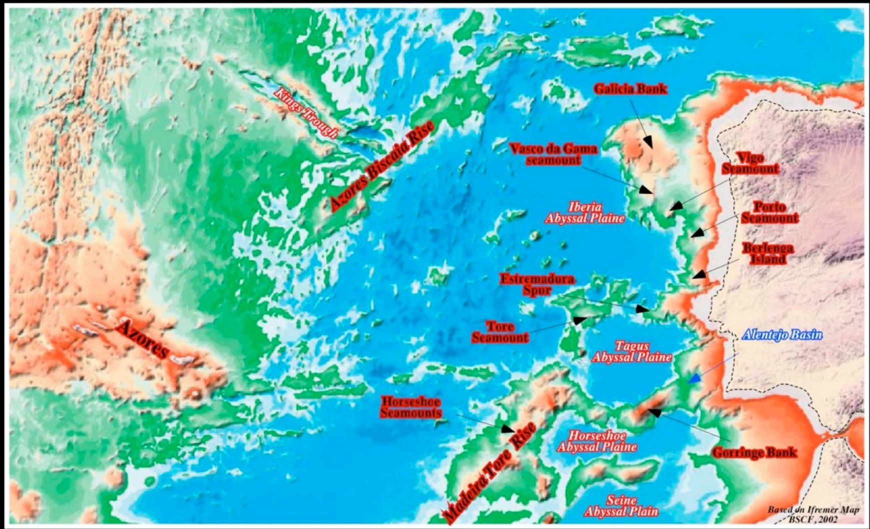
**The answer is no and yes. Two particular reasons can be advanced, which we will review next.**

# Crust




**Let's start saying the COB (continental oceanic boundary) in deep offshore Newfoundland and Iberia are quite anomalous in relation to the COB in North Africa and offshore USA, where SDRs are well known. On the other hand, the morphology of the sea floor is also quite particular, as shown next.**

# Topography & Bathymetria
## West Iberia



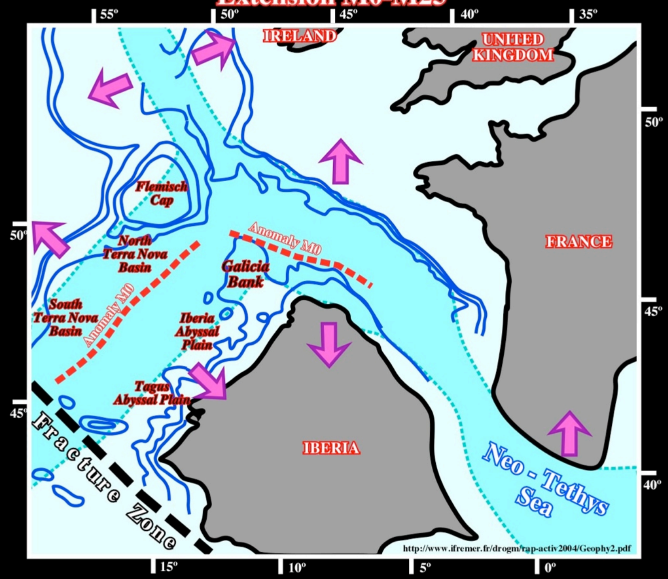

**From North to South, it is easy to recognise: Galicia Bank, Vasco da Gama - Vigo - Porto seamount,s Iberia abyssal plain, Estremadura Spur, Tore seamount, Tagus abyssal plain, Gorringe Bank, Horseshoe abyssal plain and Madeira Tore Rise. The Mid-Oceanic ridge, Azores islands, Azores Biscaia rise and Kings through are also easily recognised. As illustrated next, this bathymetry fits with the bathymetry of offshore Newfoundland.**

# Reconstruction at M0

## (± 118 Ma)

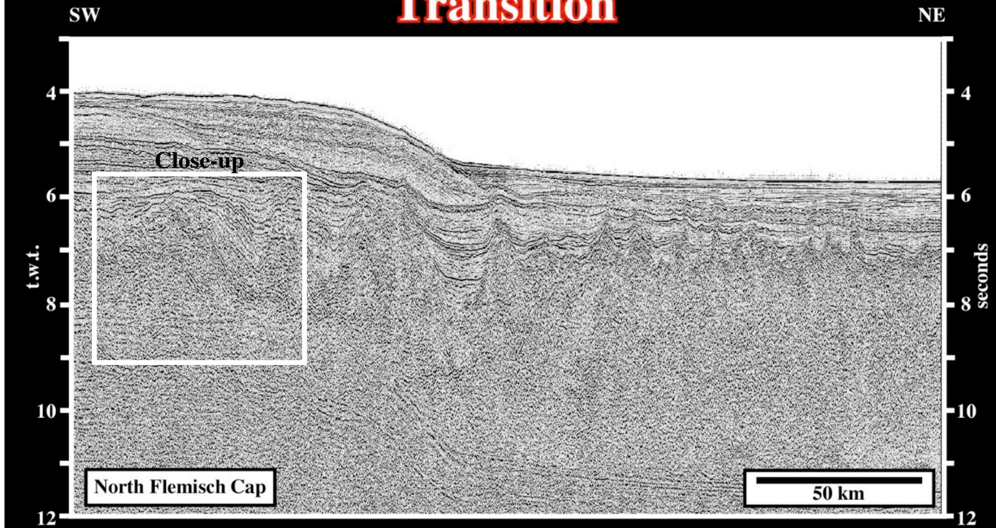

**A reconstruction at the magnetic anomaly M0 (see later), around 118 Ma, strongly suggest, at the onset of the sea-floor spreading, Galicia Bank was in adjacent to Flemisch Cap. The Iberia and Tagus Abyssal Plains seems also to match with the North and South Terra Nova basins. A major fracture zone existed already between south Newfoundland and south Iberia. A triple point, northward of Flemisch Cap and Galicia bank could be predicted.**

# Reconstruction on M0
## Extension M0-M25



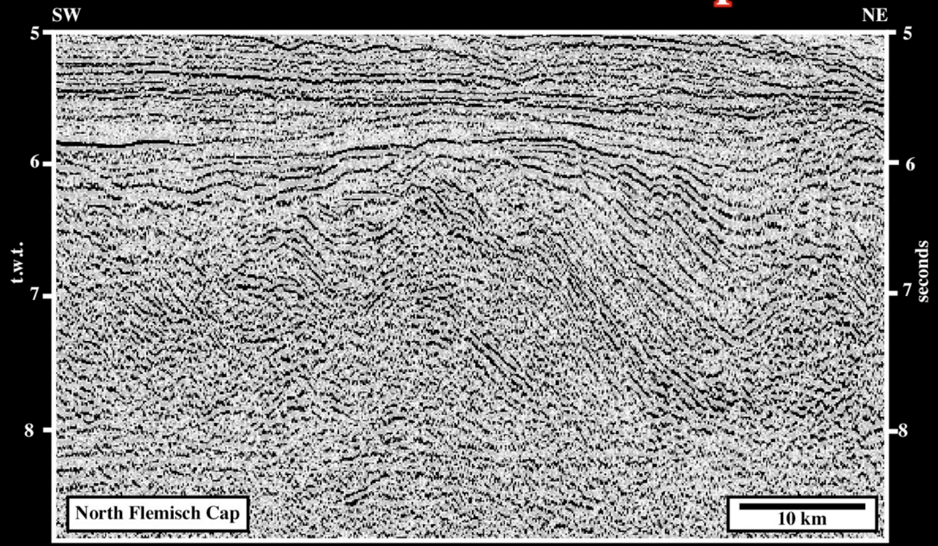

**The extension between M0 and M25 (see later) shows the lithospheric plate movements and strongly emphasized the geological particularities of Newfoundland and West Iberia offshores when compared with the conventional Altantic offshores. Notice, in north Iberia, the Neo-Tethys Sea and a triple point between Galicia Bank and Flemisch Cap in which SDRs are likely as illustrated next.**

# Sub-aerial - Oceanic Crust Transition



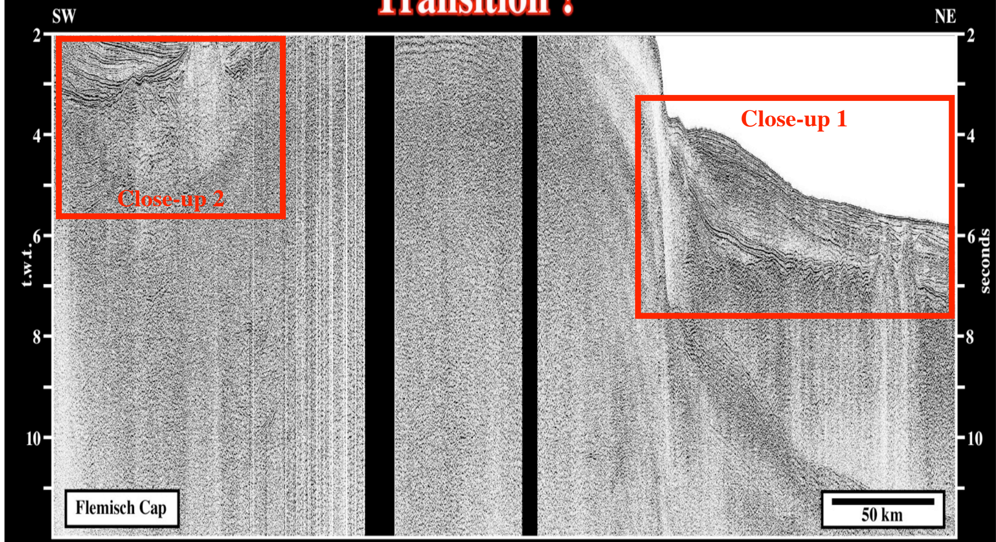

On this regional seismic line, located slightly northward of Flemisch Cap, the transition between the sub-aerial and the oceanic crust can be recognised on the left part of the line. Indeed, seaward, the oceanic crust is easily recognized by its mounded or hummocky morphology (take into account the scale) with small volcanic basins between volcanic ridges. SDRs are easily recognized in western part. Their morphology can be better recognized ion the next close-up.

# SDRs in NE Flemisch Cap



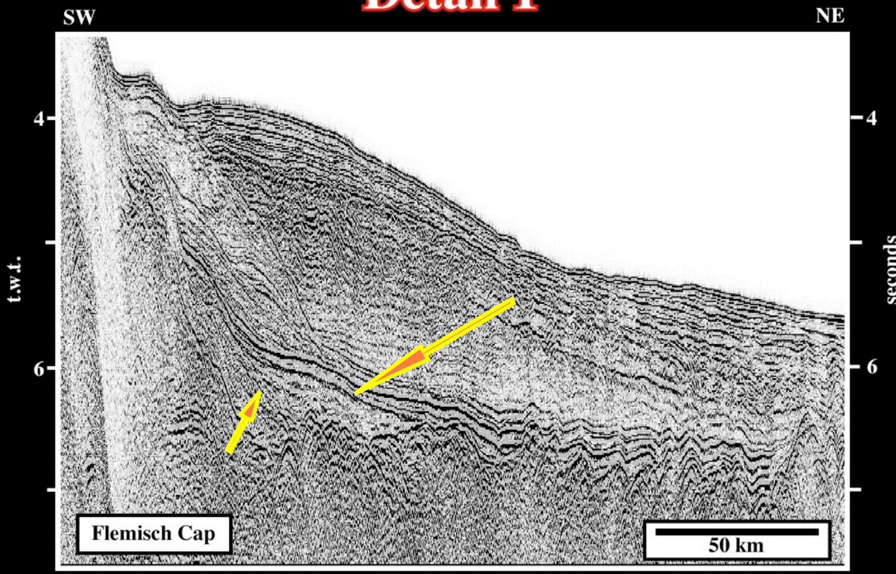

This close-up shows the stacking of successive lava flows. They thin westerward, in direction of the craton and several disconformities can be individualised. Certain structures look like delta-lavas with a SW vergence. If this reflectors correspond actually to sub-aerial lava flows, one can say that the rifting took place in a continental environment, that is to say the rift-type basins must be filled mainly by non-marine sediments.

# Sub-aerial - Oceanic Crust Transition ?



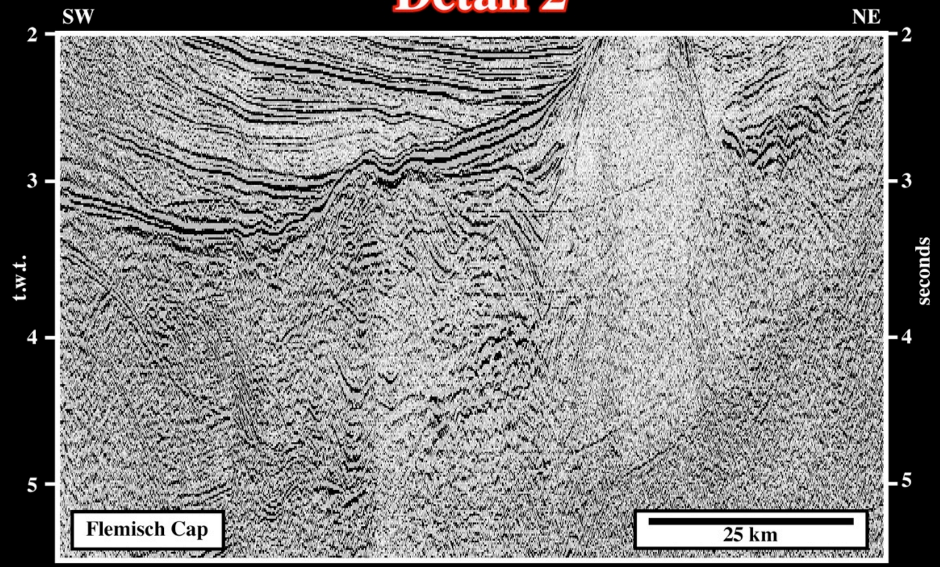

The seismic lines through Flemisch Cap are not too significant as illustrated by this line (Lithoprobe). Nevertheless, taking into account the next close-ups, it is possible to hypothesize a limit between the oceanic and sub-aerial crust eastward of the Flemisch Cap. In such highly falsifiable hypothesis the facies of the Flemisch Cap is subaerial volcanic.

# Detail 1



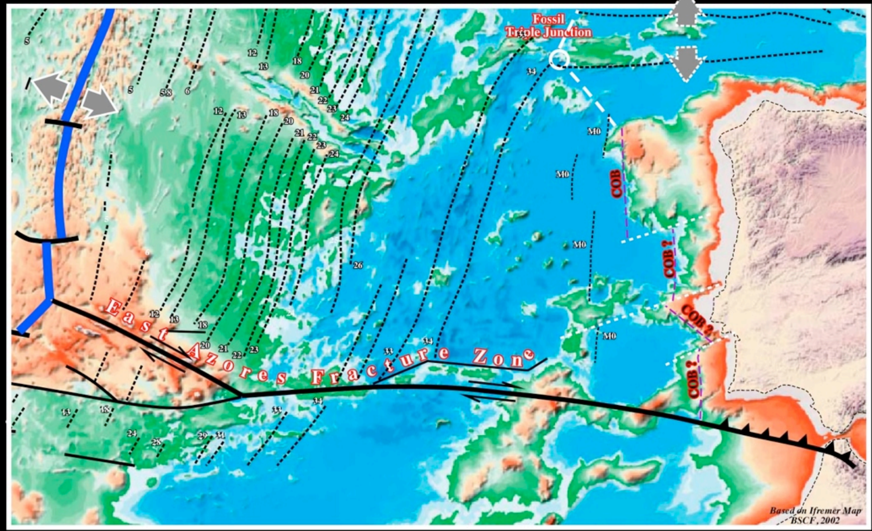

**On this close-up the oceanic crust is easily recognised in central and right part by its hummocky morphology. On the left part, thinning landward interval (arrow) can be interpreted as lava-flow connected seaward with a sheethed dyke, i.e., a spreading centre. The reflectors below such interval can so be interpreted as lava flows, i..e sub-aerial crust.**

# Detail 2

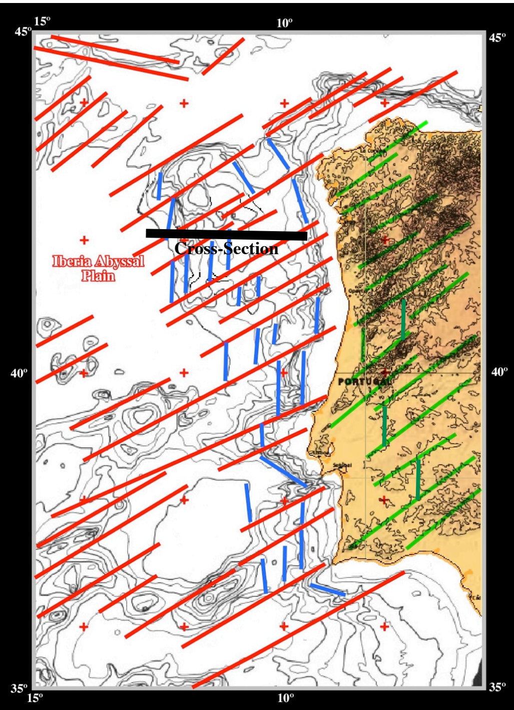



**On this close-up, located westward of Flemisch Cap, besides the volcanic intrusion and associated lava-flows visble on the eastern side of the line, some reflectors can be interpreted as seaward dipping reflectors. If such interpretation is rigth, one can hypothesise the break-up of the lithosphere took place in an sub-aerial continental environment as in conventional Atlantic margins.**

# Magnetic Anomalies & COB
## West Iberia




**Returning to West offshore Iberia, one can recognise a fossil triple junction, the Mid-Oceanic ridge, the East Azores fracture zone, the magnetic anomalies, and the hypothetical continental oceanic boundary (COB). The apparent displacement of hypothetical limit between continental and volcanic (sub-aerial or oceanic) crust seems to be controled by old fracture zones, (see next) which were more or less reactivated during sea-floor spreading.**



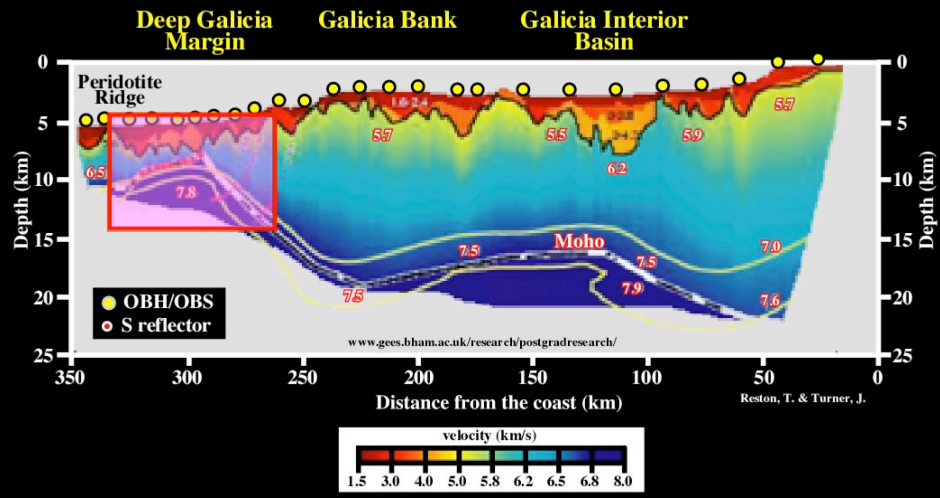

# Bathymetry & Morphologic Anomalies

**The topographic map of onshore Iberia underlines the probably presence of old fracture zones striking NE-SW, and N-S, which likely controlled the break-up of the Pangea lithosphere and subsequent sea-floor spreading.**

**The bathymetry corroborates the hypotheses that the N-S lineations could be the surface expression of rifting faults, and the NE-SW the old transform faults, which seem to follow the Pangea fracture zones.**

**A interval velocity cross-section based on a regional seismic line, and a close-up of this one corroborates (but not validate) the proposed hypotheses.**

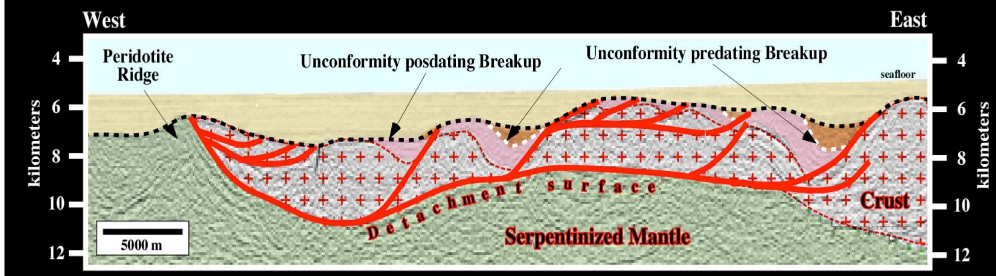
# Velocity Interval & Structural Profile




The velocity interval profile in north offshore of Iberia (Galicia Interior Basin, Galicia bank, Deep Galicia Margin) suggest that the Moho discontinuity surface is relatively shallow, i.e., ± 5 km below sea floor in Deep Galicia Margin and at around 10-15 km in Galicia Basin. In other hand, pre-rifting sediments and rift-type basin, with velocity interval lower than 5 km/s are well predicted all along of the profile. On the western end, a peridotite ridge marks the onset of the oceanic crust. The boundary between the continental and volcanic crust (subaerial or oceanic) can be observed on the close-up of the seismic line underlined by the small rectangle.

# Deep Galicia Margin

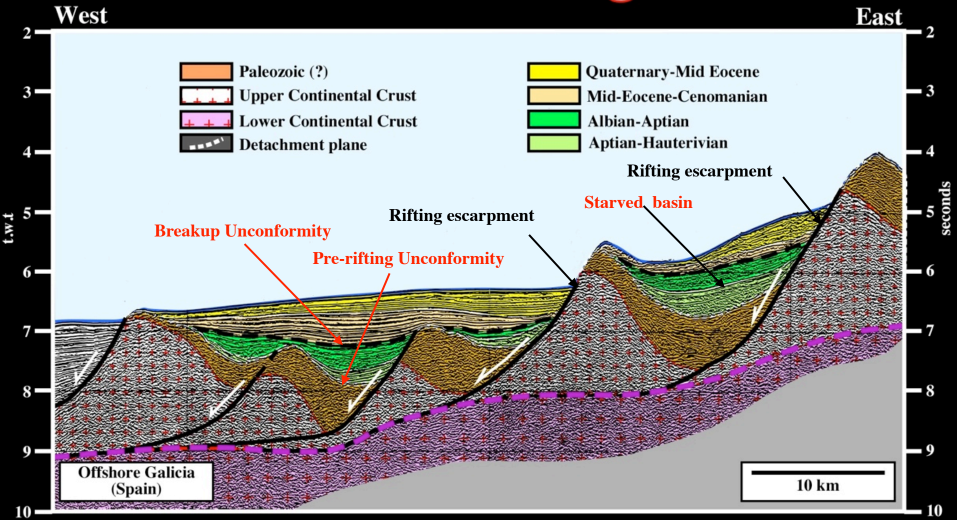
## Seismic Line




This seismic line, initially interpreted by Reston & Turner, clearly suggests that a lengthened continental crust lies over the upper mantle, which outcrops in the western end. The limit between the continental crust and the upper mantle, that is to say, the Moho discontinuity is here underlined by a detachment or décollement surface.

Four major interval must be differentiated in the continental crust: (i) a substratum, probably granite-gneiss, (ii) Paleozoic pre-rifting sediments, (iii) Mesozoic rift-type sediments and Ceno-Mesozoic post rifting sediments. The fault geometry, the morphology of the pre-rifting and break-up unconformities as well as particular filling of the rift-type basins are key elements to understand the COB, and may be why SDRs are not evident on this offshore, which several geologists have considered as a typical no volcanic margin. Let's see a parallel seismic line.

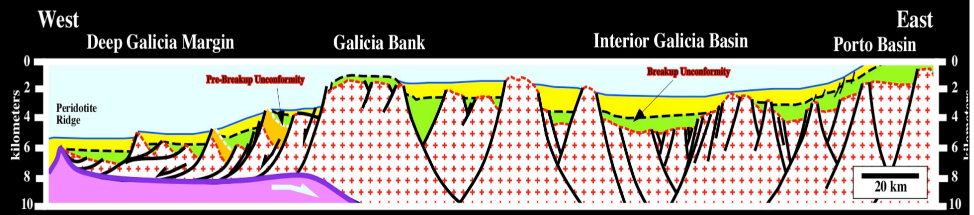
# Marine Rifting




The detachment surface, the pre-rift (bottom of green seismic interval) and break-up unconformity (in black) are evident. The rift-type basins are starved. They are partially filled and the associated sediments are deep-water.

As depicted by the rifting escarpments and the facies and environment of the rift-type sediments, it is plausible that during the rifting all or part of what became the west Iberia atypically, was under high water depth. So, when to break-up took place, the basaltic material could not flow toward the continent creating SDRs, since under water it is frozen creating what we normally dub oceanic crust. Let's now see what is going on eastward of this line, i.e the passage between the deep Galicia margin and the Galicia Bank.

# Geological Schematic Cross-Section

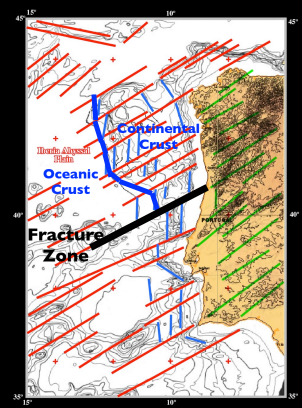


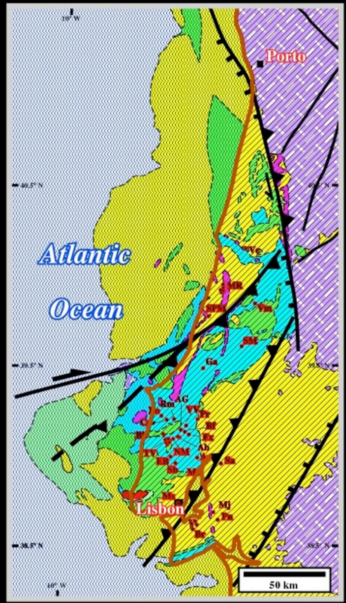

A regional schematic cross-section between Deep Galica Margin and Porto Basin can be depicted as illustrated. In this interpretation, it is hypothesised the onset of a subduction of the oceanic crust under the continental crust (Galicia Bank - Porto Basin). The downward flexure of the lithosphere throwing the upper surface of the plate (continetal crust between Galicia Bank and Deep Galicia margin) into tension creating a local extensional tectonic regime, which can be the responsible of the detachment and reactivation and deformation of pre-existing normal rifting faults.

Using the bathymetric map and the lineations interpretation, one can propose the limit between the continental and volcanic crust (COB) as illustrated.

The southern limit of such a conjecture is a major fracture zone suggested by the bathymetry and corroborated by geologic and seismic data. Indeed, southward of this fracture zone, the rift-type basins were filled by non-marine sediments and evaporites, probably potash evaporites, were deposited at the base of the margin.

On the other hand, southward of this fracture zone, a regional compressional tectonic regime, probably associated with a developed B-Subduction zone, is quite evident, as shown next.





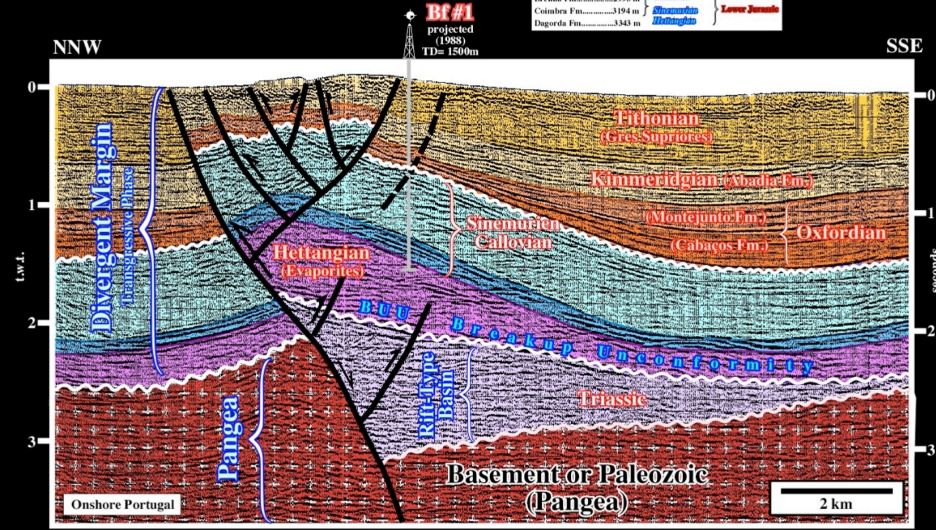

# Geological Map of Lusitania Map


A simple glance at this geological map points out that the Lusitania basin has been inverted. Indeed, Jurassic sediments outcrop in the central and topographic higher parts of the basin, while younger Cretaceous sediments outcrop in the border and lower areas. Such a tectonic inversions, which age is quite recent, is not refuted by seismic data.

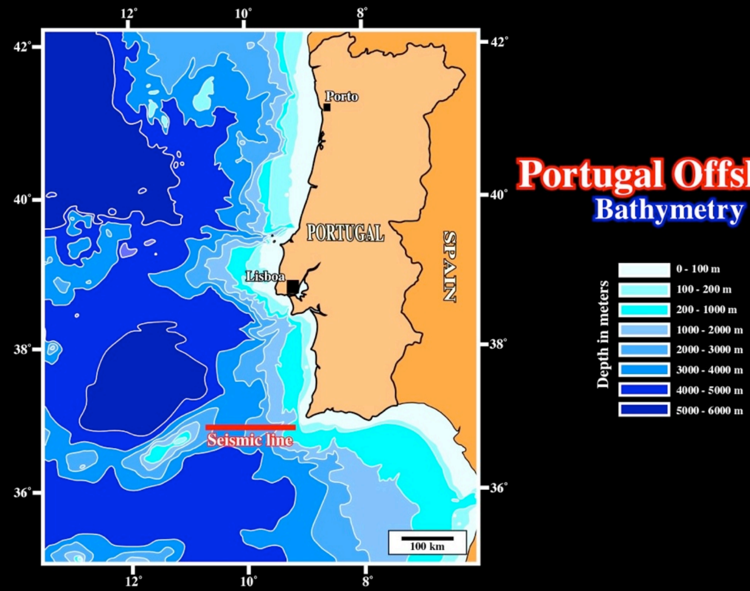
# Line AR 9-80

**Benfeito Well #1**

| | | | |
|---|---|---|---|
| Gres Superiores Fm...135 m | Portlandian | Upper Jurassic | |
| Abadia Fm...1136 m | Kimmeridgian | | |
| Montejunto Fm...1399 m | Oxfordian | | |
| Cabaços Fm...1585 m | | | |
| Brenha Fm...2993 m | Callovian | Lower Jurassic | |
| Coimbra Fm...3194 m | Sinemurian | | |
| Dagorda Fm...3343 m | Hettangian | | |

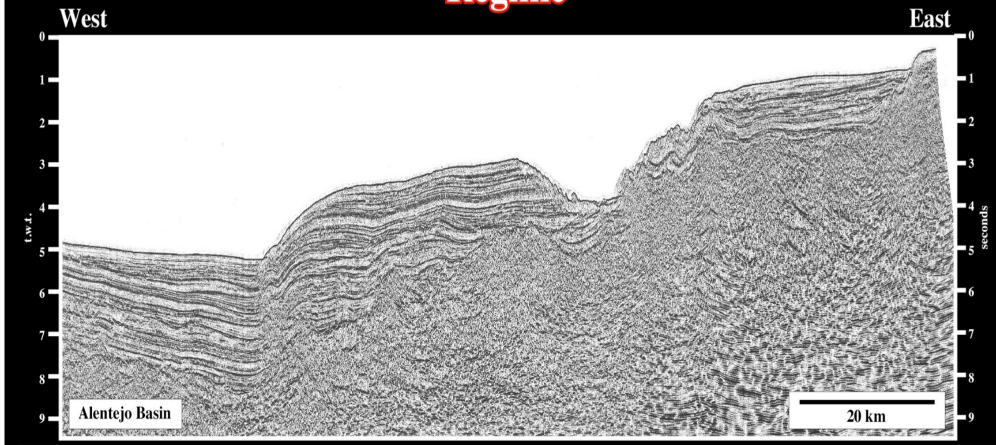



**Taking into account the discorformities and thickness variations induced by salt tectonics, particularly by compensatory subsidence (often ignored by field geologists), the rift-type basins and overlying margin sediments have been shortened, probably since Upper Miocene-Pliocene, by buckling and reactivation, in reverse movement, of the pre-existent normal fault bordering the rift type-basins, as depicted above.**

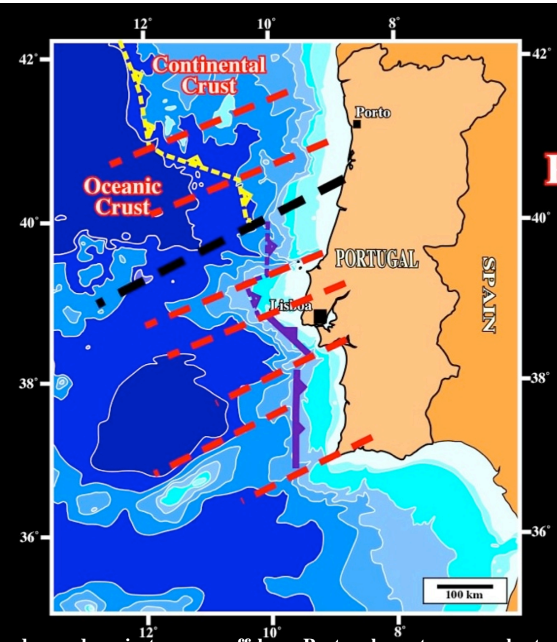



**The tectonic inversion is also corroborated by the seismic lines of the offshore, particularly in Alentejo Basin, where the sediments have been strongly shortened as illustrated by the next seismic line.**

# Regional Compressional Tectonic Regime




**The major compressional tectonic regime responsible by the shortening and uplift of the sediments of this seismic line (significant reverse fault on the western part) corroborates the hypothesis, advanced by few Portuguese geologists, that the southern part of the west offshore of Portugal is not anymore an Atlantic-type divergent margin, but a convergent margin. In other words, the second part of the Wilson cycle is already present, at least, in SW offshore of Iberia.**




# COB in Portugal Offshore

Possible B-Subduction

Hypothetical B-Subduction

Speculative B-Subduction

As a working hypothesis the COB can be proposed as depicted. A lengthening of the lithosphere and its break-up under a significant water depth, therefore without SDRs, northward of the major fracture zone, which limits a speculative subduction zone. Southward, the rifting and break-up took place in a nonmarine environment, eventually with formation of the SDRs that partially disappear in an hypothetical B-subduction zone. In Alentejo basin, due to the amplitude of the compression the B-subduction zone is considered as possible.

The advanced conjectures on offshore Portugal must, or can, be tested (criticised) by (i) new regional seismic data, (ii) tomographic studies, (iii) gravimetry studies (is there a positive gravity anomaly associated with the flexural bending?), (iv) evaporites composition (was the brine hydrothermally enriched ?), earthquake focal-mechanism. etc., etc. Please, send me your critics, since only with your criticism a new hypotheses can be advanced. Thank you very much.