Salt Tectonics

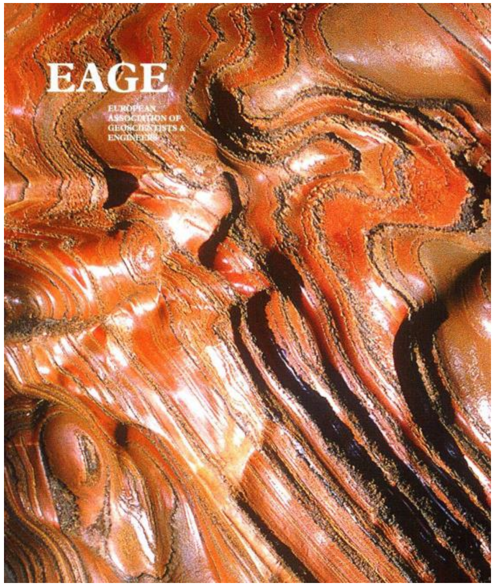
Salt is part of a group of chemically deposited minerals which crystallize by evaporation of salt-rich lake or seawater.

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

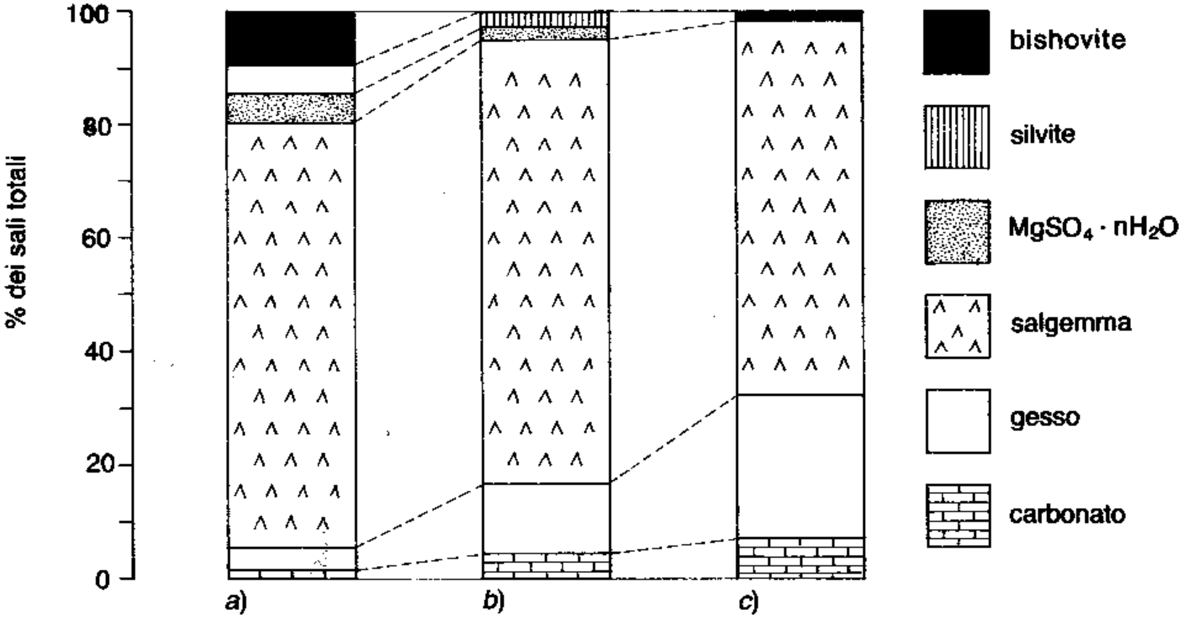
Their chemical compositions reflect the original composition of the brine. The sequence of evaporites results from variations in the chemistry of the brine from which they were deposited.

*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 is it 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.

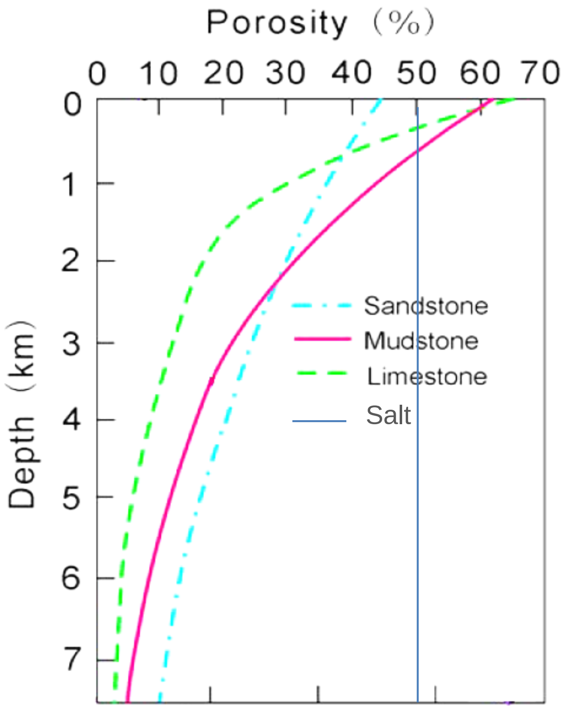
Most important, however, is its ability to **deform plastically**.

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 **2170 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 m it is lighter than surrounding rocks.

This results in an unstable situation.



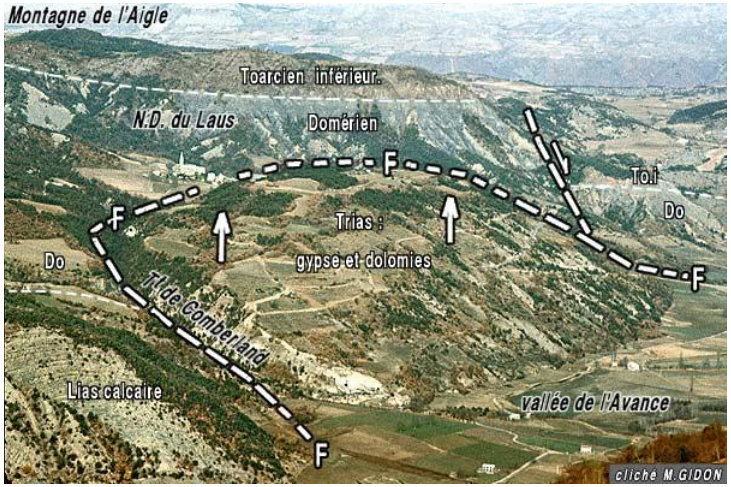
MAIN SALT EFFECT

-Because of its rheology, salt is able to mutiply tectonic deformations of the overlying layers

-Salt controls the formation of complex hydrocarbon traps or accumulation of other minerals in the overlaying sedimentary sequence →

-Evaporite impermeability controls the fluid dynamics and distribution of hydrocarbon in the sedimentary sequence

-Lateral salt flow can cause subaerial or submarine landslides →



-Salt diapirs can offer waste repositories conditions

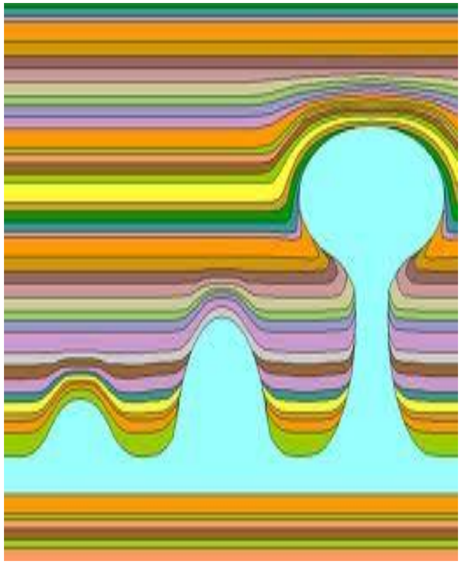
-Interaction between fluids and salt can cause erosion/dissolution of buries layers and subsequent collapse, with consequences for infrastructures.

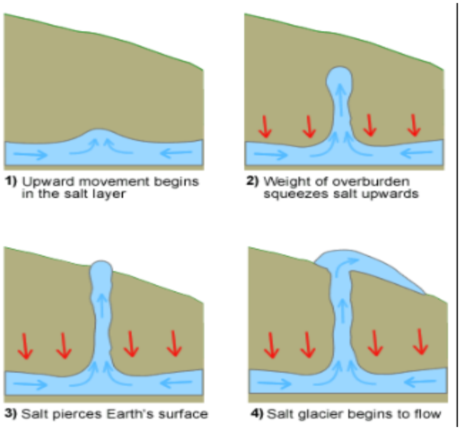
The rheological characteristics of salt origine the so called **HALOKYNETIC TECTONICS**.

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

Diapirs can assume very different shapes and sizes, depending on:

-salt volume availability
-substratum deepening
-sedimentary load
-faults activity
-different phase of halokynetic evolution



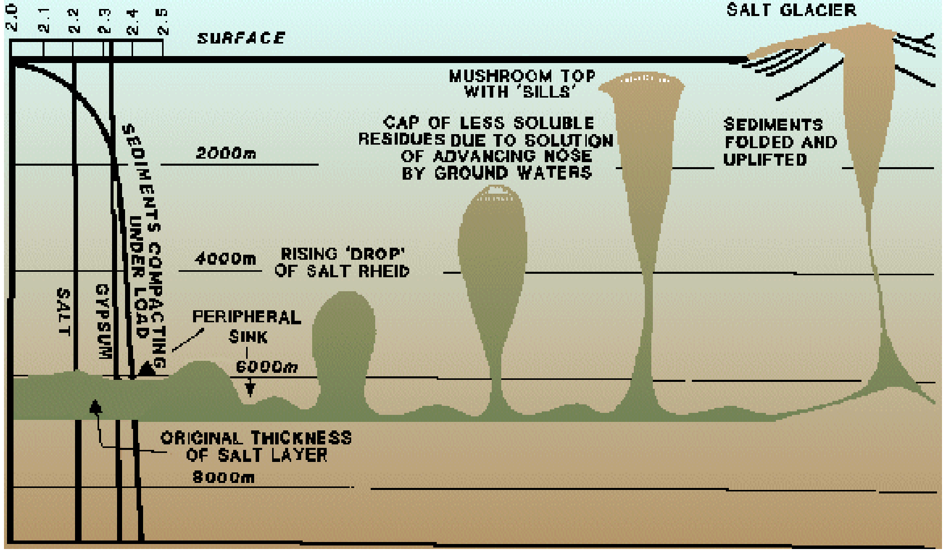


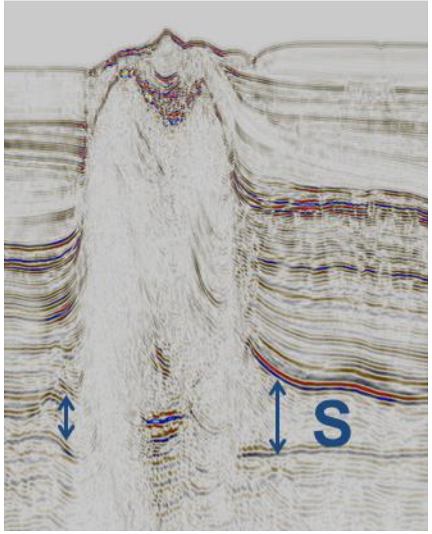
1) Upward movement begins in the salt layer

2) Weight of overburden squeezes salt upwards

3) Salt pierces Earth's surface

4) Salt glacier begins to flow



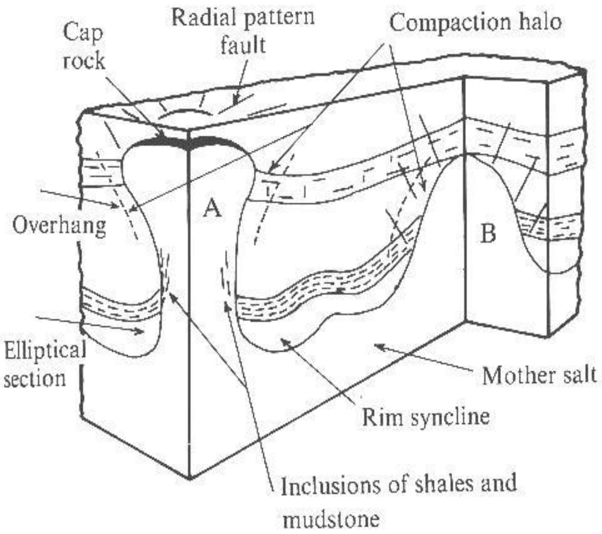


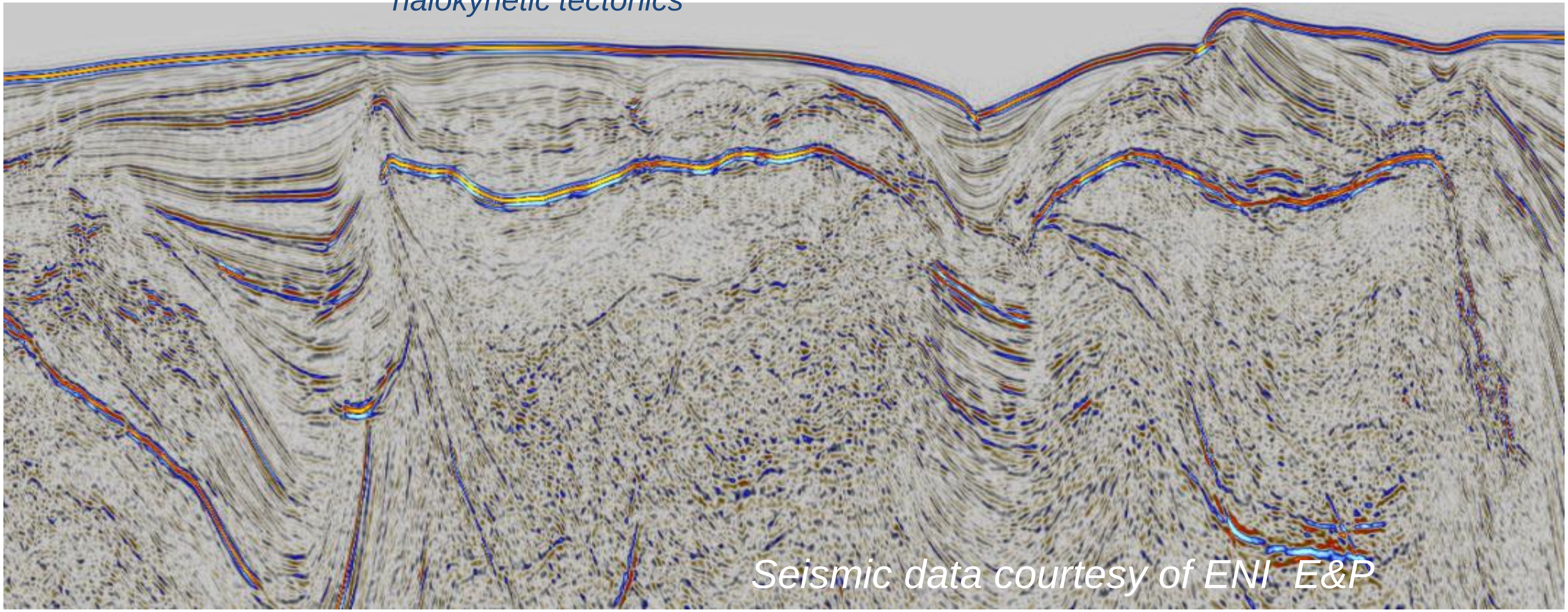
HALOKYNETIC TECTONICS

Salt seismic facies is transparent/ opaque/banked, sometimes incorporating sediments evidenced by some reflectors. Also lateral effects are present in 2D seismic.

Seismic profiles across the W-Africa margin

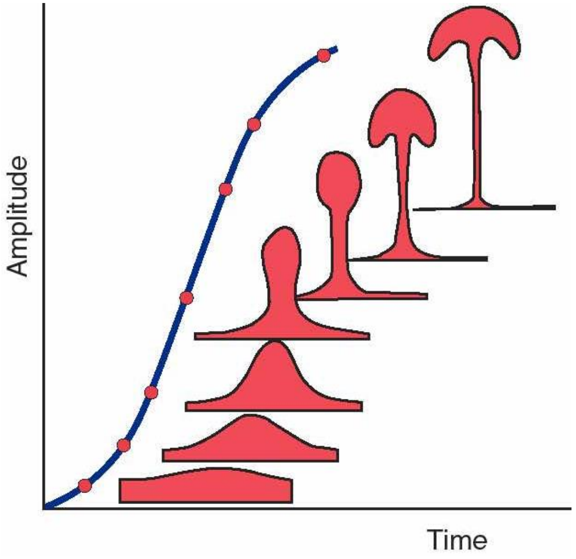
Different salt structures are evident; growth strata in the sedimentary cover date the halokynetic tectonics



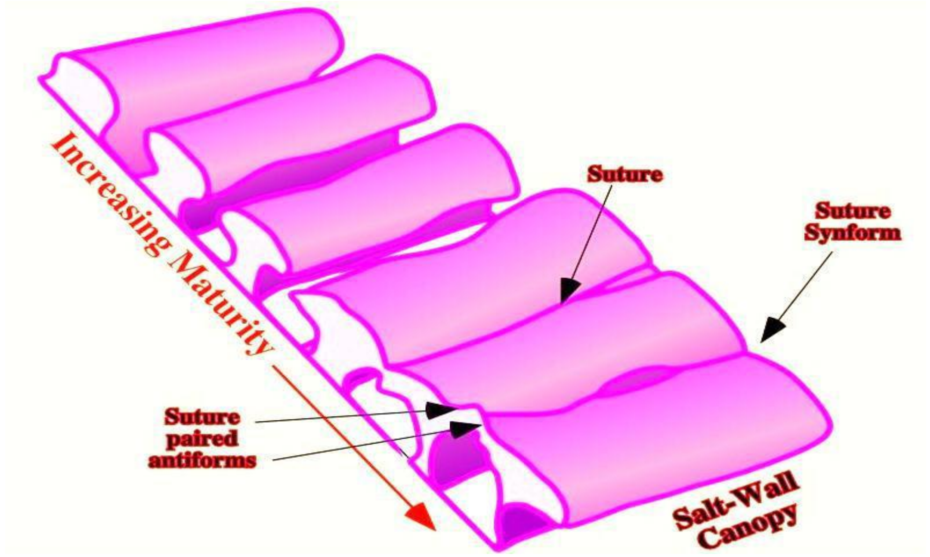


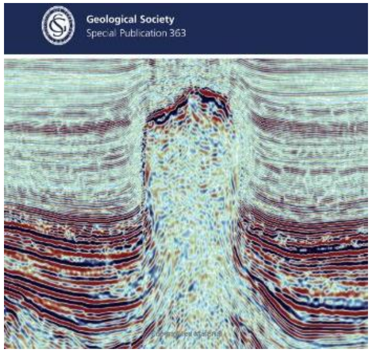
Seismic data courtesy of ENI E&P

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.



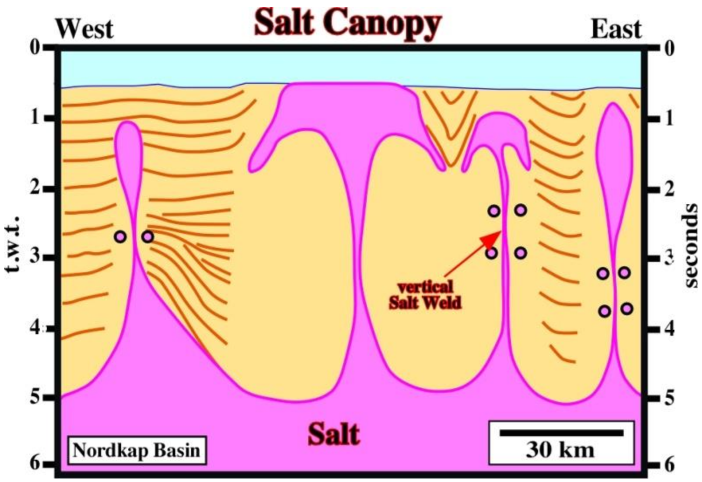
The boundary conditions for diapirism have met on a wide scale in the geological past. Several periods of structuration can be during which halokynesis has triggered, The Zechstein salt in the Netherlands has formed many diapirs during a long period of extension from the Mid Triassic to the Early Cretaceous, 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.



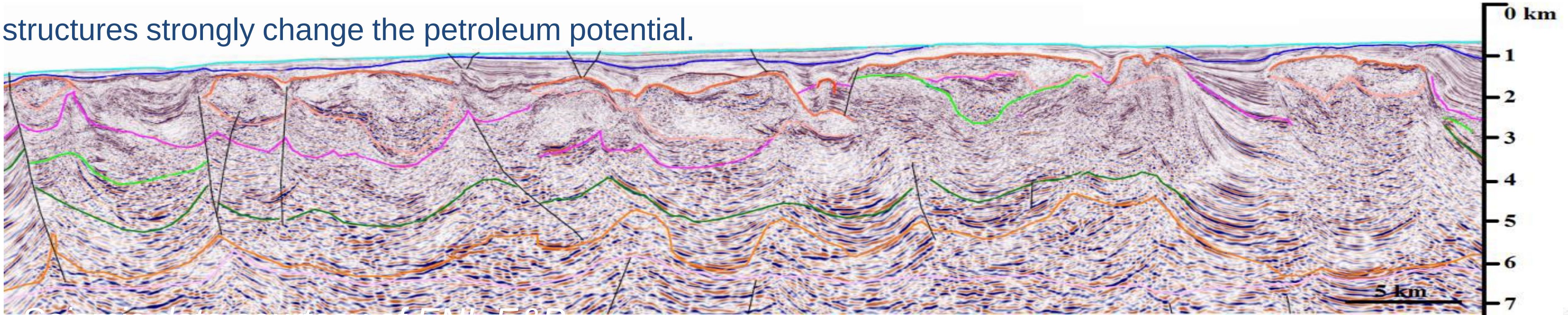


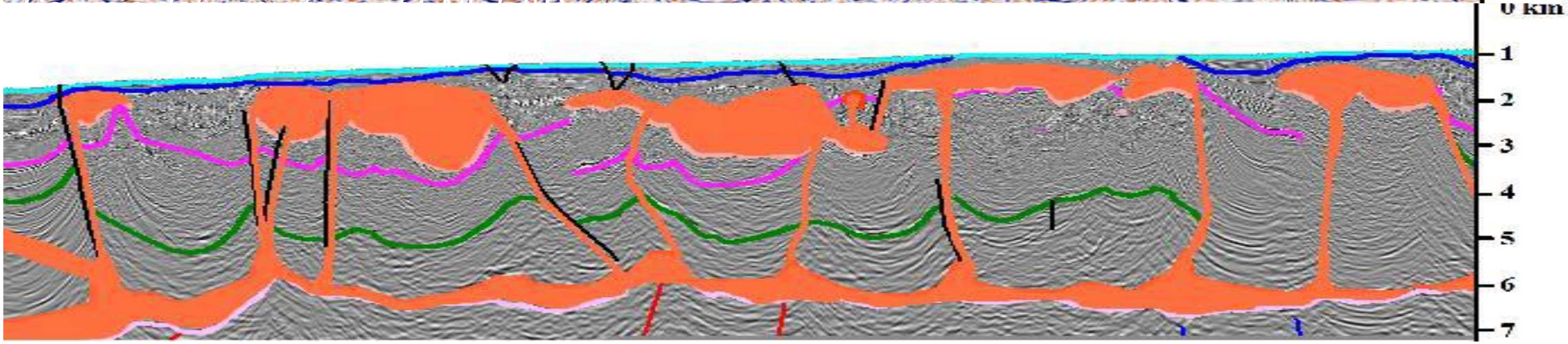
Salt Canopy

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

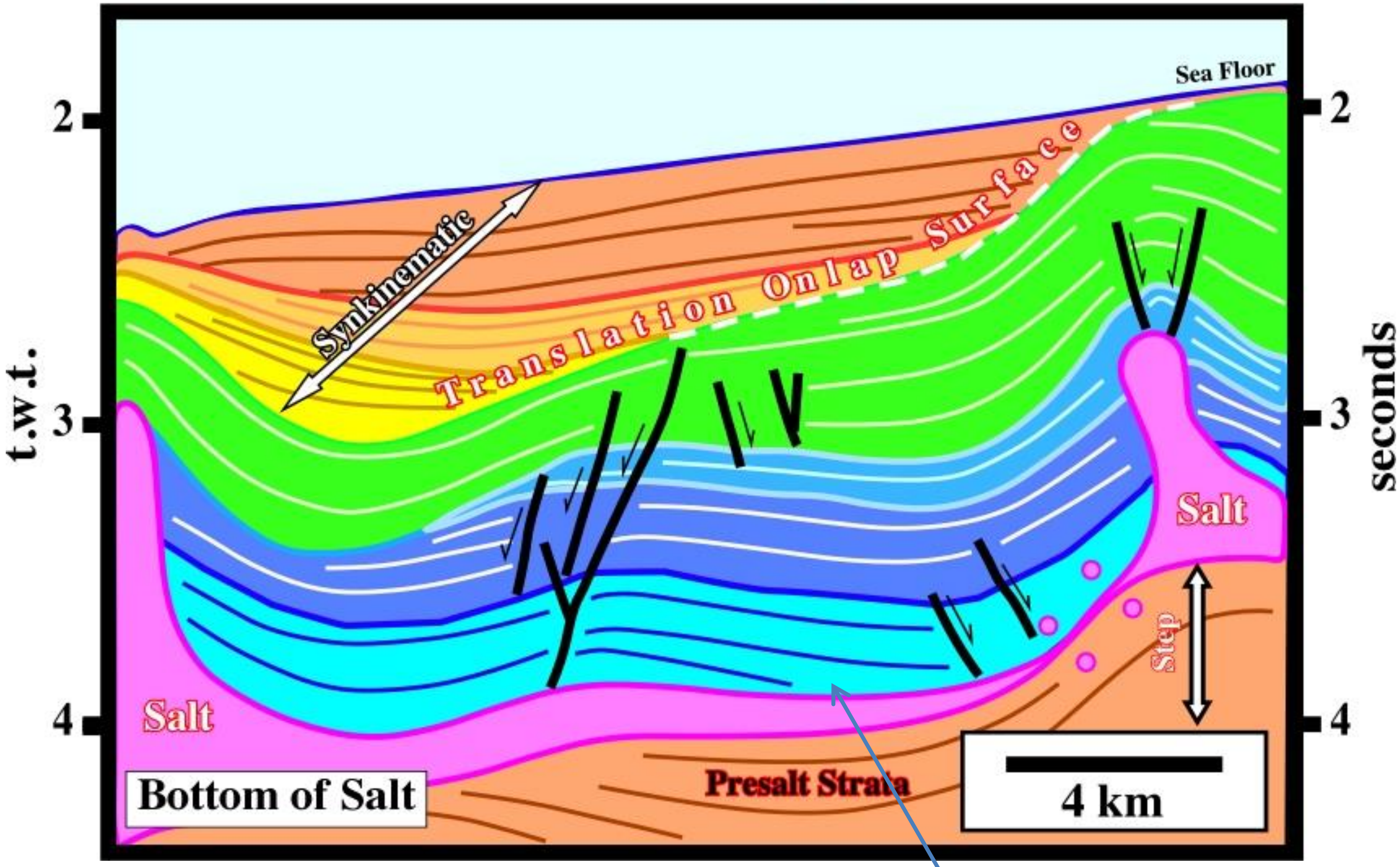


During long time, wrongly large diapiric structures (>30 km wide) were proposed for these profiles in W-Africa. It is obvious that interpretations with salt canopy structures strongly change the petroleum potential.

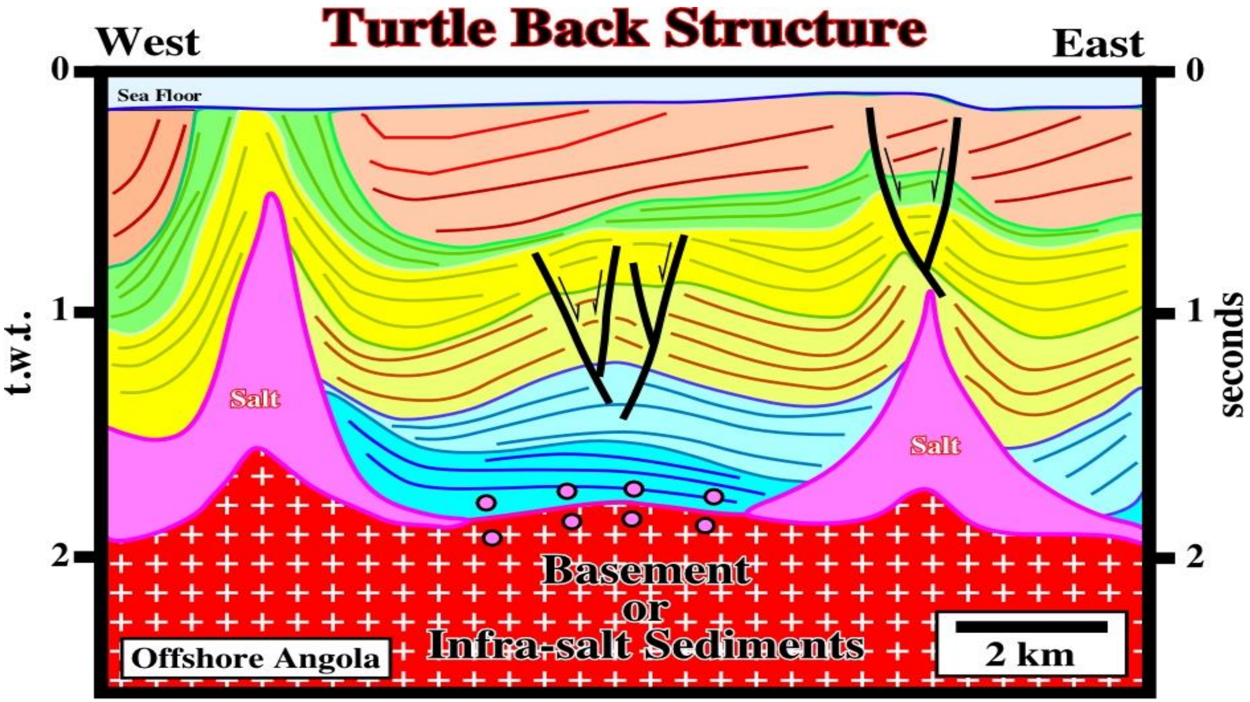




Translation Onlap Surface



Translation Onlap Surfaces: note the recent diapirs.
Translation of the overburden across a stepped salt detachment (thin salt) bends the post-salt sediments and can create apparent translation downlap surfaces 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.

Turtle structure formation

1992

Fall of diapirs during thin-skinned extension: B. C. Vendeville and M. P. A. Jackson

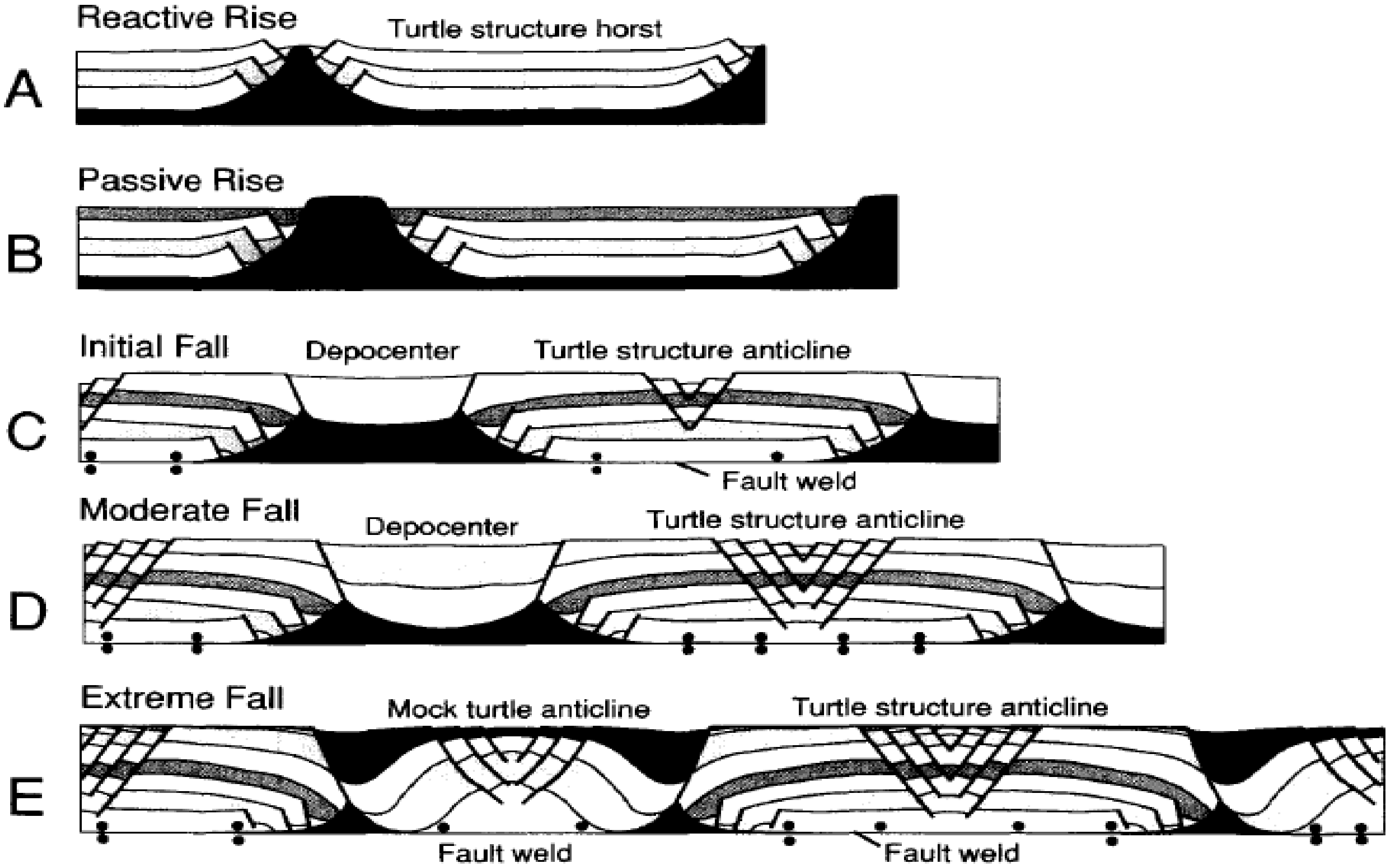
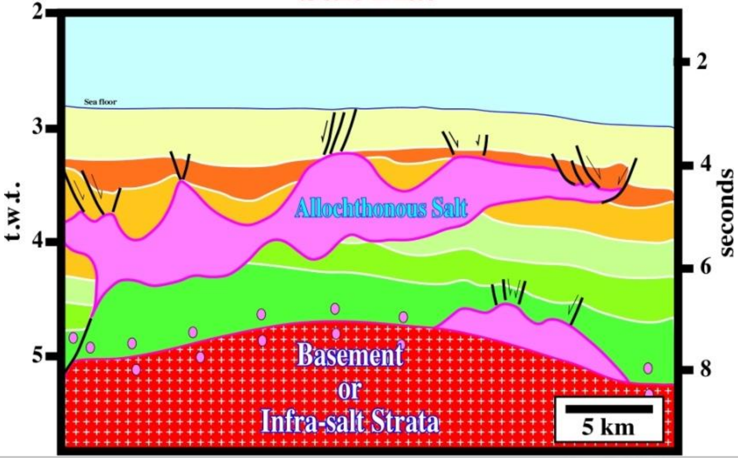


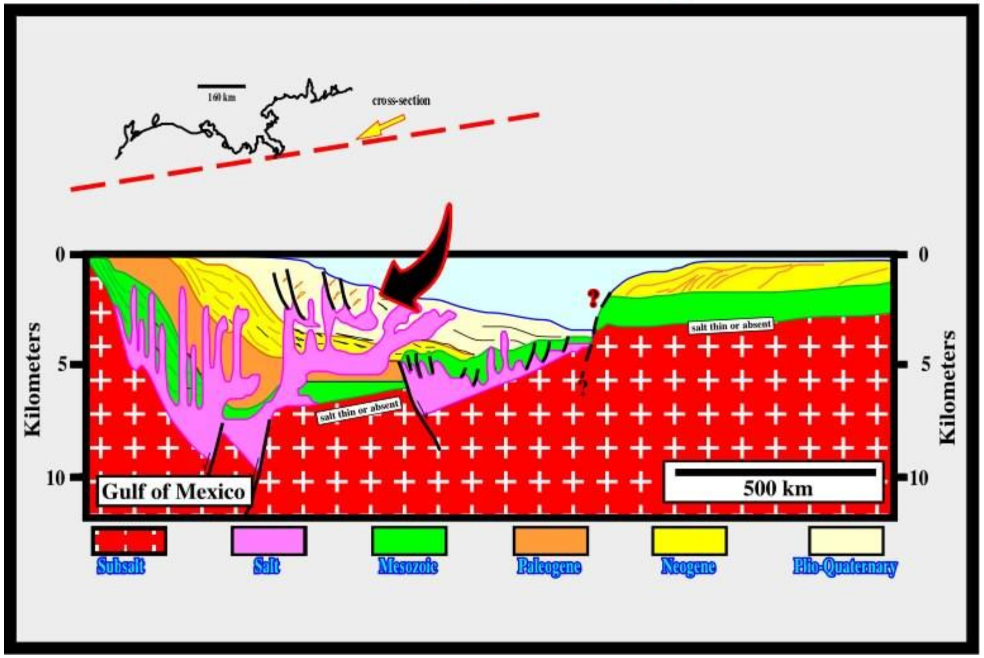
Figure 10 Schematic rise and fall of diapirs during sedimentation. Three types of extensional turtle structure successively form: turtle structure horsts, then turtle structure anticlines, then mock turtle anticlines

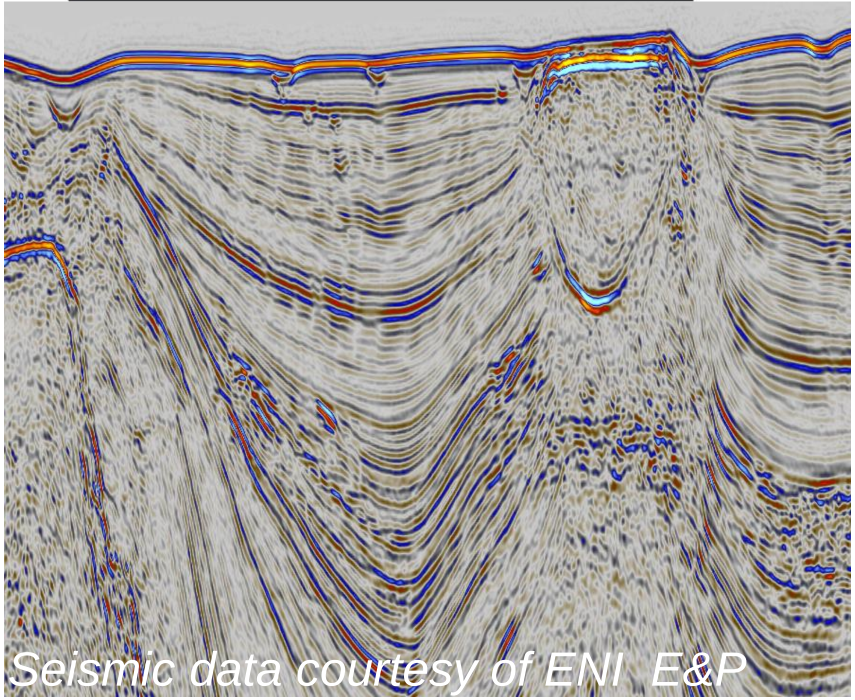
Sometimes salt diapirs become **mother layer** for new shallower salt migration, originating second-generation (or granddaughter) diapirs

Salt Flat



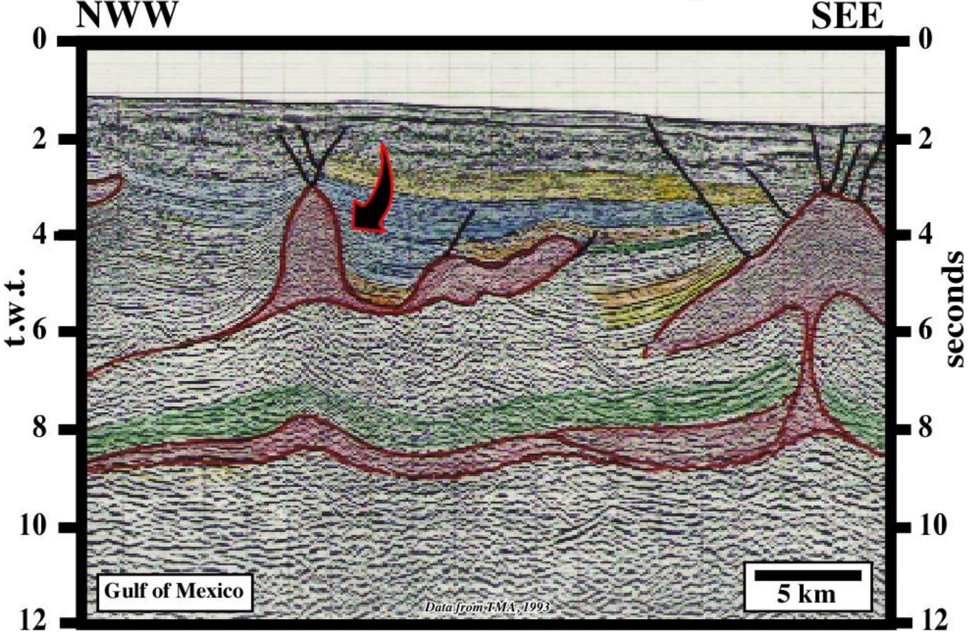
Granddaughter Diapir





Seismic data courtesy of ENI E&P

Second-Generation Diapirs



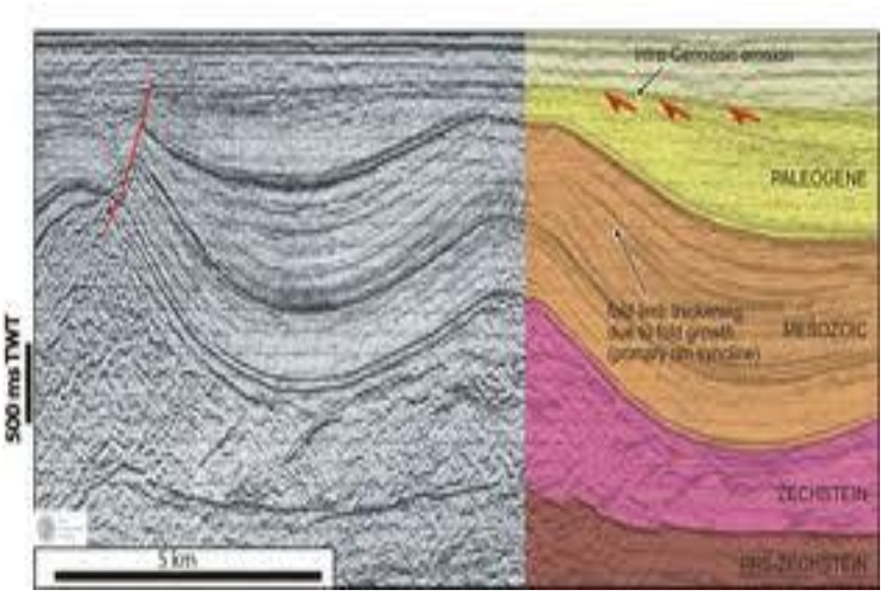
Data from TMA, 1993

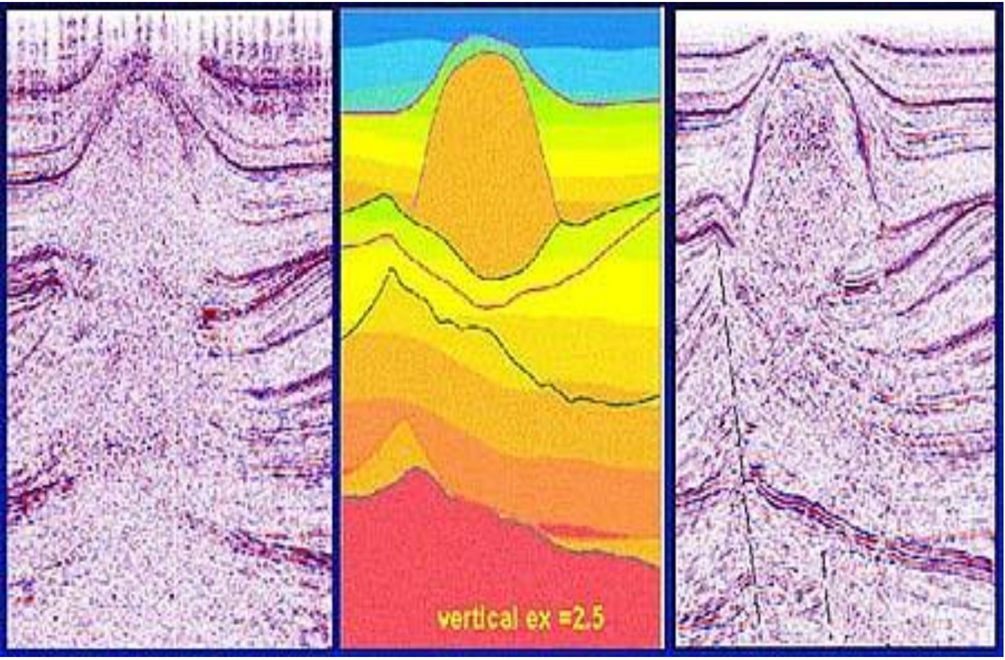
In seismic profiles:

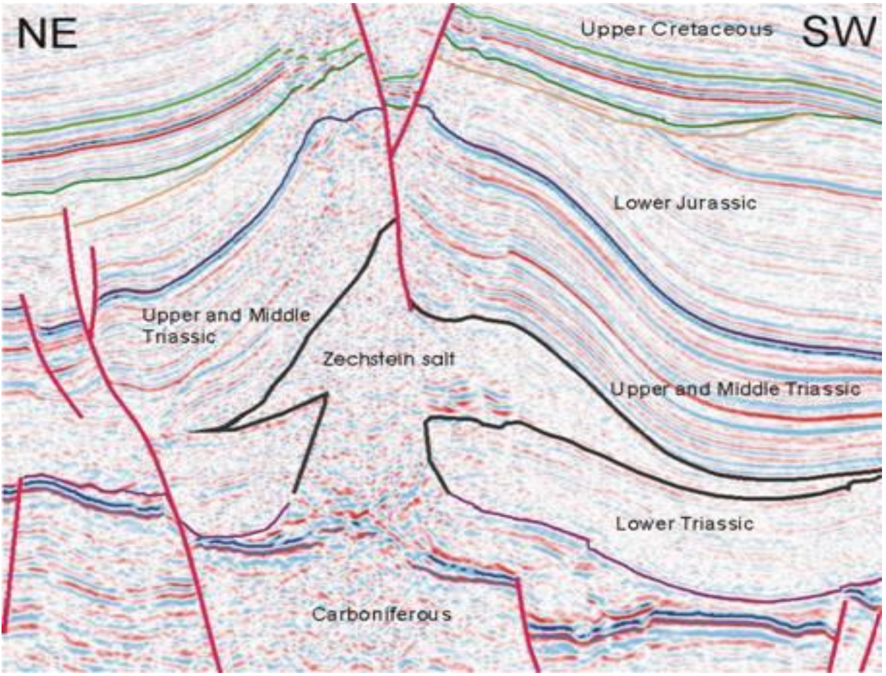
-typical velocity pull-up below the salt diapirs in the TWT profiles

-velocity inversion → negative polarity

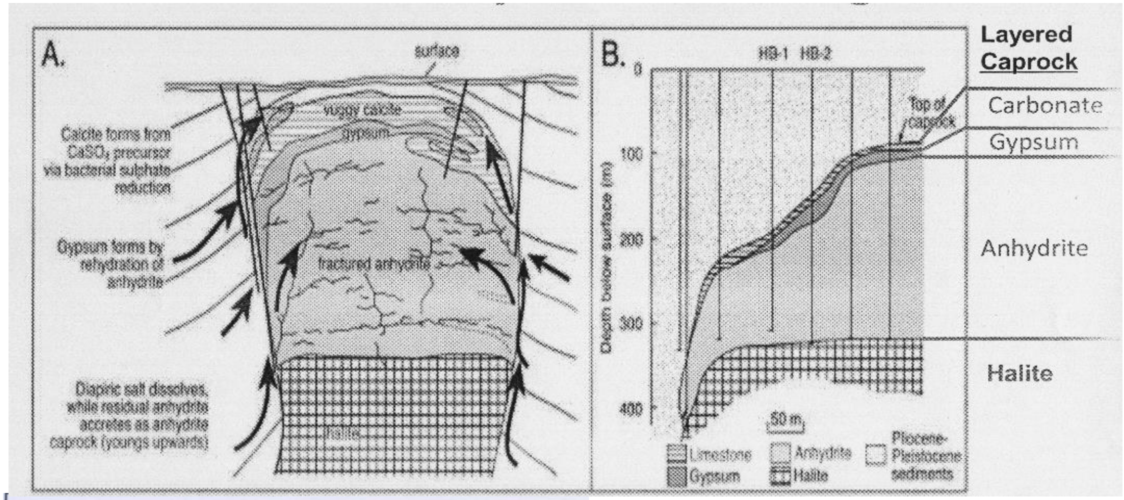
-improving of pre-salt reflectors by re-processing

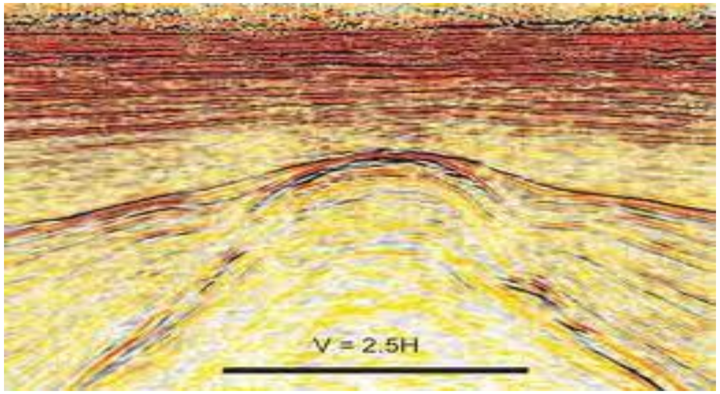


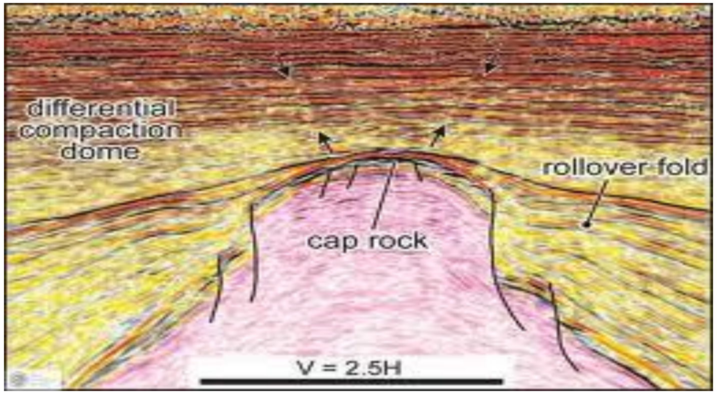


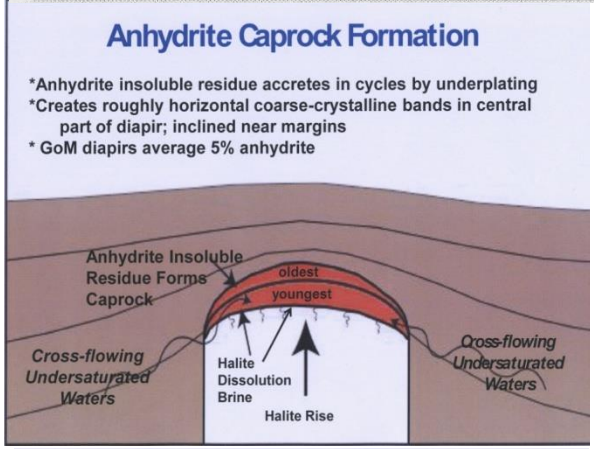


COMMON **CAPROCK** LITHOLOGIES







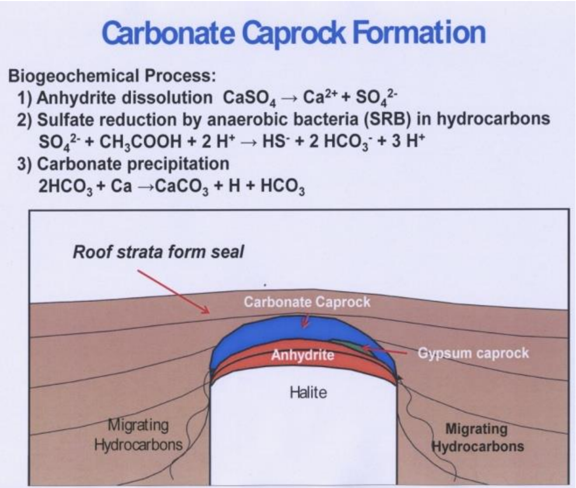


Anhydrite Caprock Formation

*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



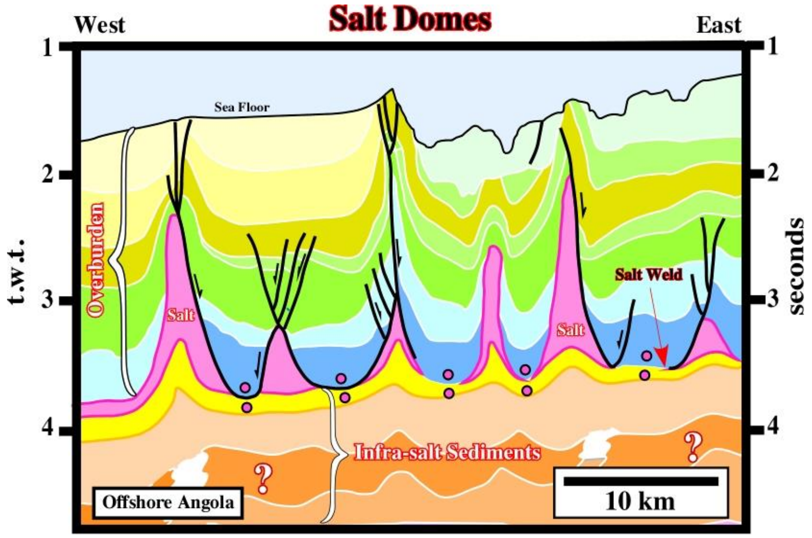
Carbonate Caprock Formation

Biogeochemical Process:

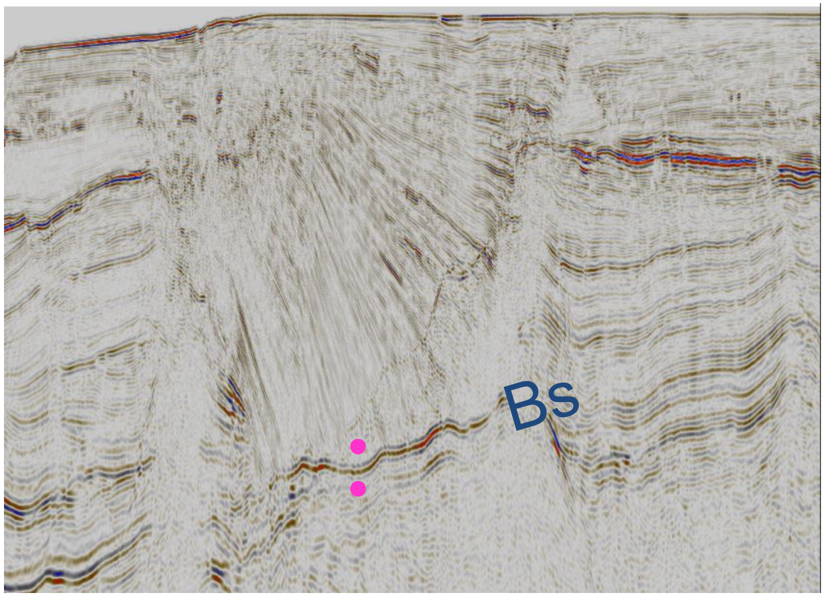
1) Anhydrite dissolution $CaSO_4 \rightarrow Ca^{2+} + SO_4^{2-}$
2) Sulfate reduction by anaerobic bacteria (SRB) in hydrocarbons $SO_4^{2-} + CH_3COOH + 2 H^+ \rightarrow HS^- + 2 HCO_3^- + 3 H^+$
3) Carbonate precipitation $2HCO_3 + Ca \rightarrow CaCO_3 + H + HCO_3$

Caprock forms by the dissolution of the upper part of a salt structure once salt supply 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.

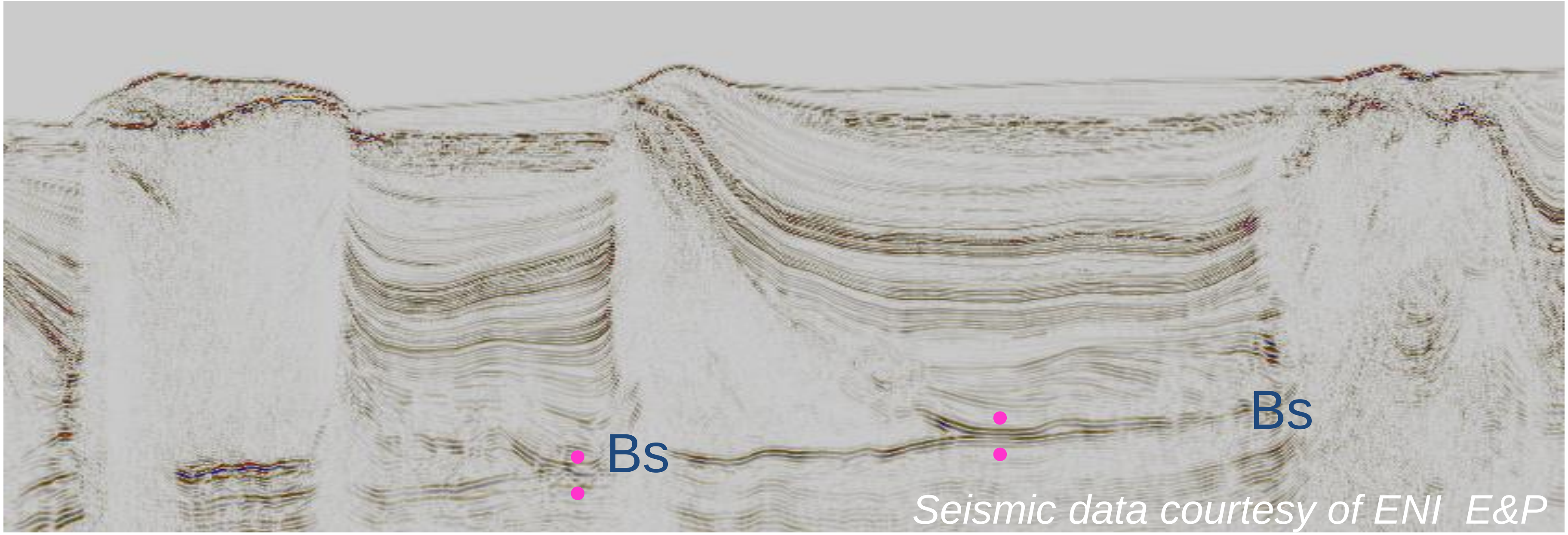
Halite (NaCl) - Anhydrite (CaSO4) - Gypsum (CaSO4-2H2O) - Limestone ($CaCO_3/CaMg(CO_3)_2$)



Welds

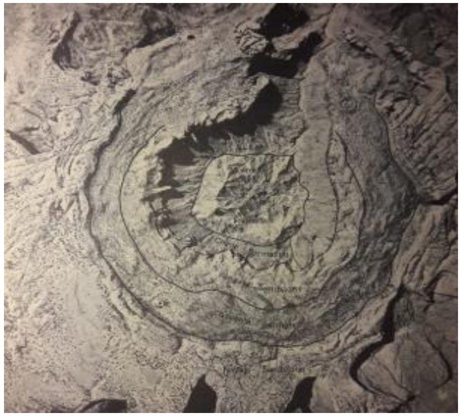


Sliding on the deepening substratum sometimes puts directly in contact the sequence covering the salt layer and the pre-salt sediments, originating a so called "weld" (symbol **:** *). Note active halokynetics in the sea bottom*

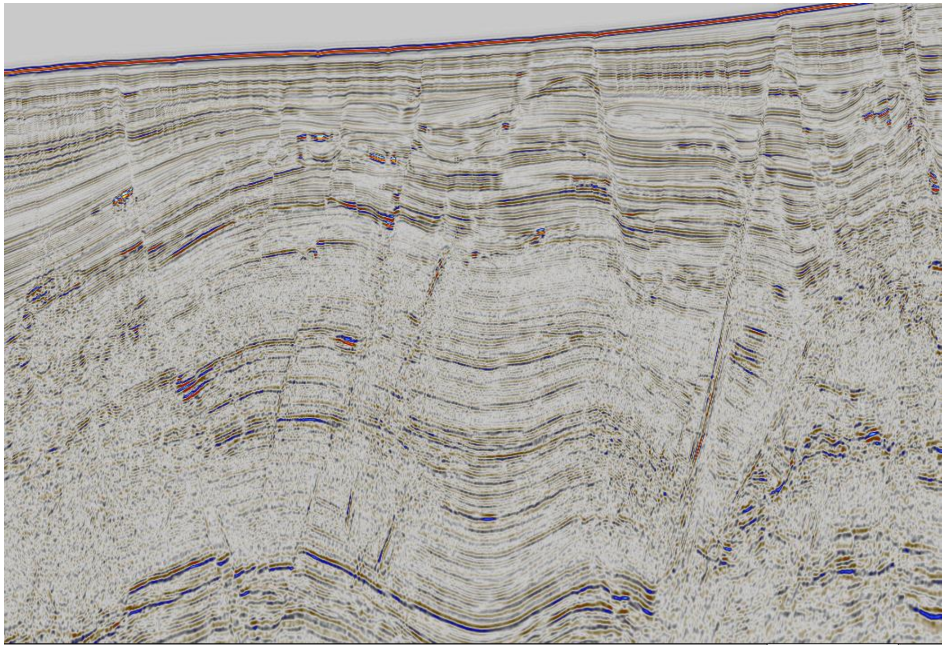


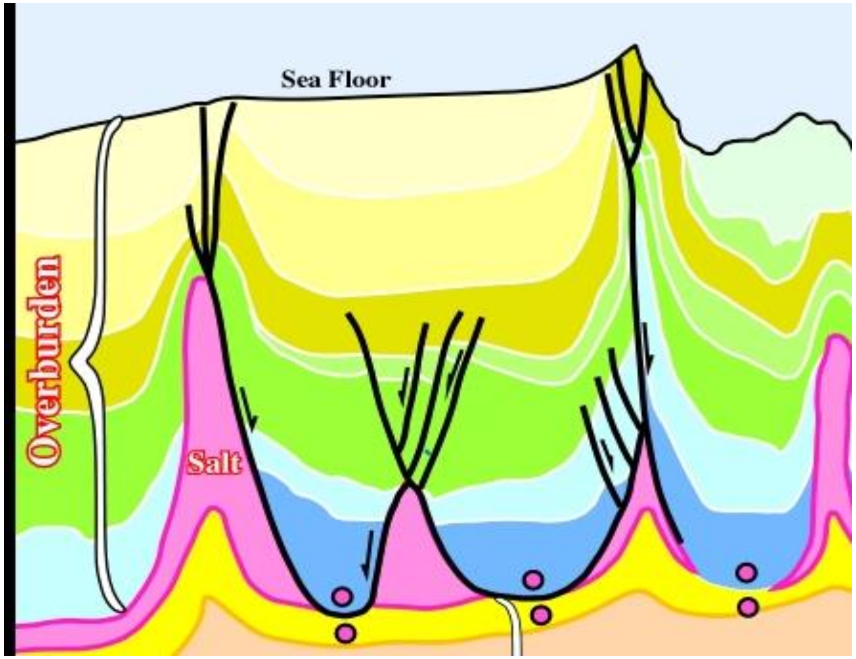
Seismic data courtesy of ENI E&P

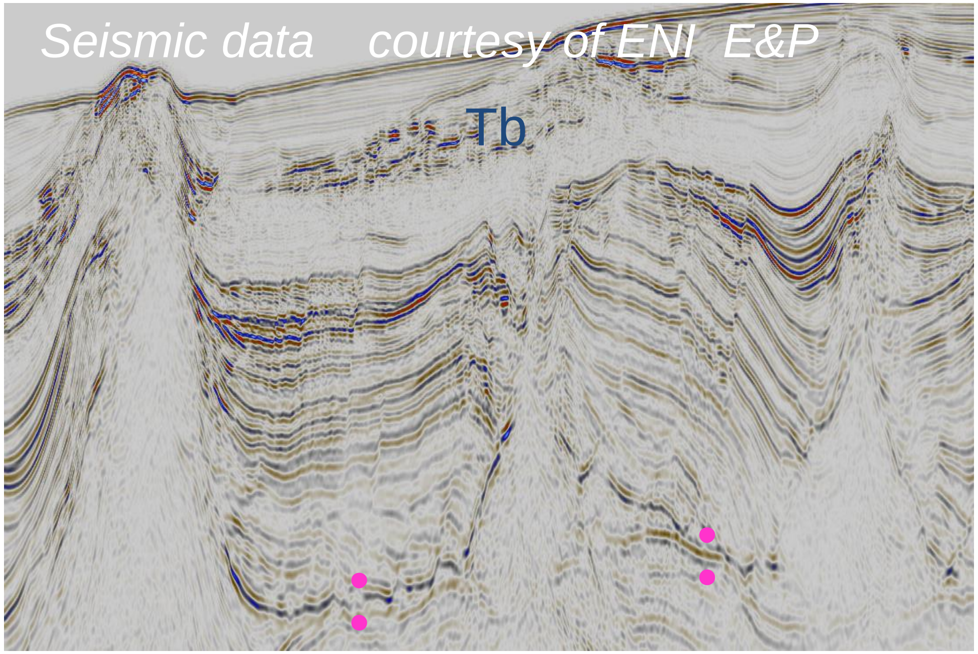
Concentric fault systems above salt domes



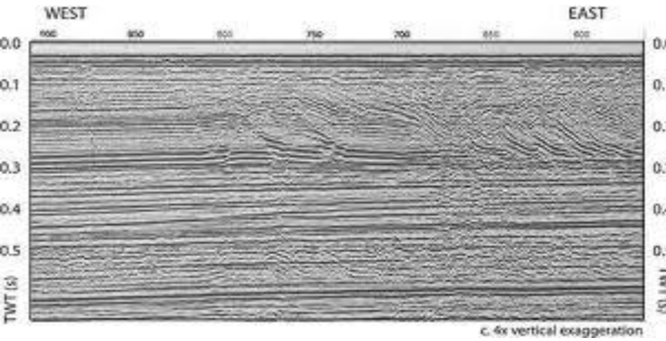
Turbiditic bodies (**Tb**):
one of the main targets
before pre-salt exploration

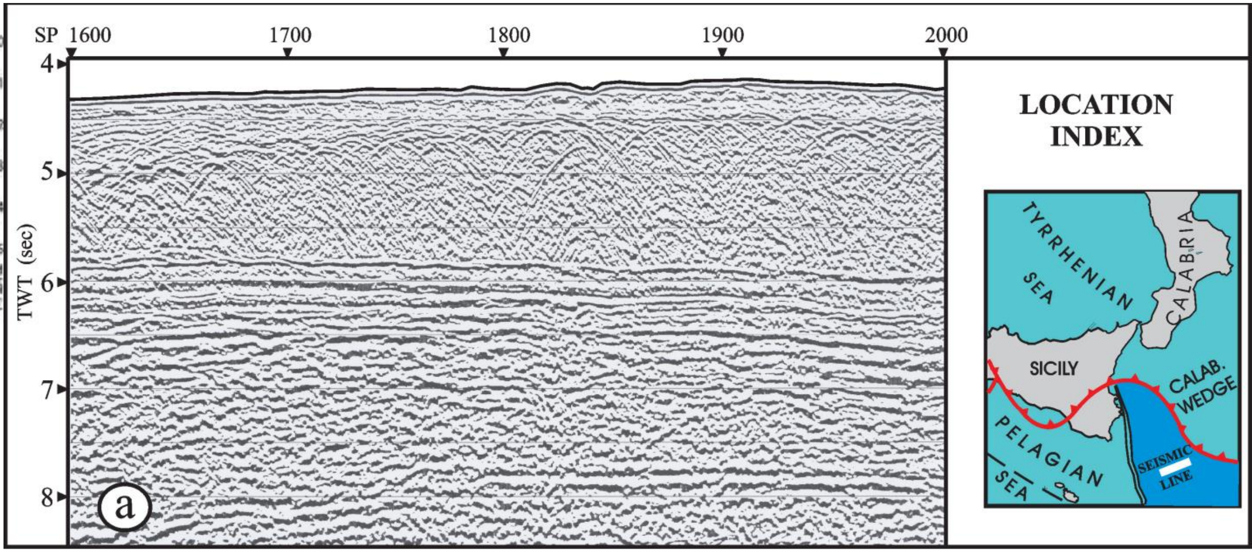






Seismic data courtesy of ENI E&P



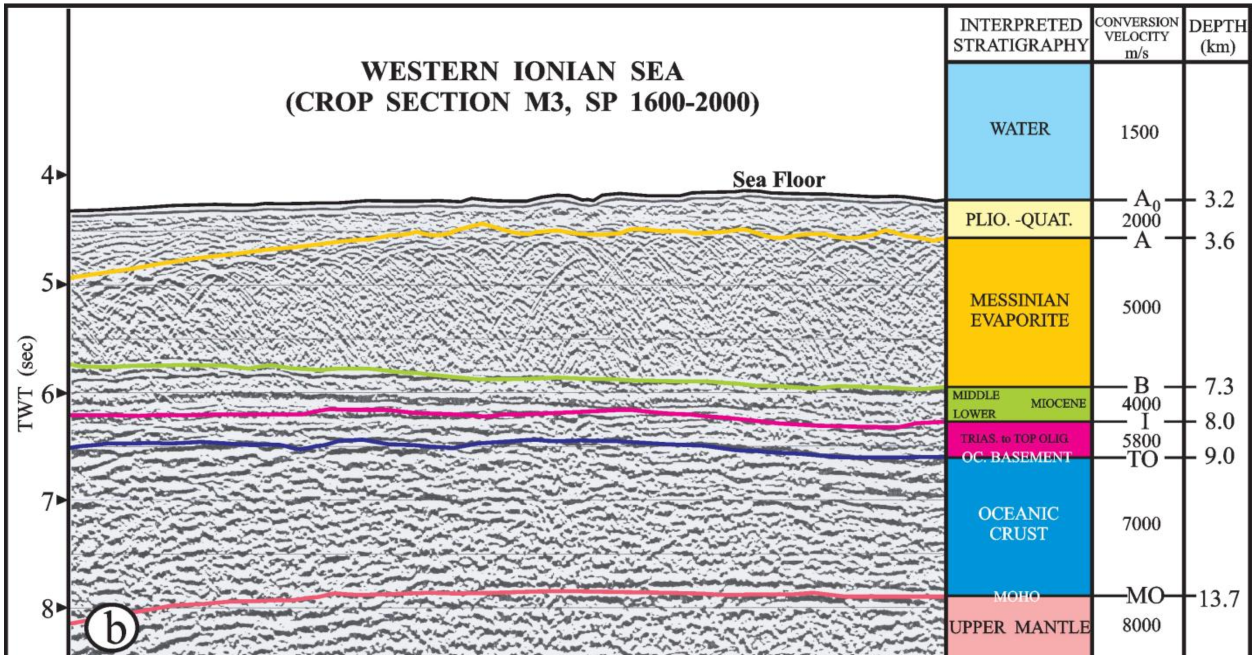


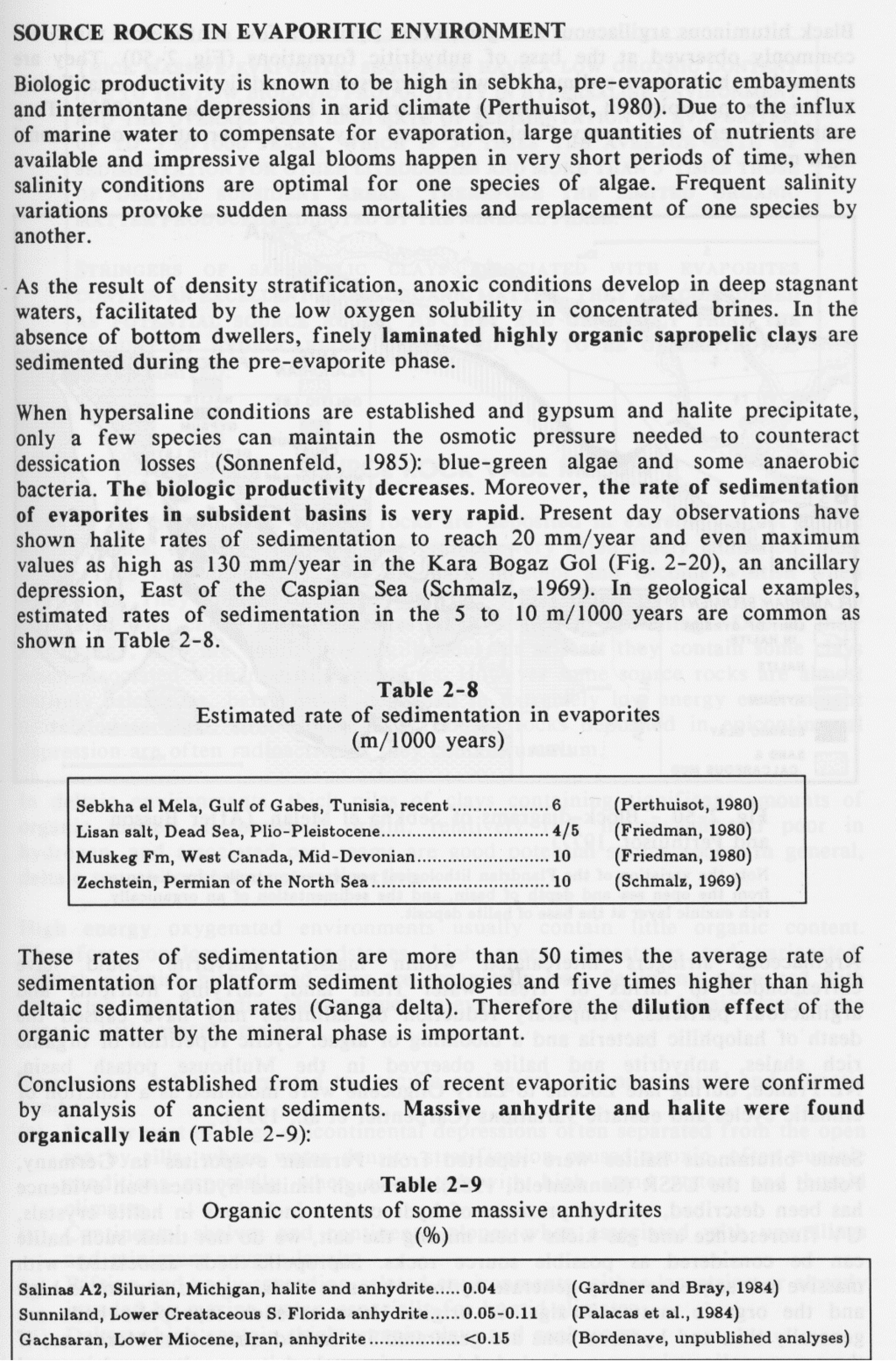
Because of its rheology, salt can highly increase tectonic deformations of the overlaying sediments:

e.g., the presence of the Messinian salt in the Ionian basin allows the compressive tectonics of the Calabrian and Mediterranean Ridges 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)

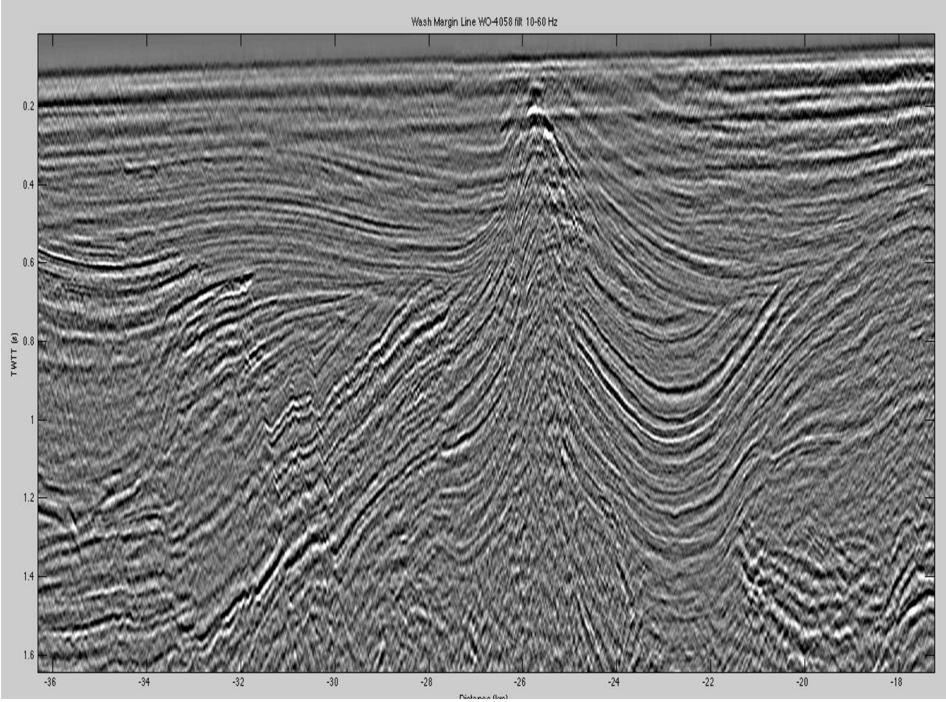
These rates of sedimentation are more than 50 times the average rate of sedimentation for platform sediment lithologies and five times higher than high deltaic sedimentation rates (Ganga delta). Therefore the **dilution effect** of the organic matter by the mineral phase is important.

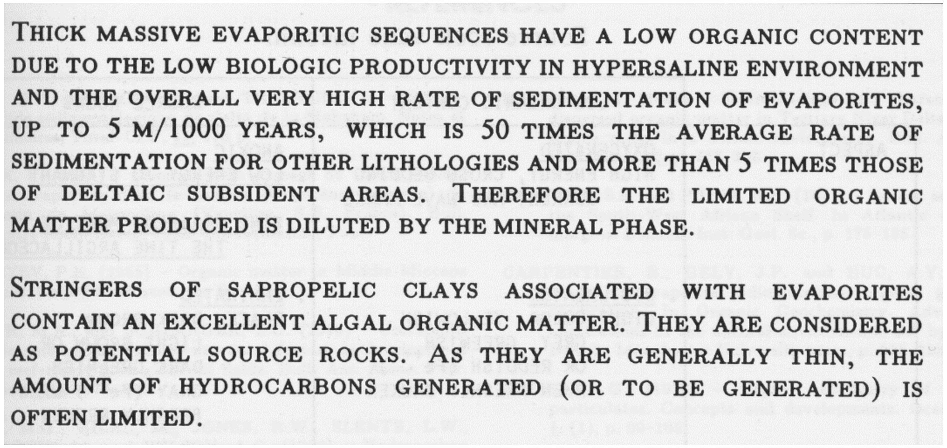
Conclusions established from studies of recent evaporitic basins were confirmed by analysis of ancient sediments. **Massive anhydrite and halite were found organically lean** (Table 2-9):

Table 2-9

Organic contents of some massive anhydrites
(%)

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



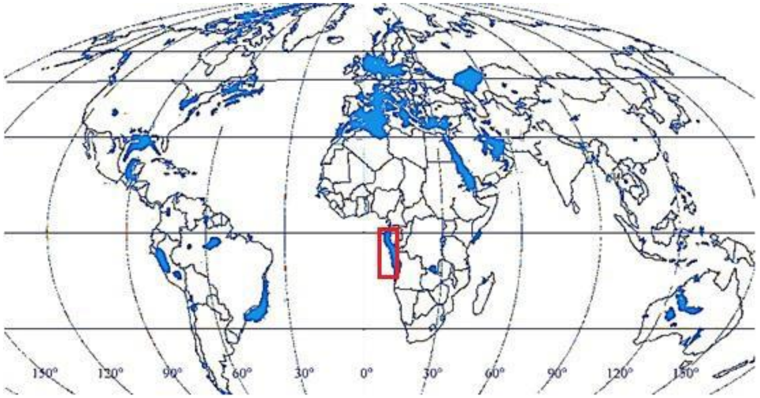


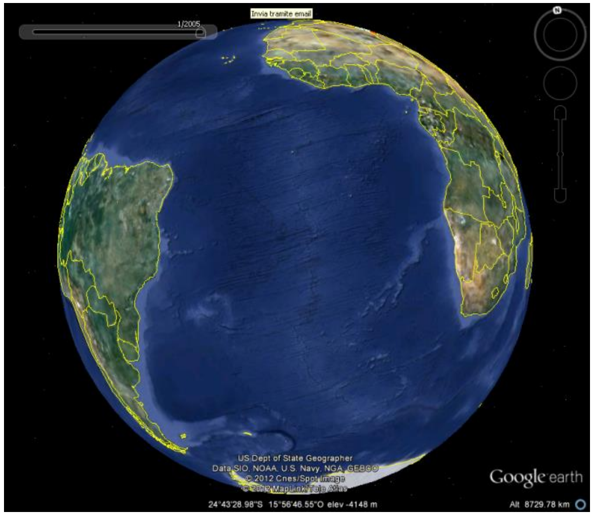
THICK MASSIVE EVAPORITIC SEQUENCES HAVE A LOW ORGANIC CONTENT DUE TO THE LOW BIOLOGIC PRODUCTIVITY IN HYPERSALINE ENVIRONMENT AND THE OVERALL VERY HIGH RATE OF SEDIMENTATION OF EVAPORITES, UP TO 5 M/1000 YEARS, WHICH IS 50 TIMES THE AVERAGE RATE OF SEDIMENTATION FOR OTHER LITHOLOGIES AND MORE THAN 5 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 (Salt Giants) in the world
… what are their common origine?
… restricted euxinic basins with high evaporation rate

Mediterranean Sea

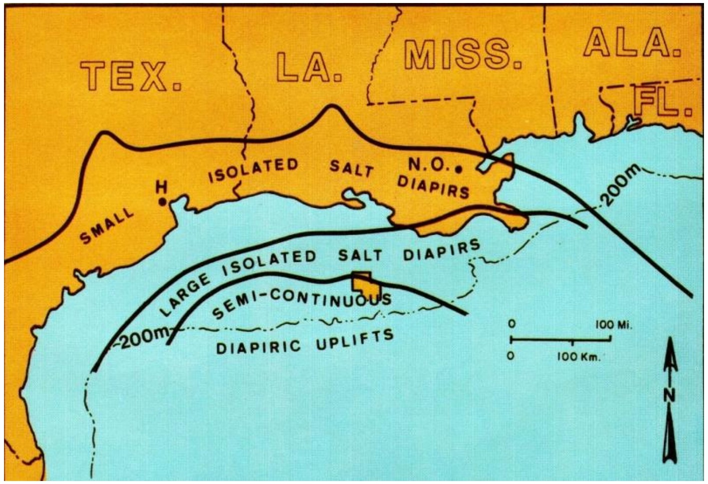




South-Atlantic margins

Pre-Caspian basin

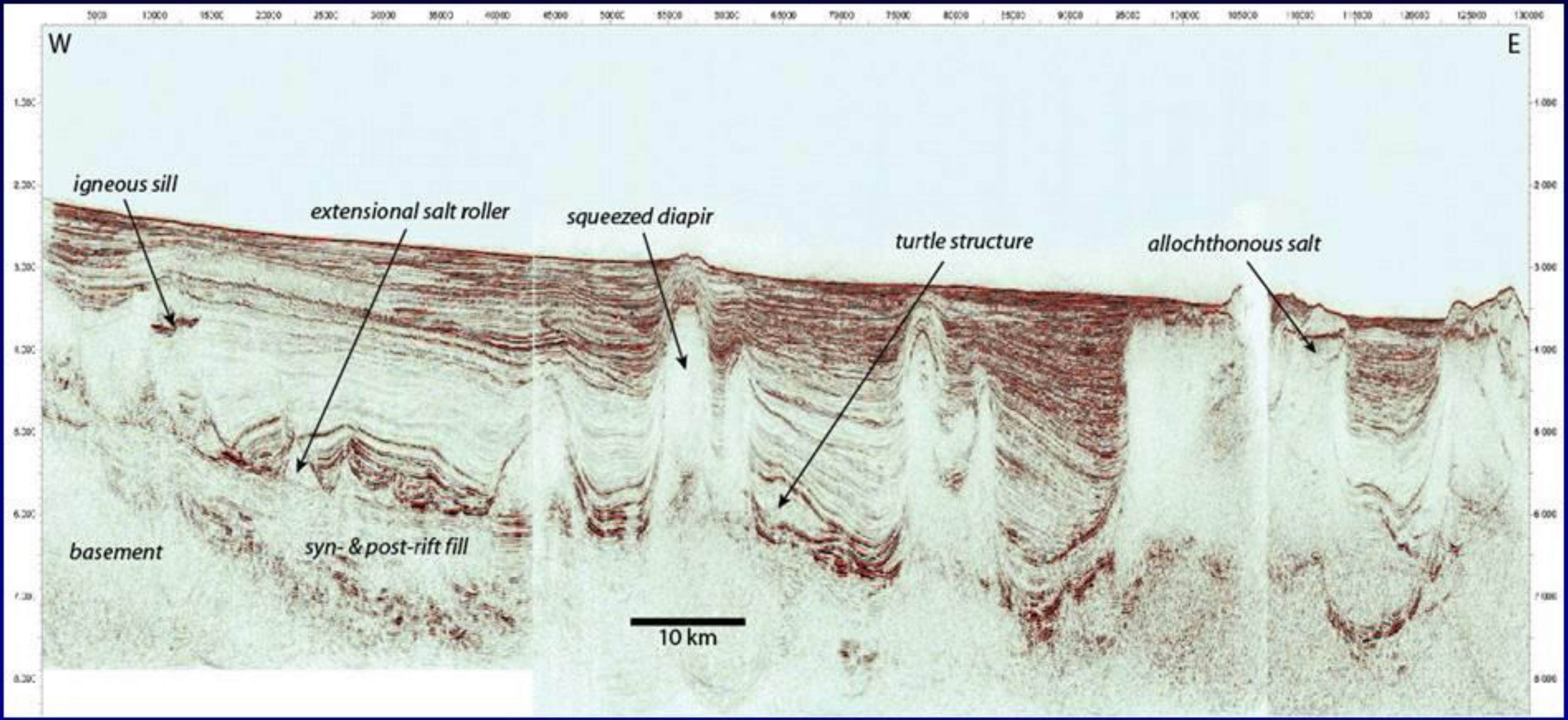
North Sea



Gulf of Mexico

Espirito Santo Basin

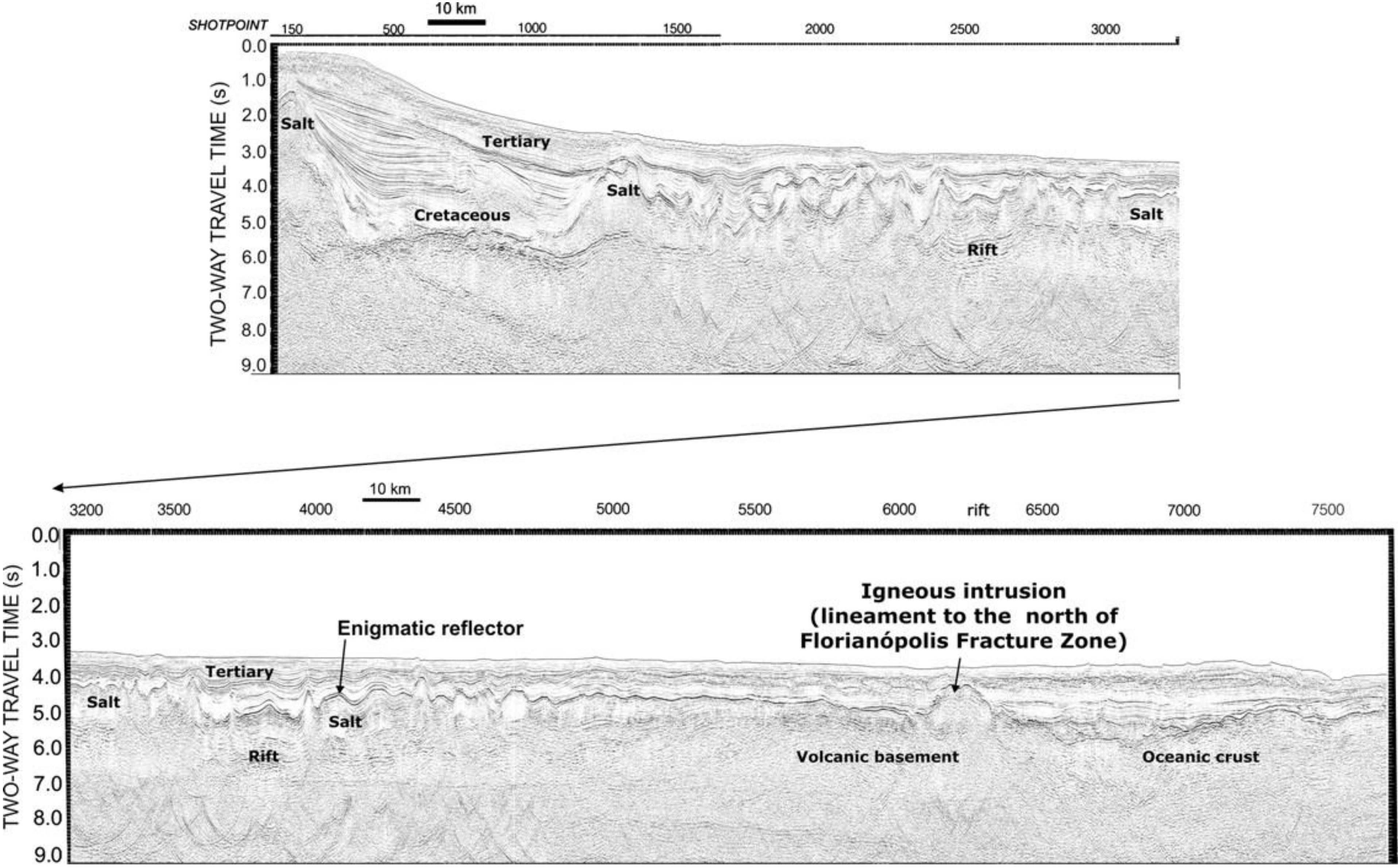
South Atlantic margin: Brasile offshore



In the lower slope of passive margins
the post-salt sequences slide
with and on the salt layer

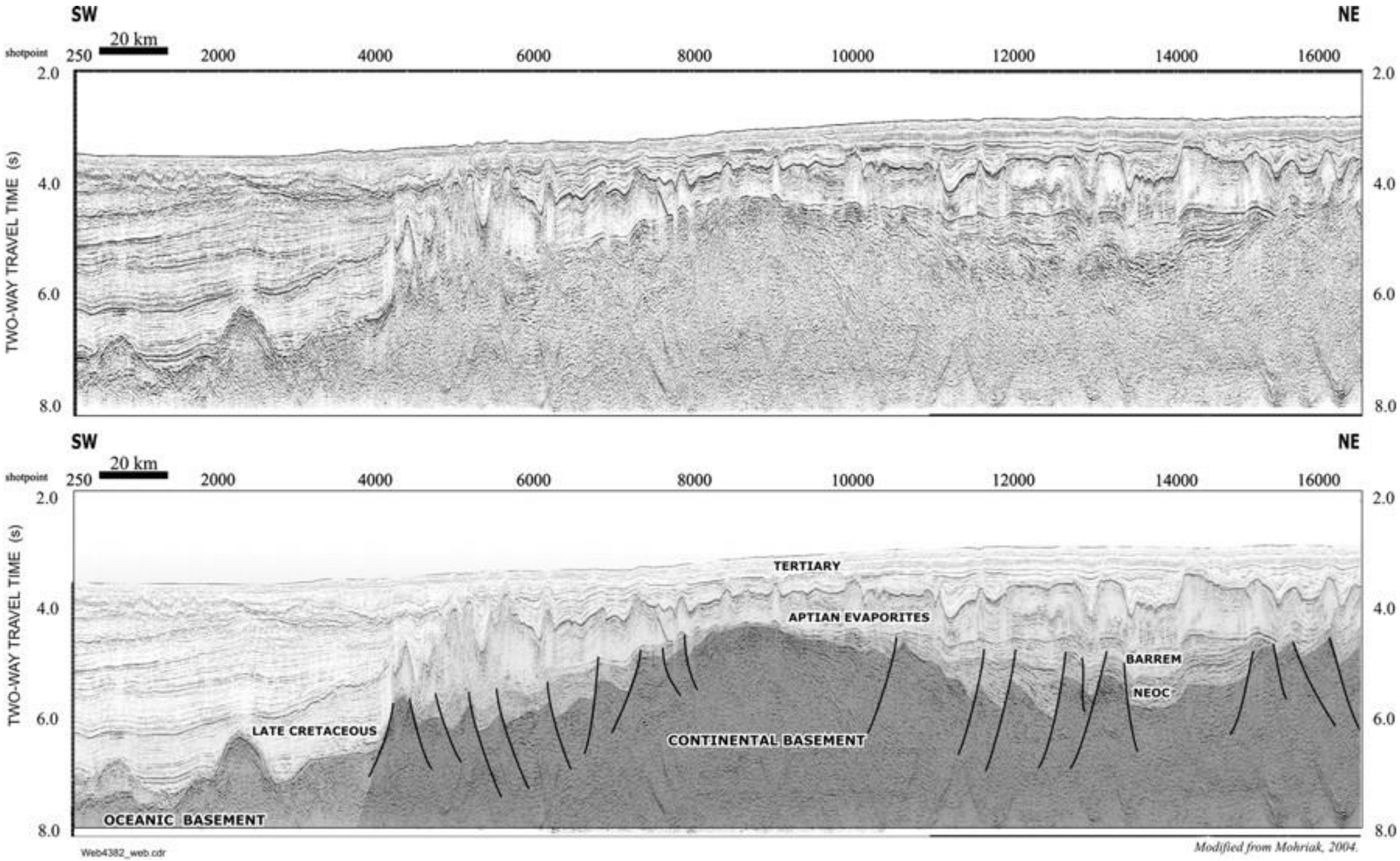
Data courtesy of CGGVeritas and C. Fiduk

Western margin of the South Atlantic Basin



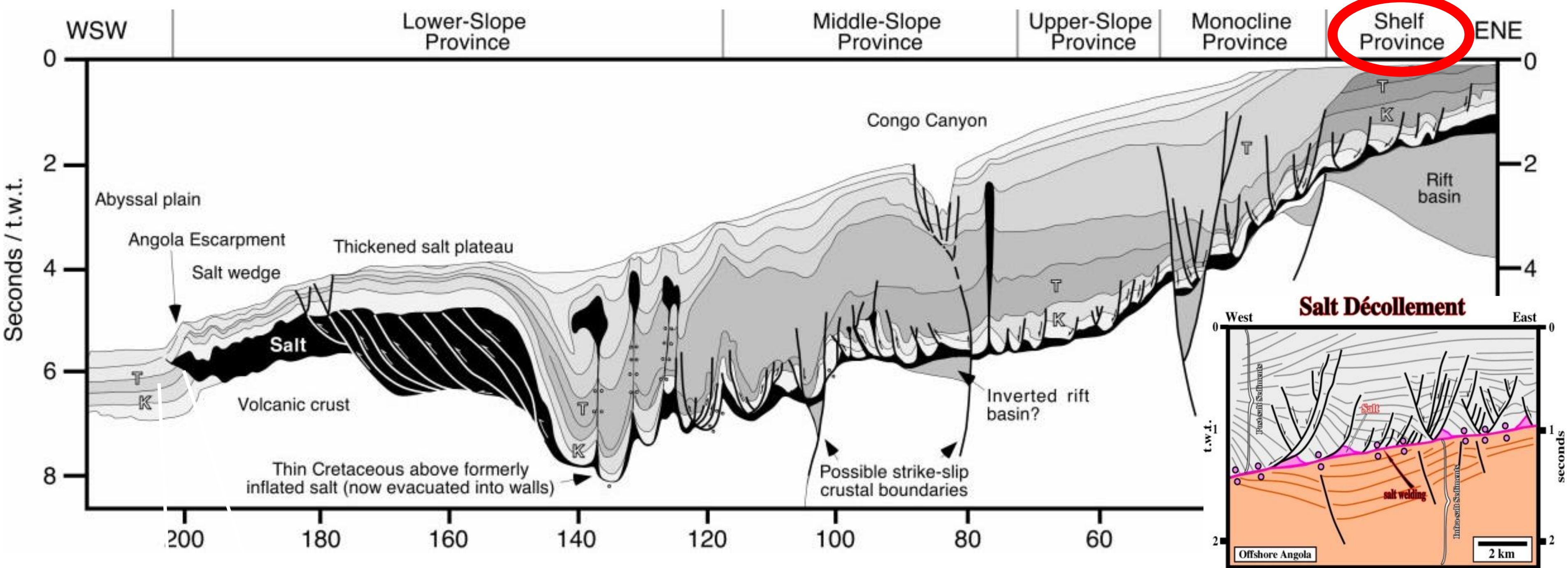
Modified from Mohriak, 2004.

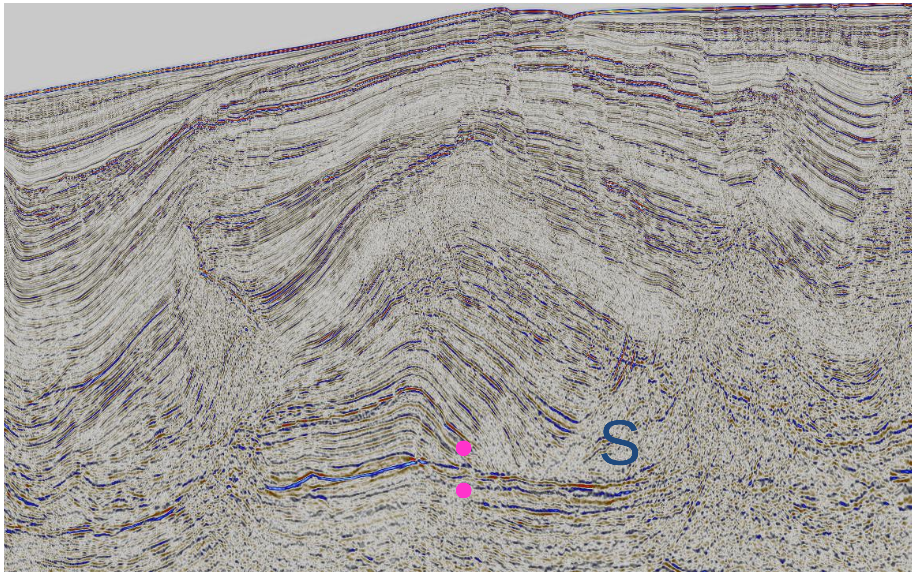
Eastern margin of the South Atlantic Basin

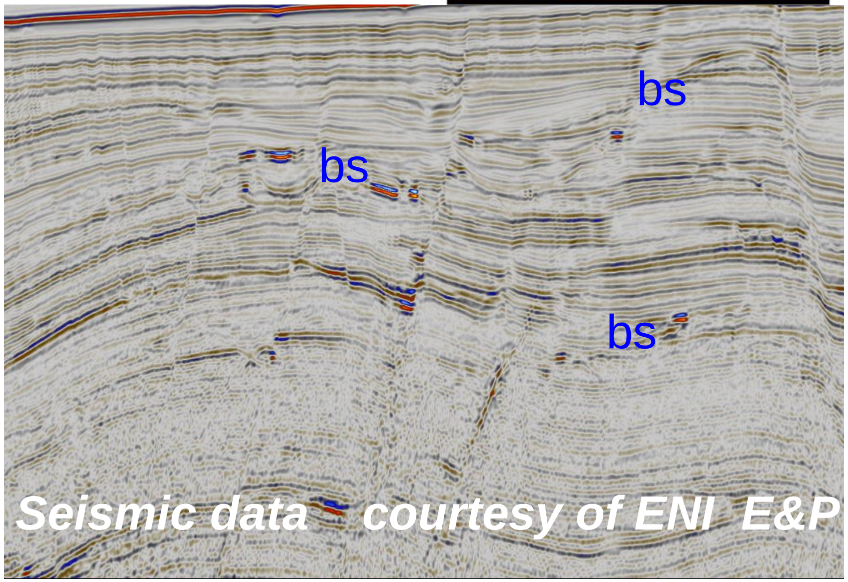


Modified from Mohriak, 2004.

West-Africa passive margin: **Shelf Province**

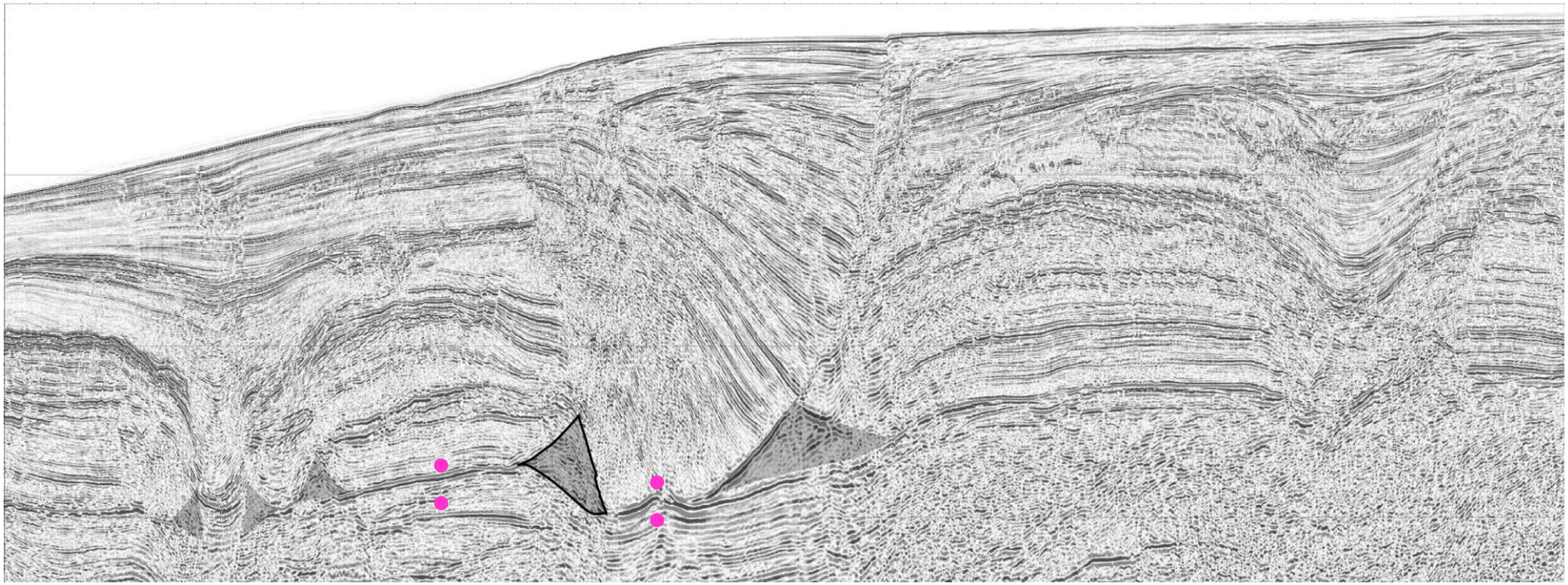






bs = bright spot

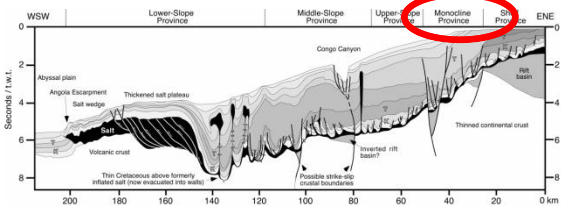
2-D seismic time section in the **raft domain**

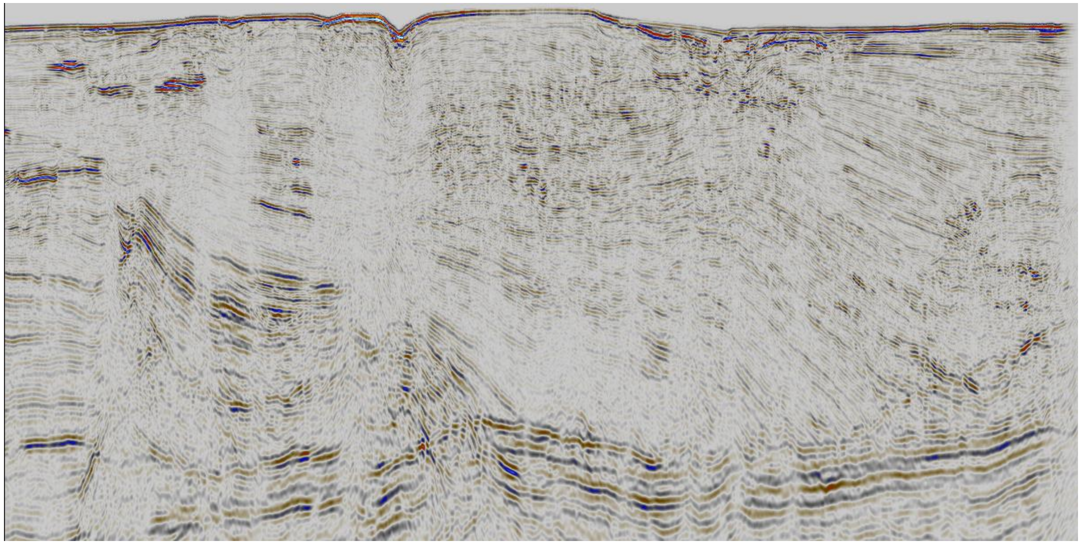


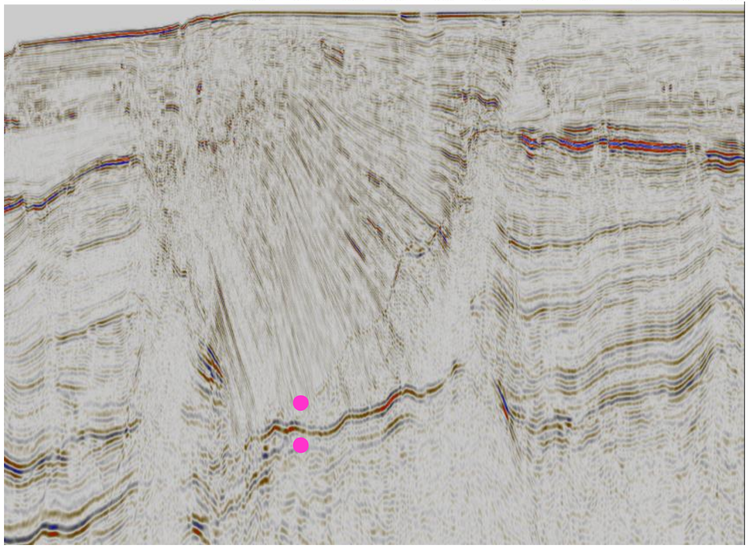
the post-salt layers were moved and rotated above the salt.
Relatively simple structure and consistent stratigraphic thickness suggest
that salt here was never thick.

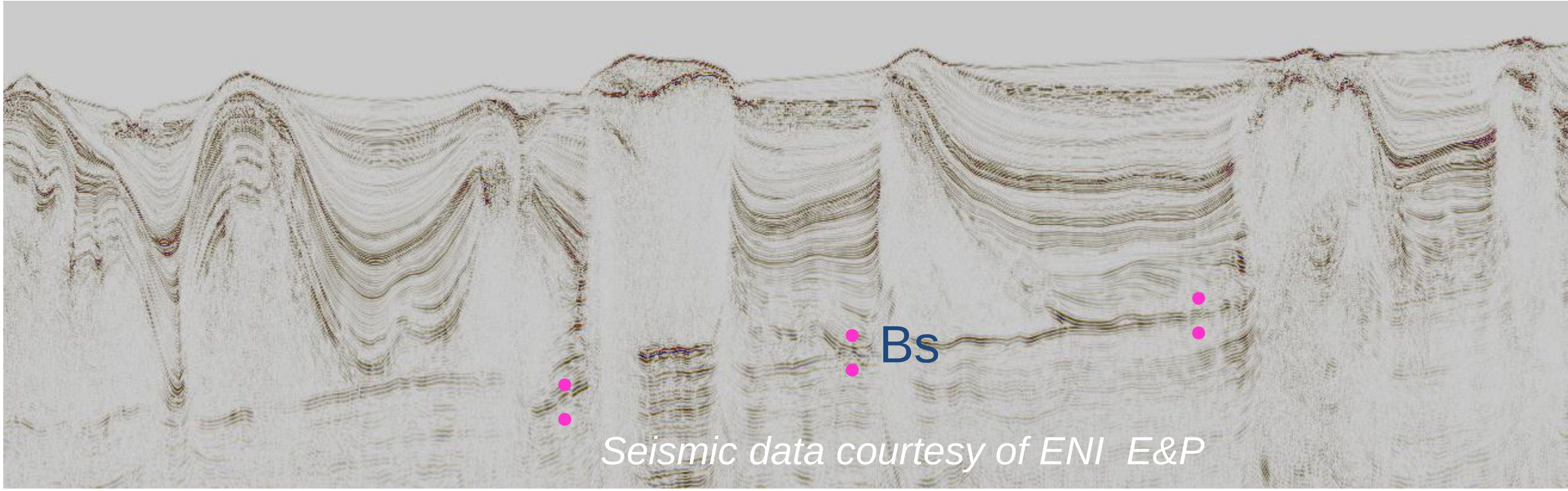
By Hudec & Jackson, 84
Seismic data courtesy of WesternGeco.

West-Africa margin: Monocline Province

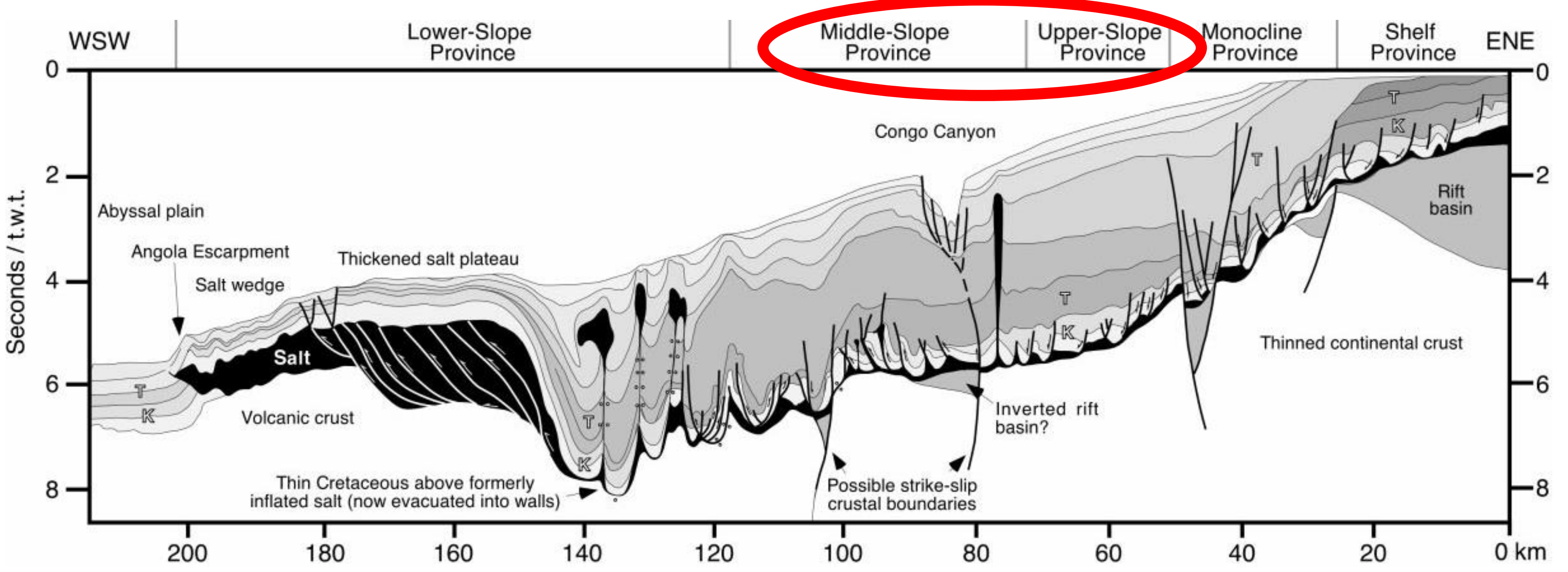




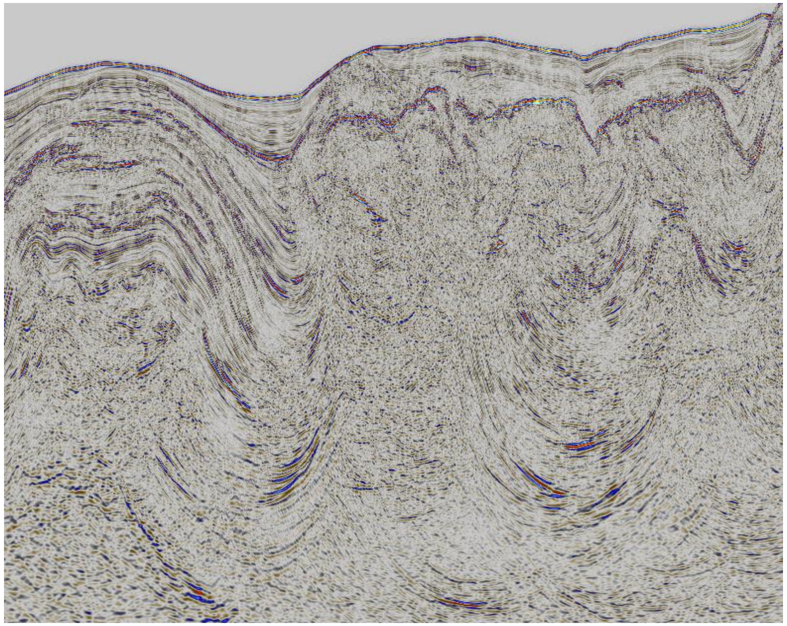


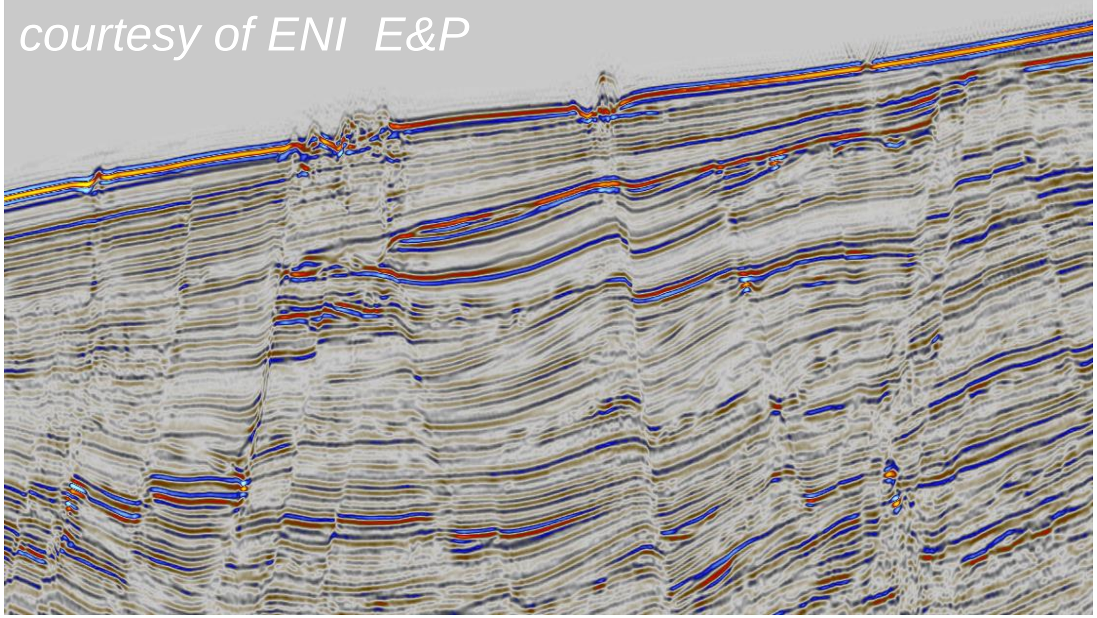


Seismic data courtesy of ENI E&P



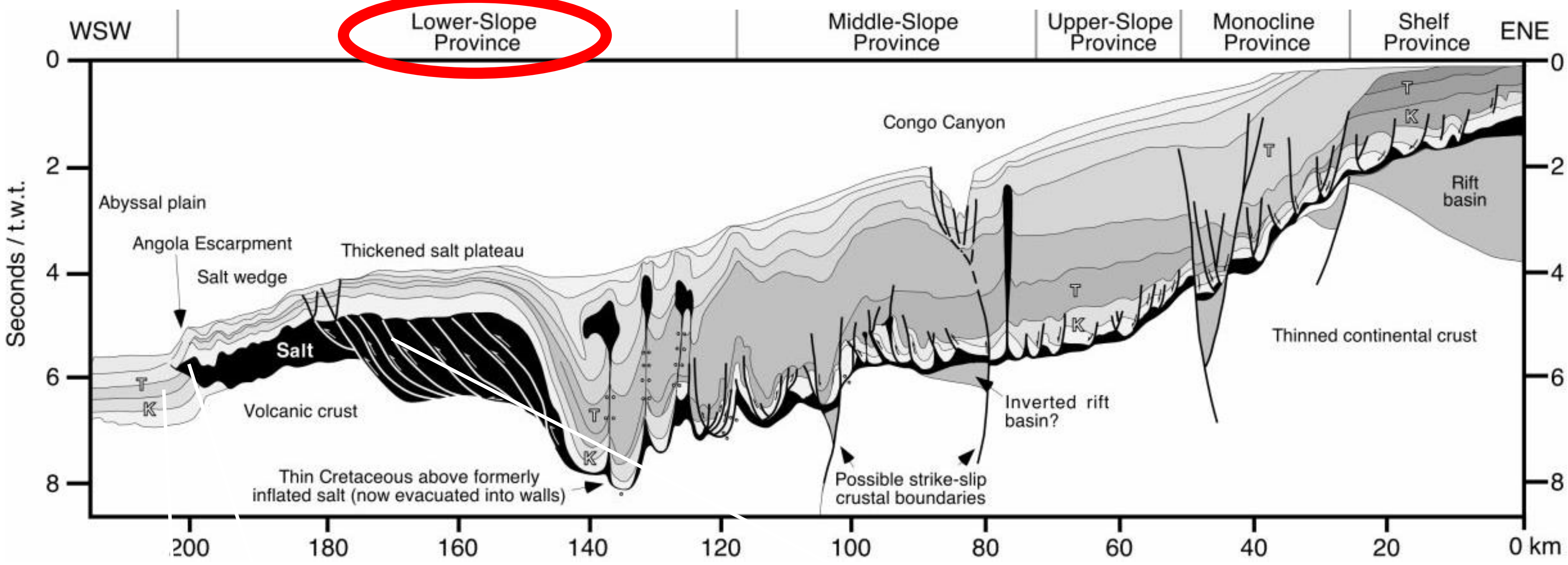
Middle and Upper Slope Provinces

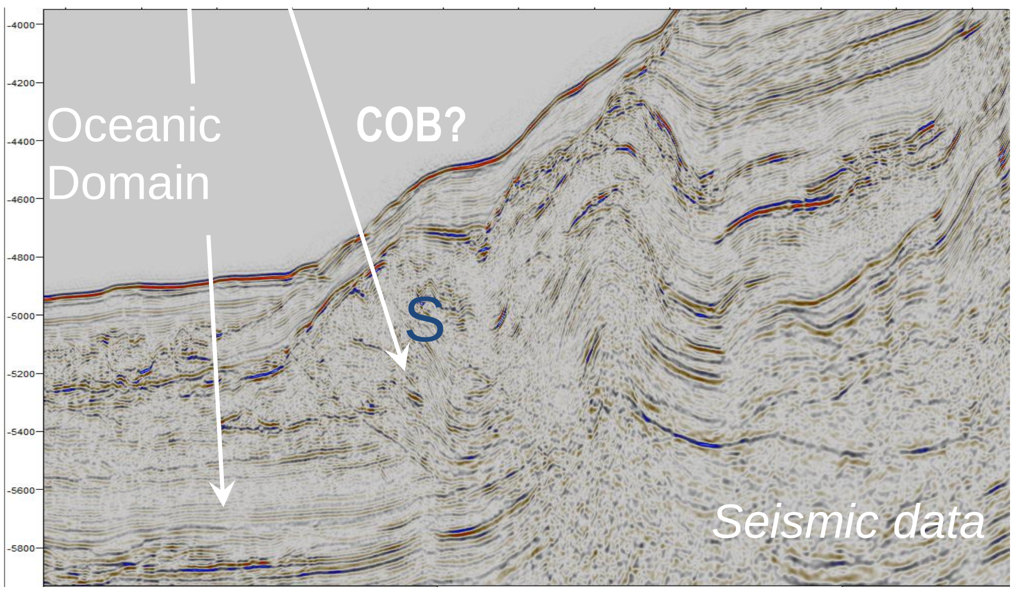


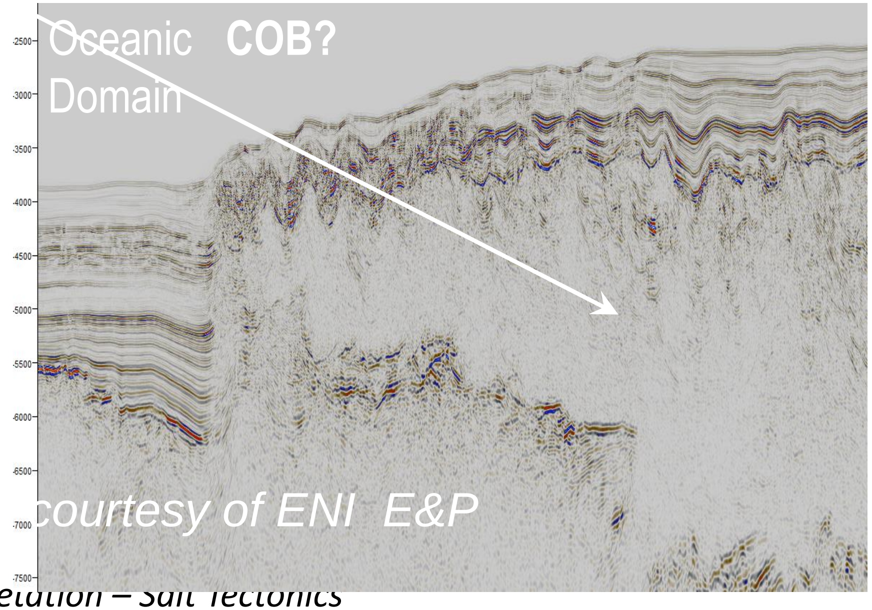


courtesy of ENI E&P

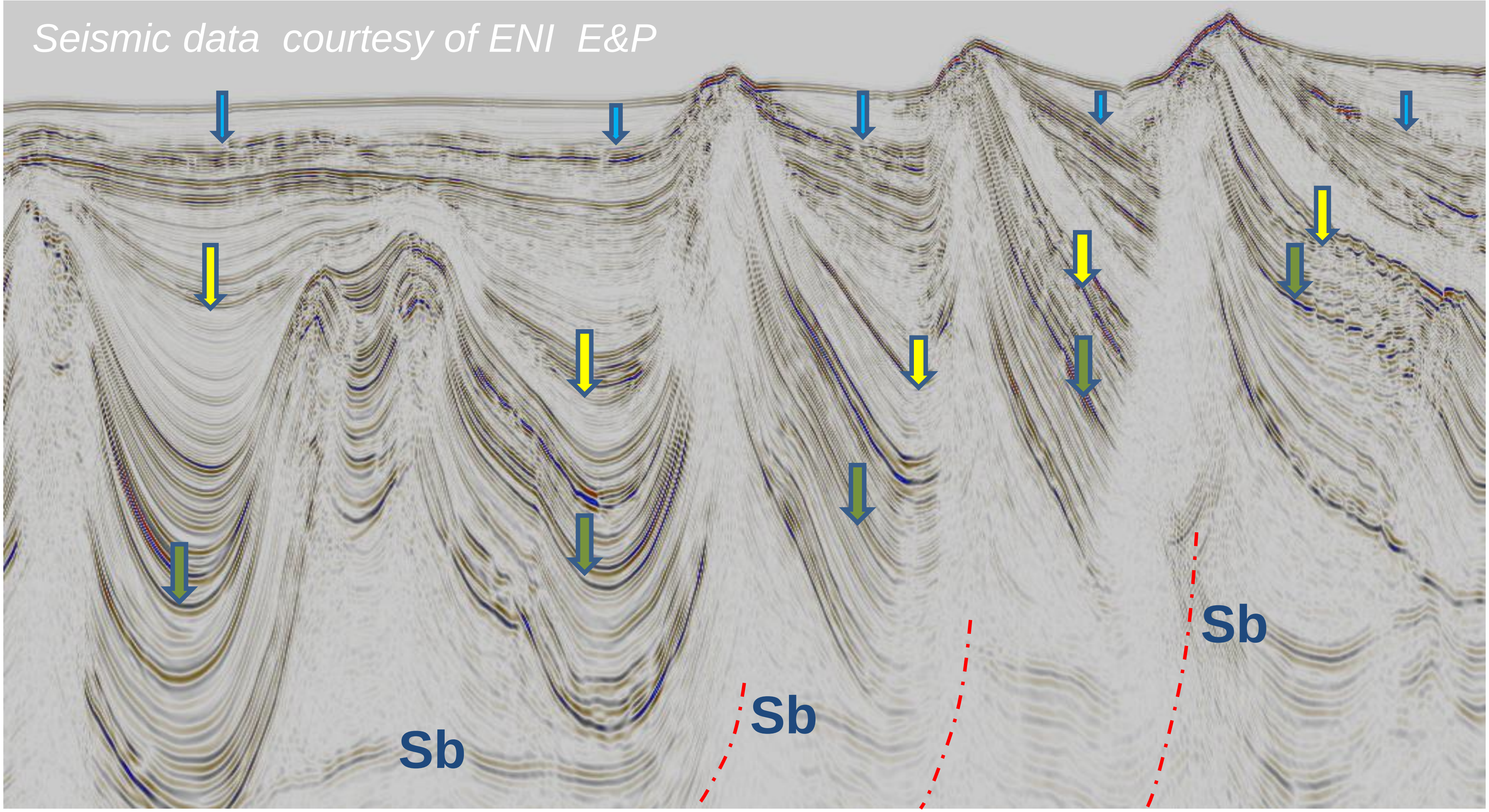
West-Africa margin: Lower Slope Province



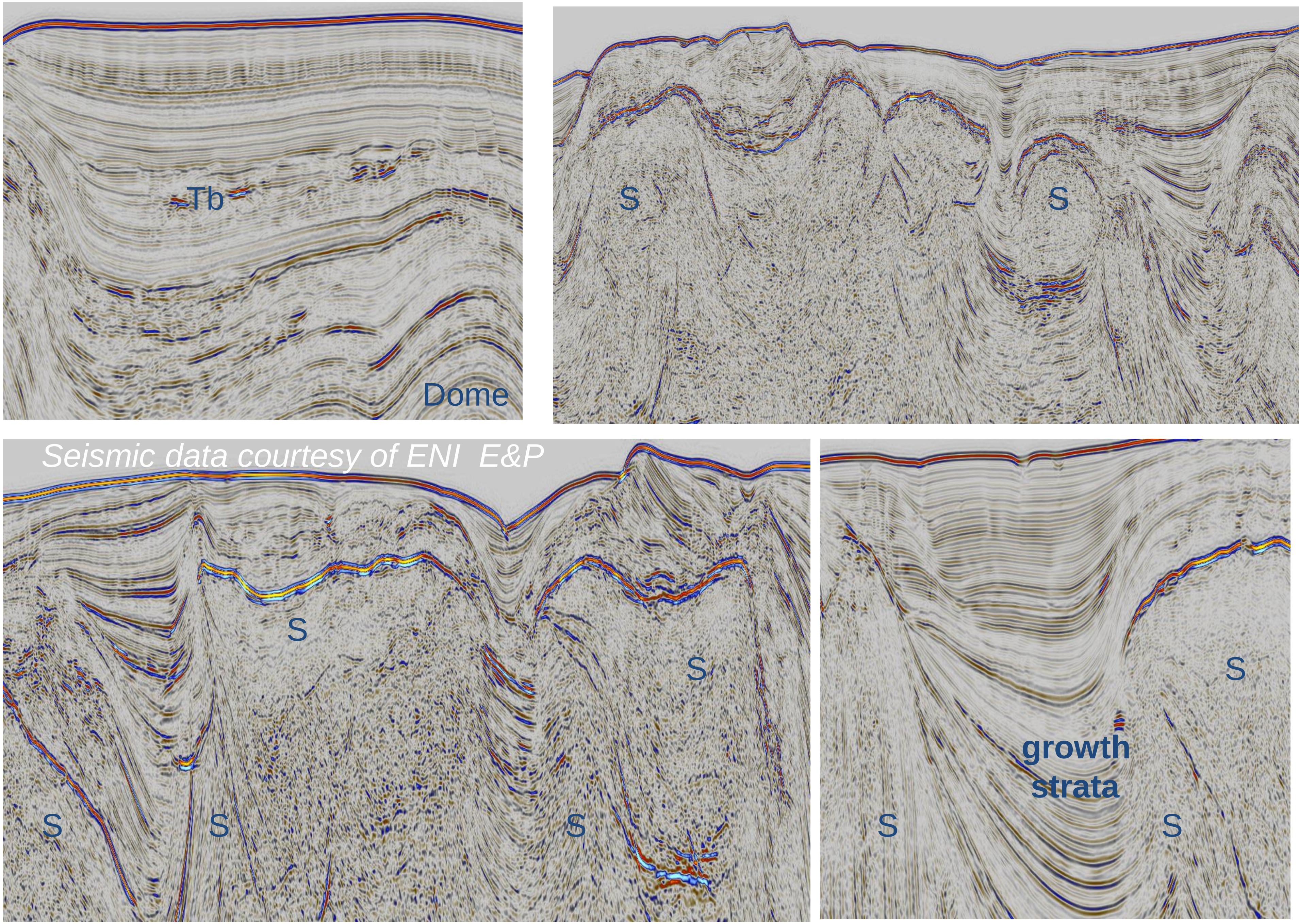




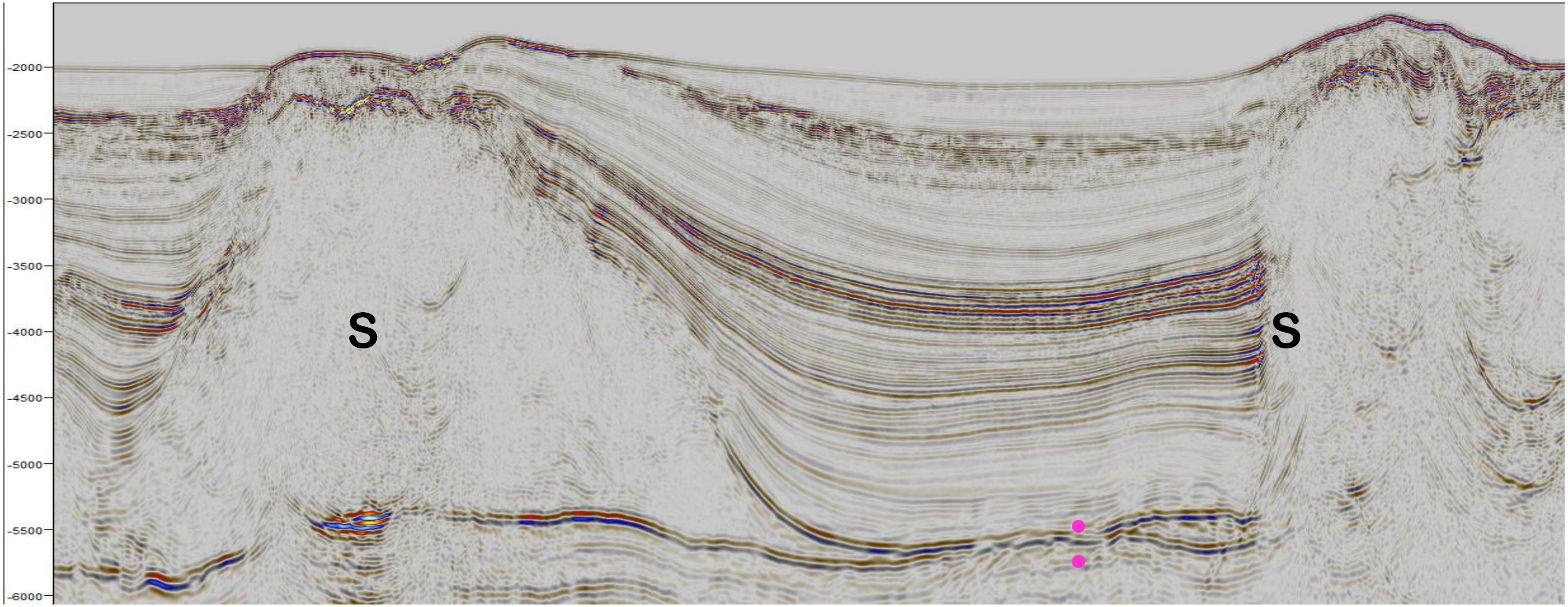
Seismic data courtesy of ENI E&P

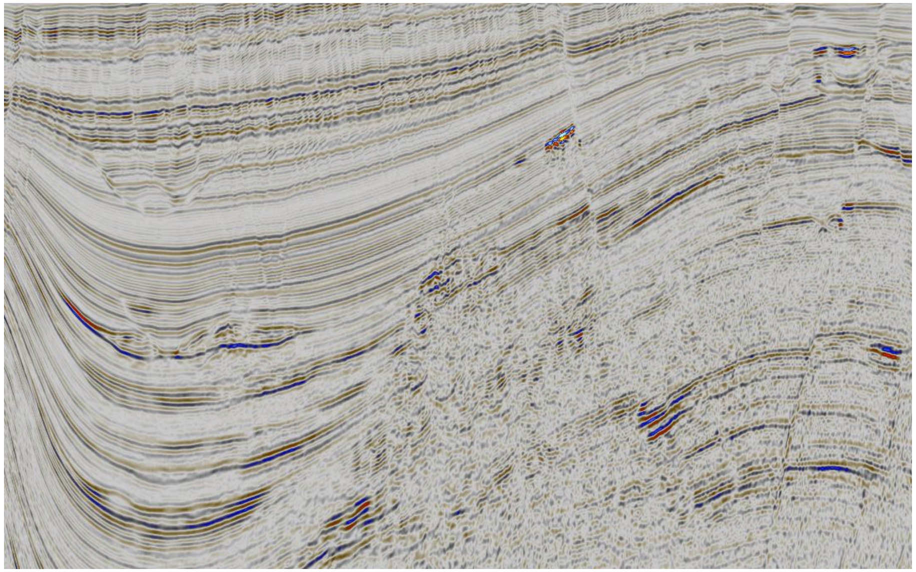


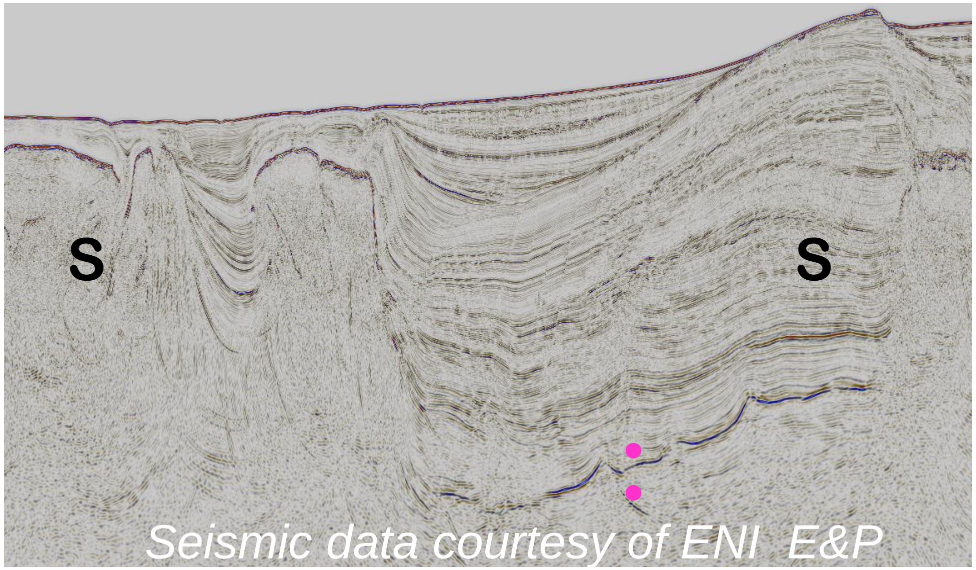
Asymmetric salt domes in the West African margin: growth strata testify their continuous activity immediately after salt deposition until present.
The base (Sb) of the salt sequence (not presence of pull-up velocity in this depth-migrated profile) suggests some basin-ward faults, probably first cause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



Seismic data courtesy of ENI E&P



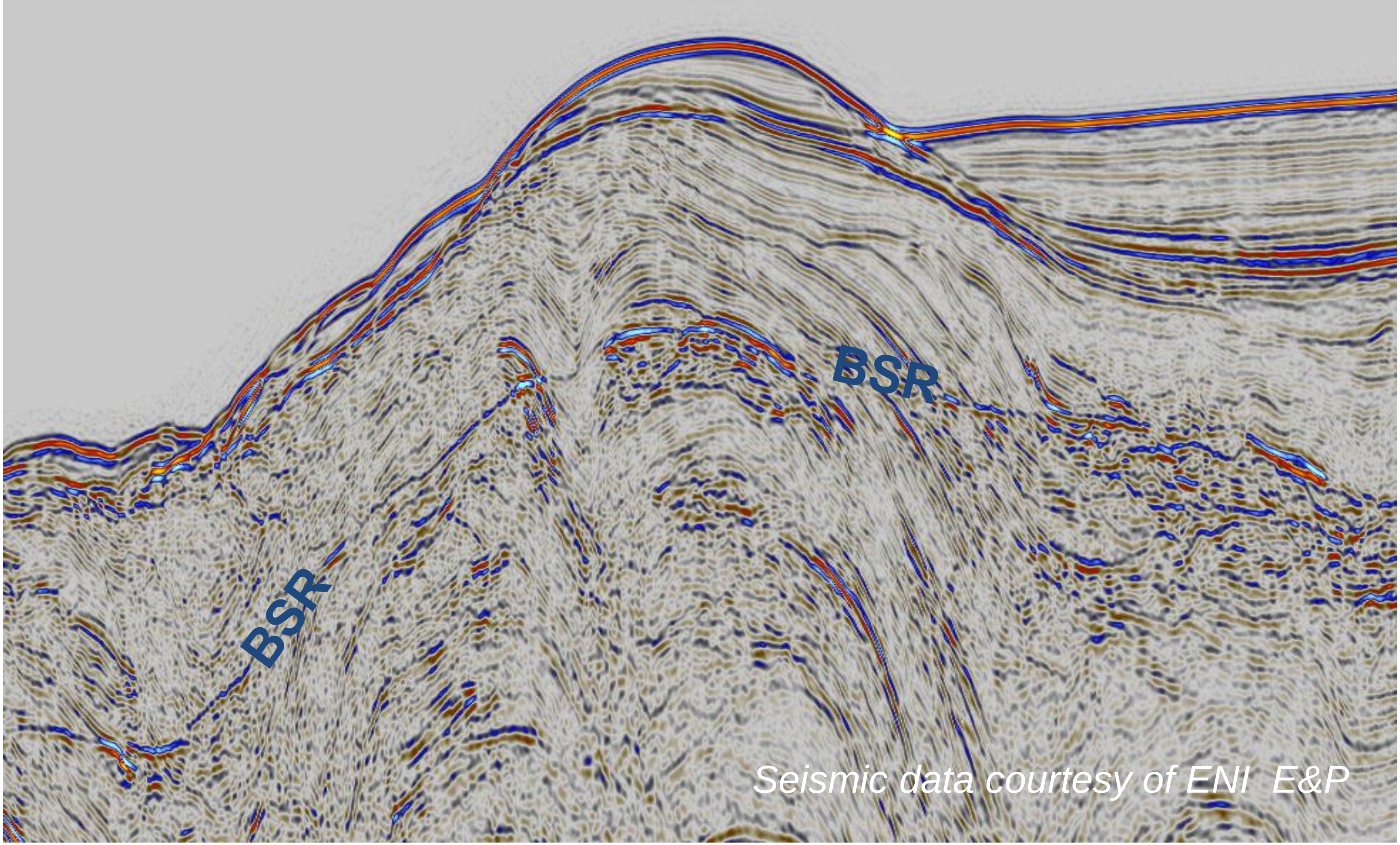




Seismic data courtesy of ENI E&P

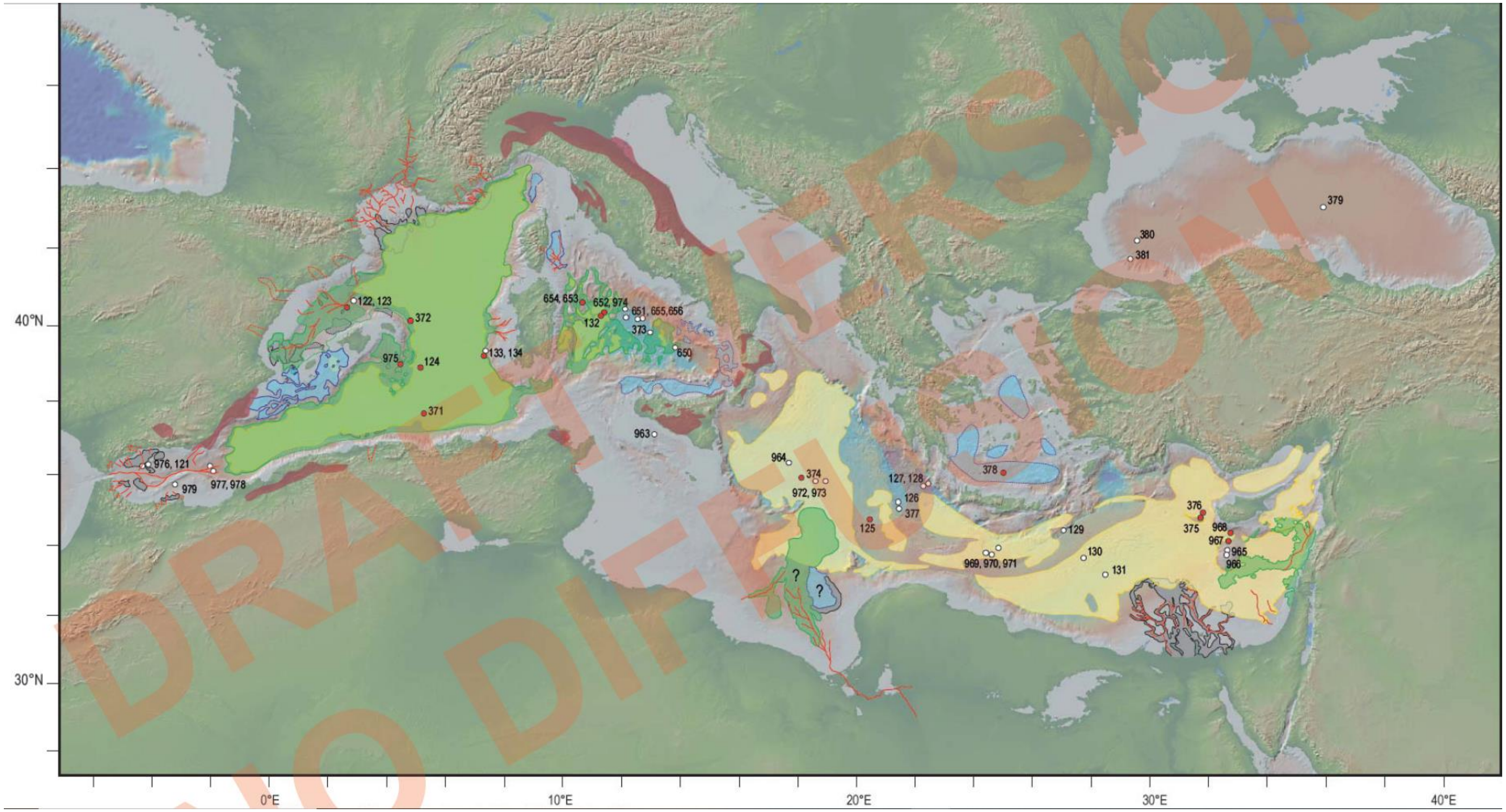
Bottom Simulating Reflector (BSR) in the W-African margin

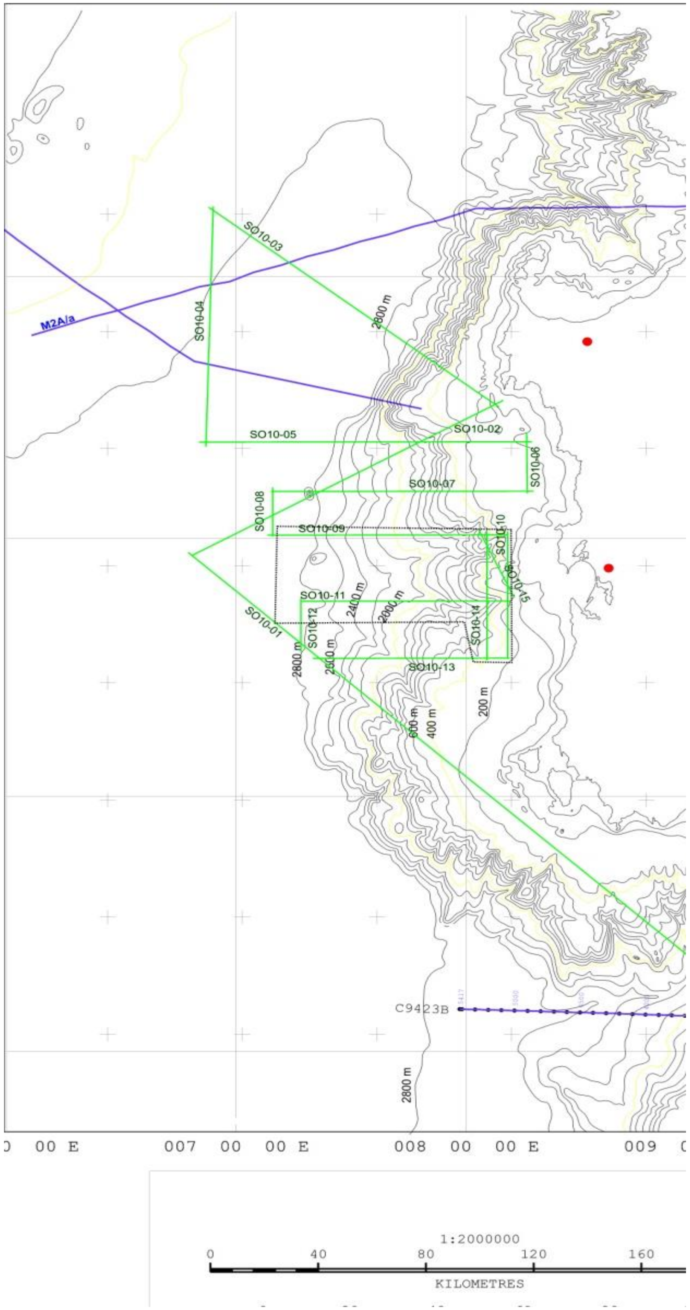
BSR marks the change of methan from hydrate (above, higher velocity and density)
to gaseous (below, lower velocity and density) state.
It depends mainly on pression, hence on load of the sedimentary cover:
for this reason the BSR is about parallel to/simulating the sea bottom



Seismic data courtesy of ENI E&P

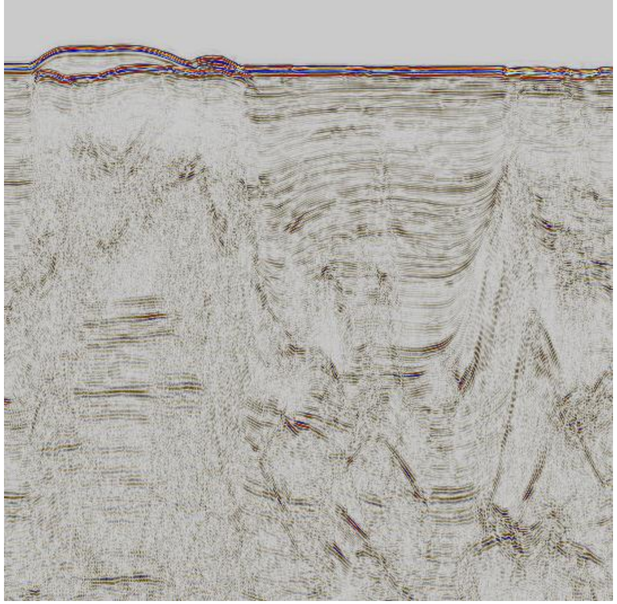
Mediterranean Sea
and
Messinian Salinity Crisis

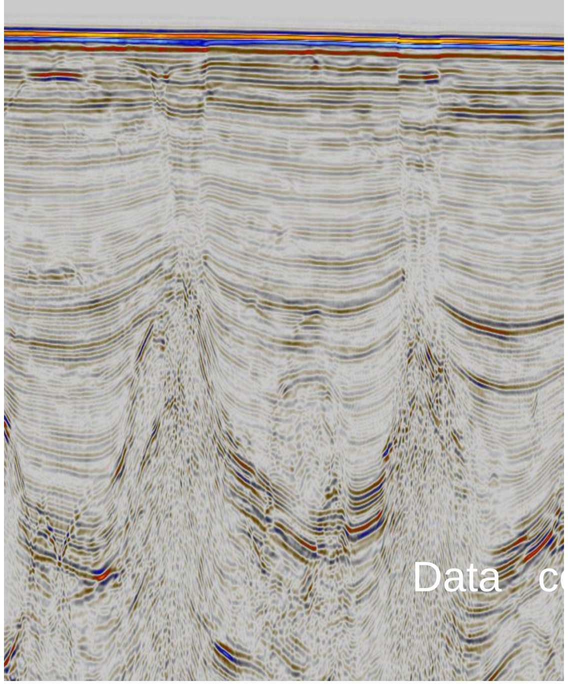


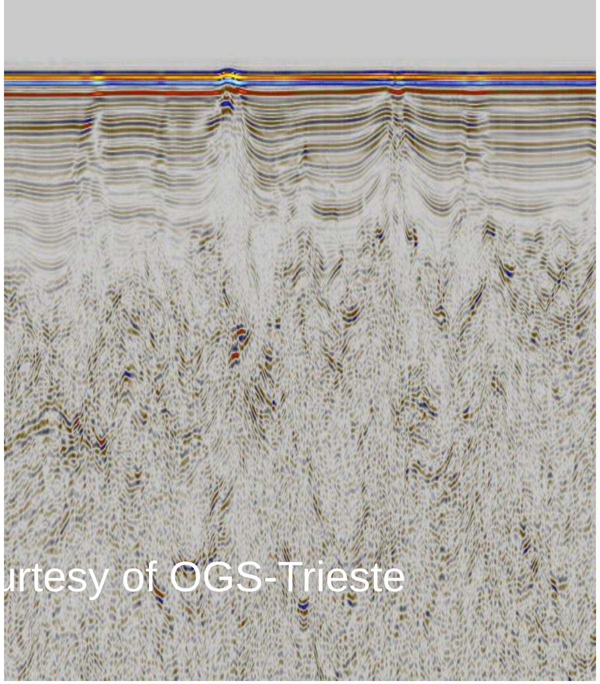


West-Sardinia Project (WS10)

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

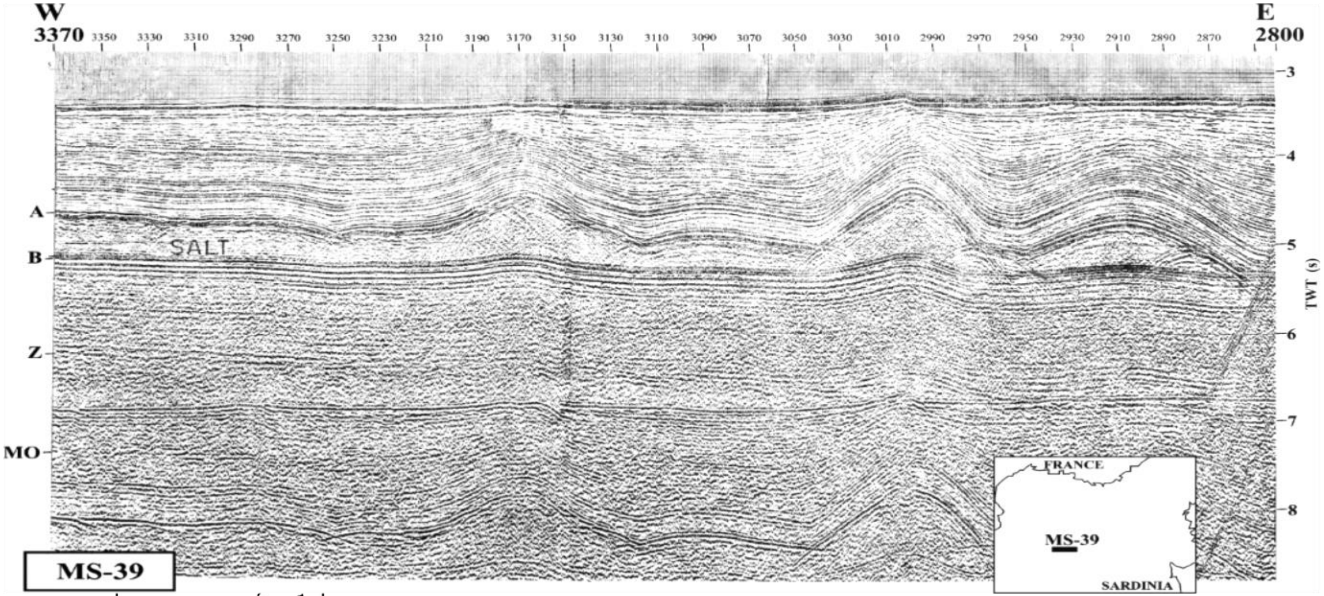


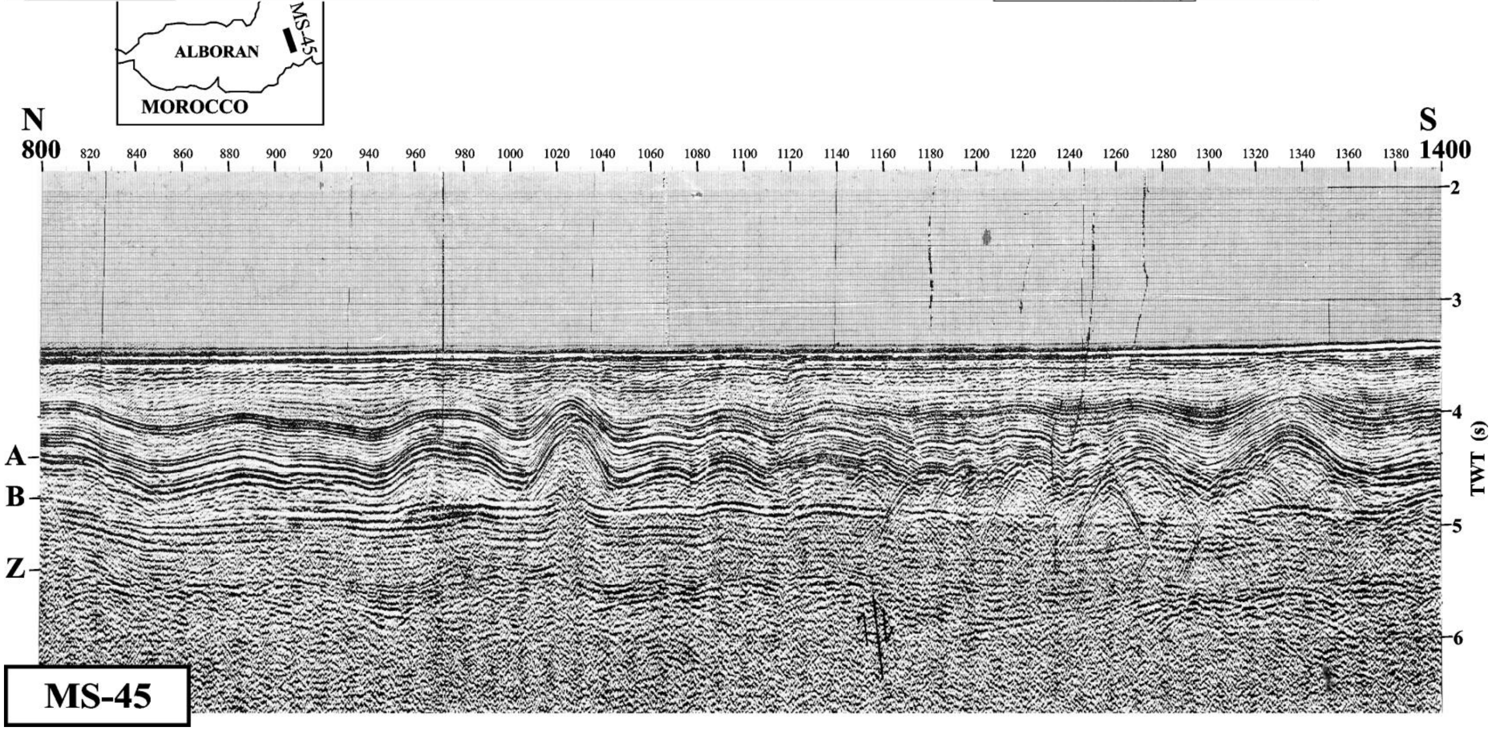


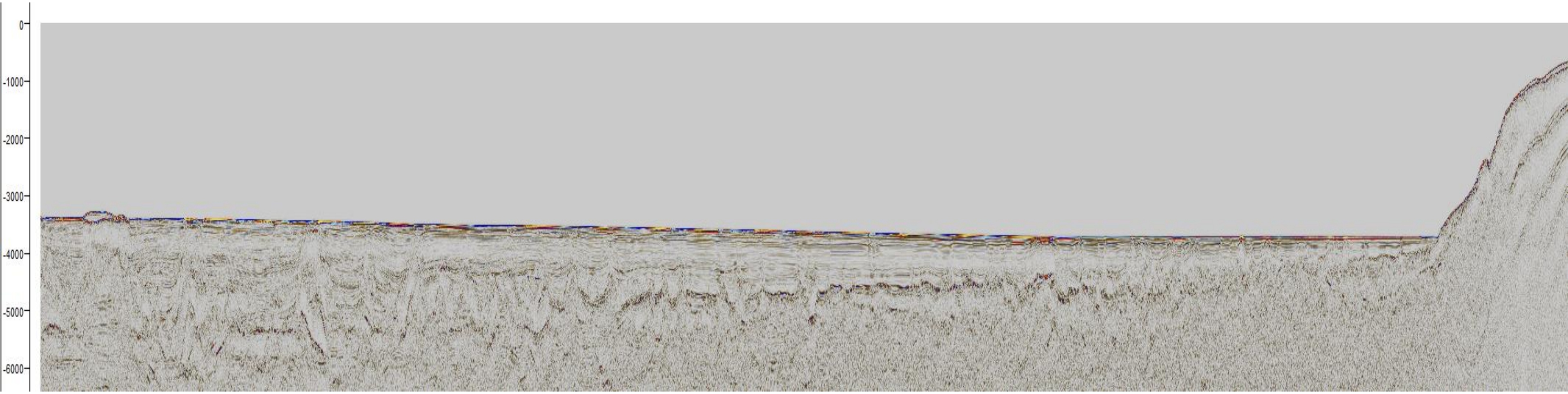


Data courtesy of OGS-Trieste

MS project Seismic Sections acquired by OGS during the 1972







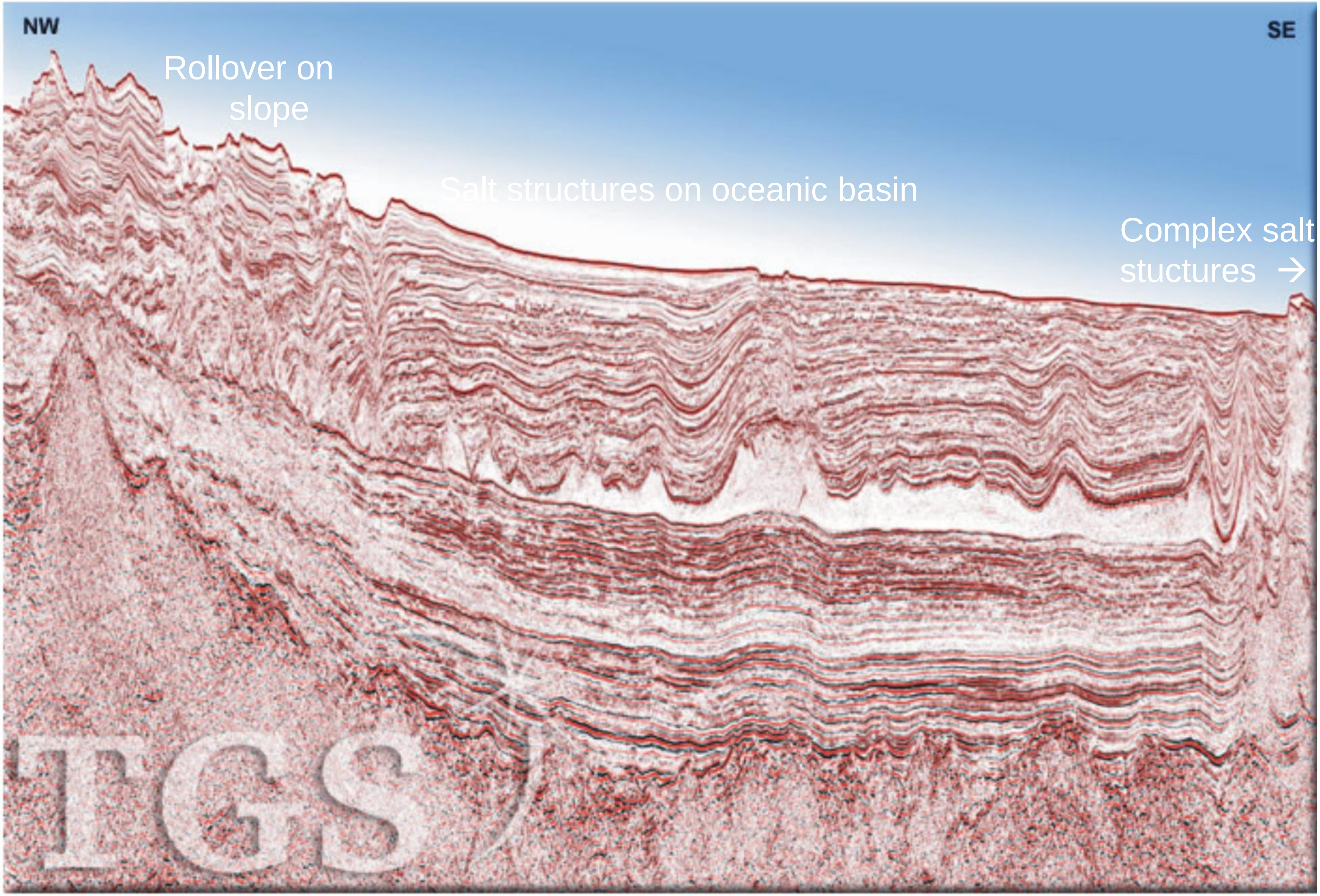
Differently than in the South Atlantic Basin, where the salt deposited during the last rifting phase (hence only in the continental margins), the evaporite sequence in the Mediterrenean Sea was caused by closure of the Strait of Gibraltar during the Messinian time.

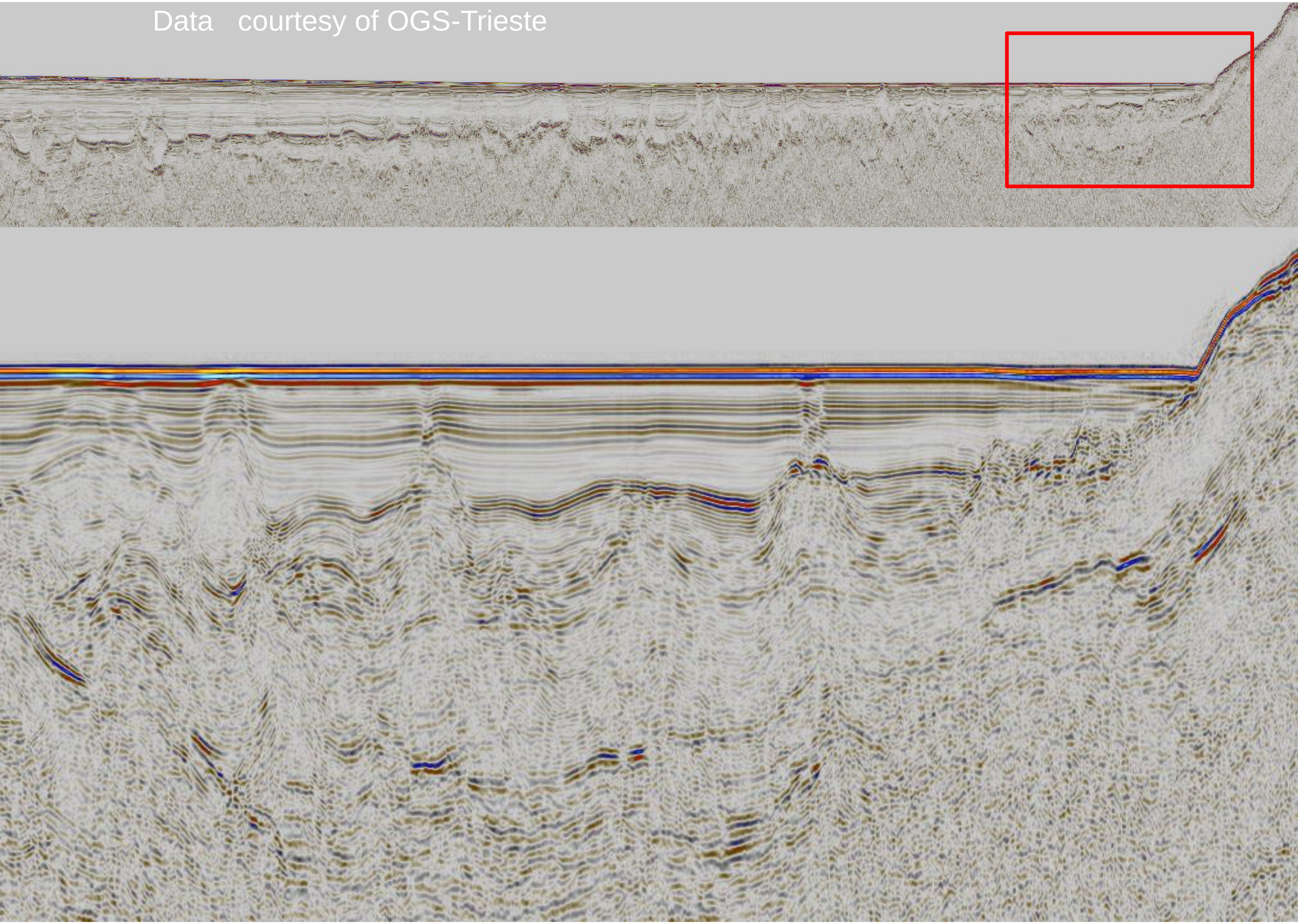
Evaporation of sea water and following sea level fall caused erosion on land and on the margins, and deposition of evaporites on the deep basin.

At that time the Sardo-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 approximately at that time.

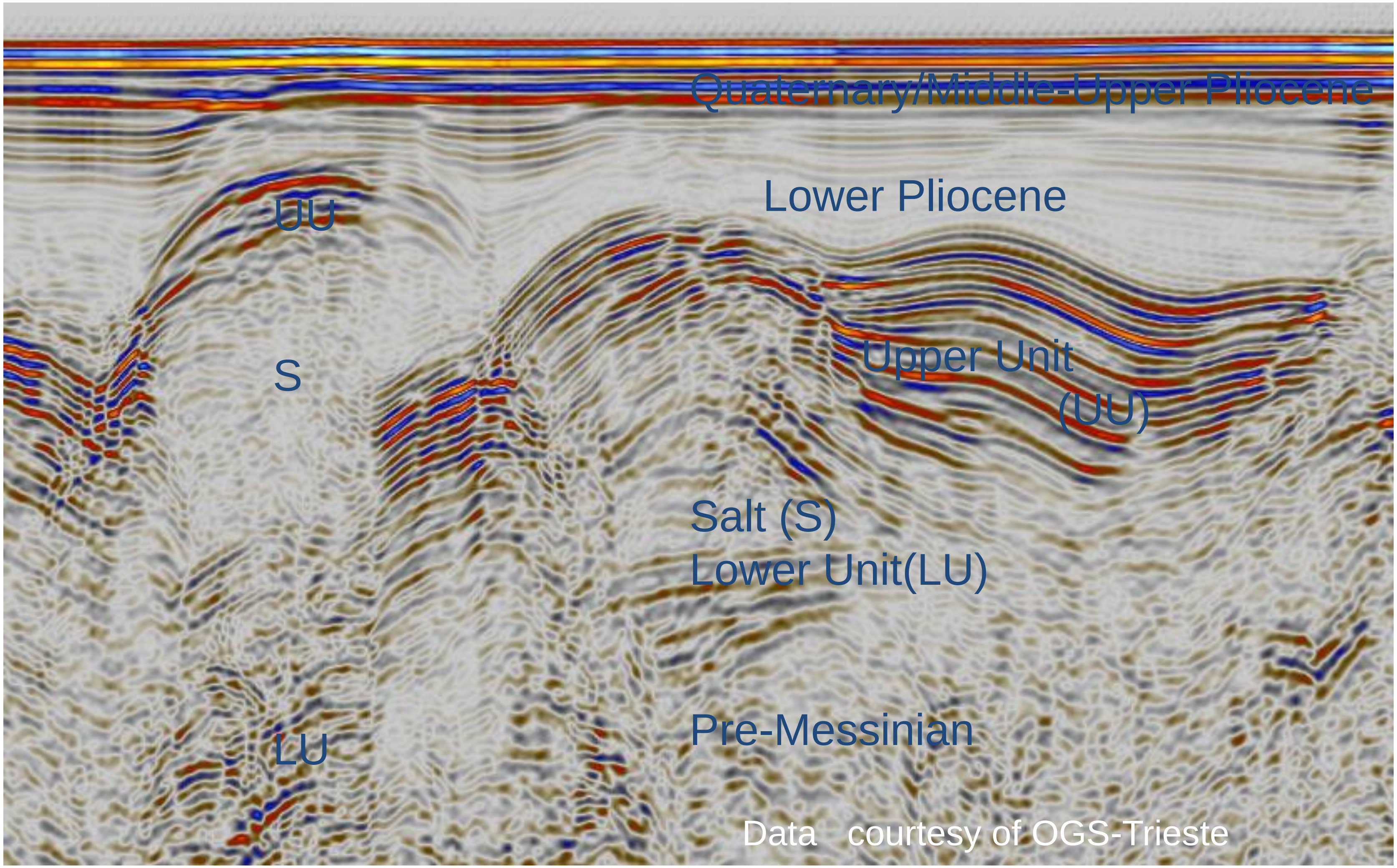
Western margin of the Liguro-Provençal Basin



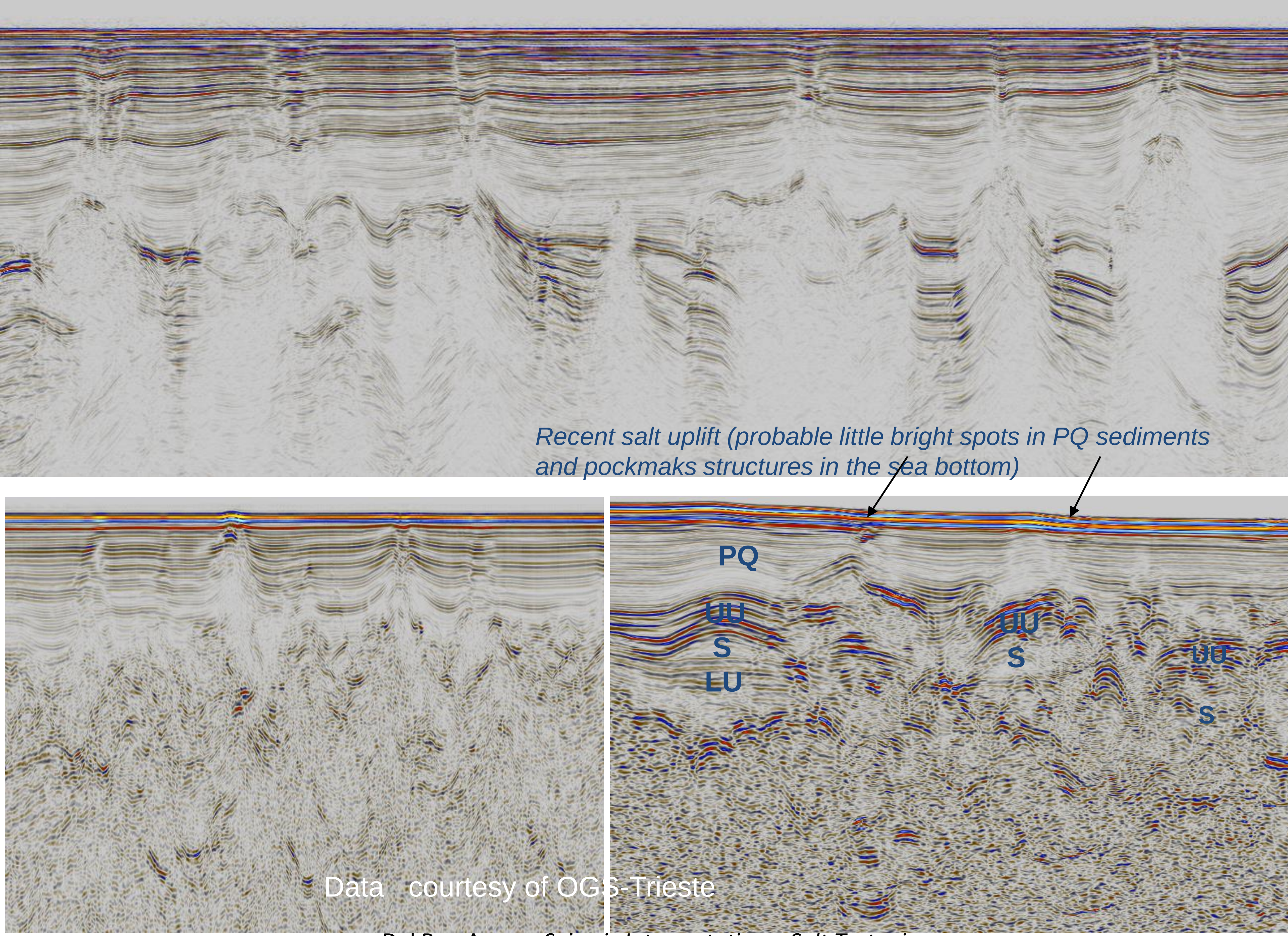


Data courtesy of OGS-Trieste

Sardo-Provençal Basin

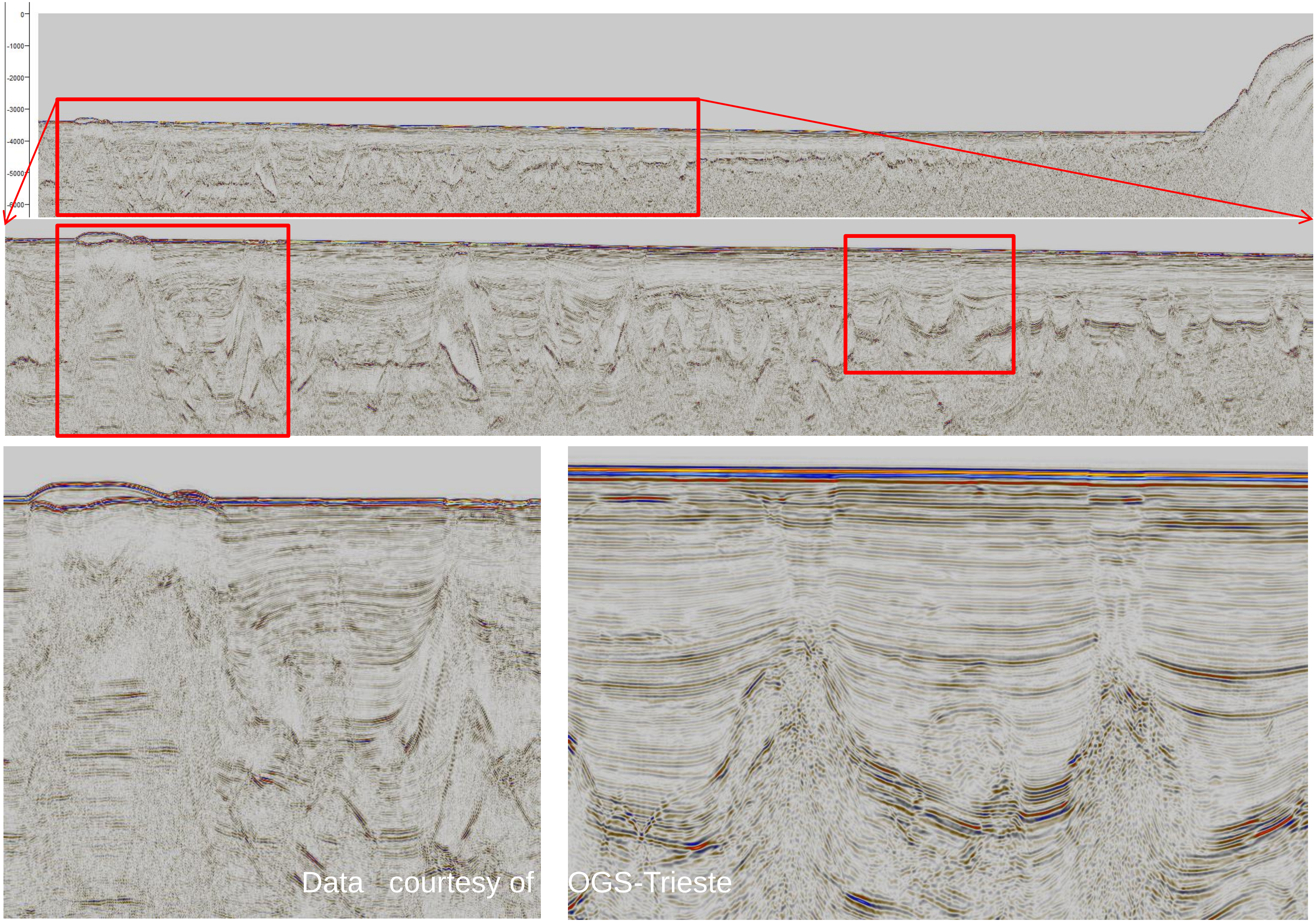


Data courtesy of OGS-Trieste

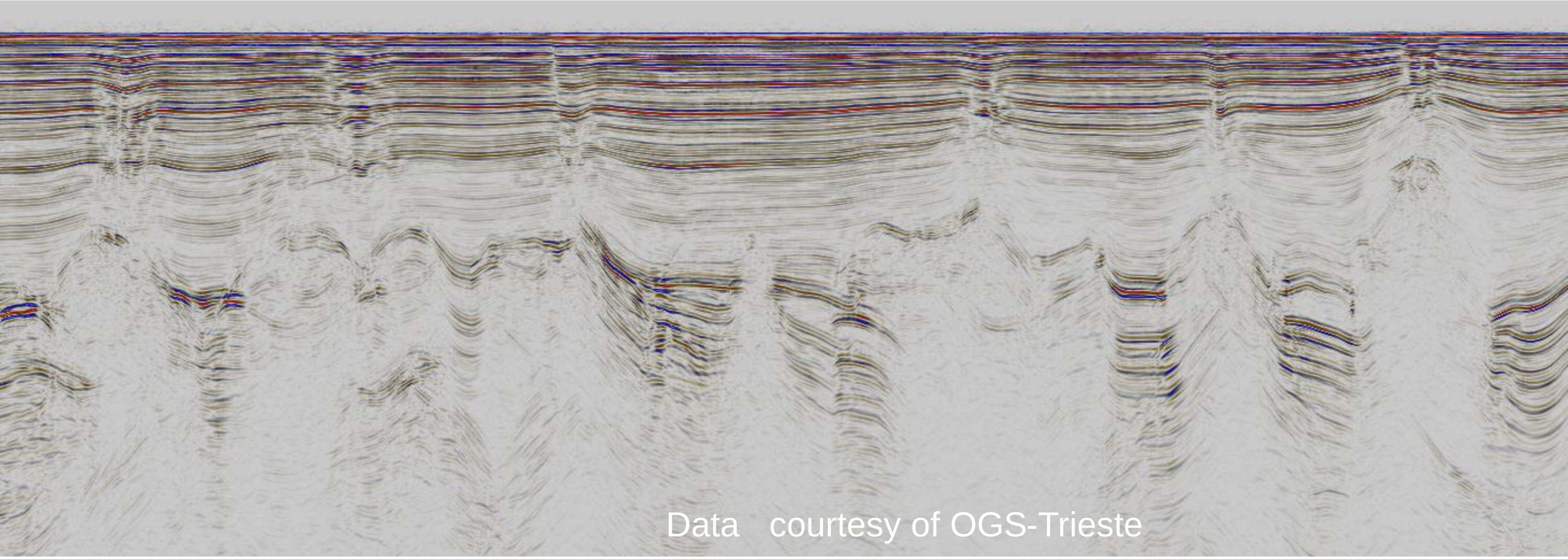


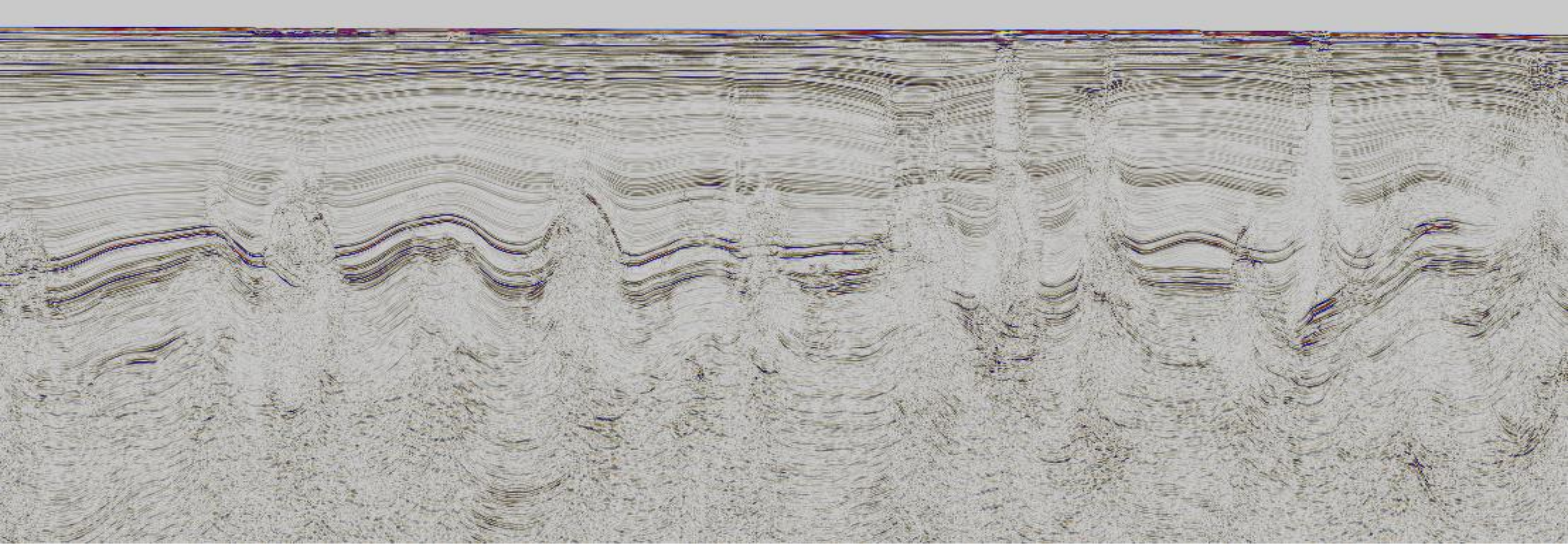
Recent salt uplift (probable little bright spots in PQ sediments and pockmaks structures in the sea bottom)

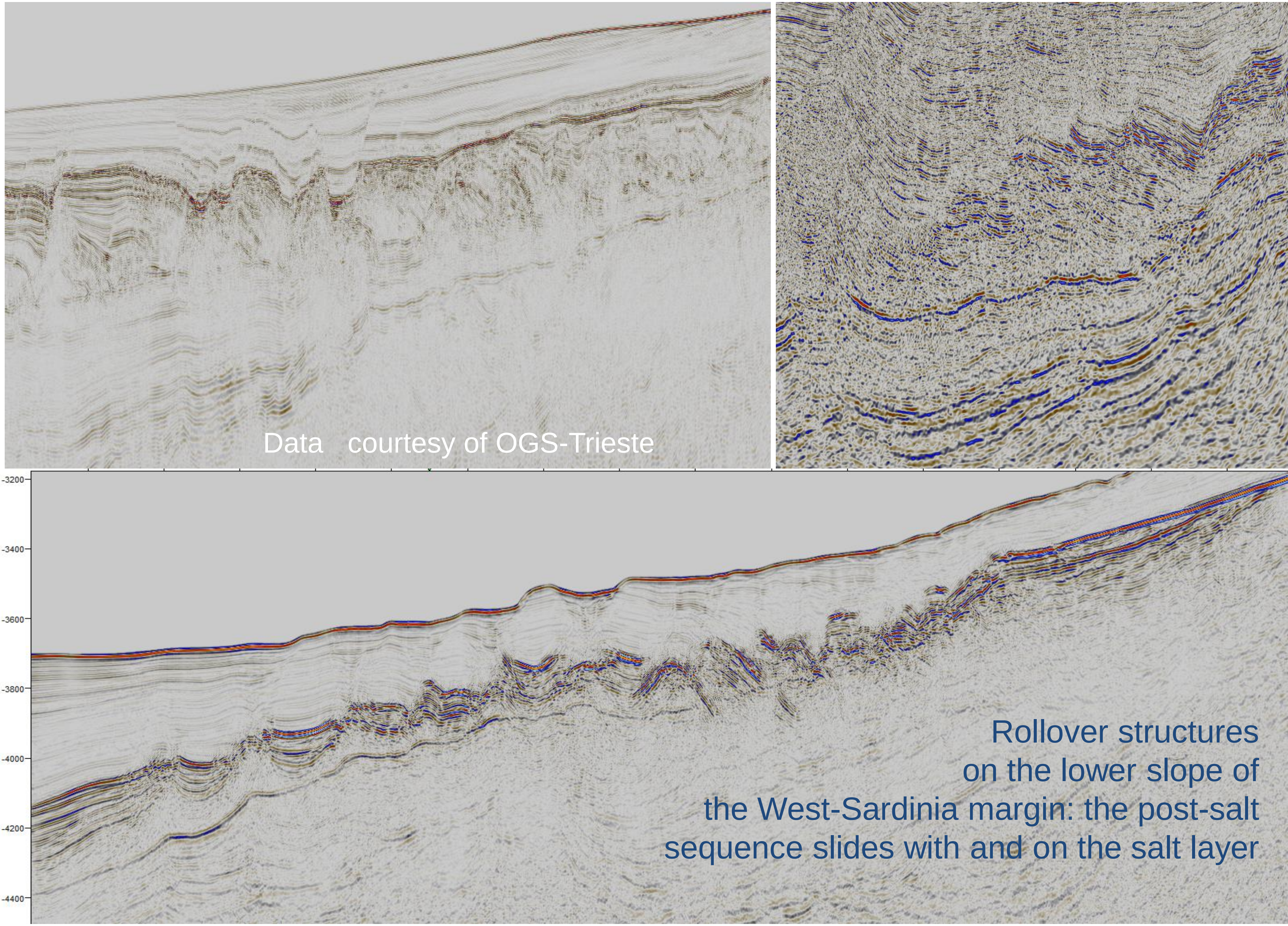
Data courtesy of OGS-Trieste



Data courtesy of OGS-Trieste


Data courtesy of OGS-Trieste

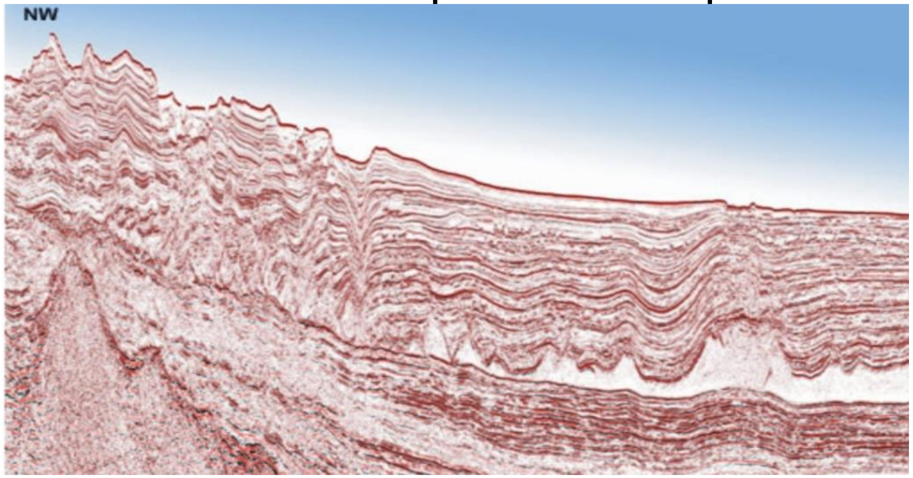


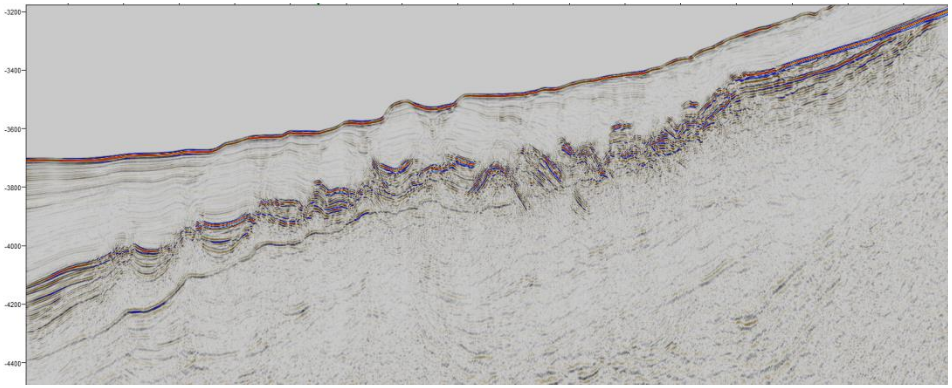


Data courtesy of OGS-Trieste

Rollover structures
on the lower slope of
the West-Sardinia margin: the post-salt
sequence slides with and on the salt layer

Rollover structures on the lower slope of the West and East Sardo-Provençal margins: the post-salt sequence slides with and on the salt layer.





Compare with the South Atlantic margins