Salt Tectonics

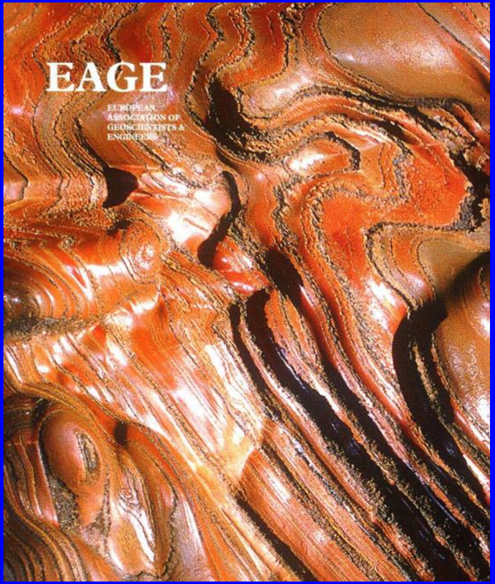
Salt is part of a group of chemically deposited minerals which crystallize by evaporation of salt-rich lake or seawater.

The largest known, and also economically most important salt occurrences on the earth are of marine origin.

Their chemical compositions reflect the original composition of the brine. The sequence of evaporites results from variations in the chemistry of the brine from which they were deposited.

The word ***salt*** *is used as a general name for evaporitic salts, like halite ($NaCl$), sylvite (KCl), carnallite ($KClMgCl_2.6H_2O$), kainite ($KClMgSO_4.2.75H_2O$), kieserite ($MgSO_4.H_2O$) and bischofite ($MgCl_2.6H_2O$).*

Eocenic evaporites (Spain) →



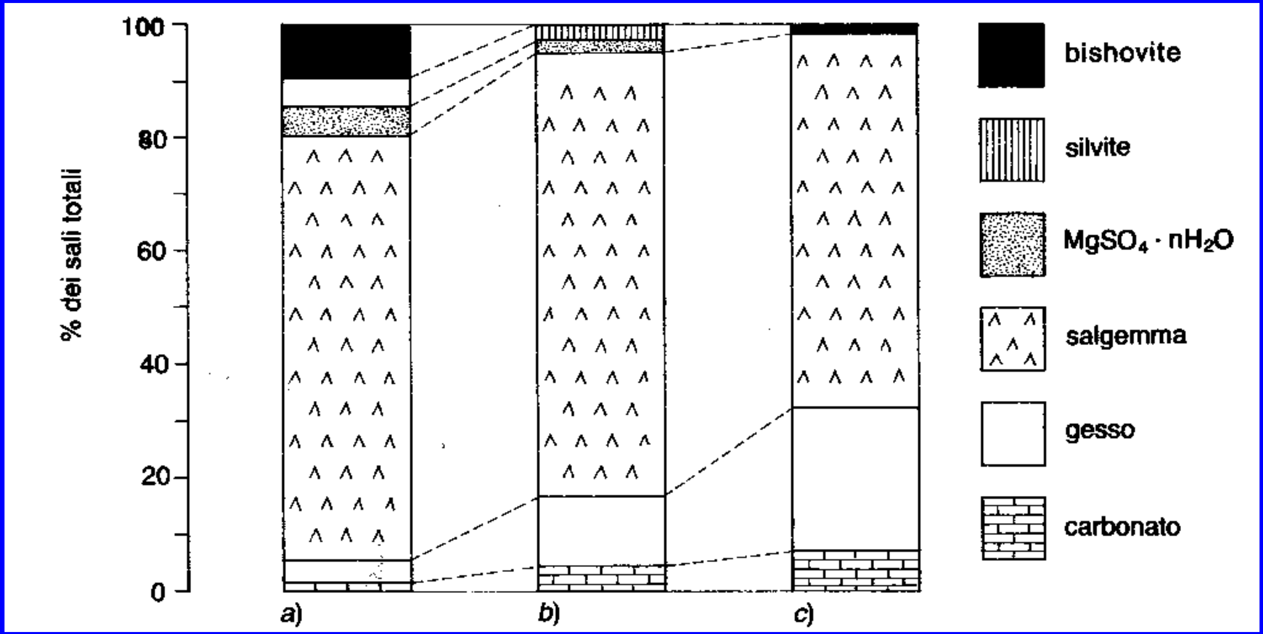
Minerals precipitate in reverse order of their solubility. In particular**:**

Calcite ($CaCO_3$) e **dolomite** ($CaMg(CO_3)_2$)

Gesso ($CaSO_4-2H_2O$) e **anidrite** ($CaSO_4$)

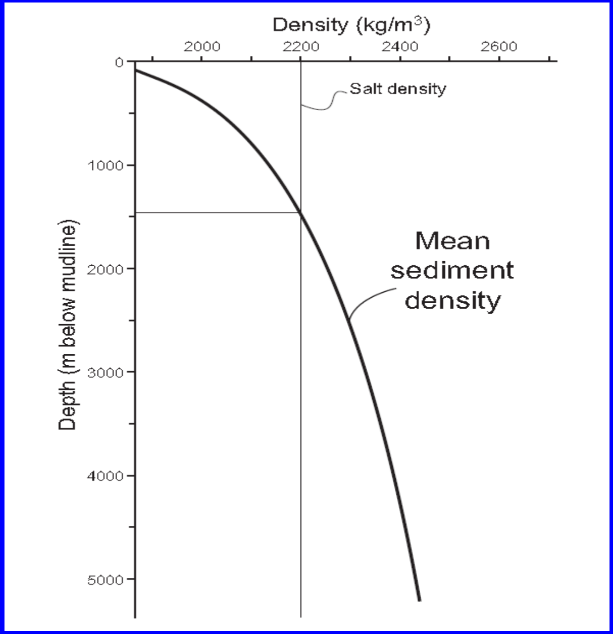
Halite cloruro di sodio o **salgemma**

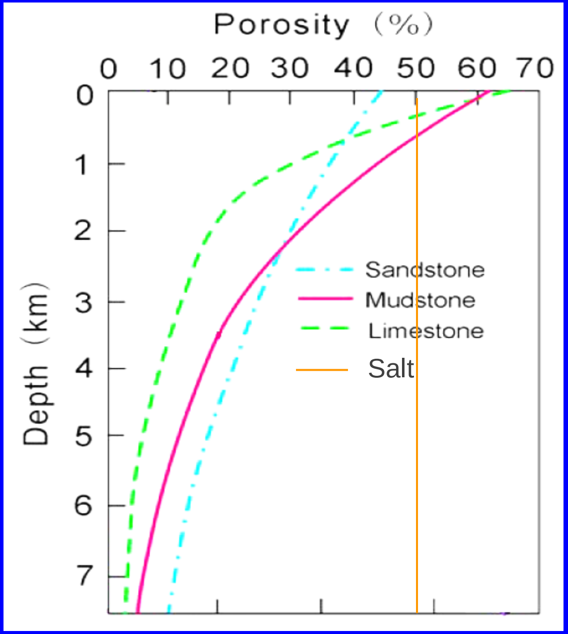
Silvite (cloruro di potassio) e **carnallite** (**cloruro idrato di potassio e magnesio**).



Relative abundance of the main precipitated by evaporation of sea water:
a) under experimental conditions for normal sea water;
b) in the succession of the Permian Zechstein;
c) average in evaporites.
Note the excess of carbonates and sulphates in the fossil sequences
(Borchert and Muir, 1964; Schmalz, 1969).

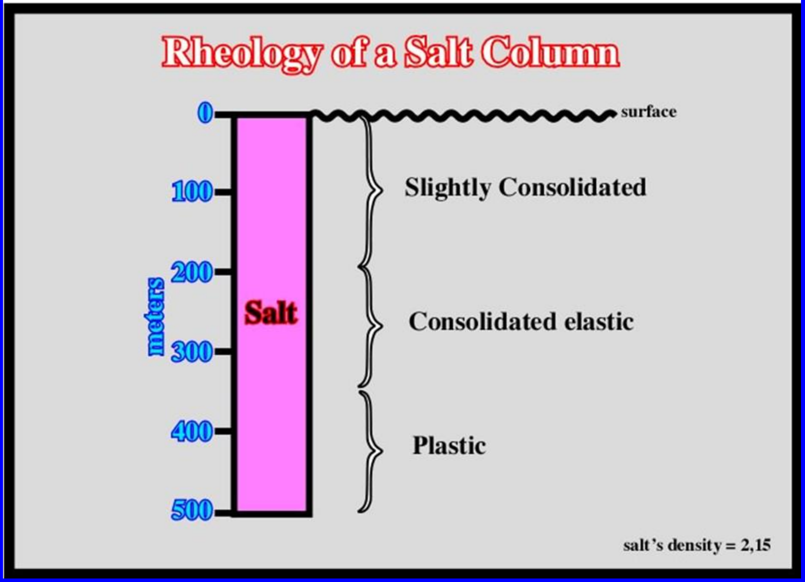
Salt is in many aspects unlike other sedimentary rocks. Not only it is able to form at geologically impressive sedimentation rates of up to 10 cm/a, i.e. up to 1000 times faster than clastic sediments (Schreiber & Hsü, 1980); furthermore it does not or hardly compact with depth since its density is controlled by its crystal structure. Most important, however, is its ability to deform plastically.





This is shown in many different settings around the world, from passive margins (e.g. Gulf of Mexico, West Africa), foldbelts (Zagros, Pyrenees), but also from rift and sag basins.

On a geological time scale, and when buried below 500 m, salt behaves in a visco-plastic way, whereas other sedimentary rocks show brittle deformation. Rock salt compacts already during early stages of burial to a tight mass with a constant density of 2168 kg/m^3.
Other sediments show an increase in density with depth owing to cementation and the reduction of pore volume as a function of overburden and pore pressures. Consequently, in near-surface positions, where sand and clay typically show densities of 1200 to 1400 kg/m^3, halite is relatively heavy, whilst below 500-1500 m it is lighter than surrounding rocks.
This results in an unstable situation.



Salt deformation starts beyond a certain pressure threshold (50-150 bars), depending on nature and composition of salt.
Plastic salt deformation can occur within a salt layer even in the absence of overburden.
A column of 500 m of salt can be considered as a vertical superposition of three salt intervals (-slightly consolidated, -consolidated elastic and -plastic) in term of rheology, because the geostatic pressure of the upper salt intervals.

PRINCIPALI EFFETTI DELLA PRESENZA DI SALE

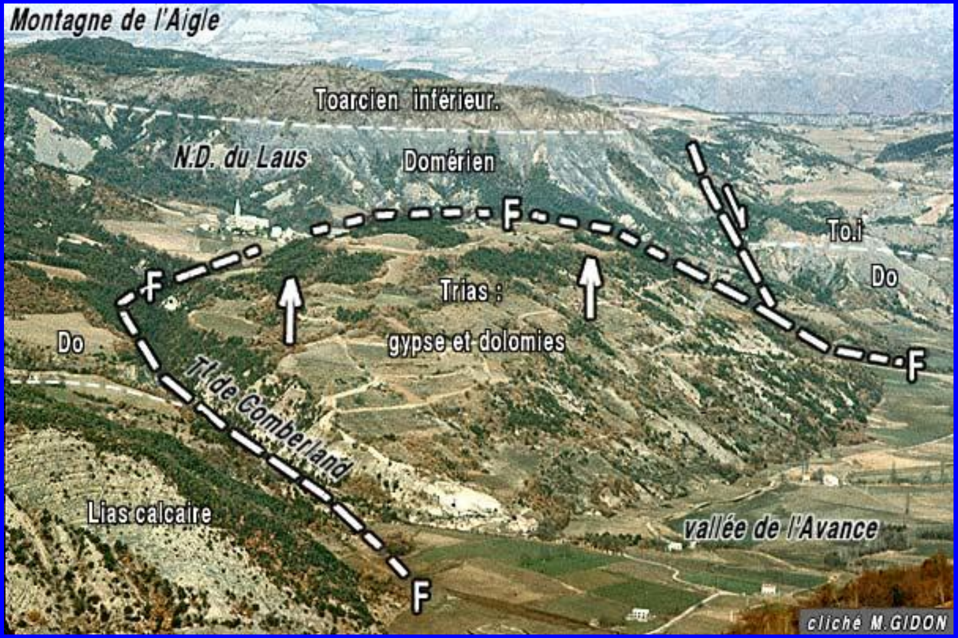
-A causa della sua reologia, il sale è in grado di moltiplicare le deformazioni tettoniche degli strati soprastanti

-Il sale controlla la formazione di trappole complesse per idrocarburi o altri minerali nelle sequenze sedimentarie che lo ricoprono

-La impermeabilità delle evaporiti controlla la dinamica dei fluidi e la loro distribuzione nell'intera sequenza sedimentaria

-Il flusso laterale di sale può causare frane subaeree o sottomarine →

-I diapiri salini possono offrire situazioni di *waste repositories*.

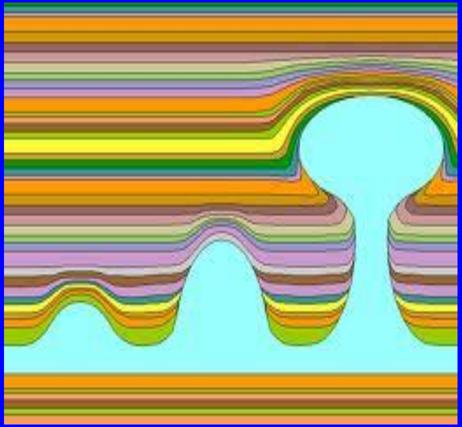


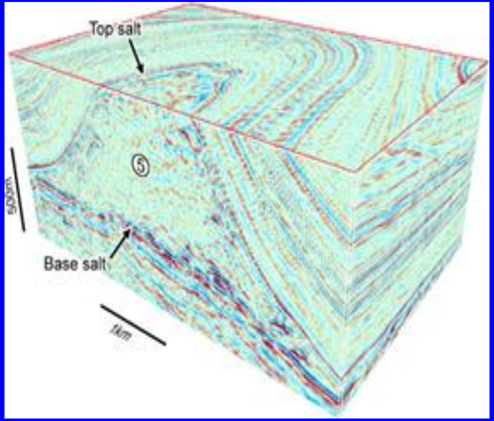
-Le interazioni di fluidi e sale possono causare erosione/dissoluzione di strati sepolti e successivo collasso, con conseguenze sulle infrastrutture.

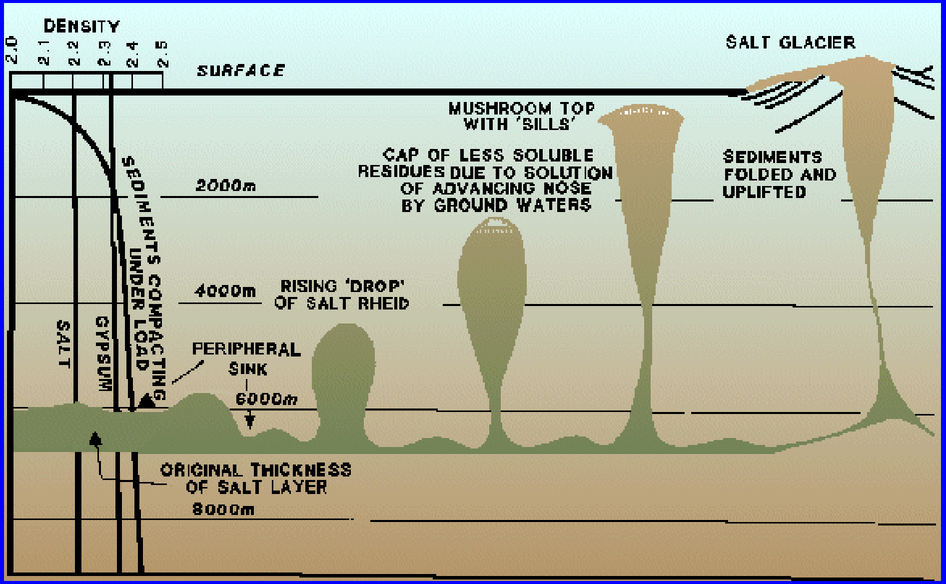
The rheological characteristics of salt origine the so called **HALOKYNETIC TECTONICS**.

Their first effect are **diapirs** (or **domes**) originated by salt flow.

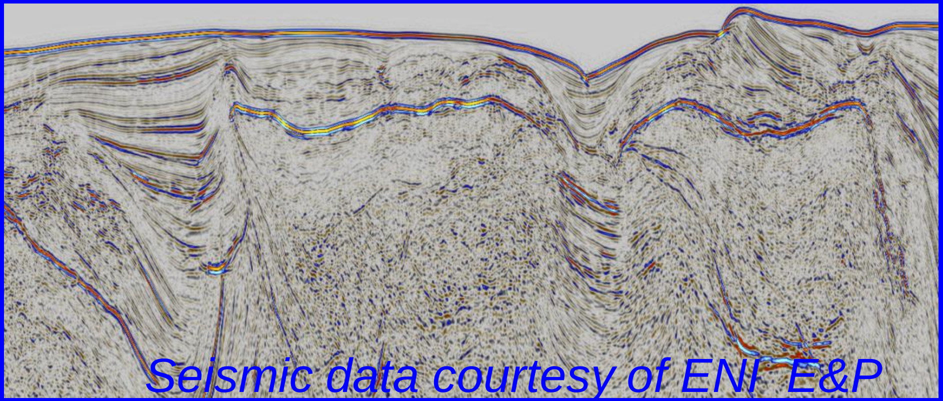
Diapirs can assume very different shapes and sizes, depending on:
-salt volume availability,
-sedimentary load
-faults activity
-deepening of the substratum
-different phase of halokynetic evolution





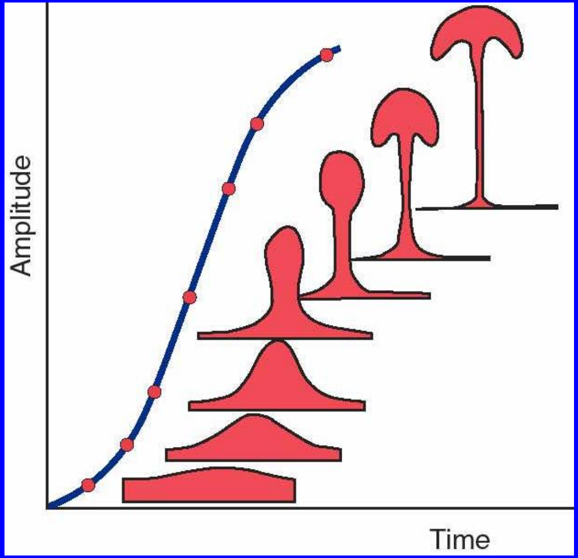


Seismic profile across the W-Africa margin: Different salt structures are evident; growth strata in the sedimentary cover date the halokynetic tectonics →

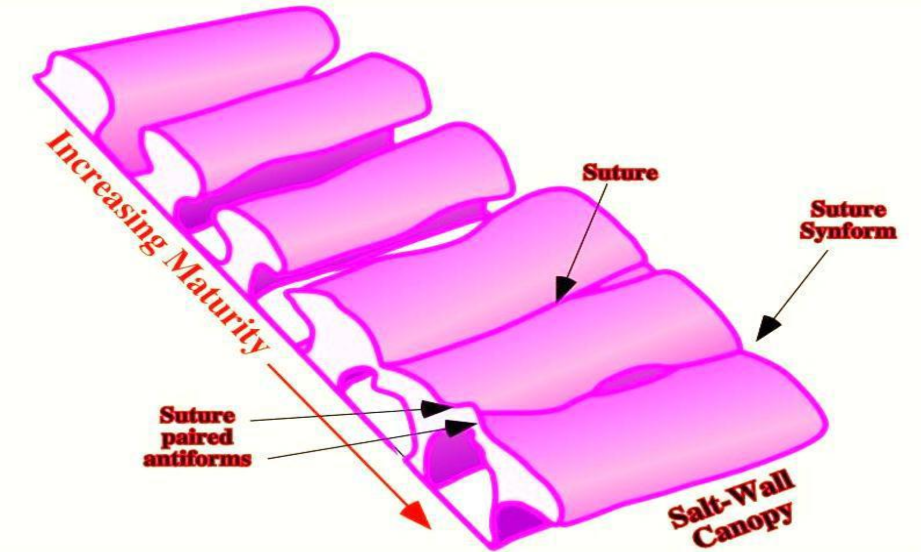


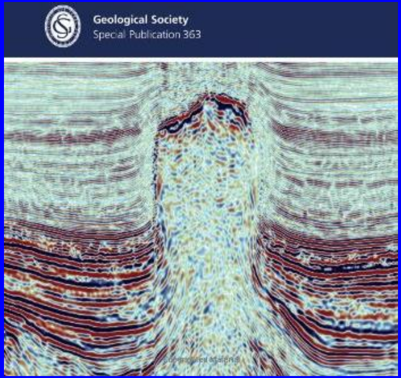
Seismic data courtesy of ENI E&P

Salt will initially flow mainly in a **lateral** sense, forming what is known as **salt pillows**. Above a pillow, the sedimentary cover is **not yet pierced**. In the next stage a pillow can evolve into a salt **diapir**. The growth of the pillow causes extension and subsequent faulting and weakening of the sedimentary cover above the evolving diapir (Jenyon, 1986; Remmelts, 1996). In cases of strong uplift, erosion may further weaken this cover. These processes take millions of years.



The boundary conditions for diapirism have met on a wide scale in the geological past. Several periods of structuration can be during which halokynesis has triggered, The Zechstein salt in the Netherlands has formed many diapirs during a long period of extension from the Mid Triassic to the Early Cretaceous, and a phase of compression during the Late Cretaceous to Early Tertiary. Many Zechstein salt structures are related to large faults in the substrate; **elongated salt walls**, like along the margins of the Dutch Central Graben are related to long fault zones, whereas isolated, **circular domes** developed over intersecting faults

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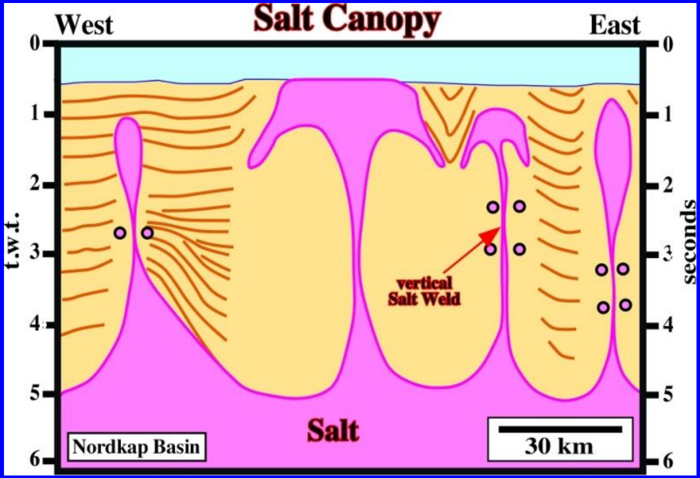
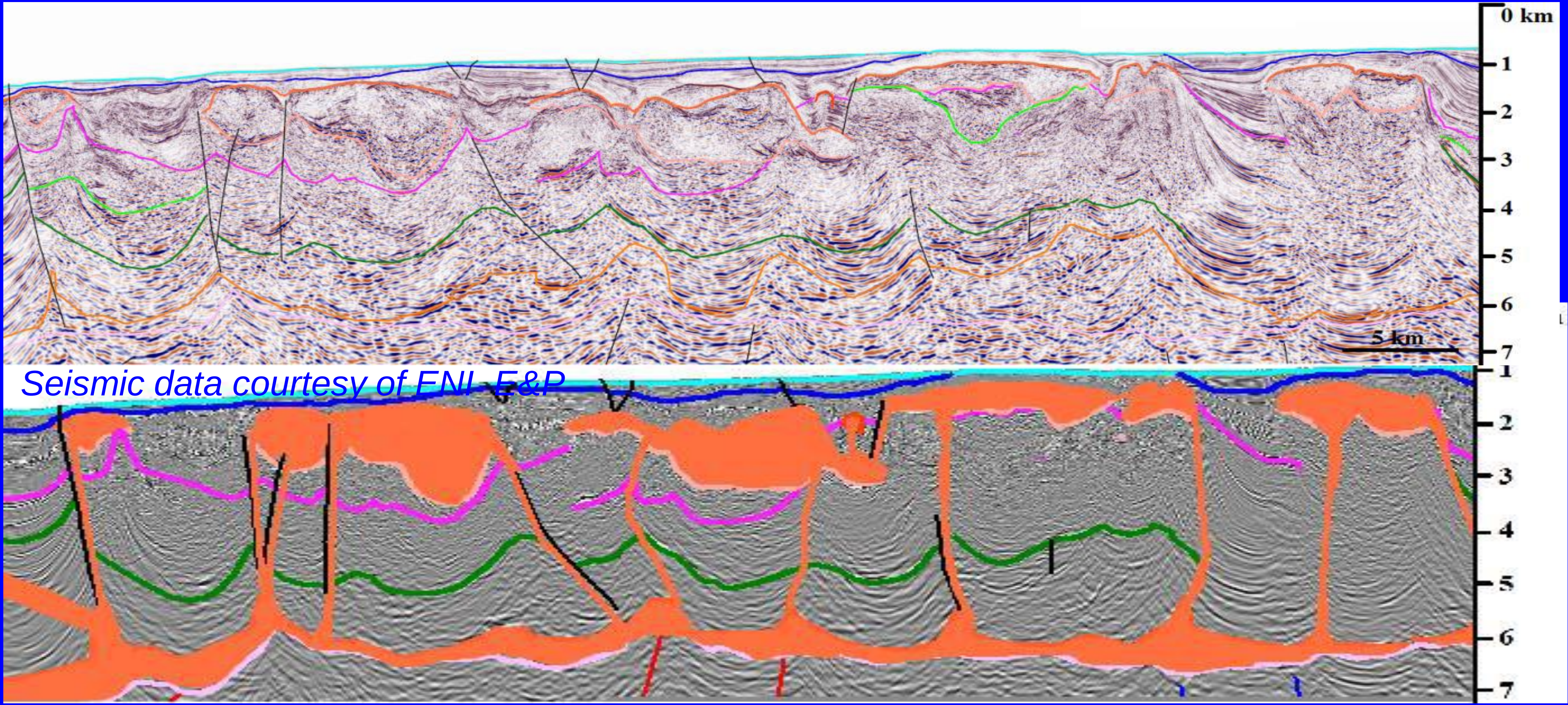
Special Publication 363

Salt Canopy



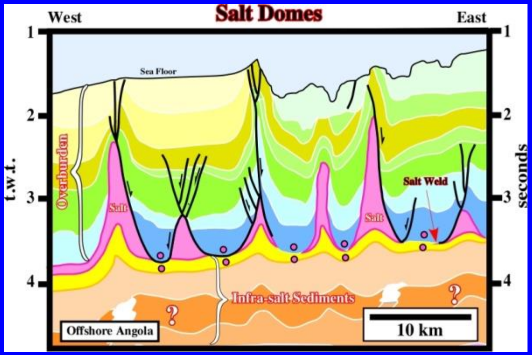
Composite diapiric structure formed by partial or complete coalescence of diapir bulbs or salt sheet. These coalescence bodies may or may not be connected to their source layer.

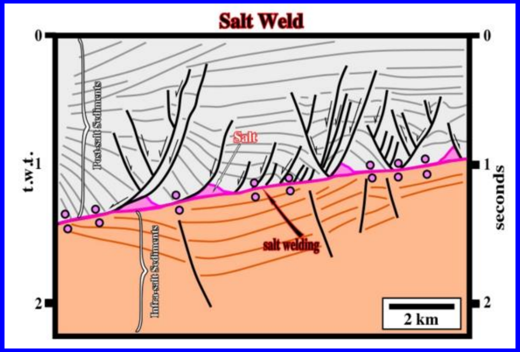
During longtime erroneously large diapiric structures (>30 km wide) were proposed for these profiles in W-Africa. With such large salt structures explorationists give up the area due to absence of significant Traps. It is obvious that interpretations with salt canopy structures strongly change the petroleum potential, at least the trapping parameter.

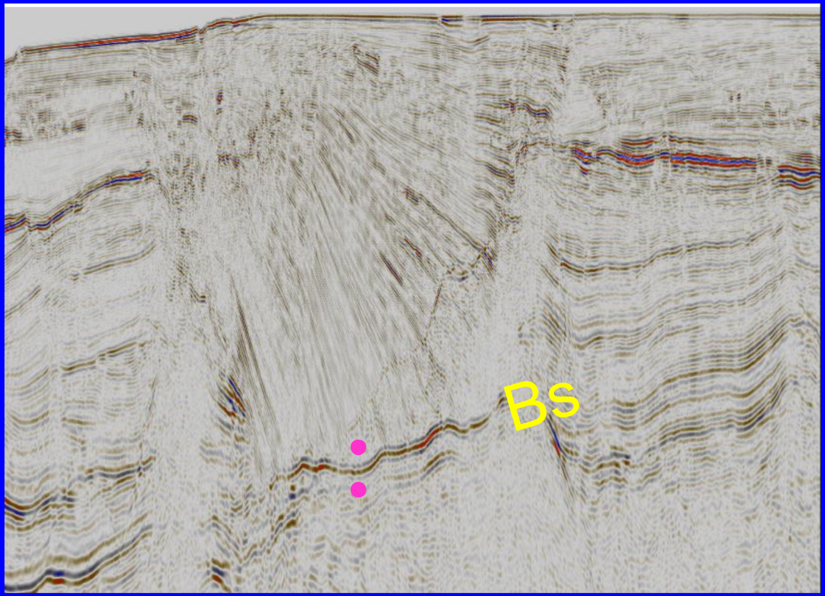


Seismic data courtesy of ENI E&P

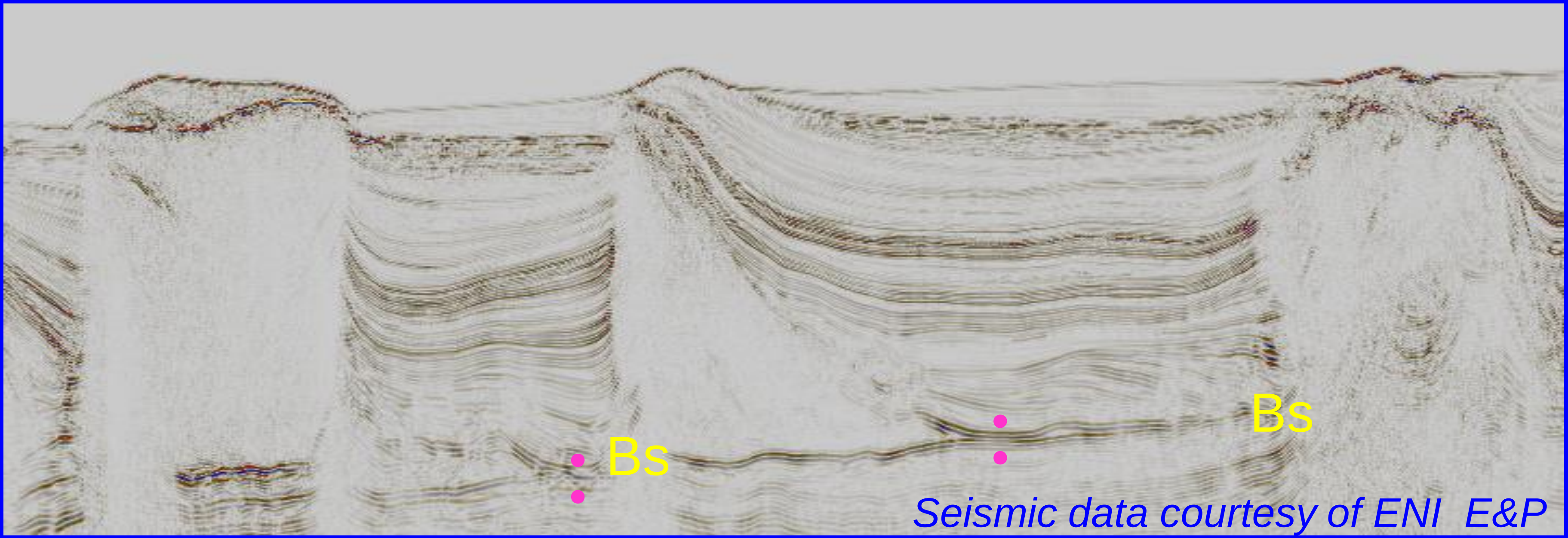
Welds（：）



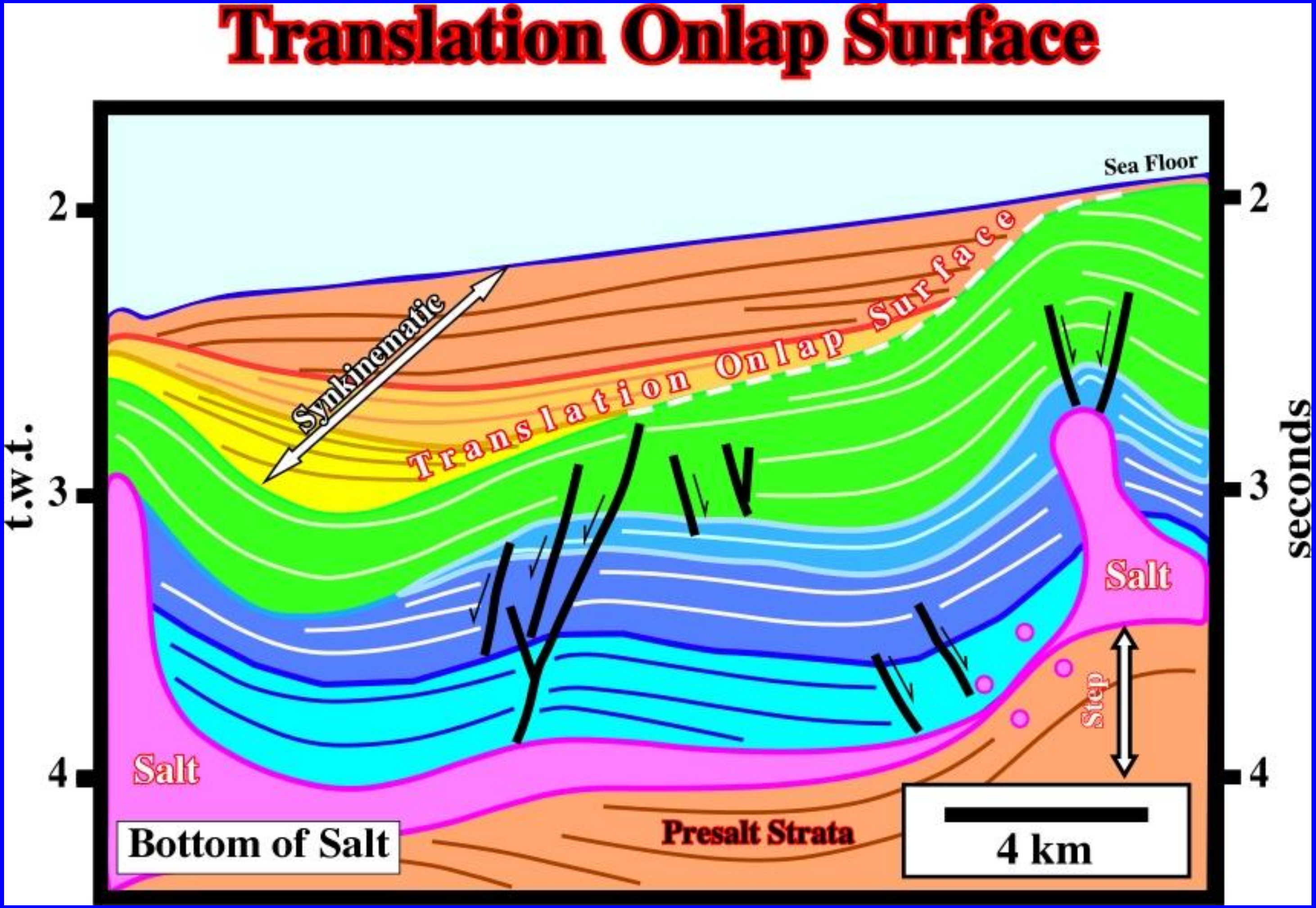




Sliding on the deepening substratum:
this sliding sometimes puts directly in contact the sequence covering the salt layer and the pre-salt sediments, originating a so called "weld" (:). Note present halokynetics

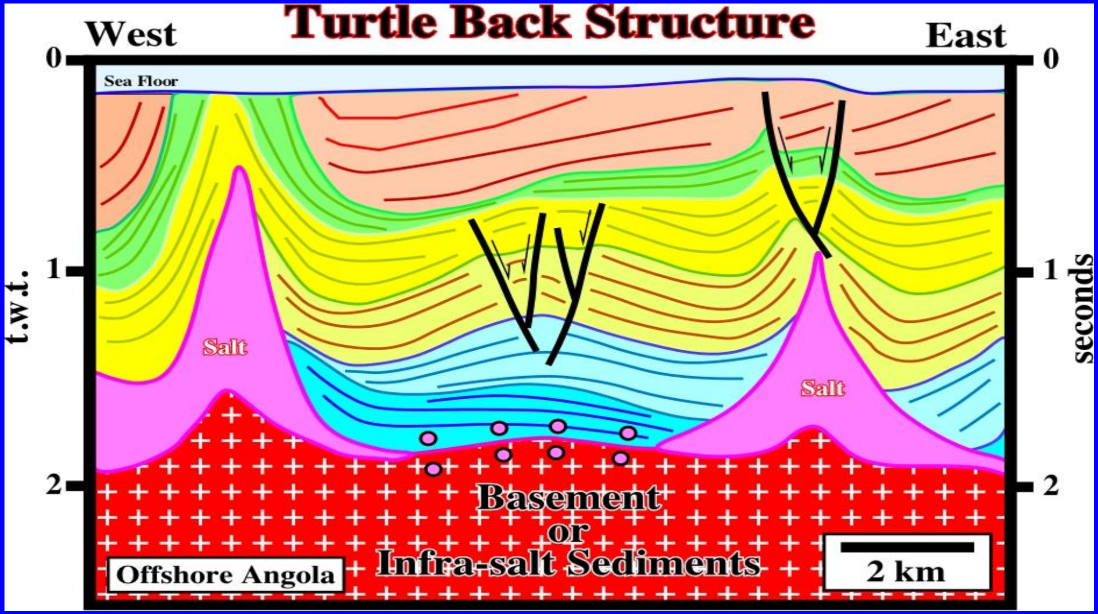


Seismic data courtesy of ENI E&P



Translation Onlap Surfaces: note the recent diapir on the left.

Translation of the overburden across a stepped salt detachment (thin salt) bends the post-salt sediments and can create apparent translation downlap surfaces (gliding onlaps) in the synkinematic layers.

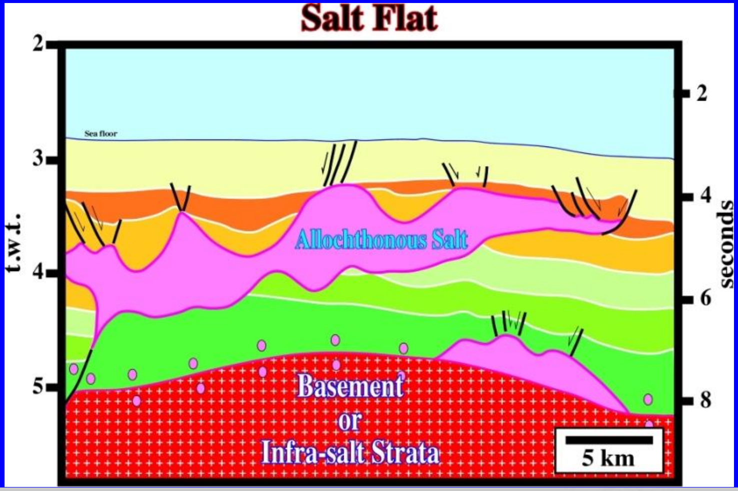


Turtle structures have a flat base and rounded crest over a sedimentary thick. The antiform may or may not be cored by a low salt pillow.

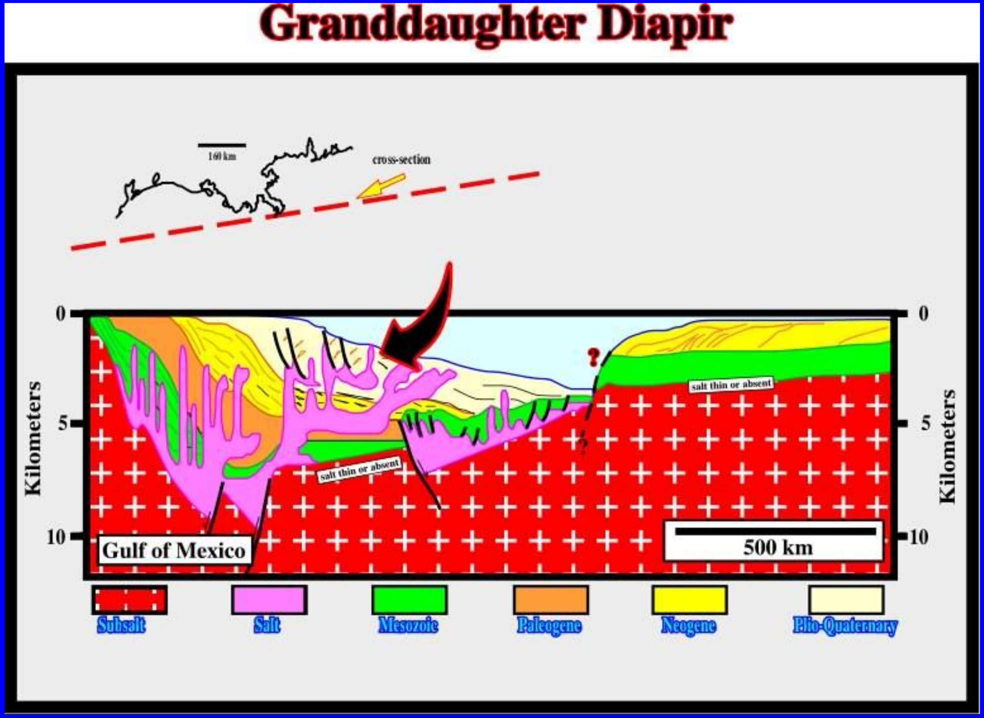
The turtle structure forms by structural inversion of a primary peripheral sink when salt is withdrawn.

Theoretically, in a real turtle back structure, there is a tectonic inversion, in which structural high points become low points and vice versa.

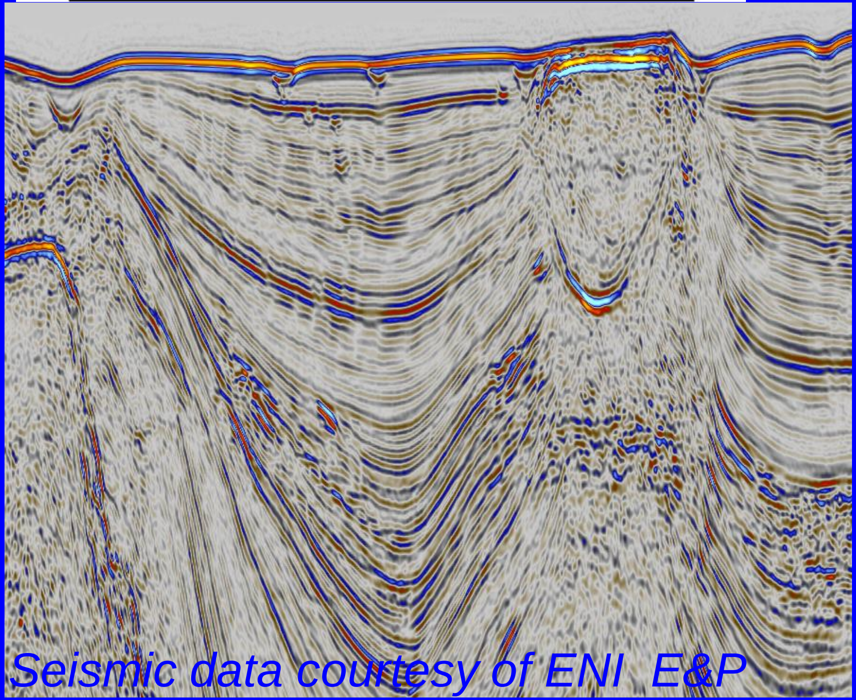
Sometimes salt diapirs become **mother** layer for new shallower salt migration, originating second-generation (or granddaughter) diapirs



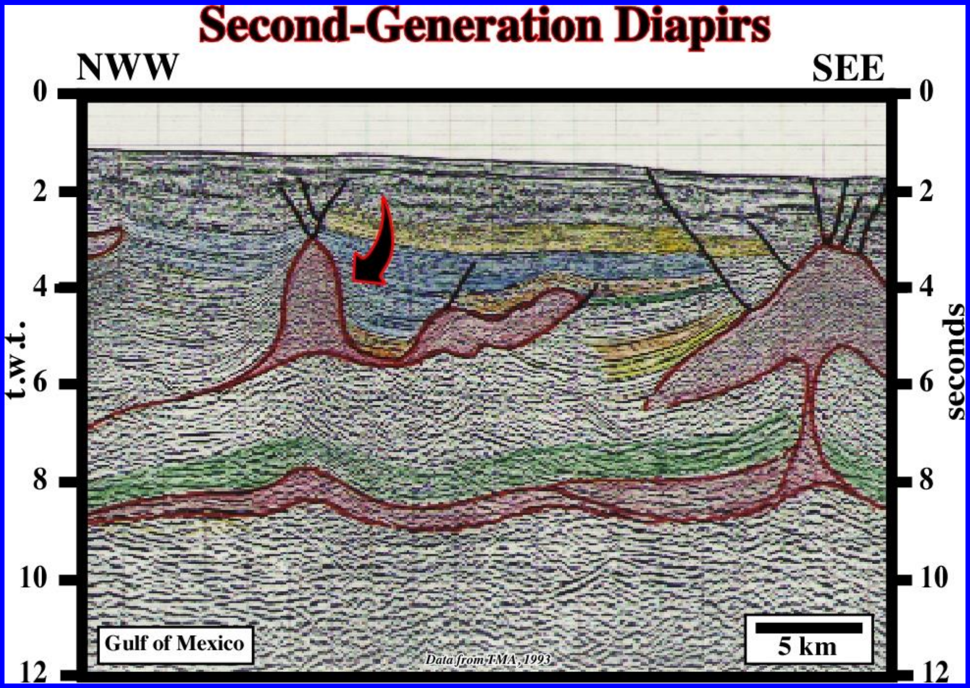
Salt Flat



Granddaughter Diapir



Seismic data courtesy of ENI E&P



Second-Generation Diapirs

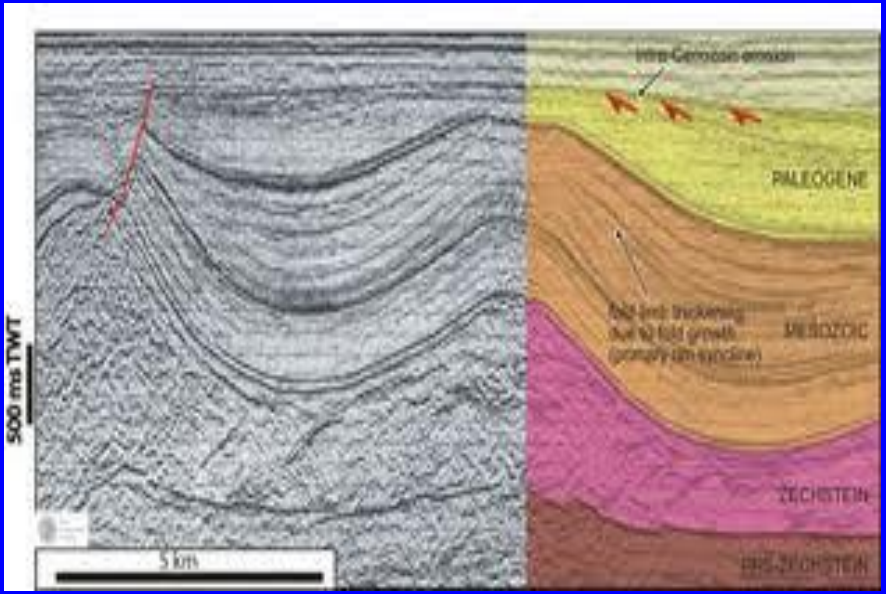
Data from TMA, 1993

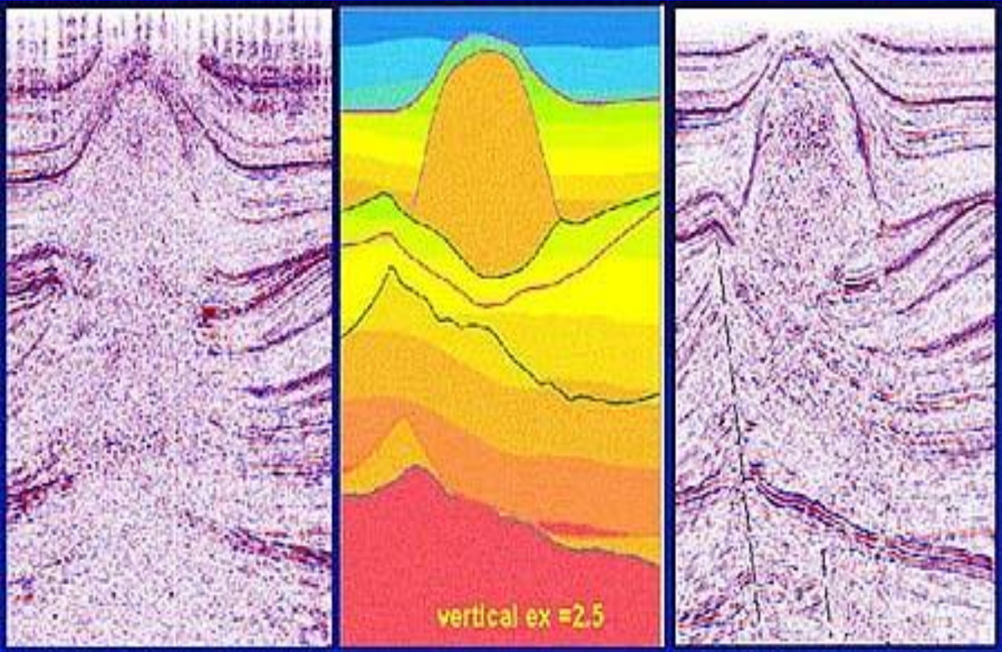
Note:

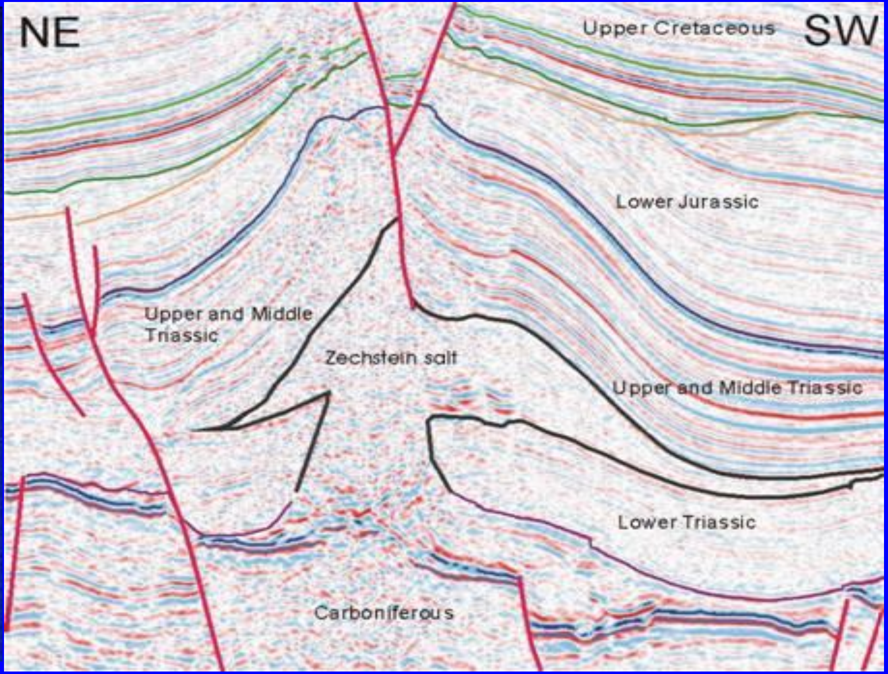
-<u>toplap</u> geometries of pre-halokynetics reflectors;

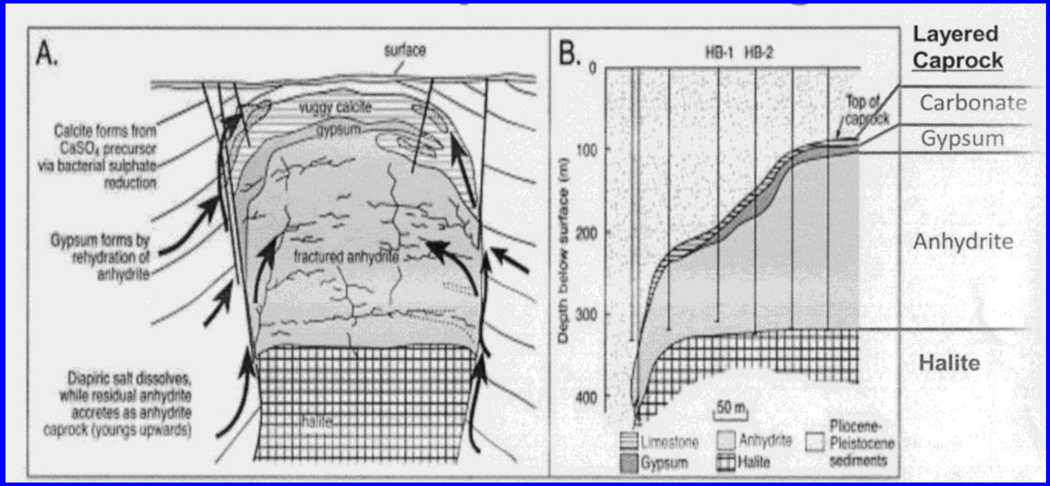
-typical <u>velocity pull-up</u> below the salt diapirs in the twt profiles

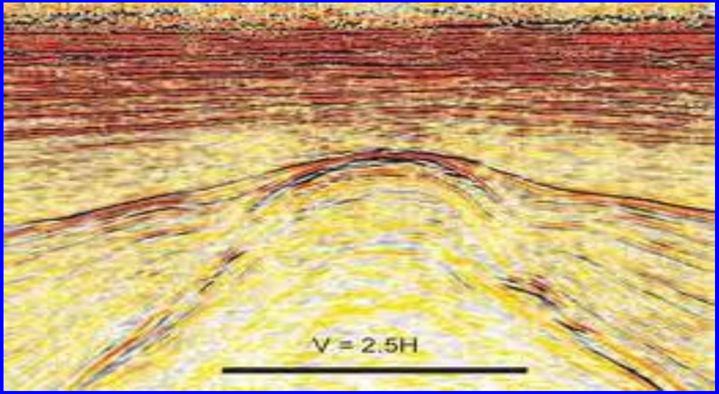
-improving of pre-salt reflectors by re-processing

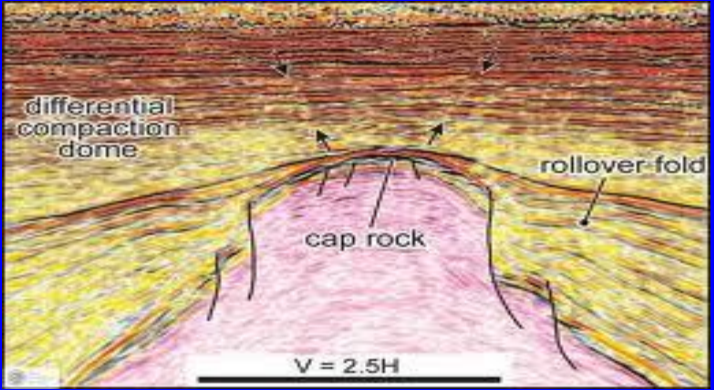


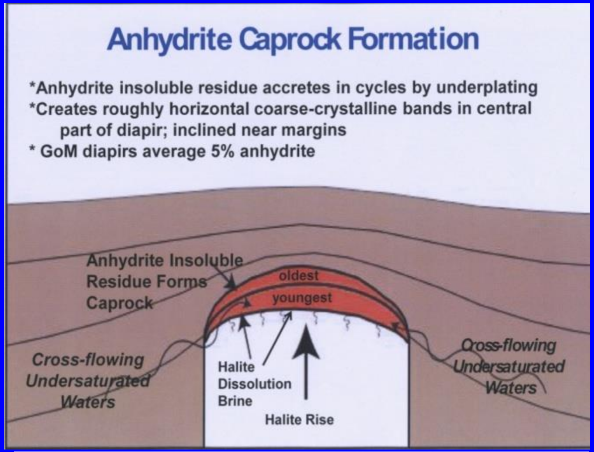






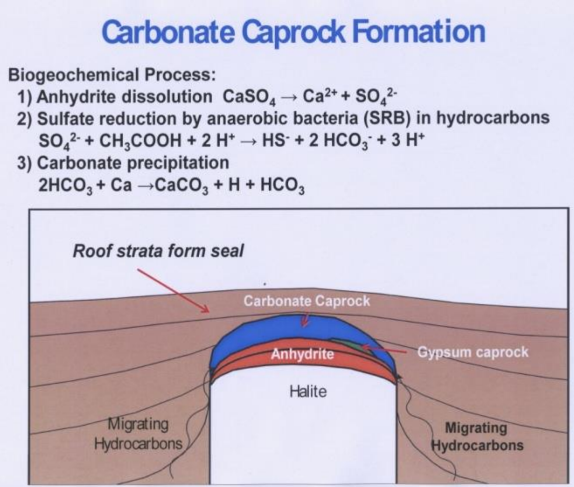






Anhydrite Caprock Formation

*Anhydrite insoluble residue accretes in cycles by underplating
*Creates roughly horizontal coarse-crystalline bands in central part of diapir; inclined near margins
* GoM diapirs average 5% anhydrite



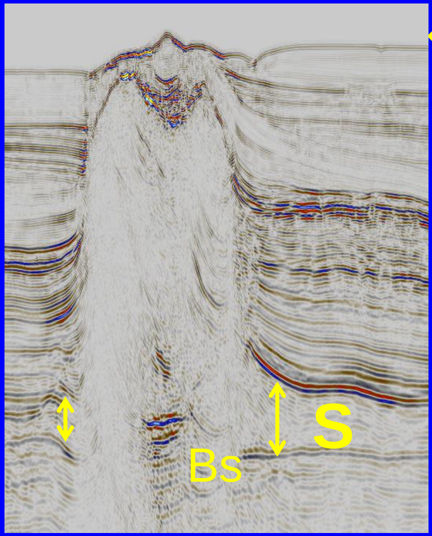
Carbonate Caprock Formation

Biogeochemical Process:
1) Anhydrite dissolution $CaSO_4 \rightarrow Ca^{2+} + SO_4^{2-}$
2) Sulfate reduction by anaerobic bacteria (SRB) in hydrocarbons
$SO_4^{2-} + CH_3COOH + 2\,H^+ \rightarrow HS^- + 2\,HCO_3^- + 3\,H^+$
3) Carbonate precipitation
$2HCO_3 + Ca \rightarrow CaCO_3 + H + HCO_3$

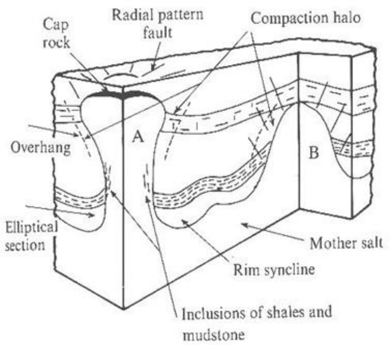
COMMON CAPROCK LITHOLOGIES

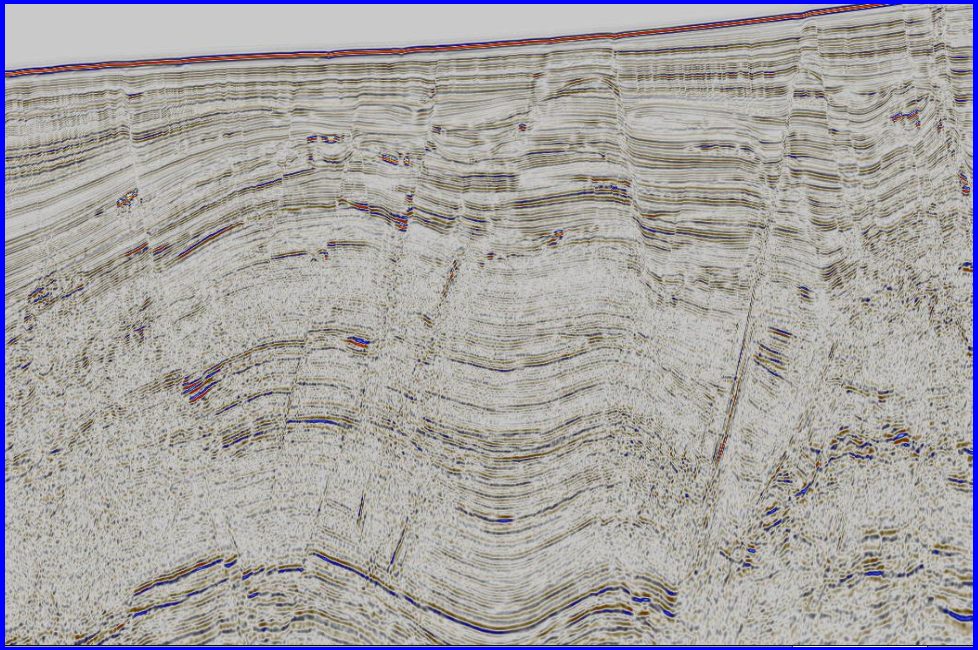
Caprock forms by the dissolution of the upper part of a salt structure once salt supply dwindles the rate of rise slows and it is flushed by undersaturated phreatic waters (black arrows in Fig.A). Dissolution of the halite leaves behind anhydrite that then accretes into an anhydrite caprock. The upper portion of the anhydrite unit rehydrates to gypsum that is then converted to limestone by bacterial sulphate reduction.

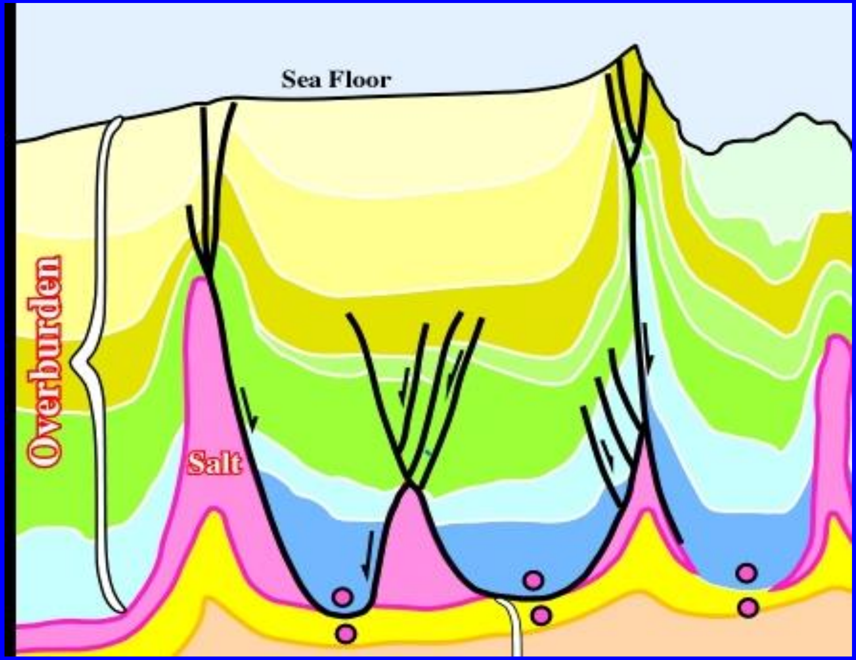
Concentric fault systems above salt domes

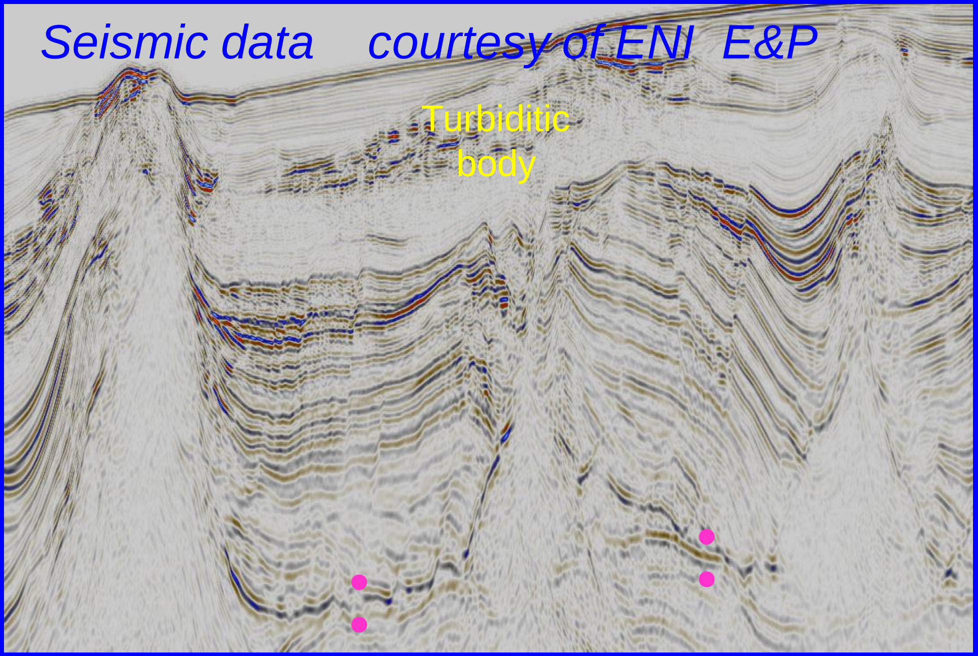


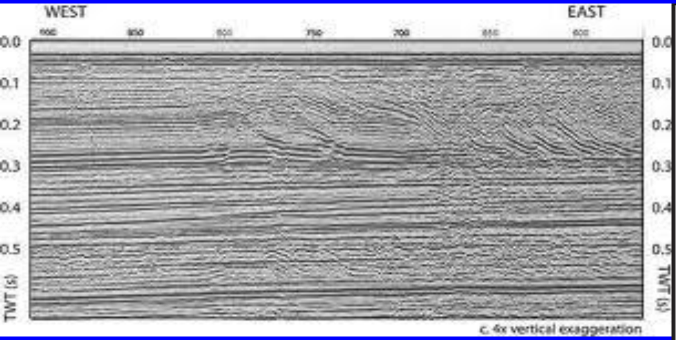
← Note different depths of sea bottom and other reflectors and of salt thickness







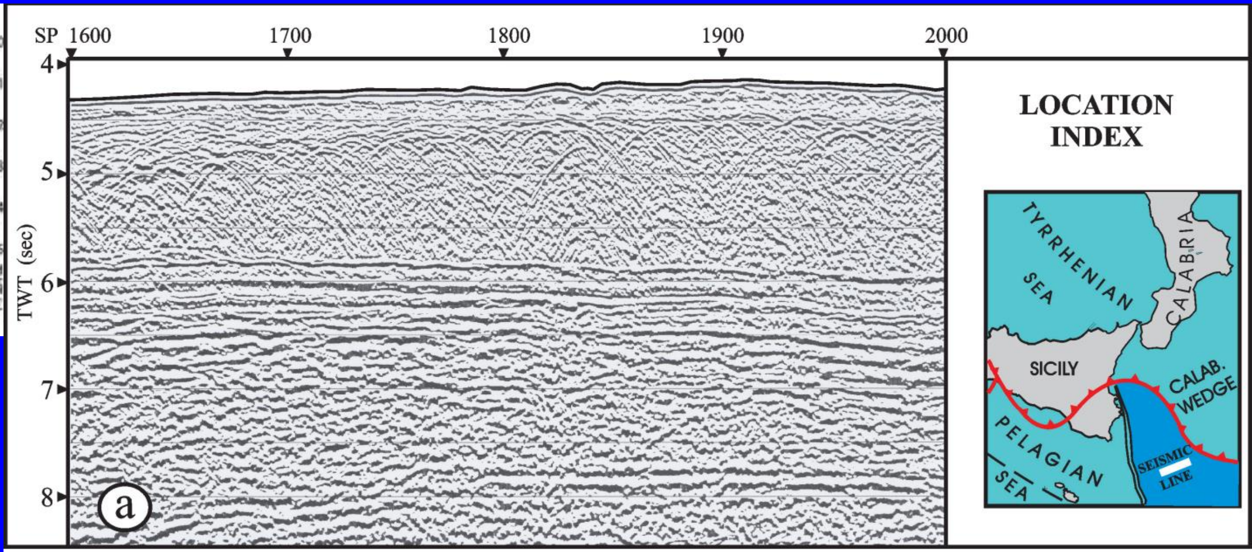

Seismic data courtesy of ENI E&P



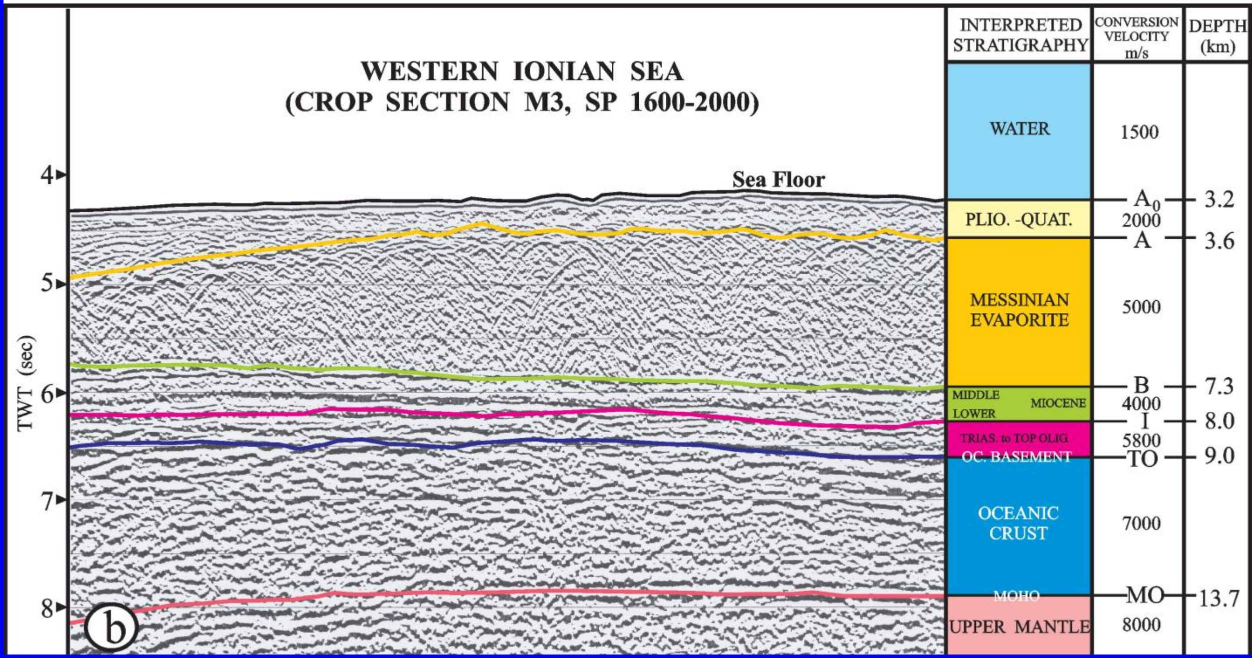
Because of its rheology, salt can highly increase tectonic deformations of the overlaying sediments.

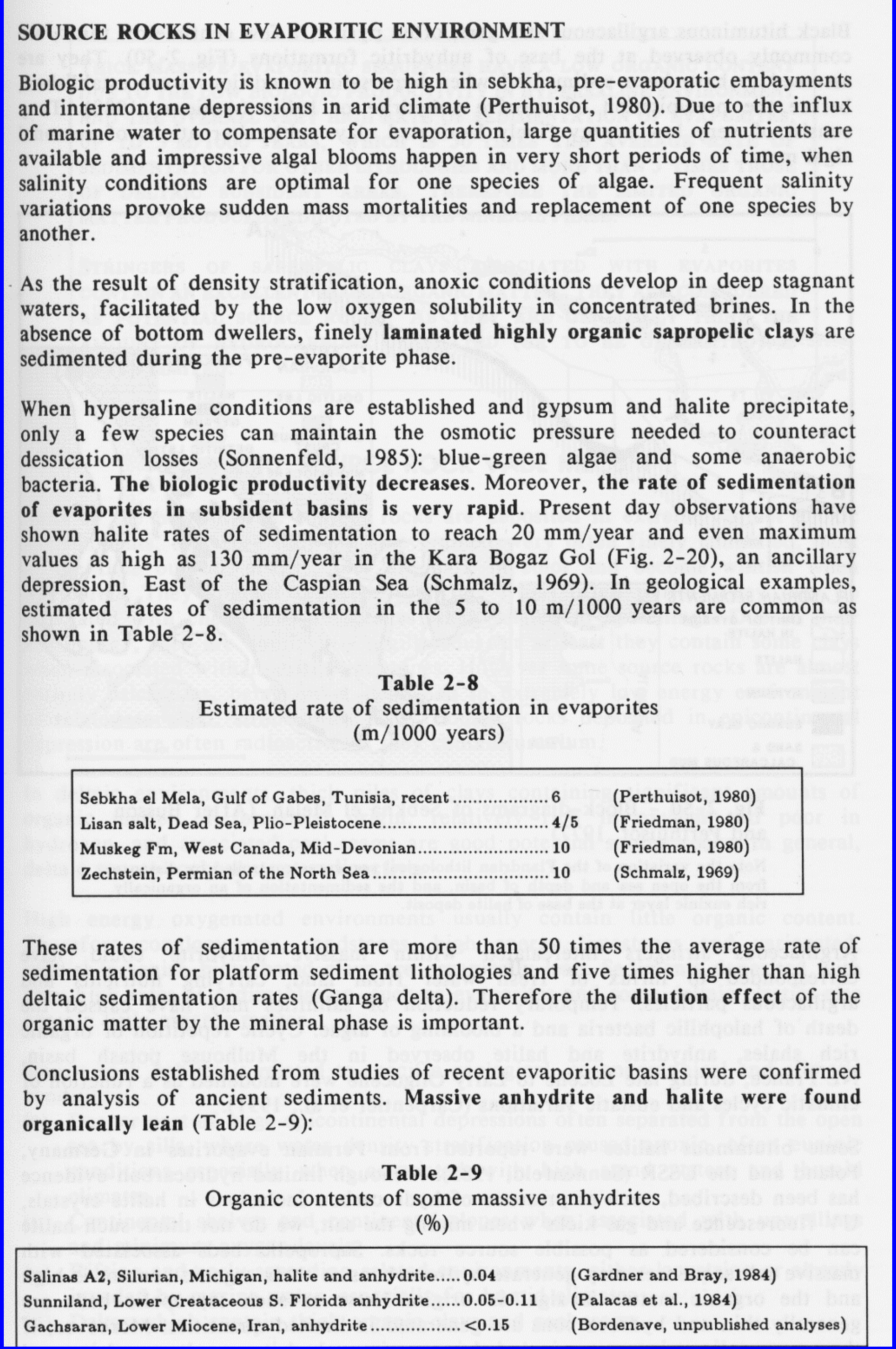
E.g., the presence of the Messinian salt in the Ionian basin allows the compressive tectonics of the Calabrian and Hellenic Arcs to expand on a very large gently deformed region called “cobblestone area”.

Note that compressive stress doesn’t affect the pre-salt sequence.



INTERPRETED CRUSTAL SEISMIC STRATIGRAPHY OF THE IONIAN SEA





SOURCE ROCKS IN EVAPORITIC ENVIRONMENT

Biologic productivity is known to be high in sebkha, pre-evaporatic embayments and intermontane depressions in arid climate (Perthuisot, 1980). Due to the influx of marine water to compensate for evaporation, large quantities of nutrients are available and impressive algal blooms happen in very short periods of time, when salinity conditions are optimal for one species of algae. Frequent salinity variations provoke sudden mass mortalities and replacement of one species by another.

As the result of density stratification, anoxic conditions develop in deep stagnant waters, facilitated by the low oxygen solubility in concentrated brines. In the absence of bottom dwellers, finely **laminated highly organic sapropelic clays** are sedimented during the pre-evaporite phase.

When hypersaline conditions are established and gypsum and halite precipitate, only a few species can maintain the osmotic pressure needed to counteract dessication losses (Sonnenfeld, 1985): blue-green algae and some anaerobic bacteria. **The biologic productivity decreases.** Moreover, **the rate of sedimentation of evaporites in subsident basins is very rapid.** Present day observations have shown halite rates of sedimentation to reach 20 mm/year and even maximum values as high as 130 mm/year in the Kara Bogaz Gol (Fig. 2-20), an ancillary depression, East of the Caspian Sea (Schmalz, 1969). In geological examples, estimated rates of sedimentation in the 5 to 10 m/1000 years are common as shown in Table 2-8.

Table 2-8

Estimated rate of sedimentation in evaporites
(m/1000 years)

Sebkha el Mela, Gulf of Gabes, Tunisia, recent	6	(Perthuisot, 1980)
Lisan salt, Dead Sea, Plio-Pleistocene	4/5	(Friedman, 1980)
Muskeg Fm, West Canada, Mid-Devonian	10	(Friedman, 1980)
Zechstein, Permian of the North Sea	10	(Schmalz, 1969)

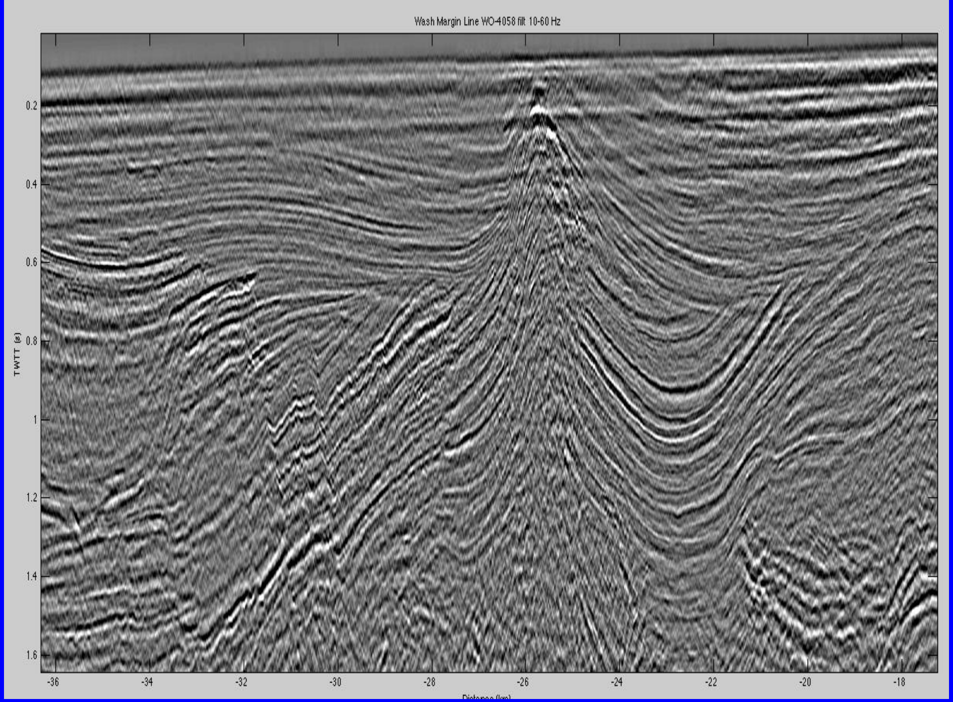
These rates of sedimentation are more than 50 times the average rate of sedimentation for platform sediment lithologies and five times higher than high deltaic sedimentation rates (Ganga delta). Therefore the **dilution effect** of the organic matter by the mineral phase is important.

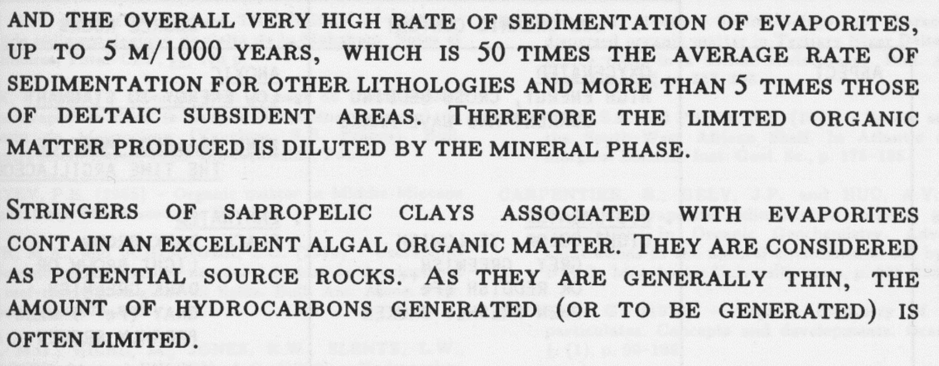
Conclusions established from studies of recent evaporitic basins were confirmed by analysis of ancient sediments. **Massive anhydrite and halite were found organically lean** (Table 2-9):

Table 2-9

Organic contents of some massive anhydrites
(%)

Salinas A2, Silurian, Michigan, halite and anhydrite	0.04	(Gardner and Bray, 1984)
Sunniland, Lower Creataceous S. Florida anhydrite	0.05-0.11	(Palacas et al., 1984)
Gachsaran, Lower Miocene, Iran, anhydrite	<0.15	(Bordenave, unpublished analyses)



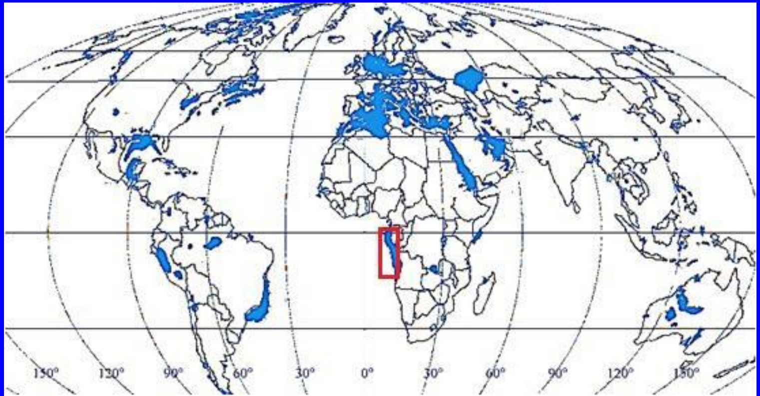


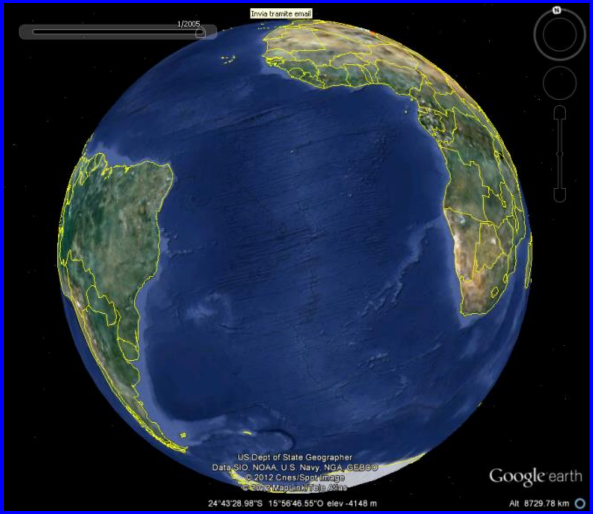
Thick massive evaporitic sequences have a low organic content due to the low biologic productivity in hypersaline environment and the overall very high rate of sedimentation of evaporites, up to 5 m/1000 years, which is 50 times the average rate of sedimentation for other lithologies and more than 5 times those of deltaic subsident areas. Therefore the limited organic matter produced is diluted by the mineral phase.

Stringers of sapropelic clays associated with evaporites contain an excellent algal organic matter. They are considered as potential source rocks. As they are generally thin, the amount of hydrocarbons generated (or to be generated) is often limited.

Main evaporite sequences in the world
… what are their common origine?
… restricted euxinic basins with high evaporation rate

Mediterranean Sea

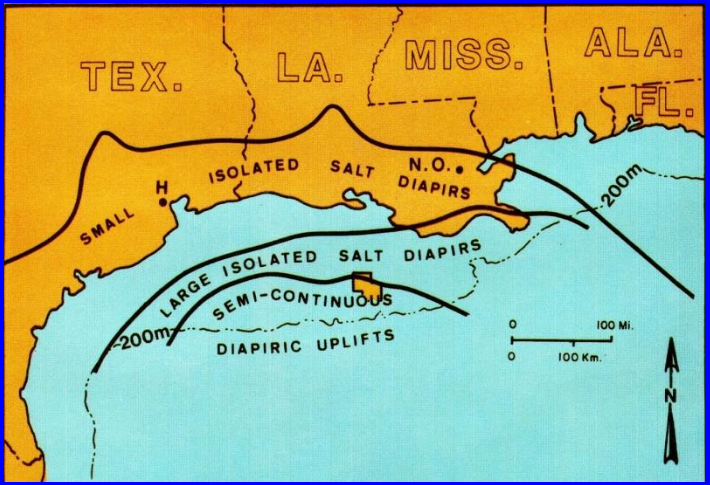




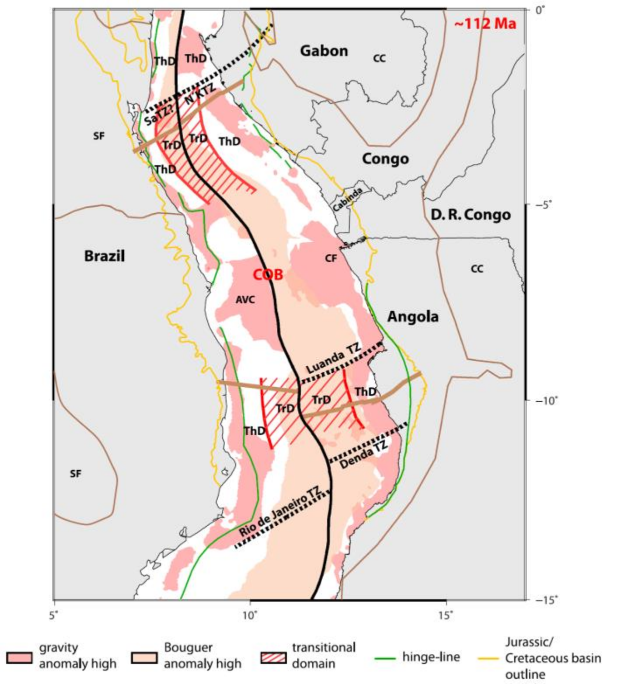
South-Atlantic margins

Pre-Caspian basin

North Sea

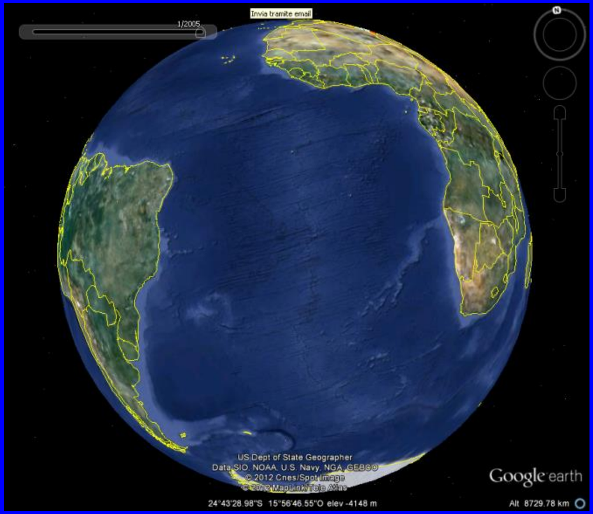


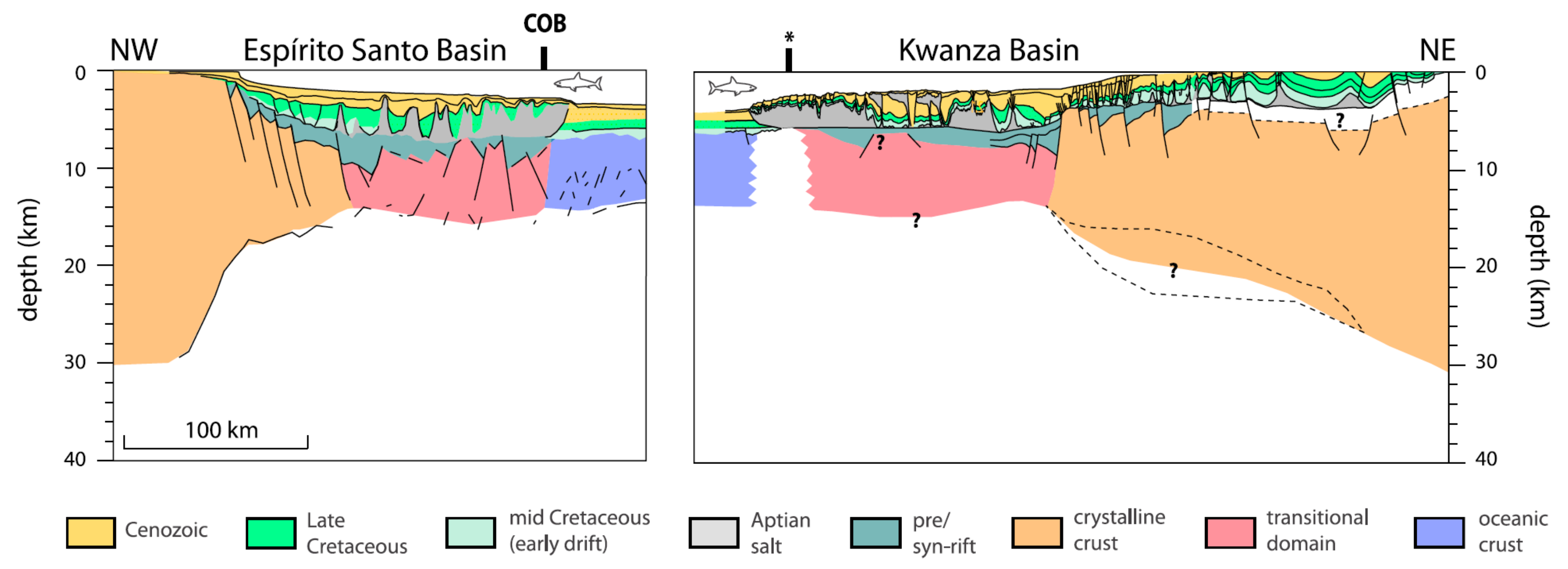
Gulf of Mexico

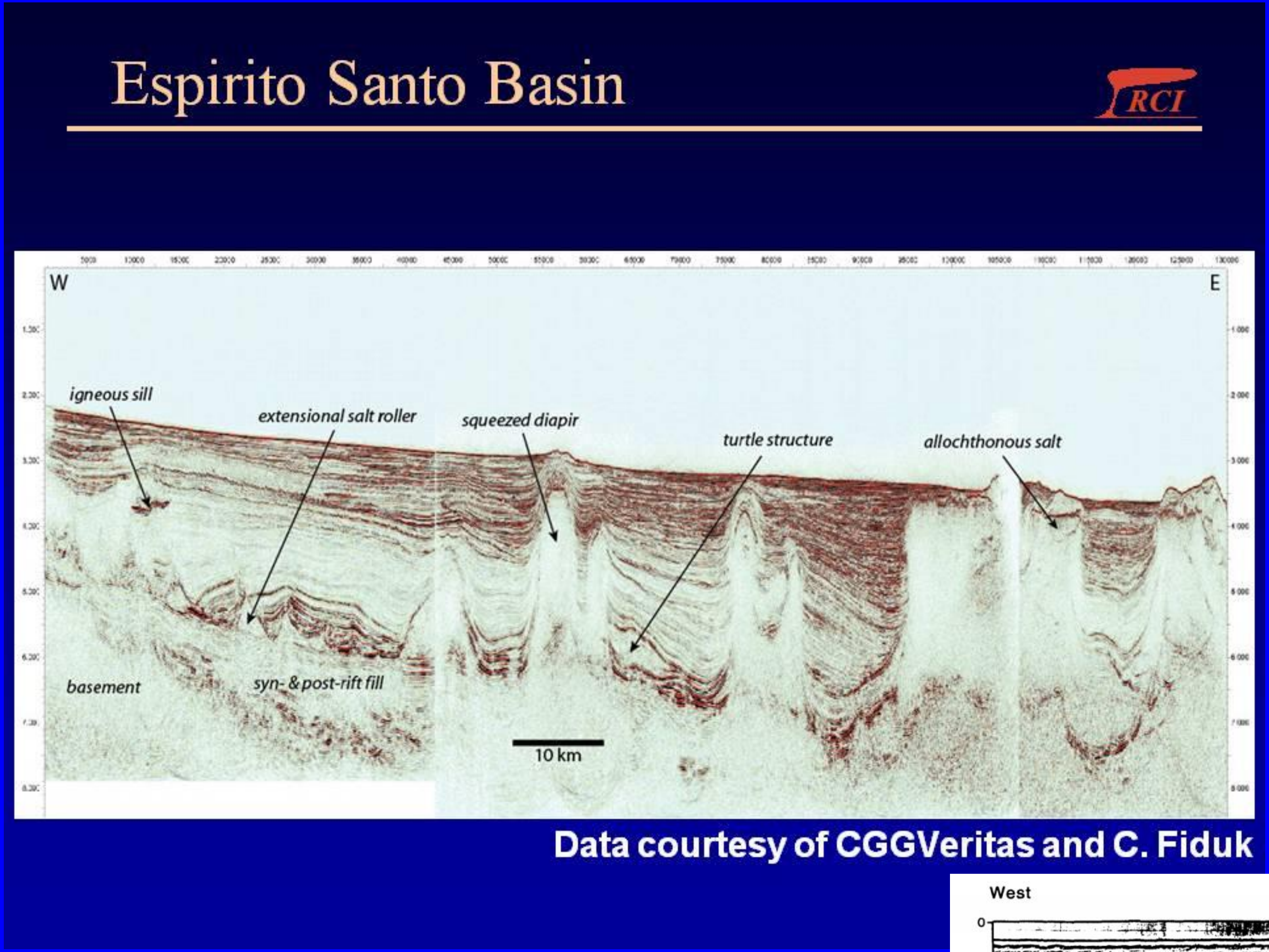


South-Atlantic margins

… restricted euxinic basins with high evaporation rate

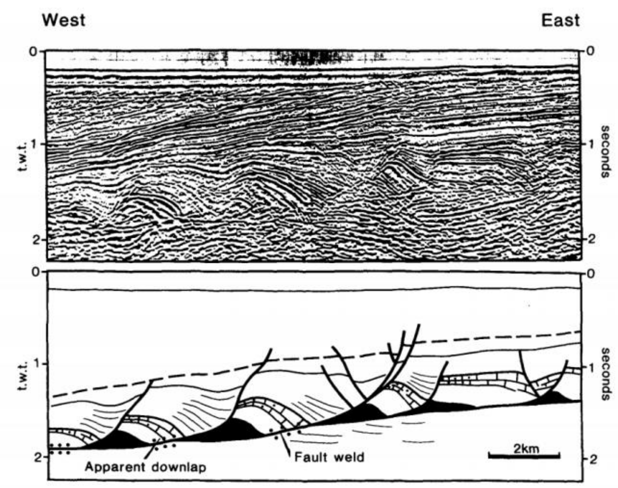






Espirito Santo Basin

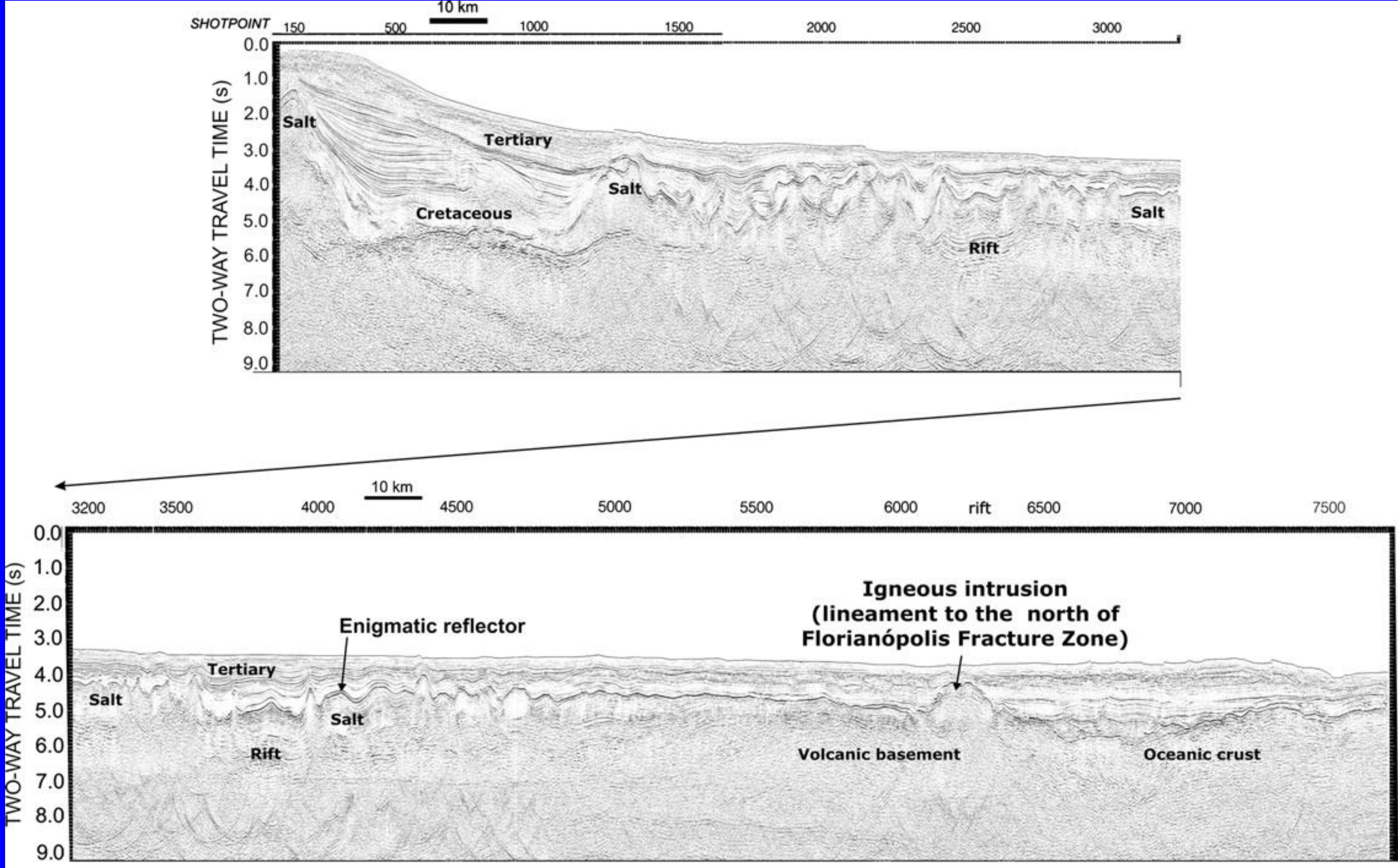
Data courtesy of CGGVeritas and C. Fiduk



South Atlantic margins

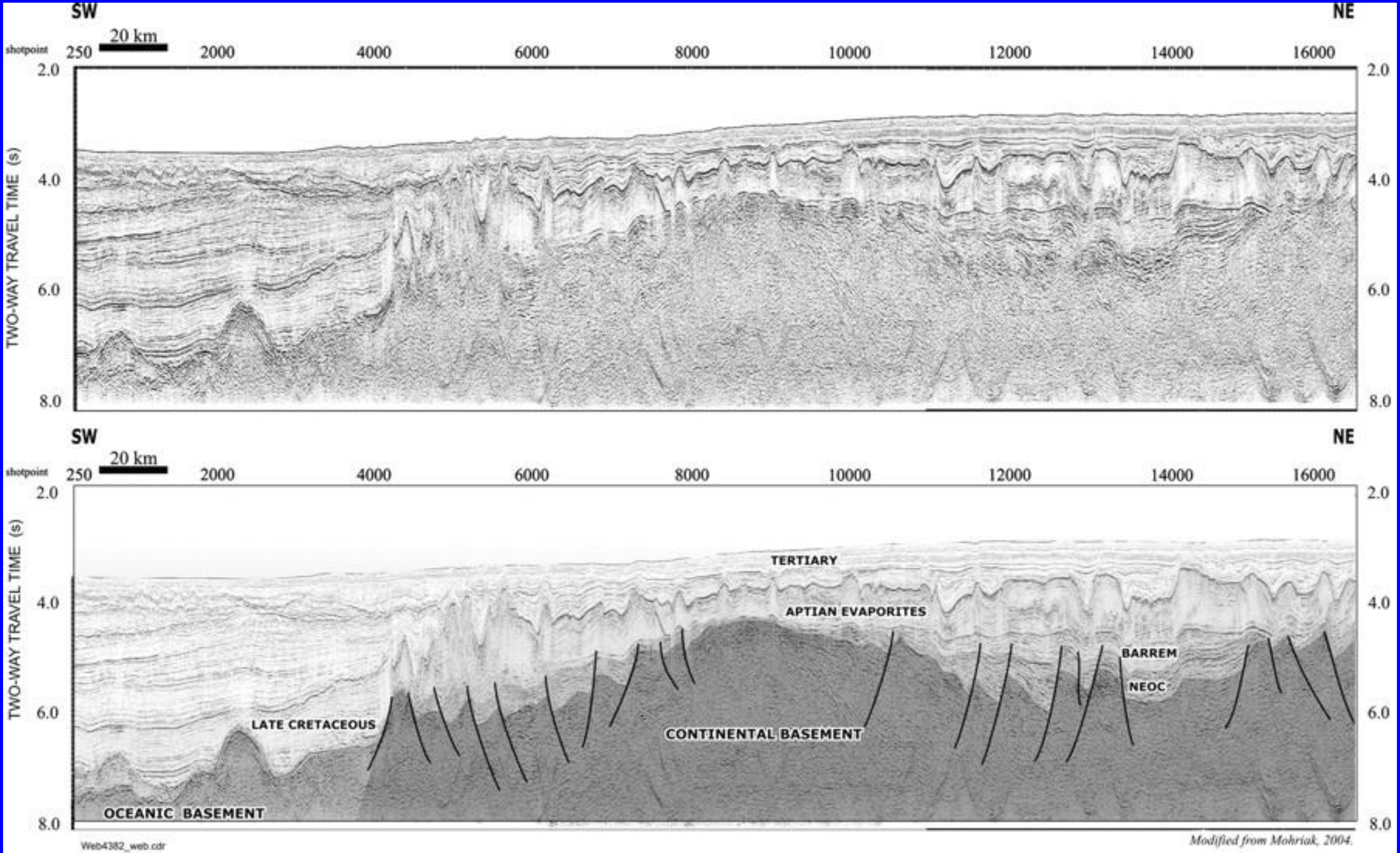
Rollover: in the lower slope of passive margins the post-salt sequences slide with/on the salt layer

Western margin of the South Atlantic Basin (Brasilian offshore)



Modified from Mohriak, 2004.

Eastern margin of the South Atlantic Basin (West Africa margin)



Modified from Mohriak, 2004.

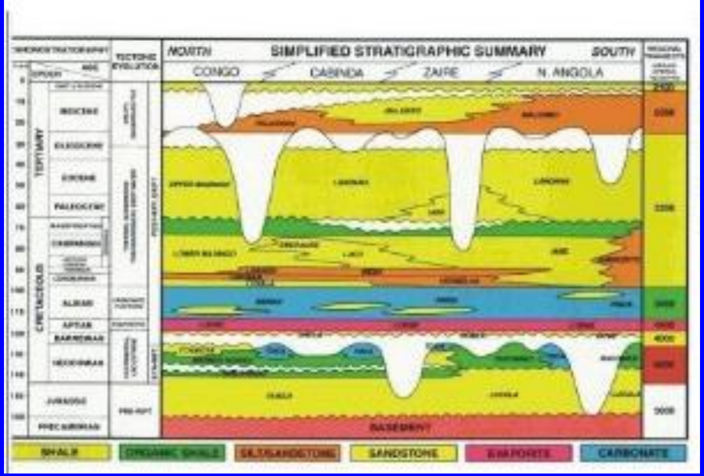
West Africa margin

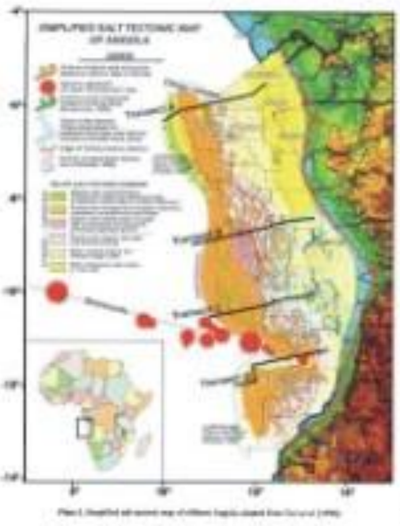
Model of evolution of the W-Africa passive margin since the end of Aptian (…..).
Salt deposited during the end of the rift phase in the thinned continental crust.

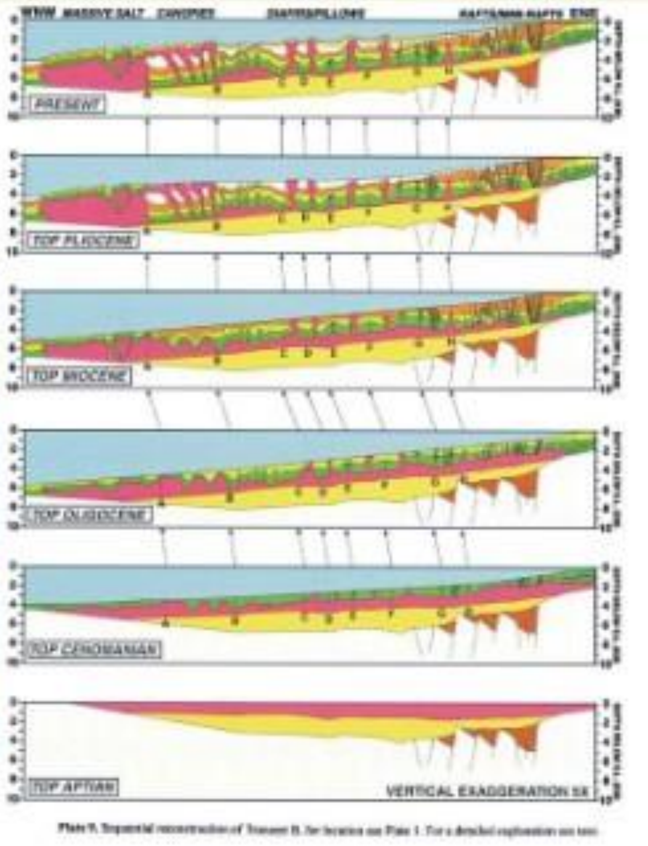
Thermal subsidence during the drift phase played a leading role triggering off:

- deepening of the substratum,
- collapse of salt and its sedimentary cover toward the deep basin (extensional faults on the East),
- accumulation of salt in a thick pile along the lower continental slope (compressional faults on the west)

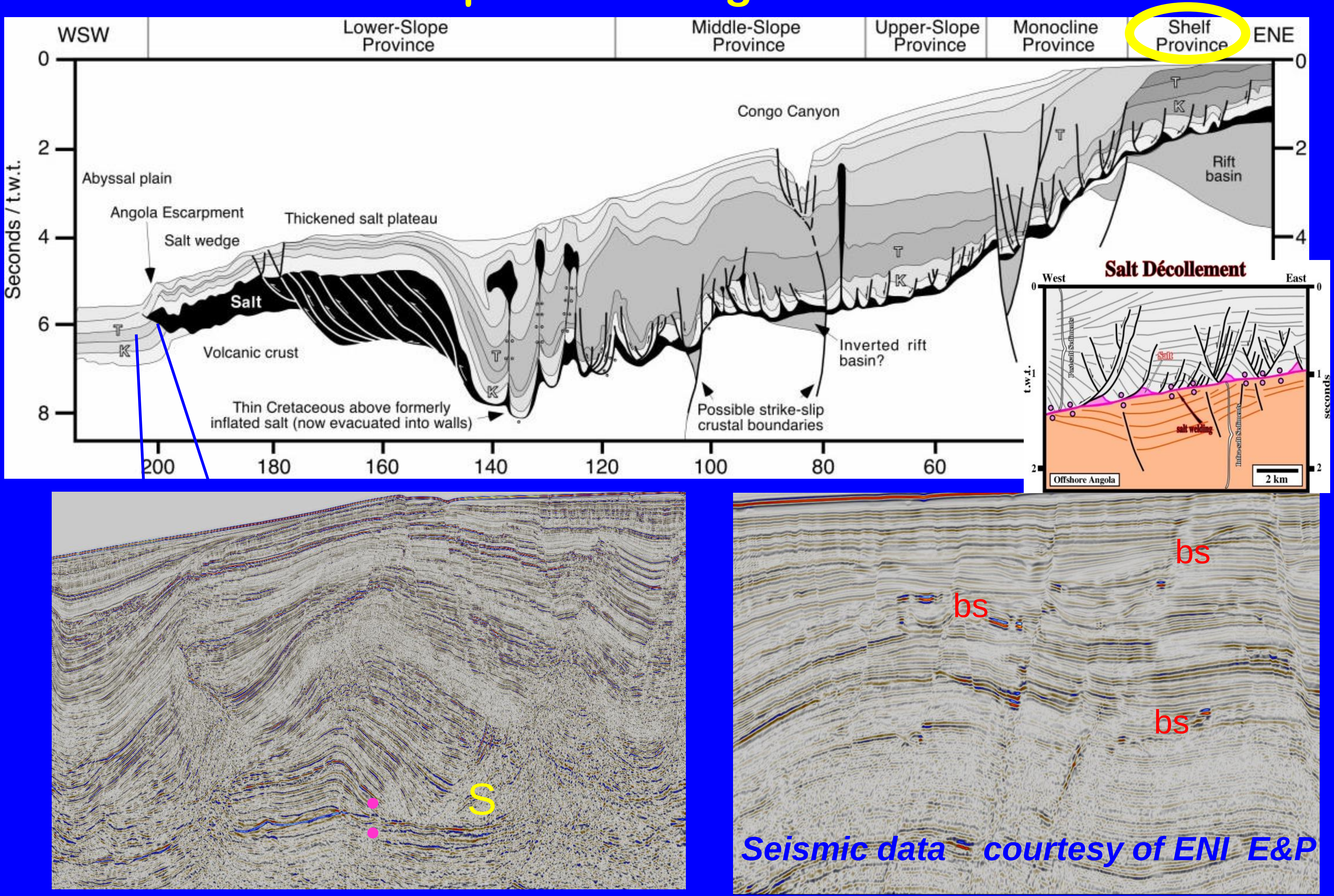
Chronostratigraphis profile representing the lithological distribution on the different sectors of the W-Africa margin: note the "thin" (from the temporal/not thickness point of view) salt layer ↓





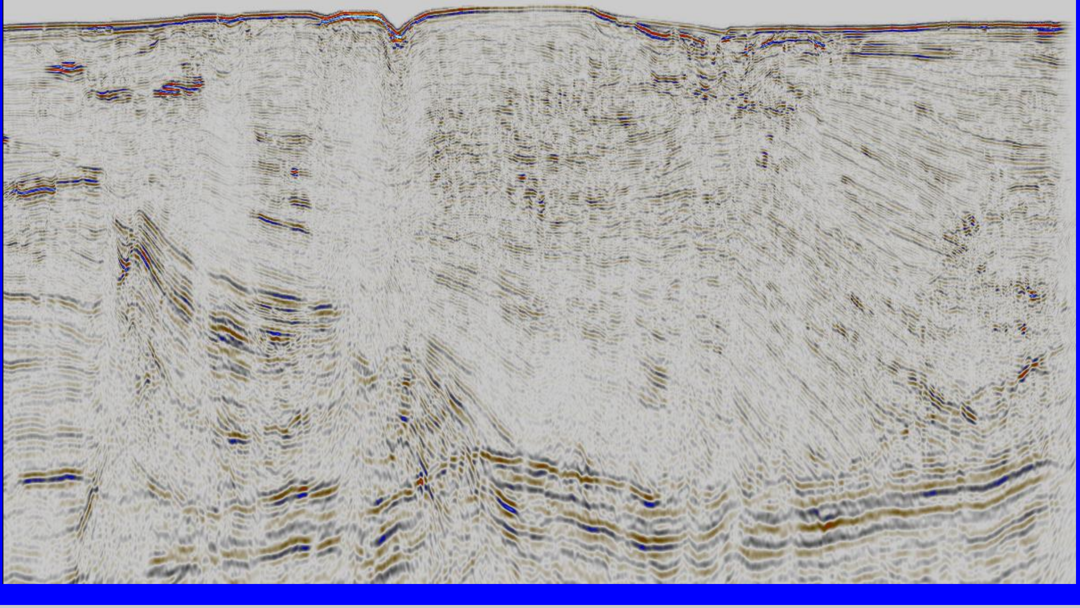


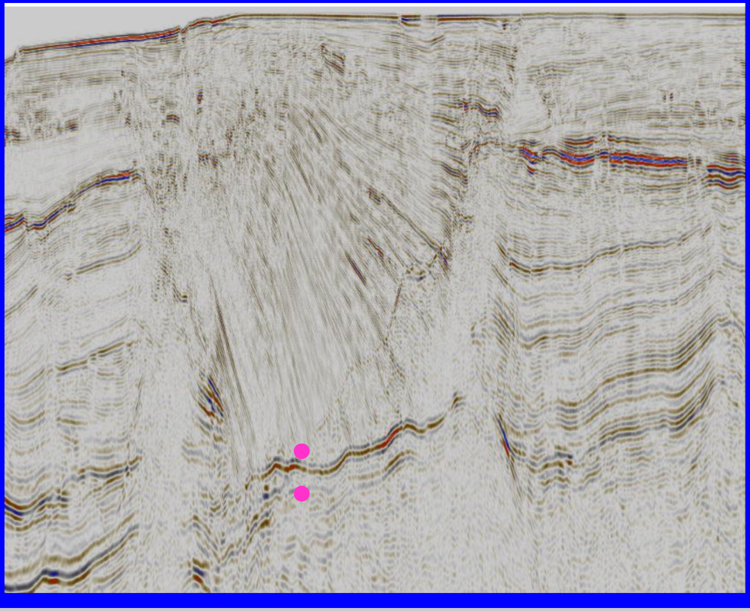
West-Africa passive margin: Shelf Province

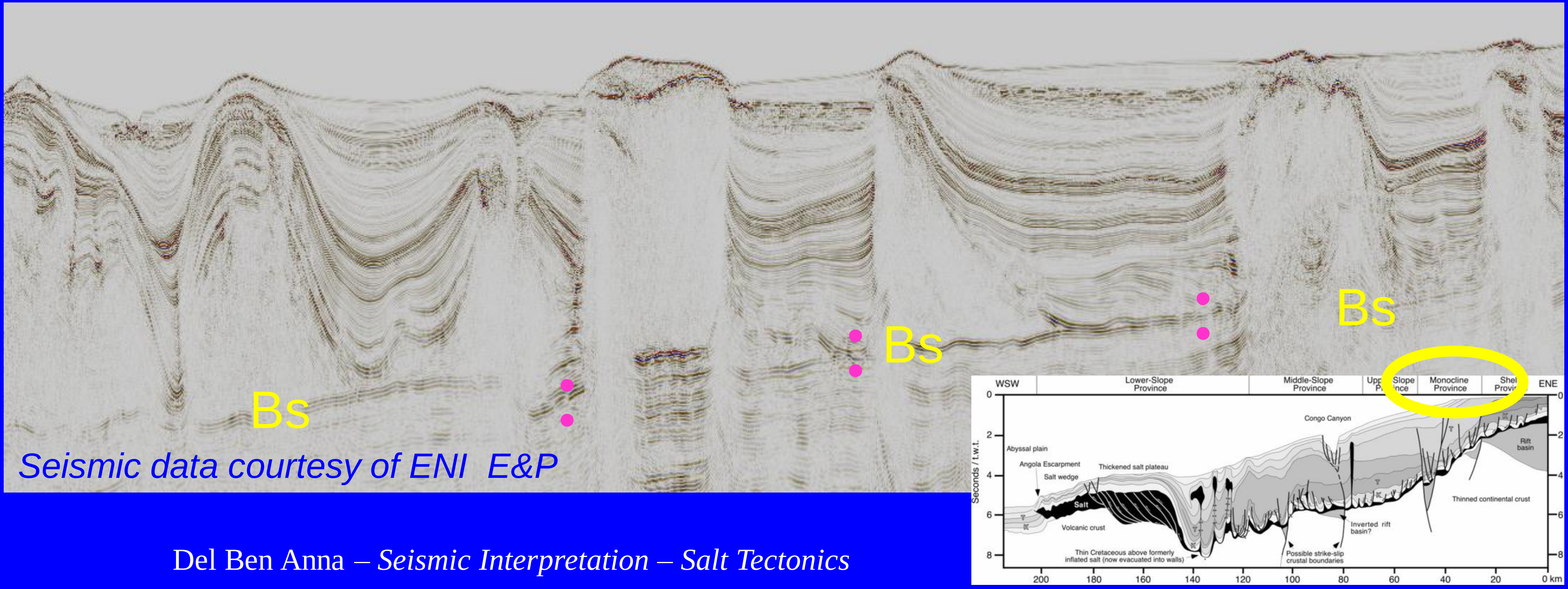


Seismic data courtesy of ENI E&P

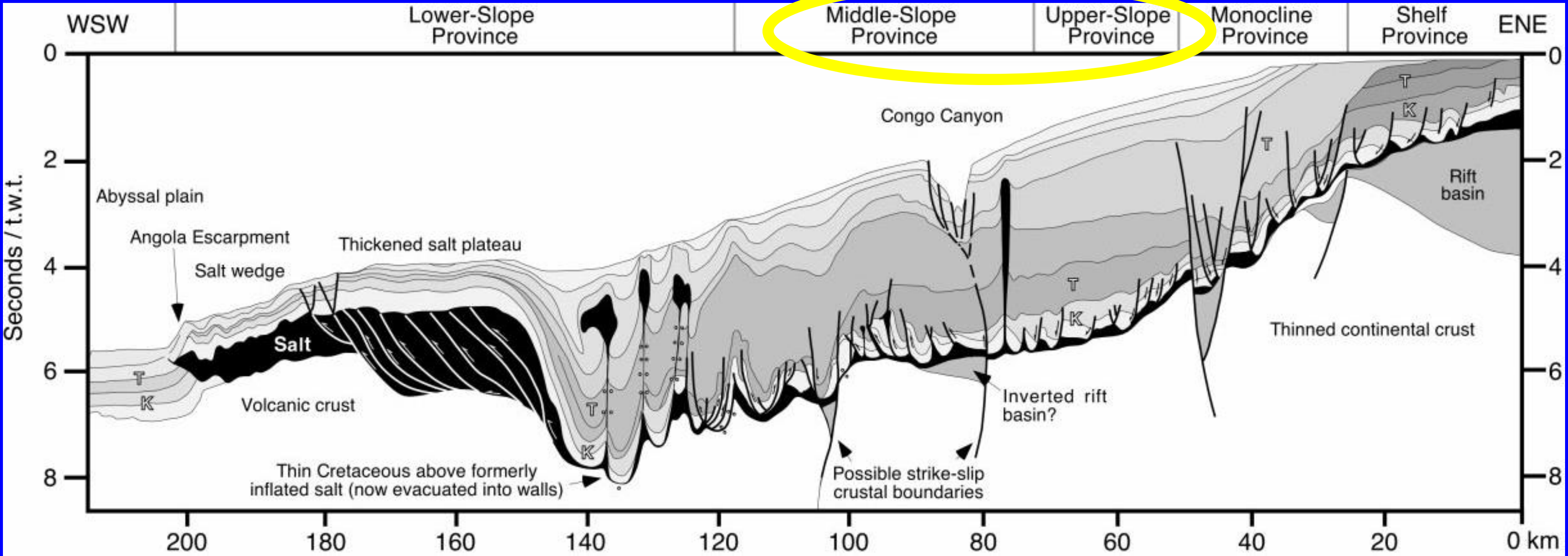
West-Africa margin: Monocline Province



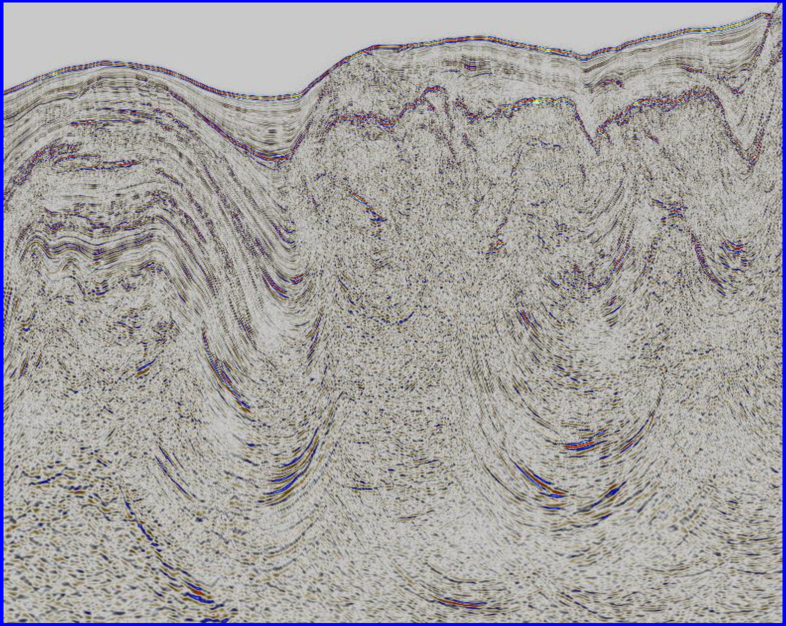


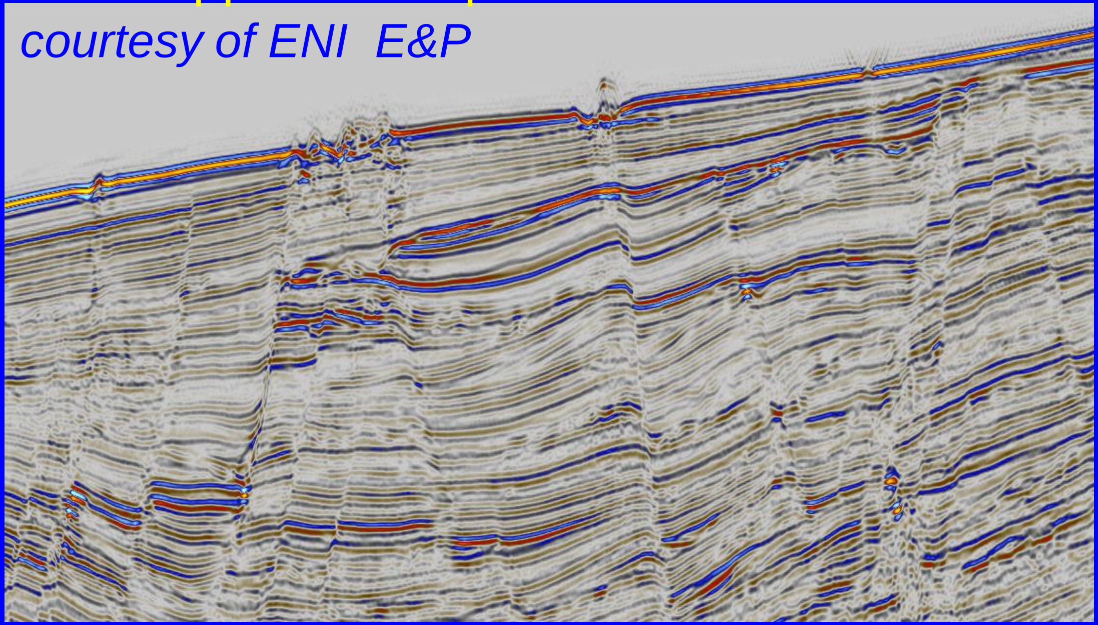


Seismic data courtesy of ENI E&P



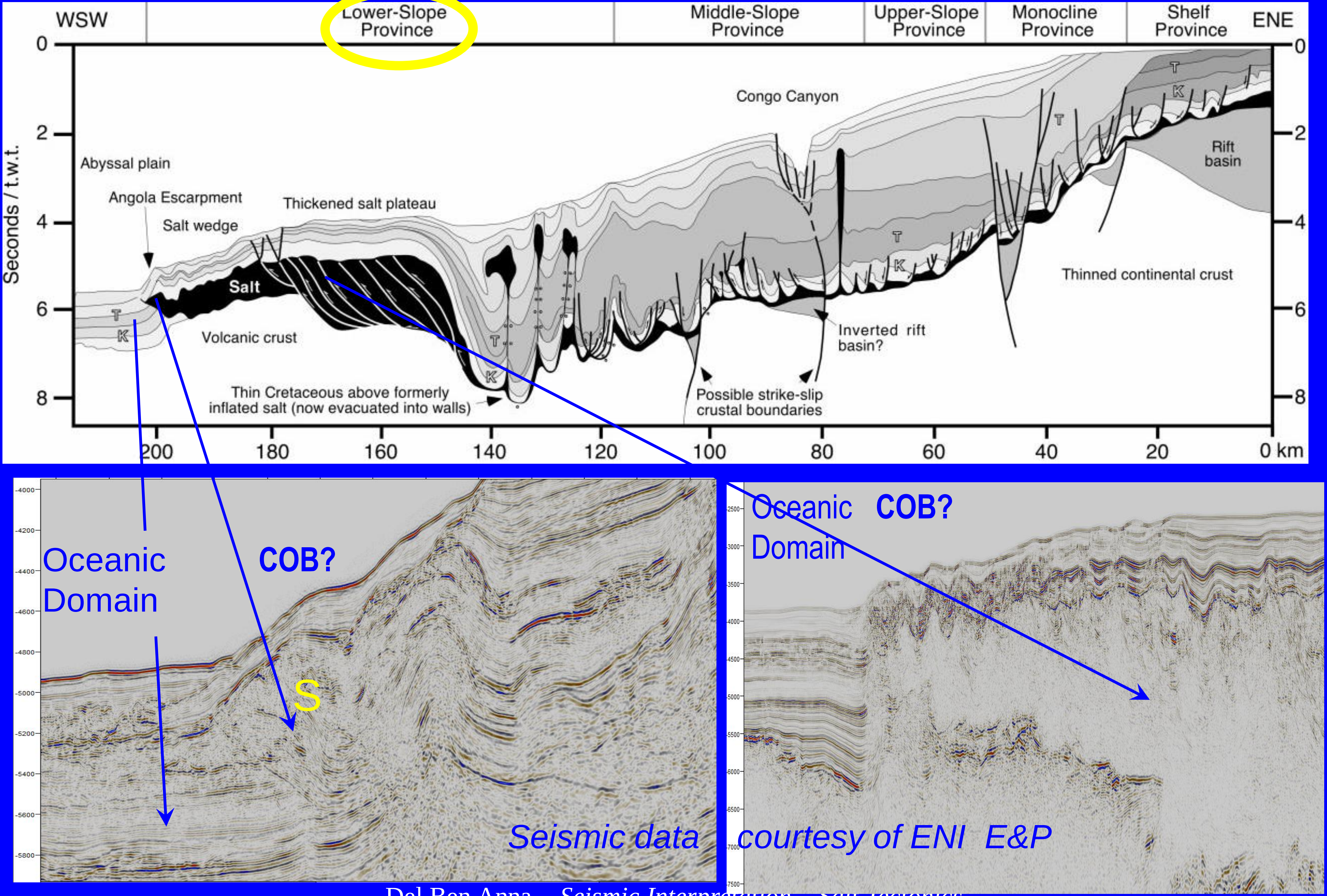
Middle and Upper Slope Provinces





courtesy of ENI E&P

West-Africa margin: Lower Slope Province



Oceanic Domain

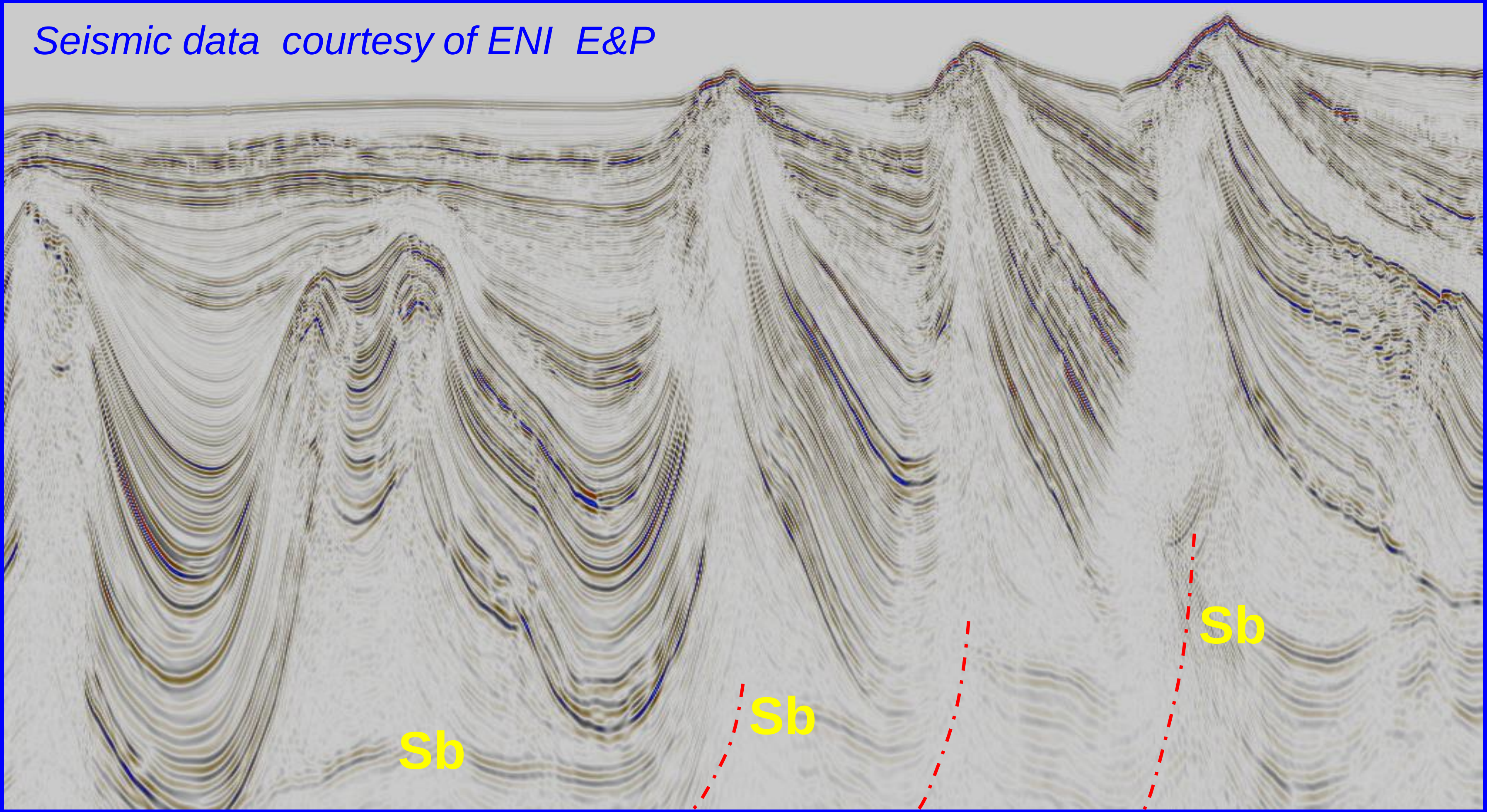
COB?

S

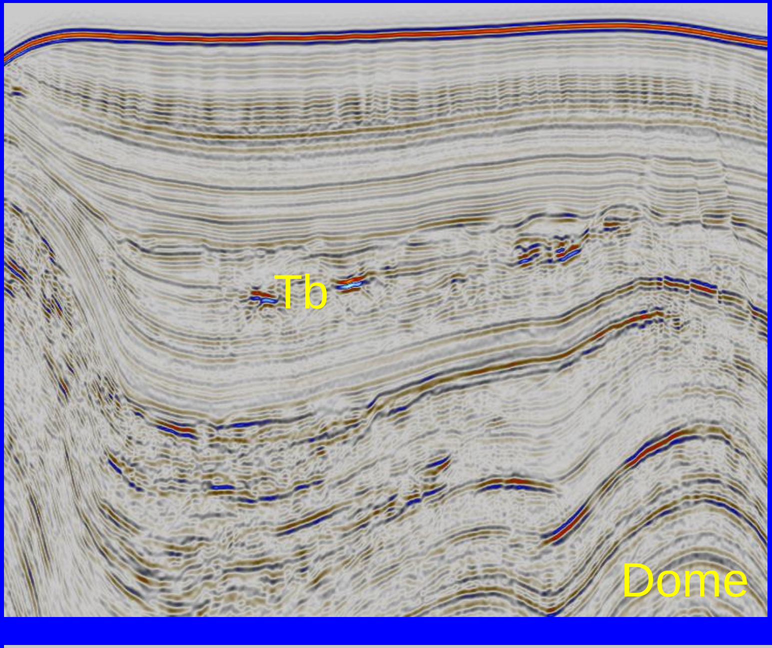
Oceanic Domain

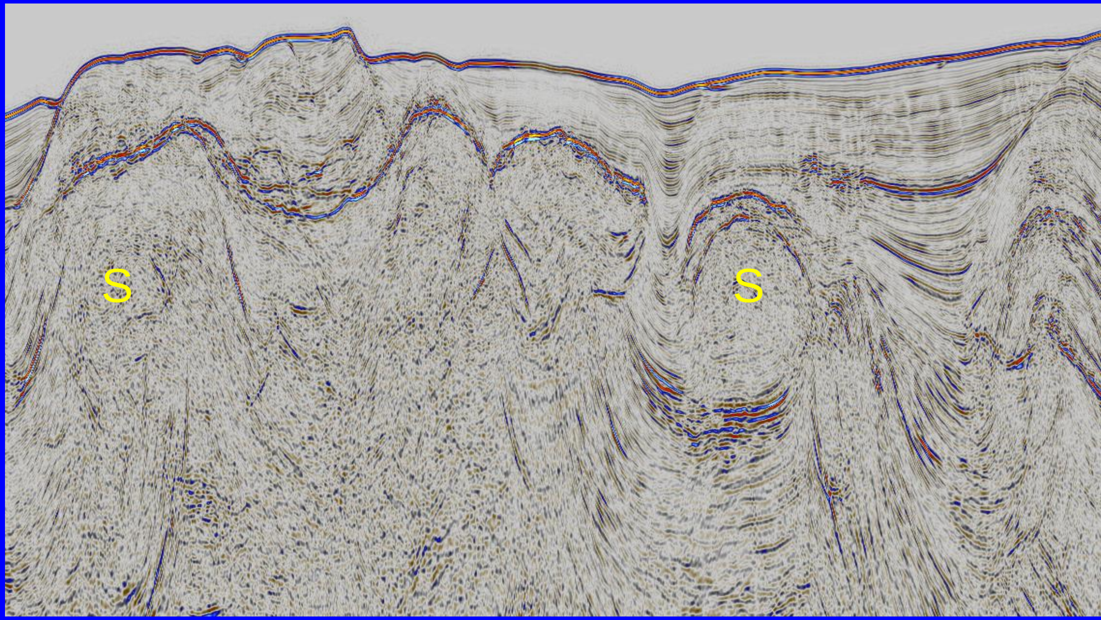
COB?

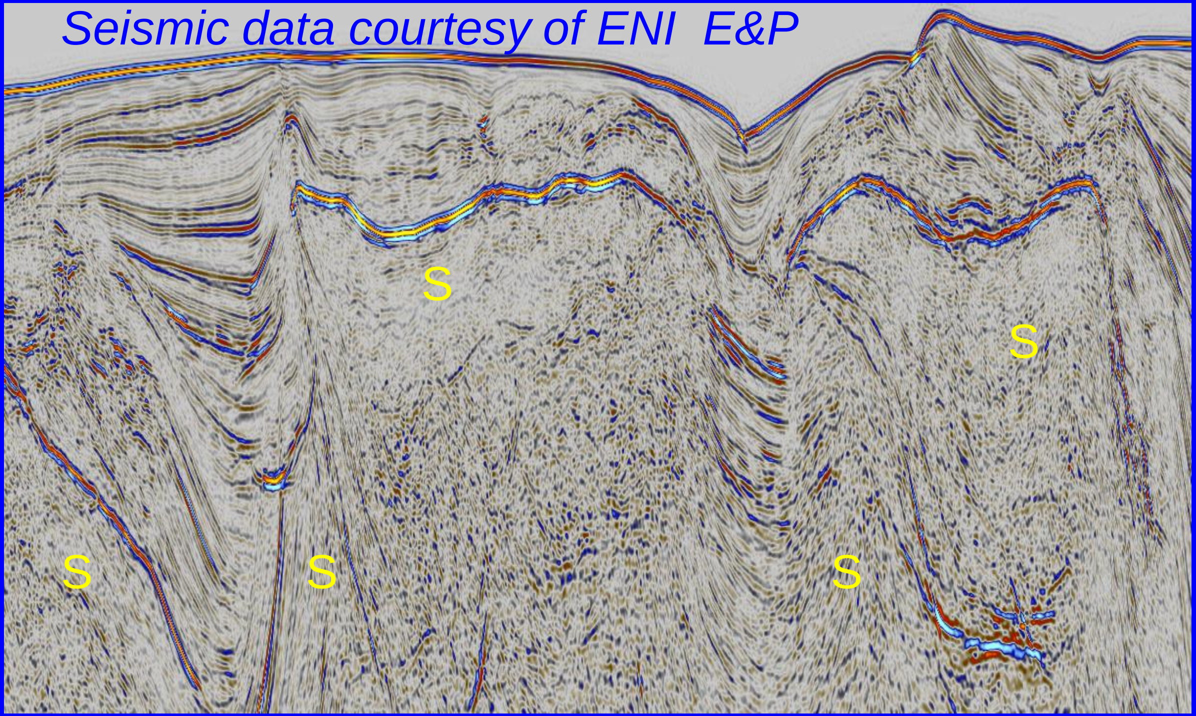
Seismic data courtesy of ENI E&P

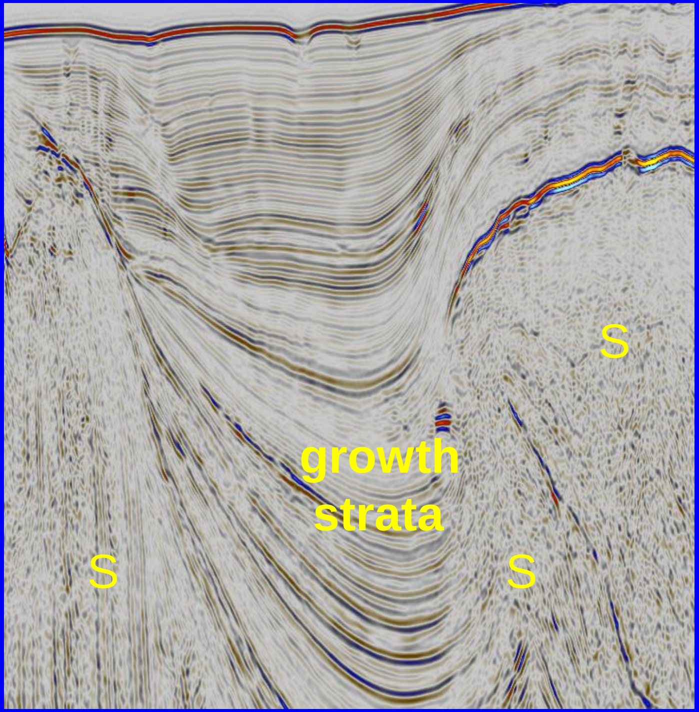


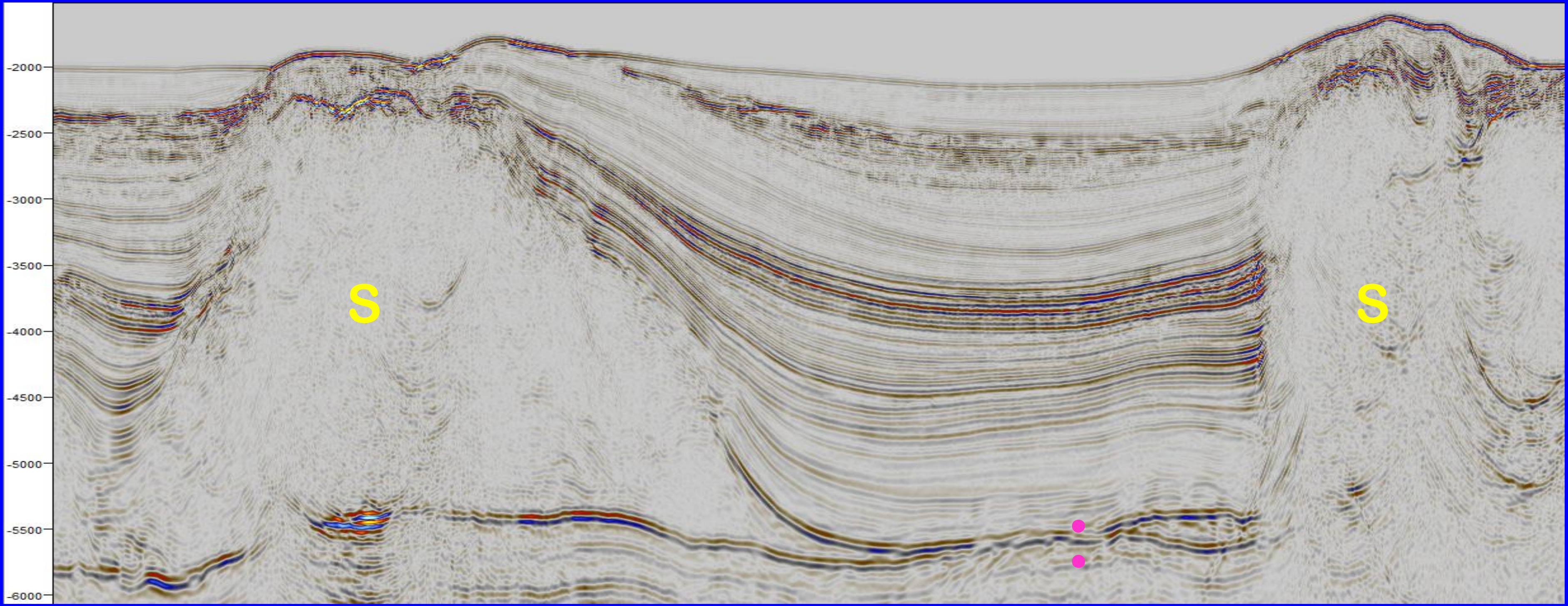
Asymmetric salt domes in the West African margin: growth strata testify their continuous activity immediately after salt deposition until present.
The base (Sb) of the salt sequence (not presence of pull-up velocity in depth-migrated profiles) suggests some basin-ward faults,
probably first cause of halokynetic process

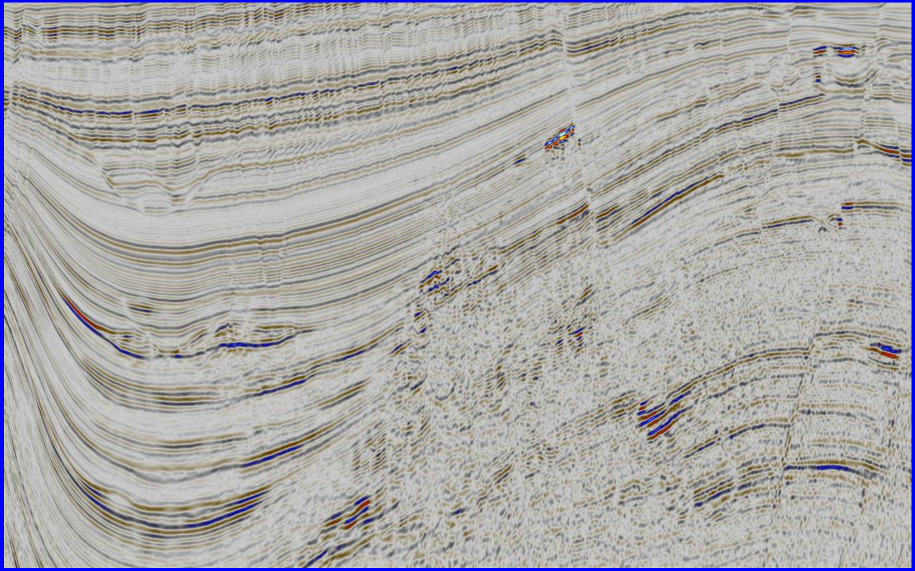


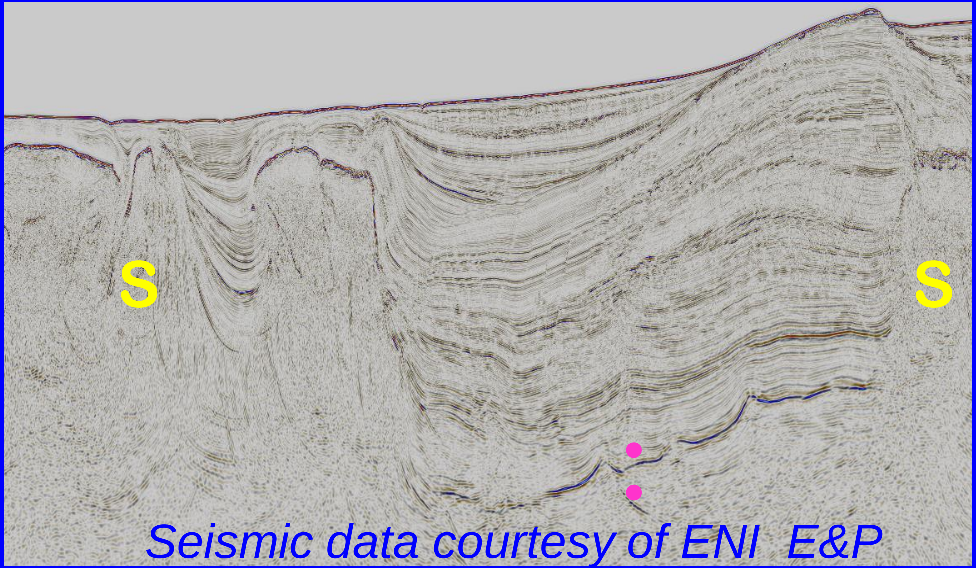



Seismic data courtesy of ENI E&P





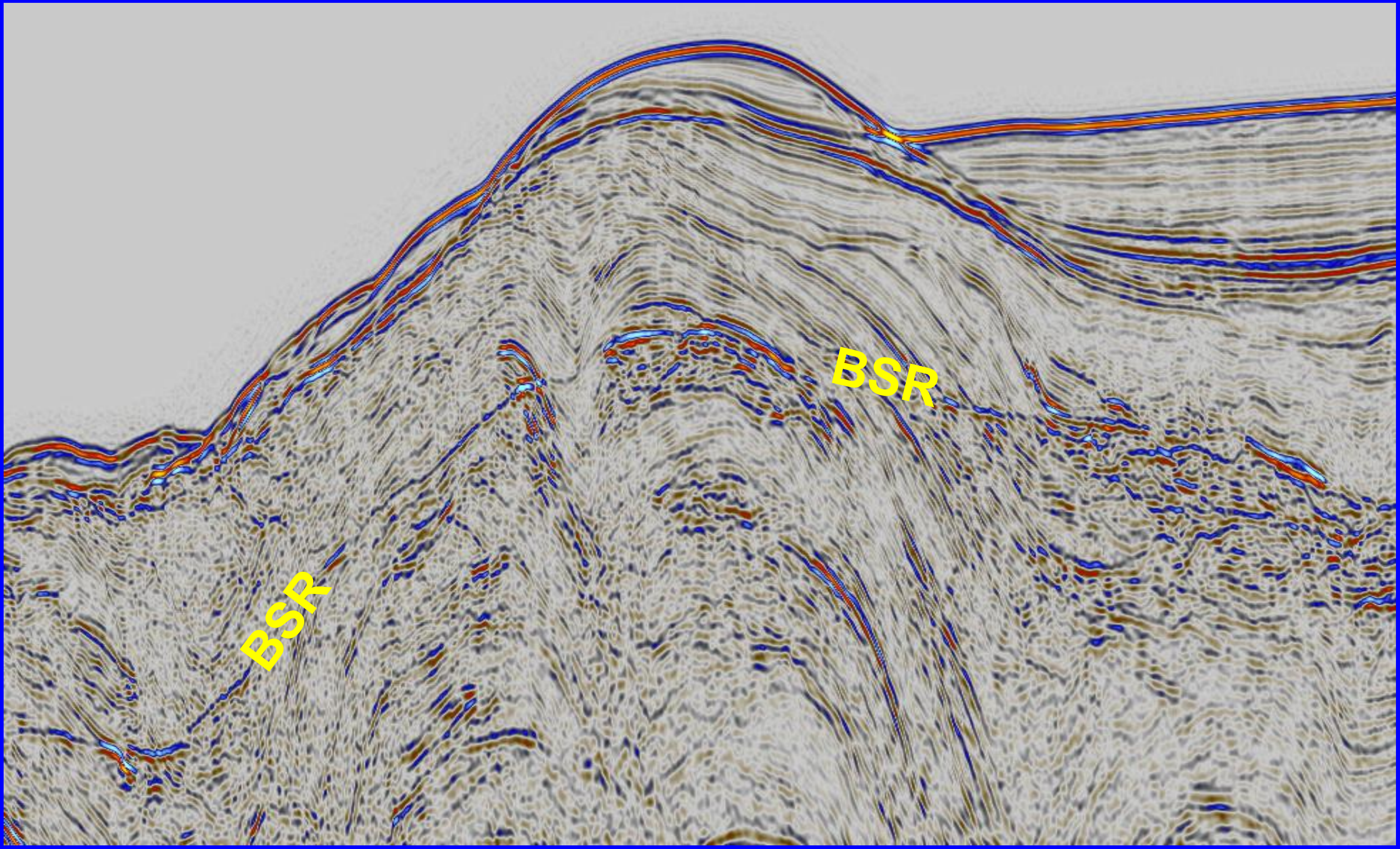




Seismic data courtesy of ENI E&P

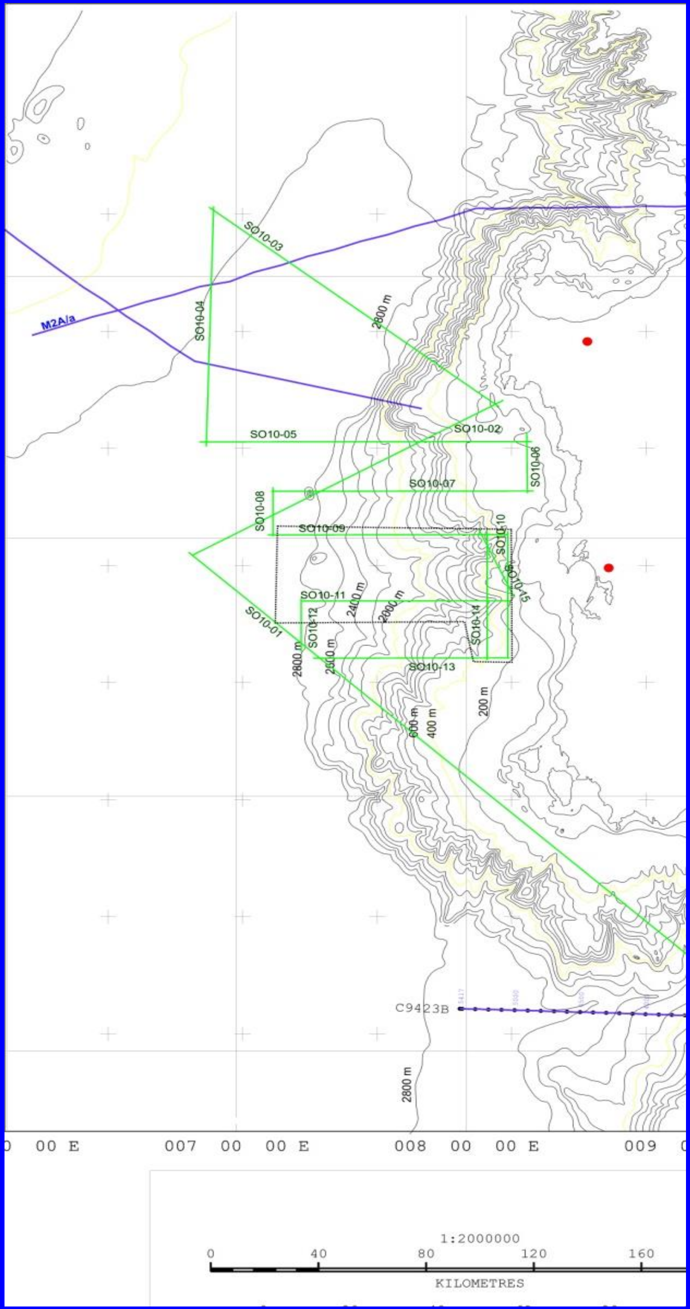
Bottom Simulating Reflector (BSR) in the W-African margin

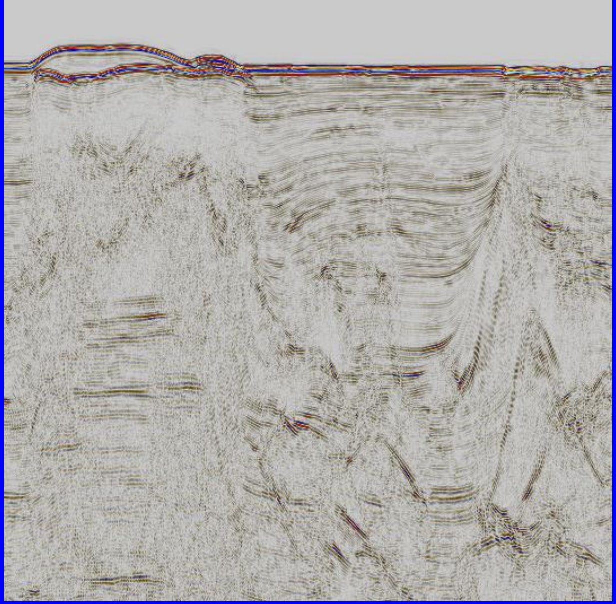
BSR marks the change of methan from hydrate (above, higher velocity and density)
to gaseous (below, lower velocity and density) state.
It depends mainly on pression, hence on load of the sedimentary cover:
for this reason the BSR is about parallel to the sea bottom

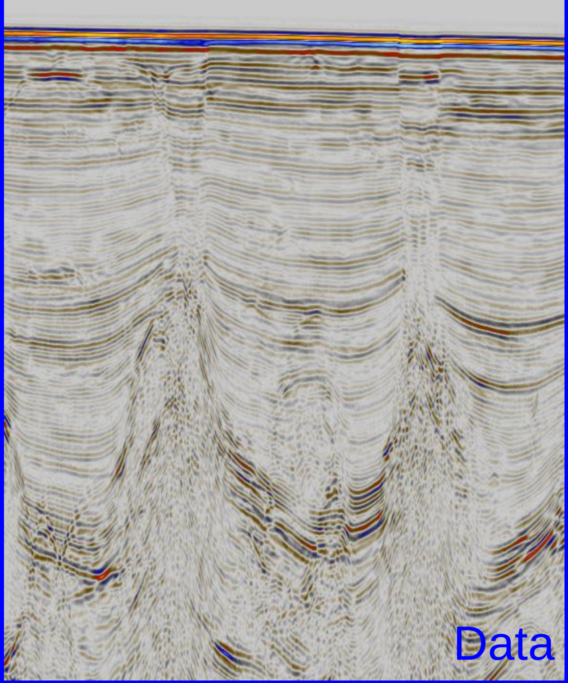


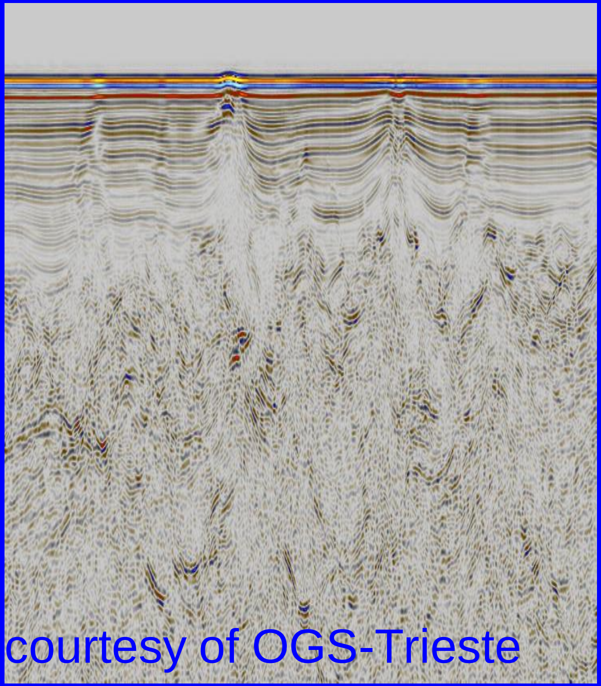
West-Sardinia Project (WS10)

Aim of this project was exploration of the West Sardinian passive margin and of the eastern Liguro-Provençal Basin



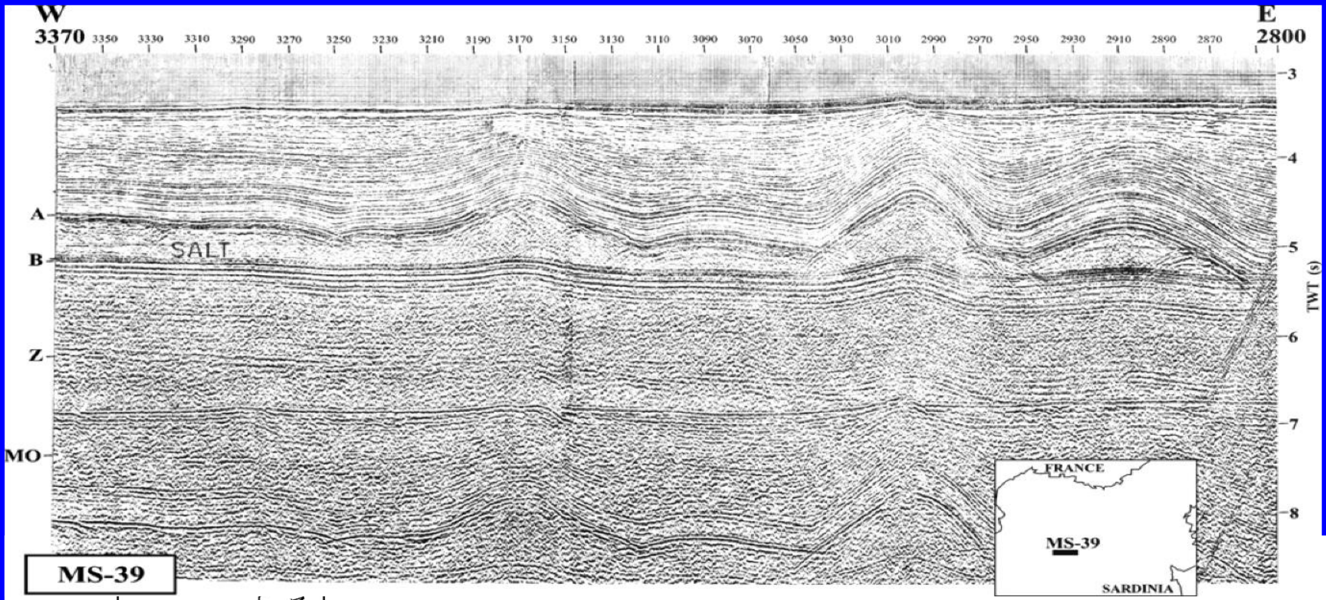


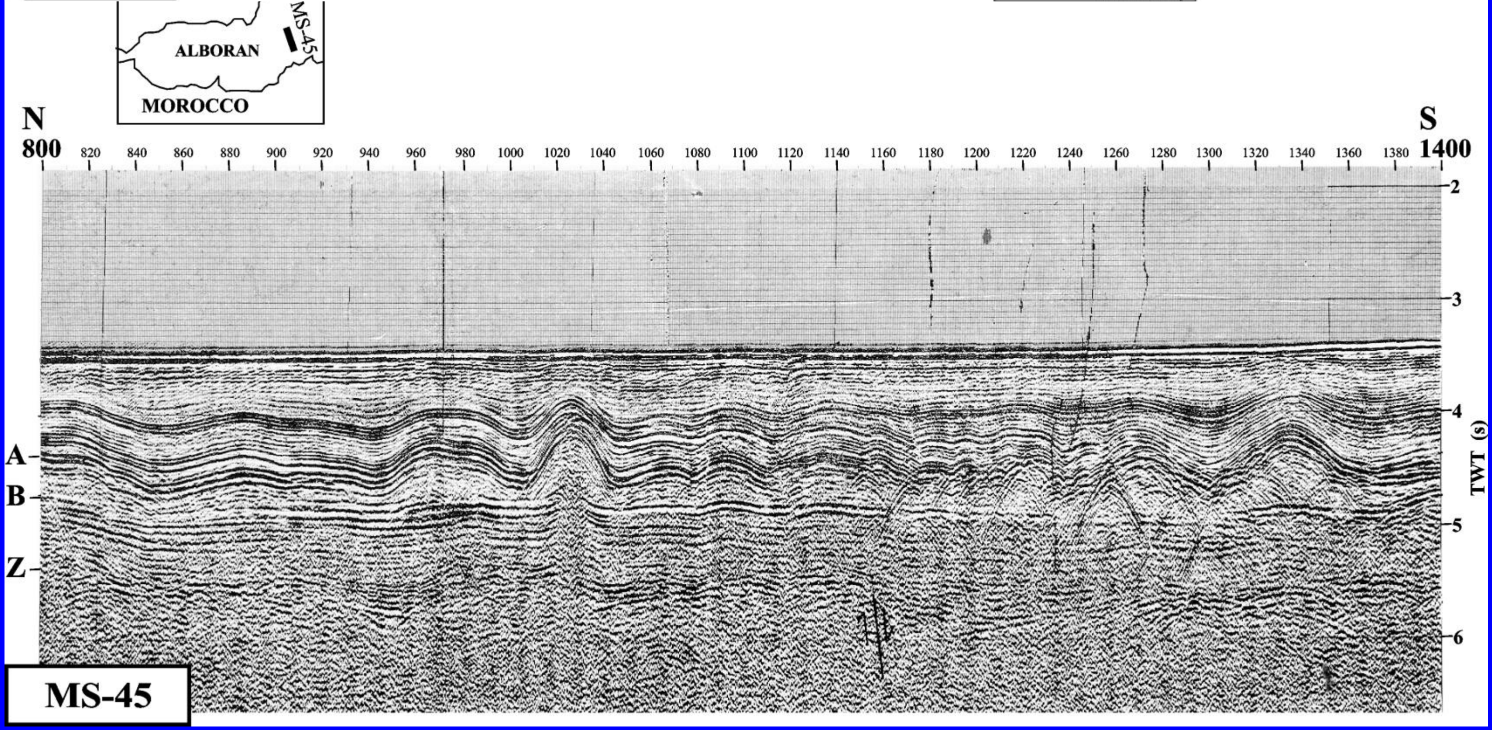


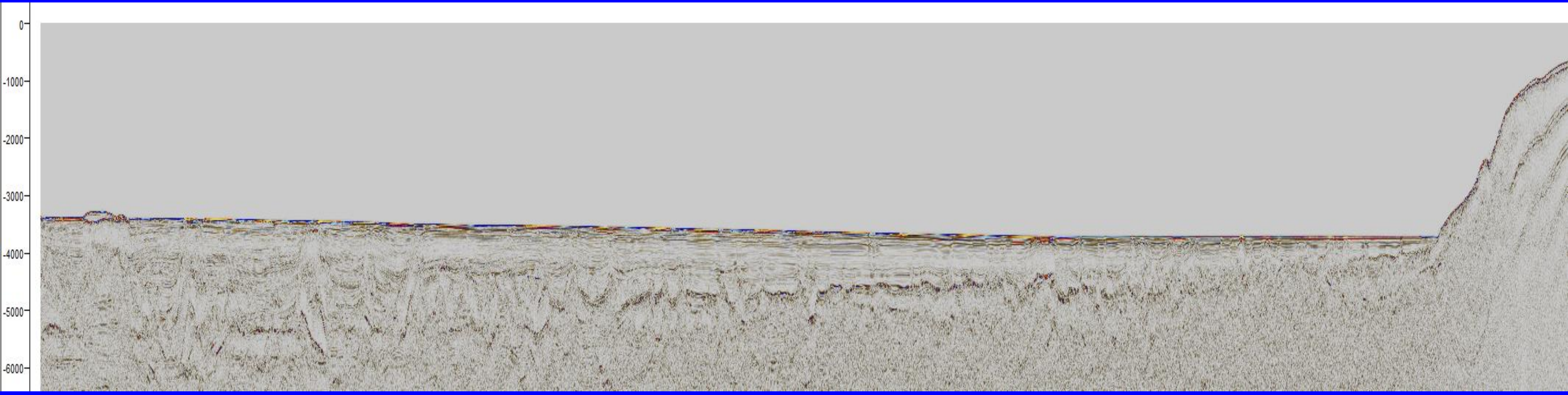


Data courtesy of OGS-Trieste

MS project Seismic Sections acquired by OGS during the 1972







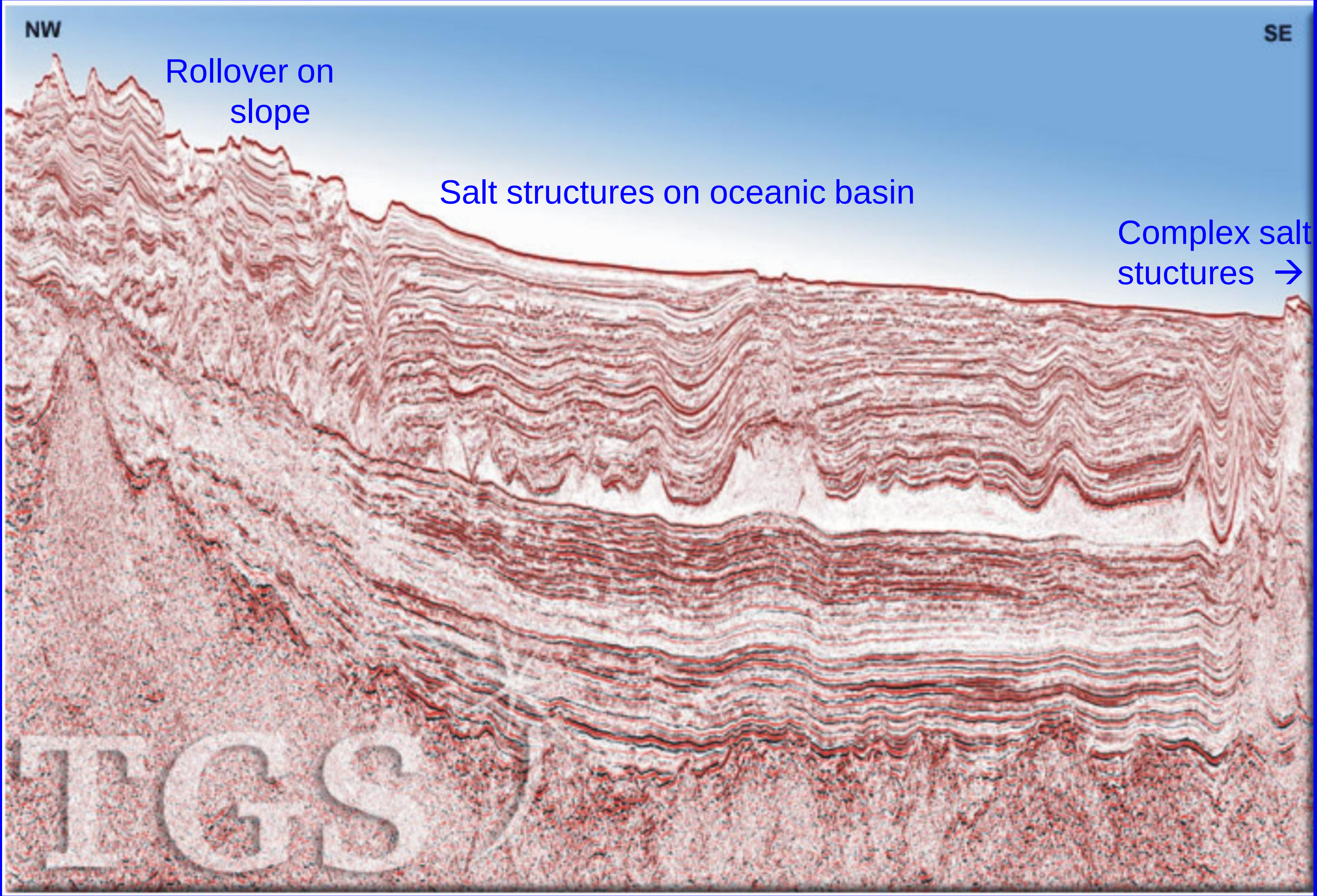
Differently than in the South Atlantic Basin, where the salt deposited during the last rifting phase (hence only in the continental margins), the evaporite sequence in the Mediterrenean Sea was caused by closure of the Strait of Gibraltar during the Messinian time.

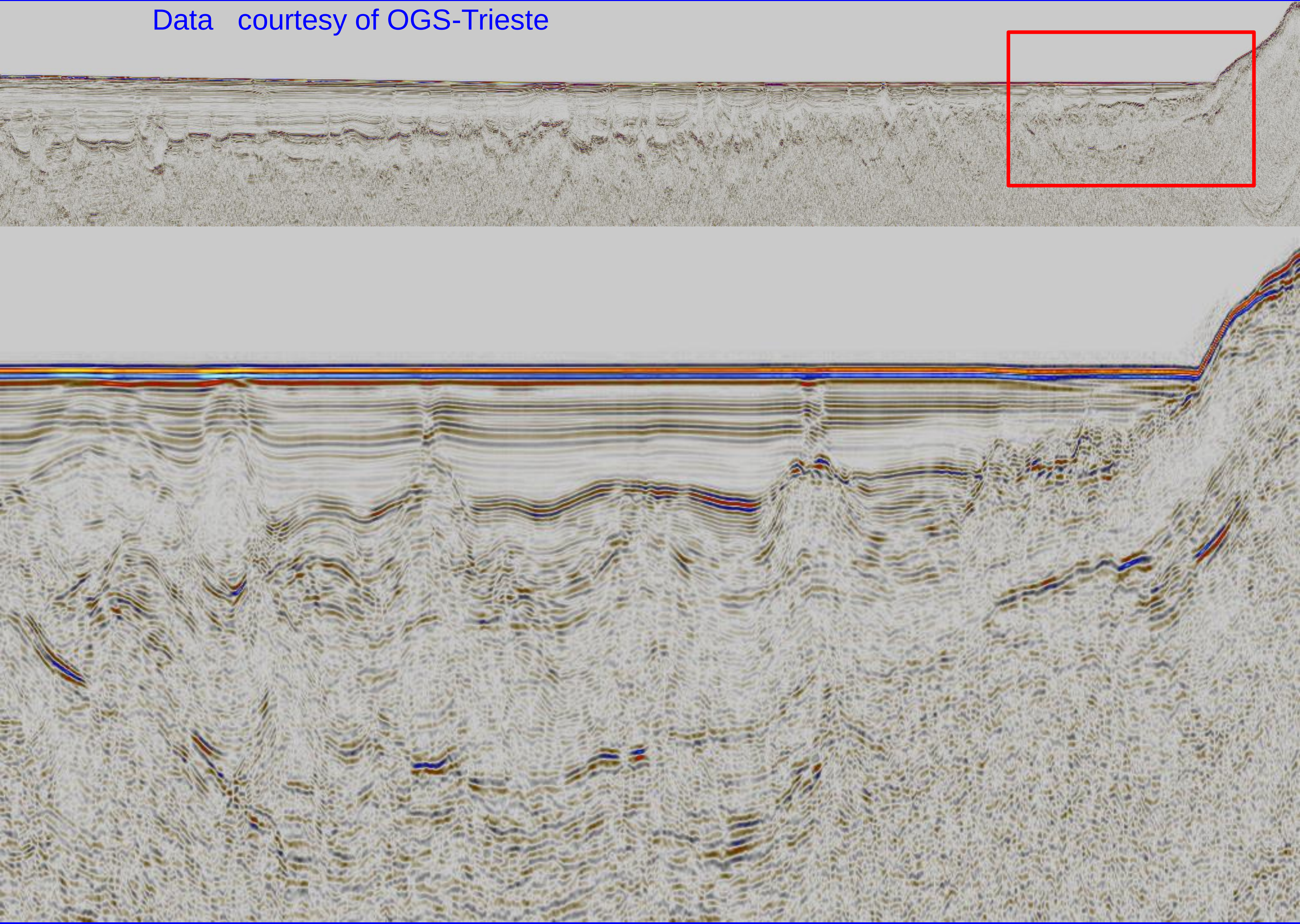
Evaporation of sea water and following sea level fall caused erosion on land and on the margins, and deposition of evaporites on the deep basin.

At that time the Liguro-Provençal Basin was in a post-drift phase (oceanic opening developed during Upper Oligocene-Lower Miocene) with a sea bottom fall of 1500 m.

Other Mediterranean basins were in a post-drift phase (Levantine and Ionian Basins), while rifting of theTyrrhenian basin phase started at that time.

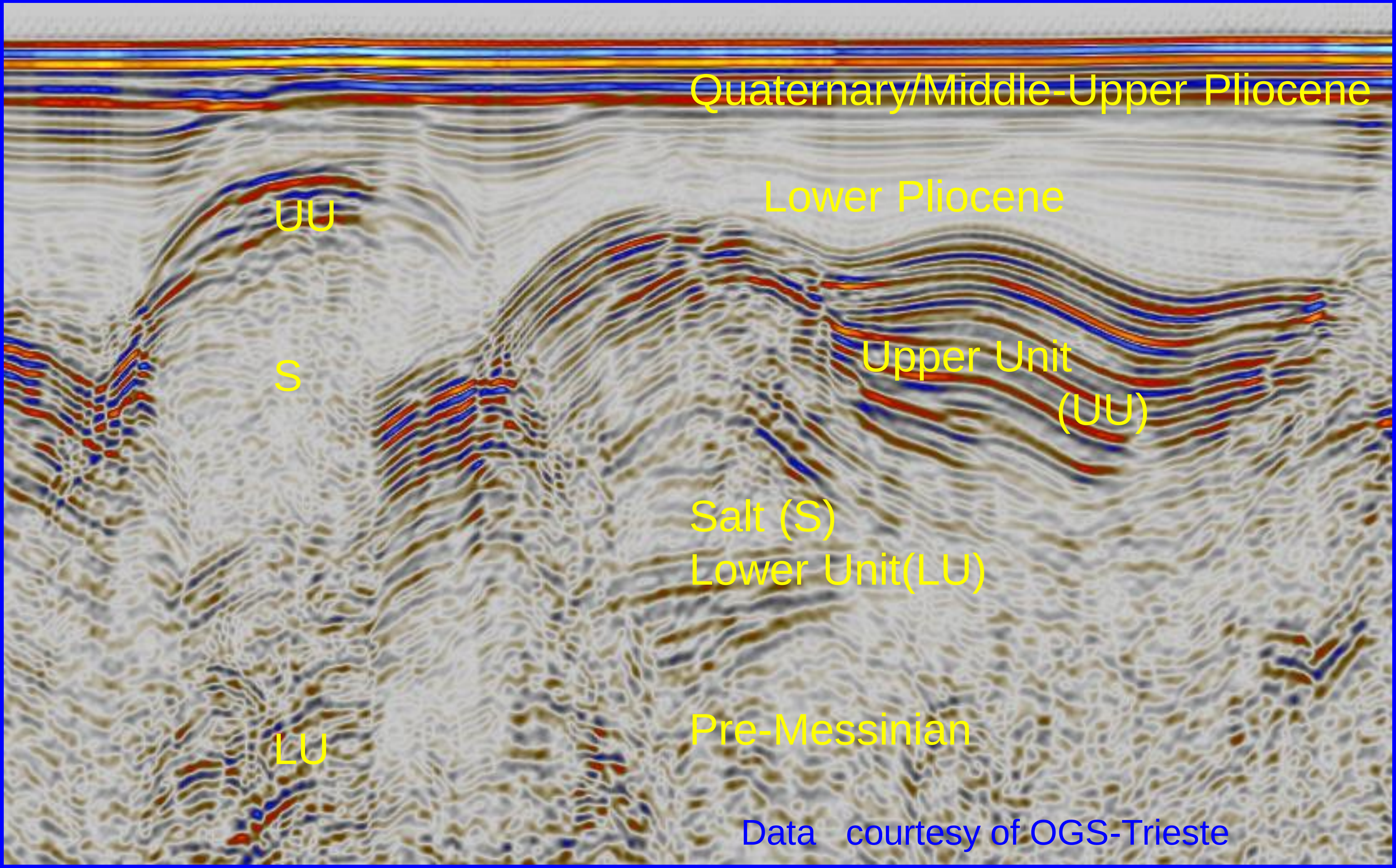
Western margin of the Liguro-Provençal Basin



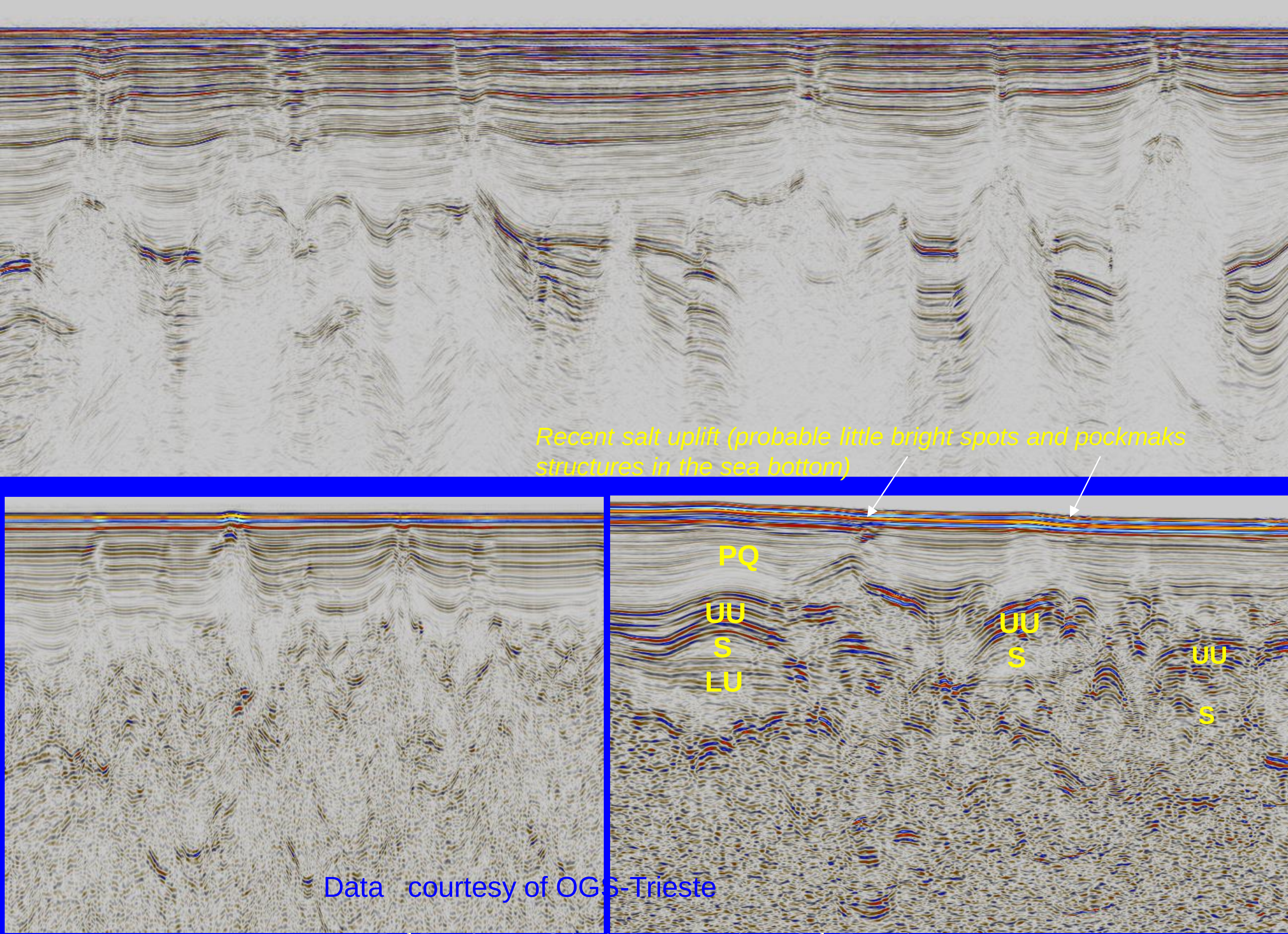


Data courtesy of OGS-Trieste

Liguro-Provençal Basin

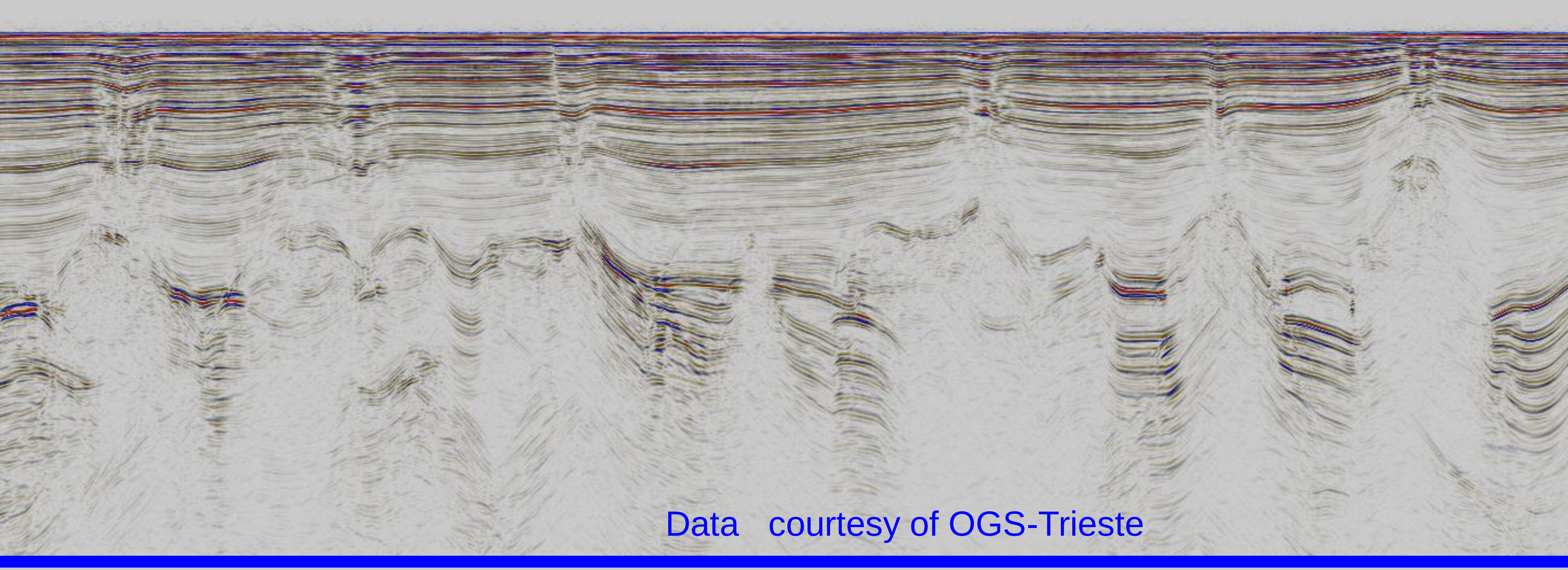


Data courtesy of OGS-Trieste

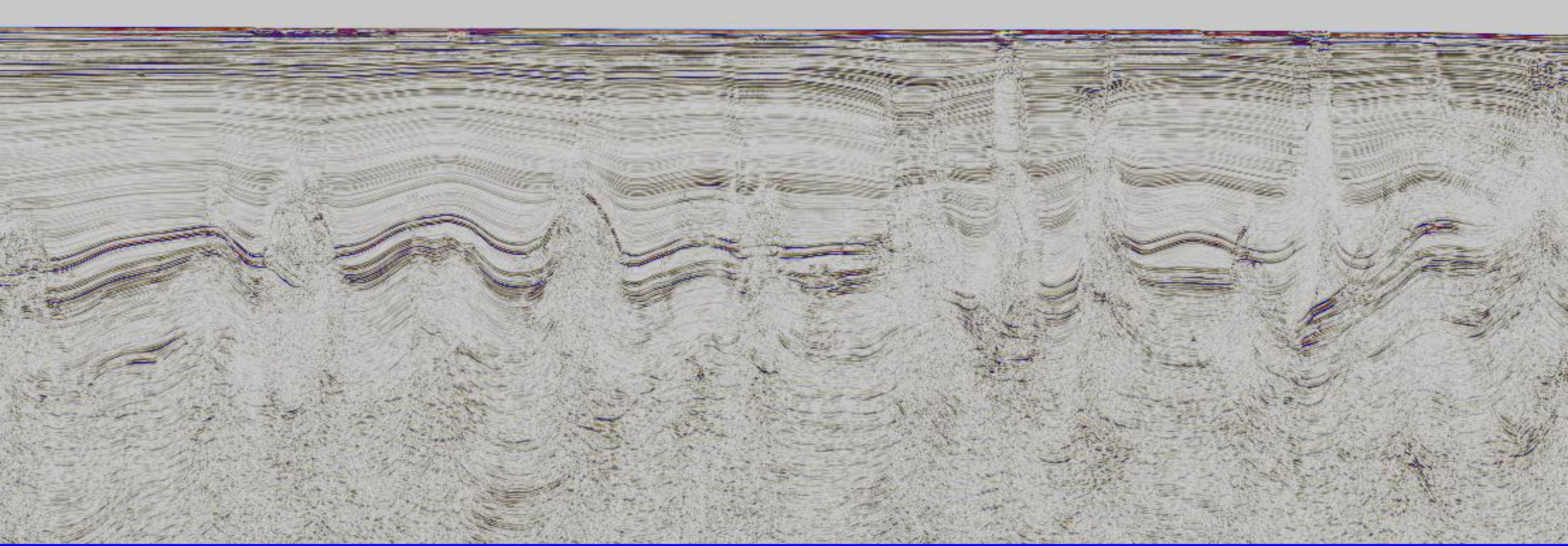


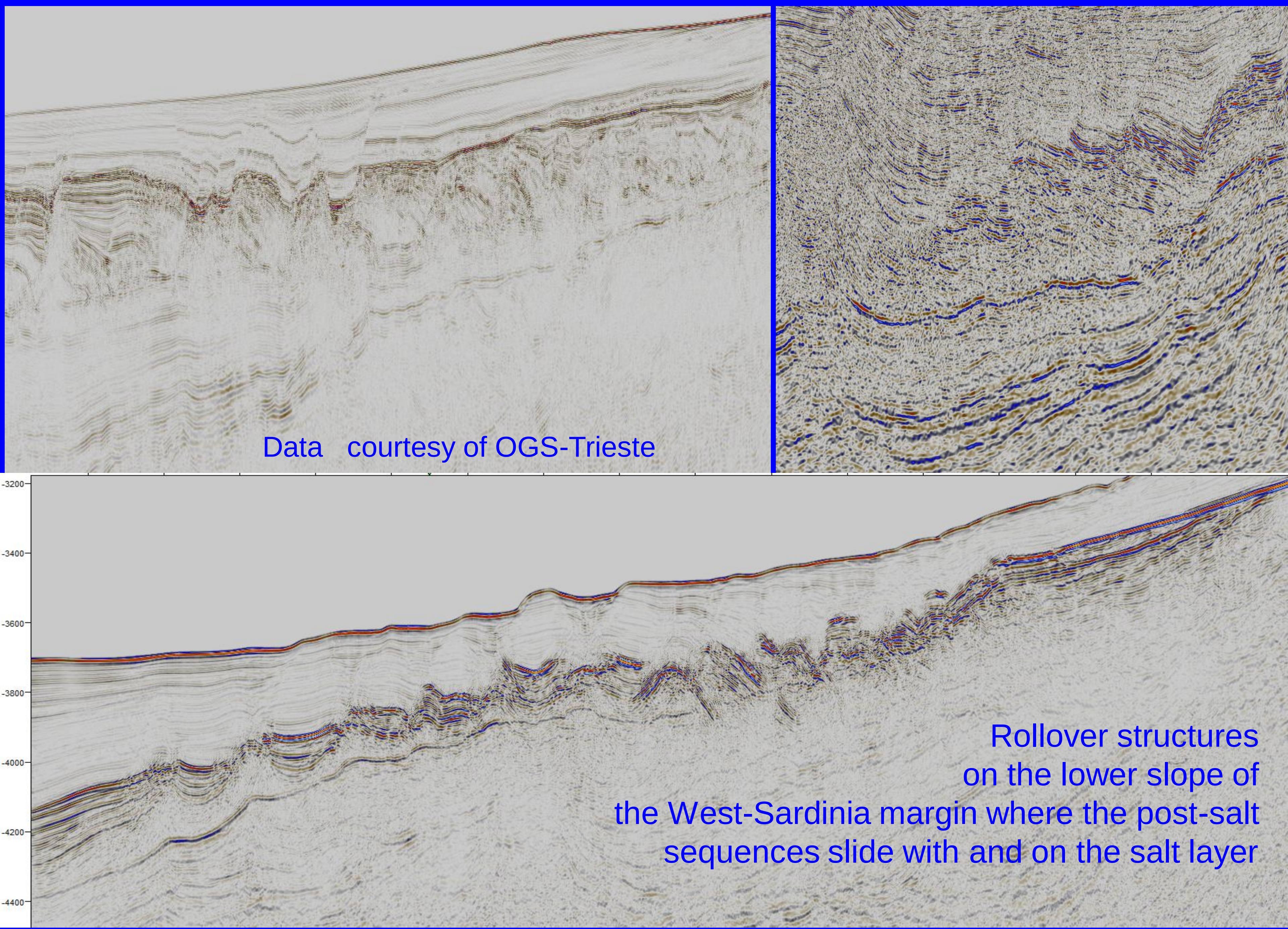
Recent salt uplift (probable little bright spots and pockmaks structures in the sea bottom)

Data courtesy of OGS-Trieste



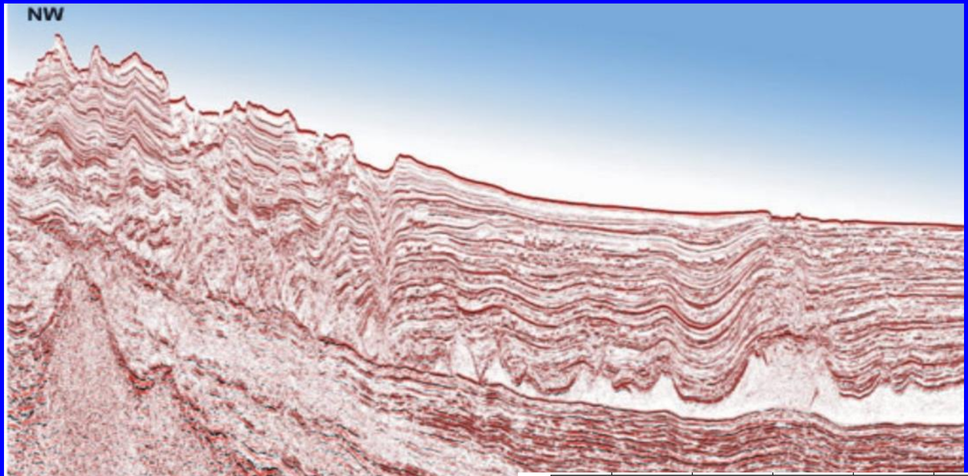
Data courtesy of OGS-Trieste



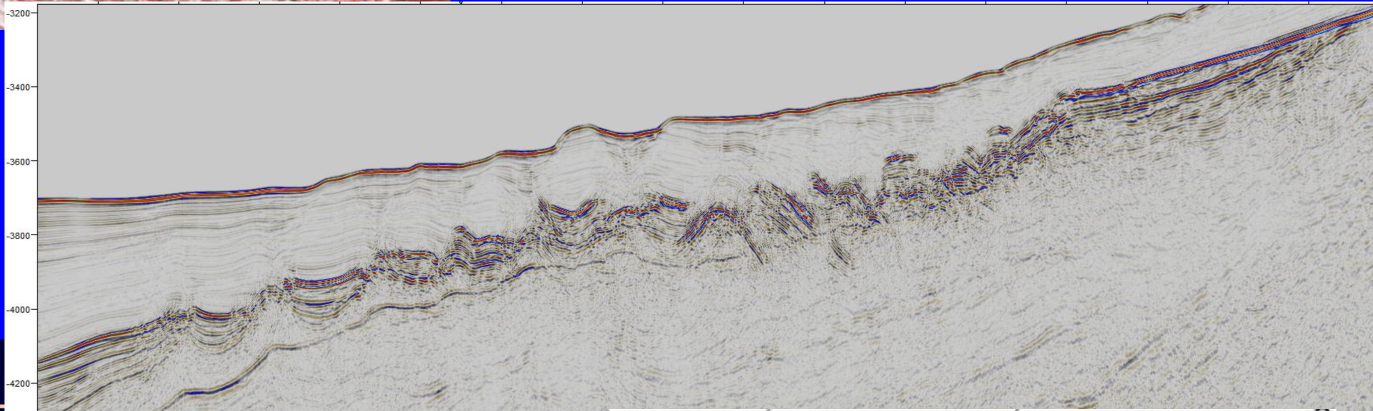


Data courtesy of OGS-Trieste

Rollover structures
on the lower slope of
the West-Sardinia margin where the post-salt
sequences slide with and on the salt layer



Rollover structures on the lower slope of the West and East Liguro-Provencal margins where the post-salt slide with and on the salt layer; compare with the South Atlantic margins



Espirito Santo