# Mud Diapirs and Mud Volcanoes Associated with Gas Hydrates System in the Sinu Fold Belt of Colombia, South Western Caribbean and its Significant in the Petroleum System*

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## Abstract

The accretionary Sinú Fold belt of Colombia presents numerous gas and oil seeps often associated with mud volcanoes. Truncation and folding of reservoir rocks against mud diapirs have been erroneously considered as potential structures for hydrocarbon traps ignoring the significance of thick Gas Hydrate Zones (GHZ) present in large offshore areas of the South Western Caribbean Sea. Seismic images of the Sinú Fold belt clearly indicates that mud diapirs and volcanoes are associated with GHZ that are present at shallow depths as indicated by the Bottom Sea Reflector (BSR) as it is observed in large and numerous offshore areas in the South Western Caribbean Sea. Hydrocarbon generation and migration in the Sinú Fold belt, Colombia, started in the Paleocene, following gas migration through fault planes took place reaching the sea floor, these thermogenic gases including oil and condensate, were progressively trapped as gas hydrates forming seals as the GHZ became thicker and larger in area. Then in a continuous basin subsidence, and a high sedimentation rate gas hydrates layers were buried and preserved due to a low geothermal gradient. As gas hydrates layers were buried to deeper depth, temperature increased, and the Gas Hydrate Stable Zone became unstable and melted down liberating great volumes of gas and oil that migrates upward forming mud diapirs and mud volcanoes as they reached the sea floor and coastal surface. These sequences of events indicates that mud diapirs and volcanoes are the results of destruction of the Gas Hydrate Stable Zone that was previously formed by migration and trapping of thermogenic gases originated in deep hydrocarbon kitchen beneath the strata were mud diapirs were derived from. This new interpretation considers that mud diapirs and volcanoes constitute the seal formation rock of the petroleum system, also this new interpretation explains the lack of hydrocarbon discoveries in the Sinú Fold belt of Colombia and propose to explore beneath the mud diapirs and gas hydrates zones in the Sinú Fold belt and other similar location in the South western Caribbean Sea. Carbon isotopic analysis (13C/12C) on methane samples obtained from mud volcanoes in the Sinú Fold belt indicate a mixture of thermogenic and biogenic gases. This situation is explained by the presence of a bacteria consortium that generate methane during microbial degradation of oil. However, the petroleum system explained above indicate that thermogenic gases and associated oils are the main hydrocarbon resource in the south western Caribbean sea.

## Selected References


Bernal-Olaya, R., J. Sanchez, P. Mann, and M. Murphy, 2015, Along Strike Crustal Thickness Variations of the Subducting Caribbean Plate Produces Two Distinctive Styles of Thrusting in the Offshore South Caribbean Deformed Belt, Colombia, *in* C. Bartolini and P. Mann (eds.), Petroleum Geology and Potential of the Colombian Caribbean Margin: American Association of Petroleum Geologists Memoir 108, p. 295-322.

Cediel, F., and C. Cáceres, 2000. Geological Map of Colombia, Third Edition: Geotec Ltd., Bogotá, digital format with legend and tectonostratigraphic chart.

Duque-Caro, H., 1984, Structural Style, Diapirism, and Accretionary Episodes of the Sinu–San Jacinto Terrane, Southwestern Caribbean Borderland, *in* W.E. Bonini, R.B. Hargraves, and R. Shagam (eds.), The South American–Caribbean Plate Boundary and Regional Tectonics: Geological Society of America Memoir 162, p. 303-316.

Guzman, G., E. Gomez, and B. Serrano, 2004, Geologia de los cinturones del Sinu, San Jacinto y Borde occidental del Valle Inferior del Magdalena, Caribe Colombiano. Ingeominas (Colombian Geological Survey) Report, Bogotá.

Hyndman, R.D., and S.R. Dallimore, 2000, Natural Gas Hydrate Studies in Canada; Offshore West Coast and Arctic Mackenzie Delta; GeoCanada 2000; The Millennium Geoscience Summit: Abstract Volume (Geological Association of Canada), 25.

Liu, X., and P.B. Flemings, 2007, Dynamic Multiphase Flow Model of Hydrate Formation in Marine Sediments: Journal of Geophysical Research, v. 112/B03101. doi:10.1029/2005JB004227

López, C., 2005, Determinacion del gradiente geotérmico a partir del reflector simulador de fondo. Tesis de pregrado, Universidad Industrial de Santander, Bucaramanga, 100 pp.

Mantilla-Pimiento, A.M., 2007, Crustal Structure of the SW Colombian Caribbean Margin: Geological Interpretation of Geophysical Data: Ph.D., Institute of Geosciences, Friedrich-Schiller Universität Jena, Germany, 98 p.

Tinivella, U., and M. Giustiniani, 2013, An Overview of Mud Volcanoes Associated to Gas Hydrate System, in Updates in Volcanology - New Advances in Understanding Volcanic Systems, p. 225-267. doi.org/10.5772/51270

# Mud Diapirs and Mud Volcanoes Associated with Gas Hydrates System in the Sinu Fold Belt of Colombia, South Western Caribbean and its Significant in the Petroleum System.

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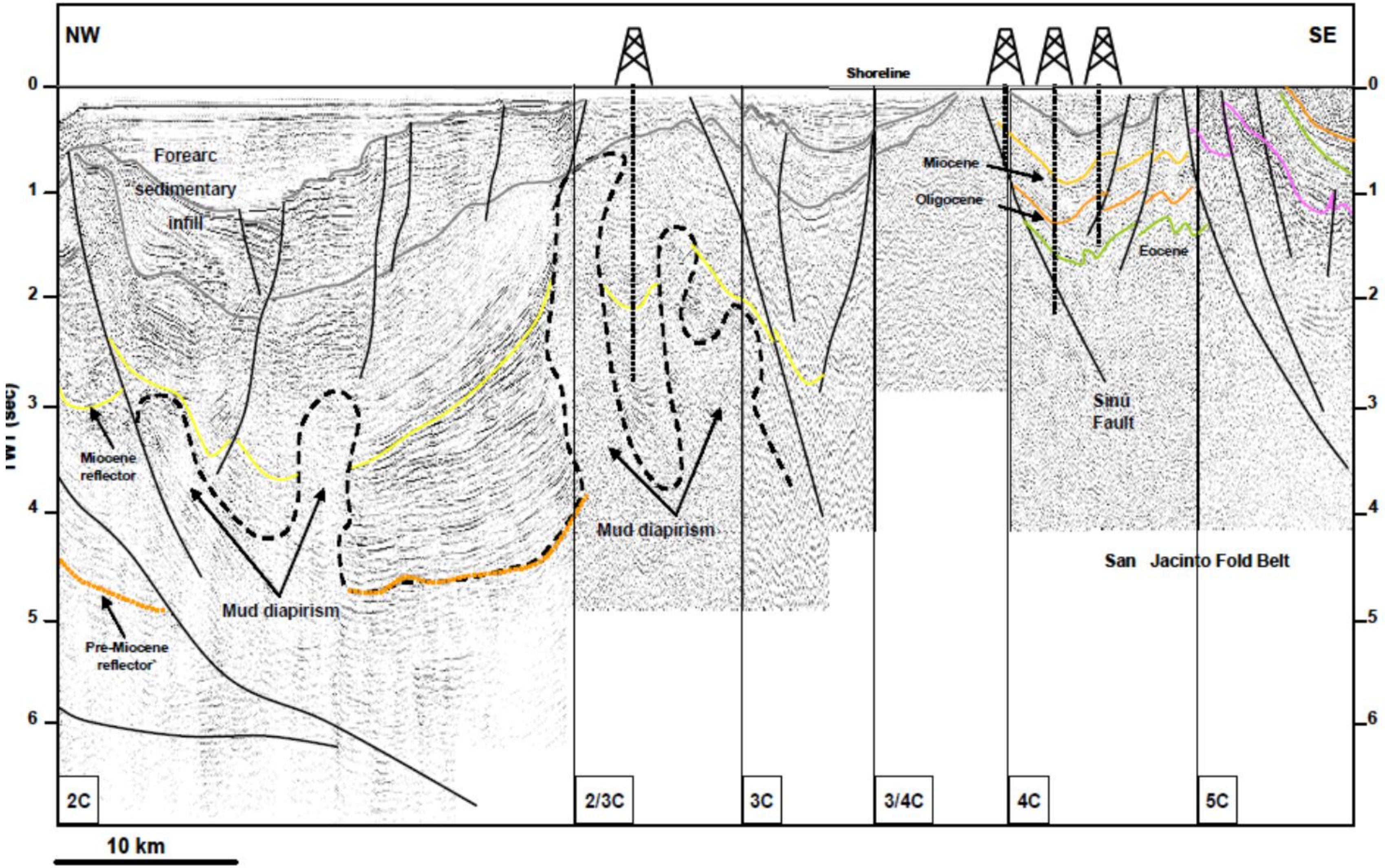
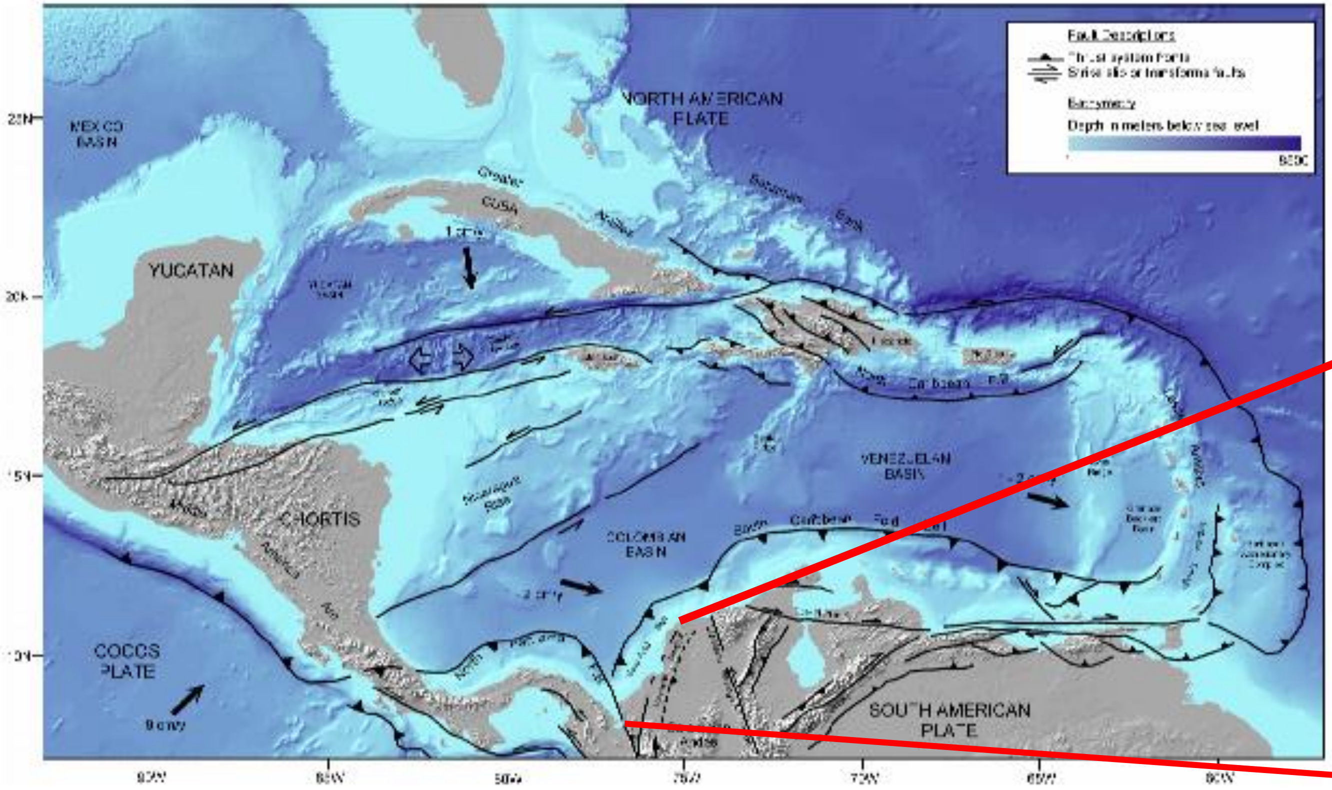
# Statement of the problem

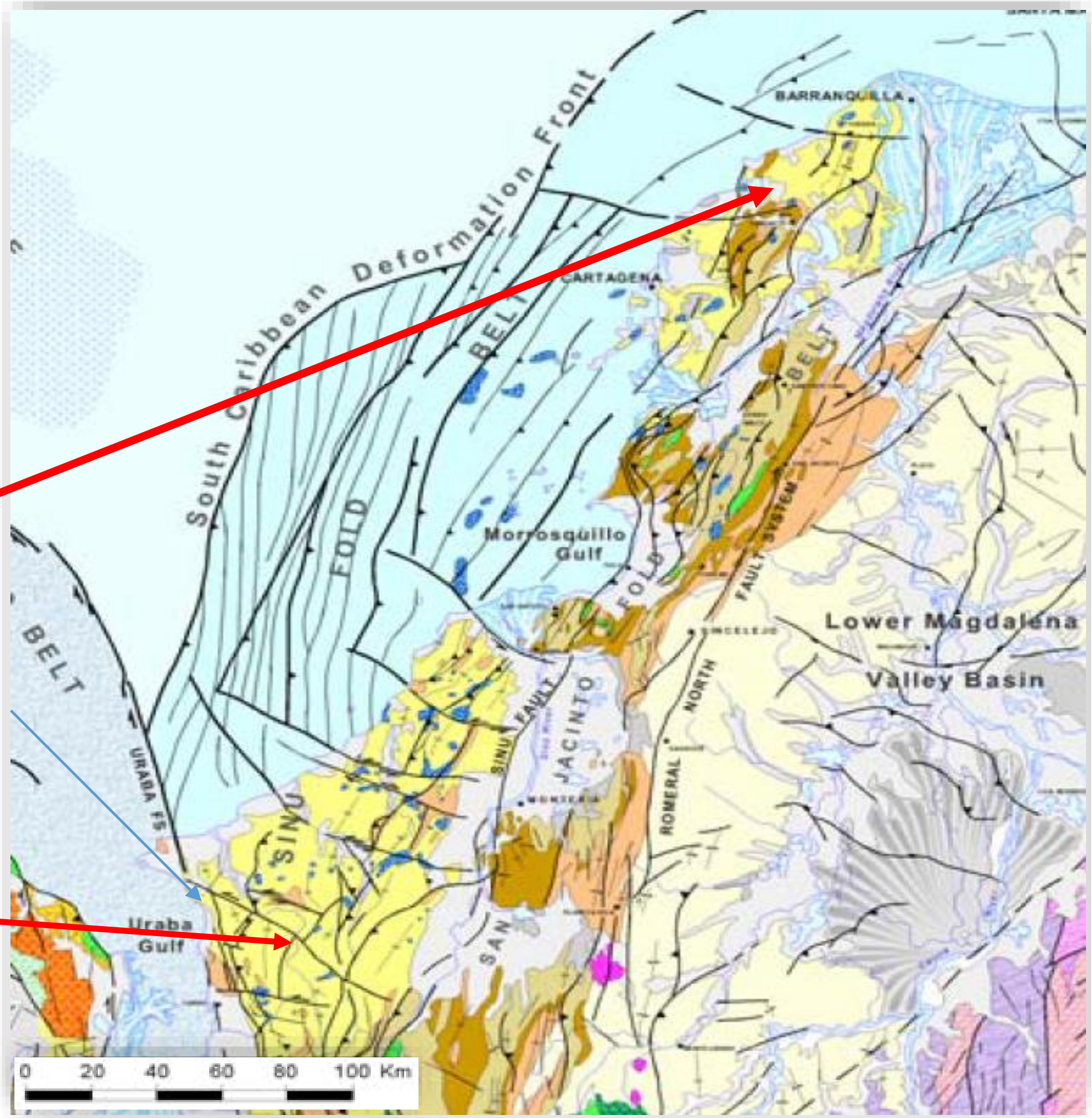



The Sinú fold-belt presents numerous gas and oil seeps often associated with mud volcanoes. Truncation and folding structures against mud diapirs have been erroneously considered traps for hydrocarbons, and non-economic reservoirs have been found yet.

# Geological setting of mud diapirs and volcanoes in the Sinú Fold Belt, Colombia



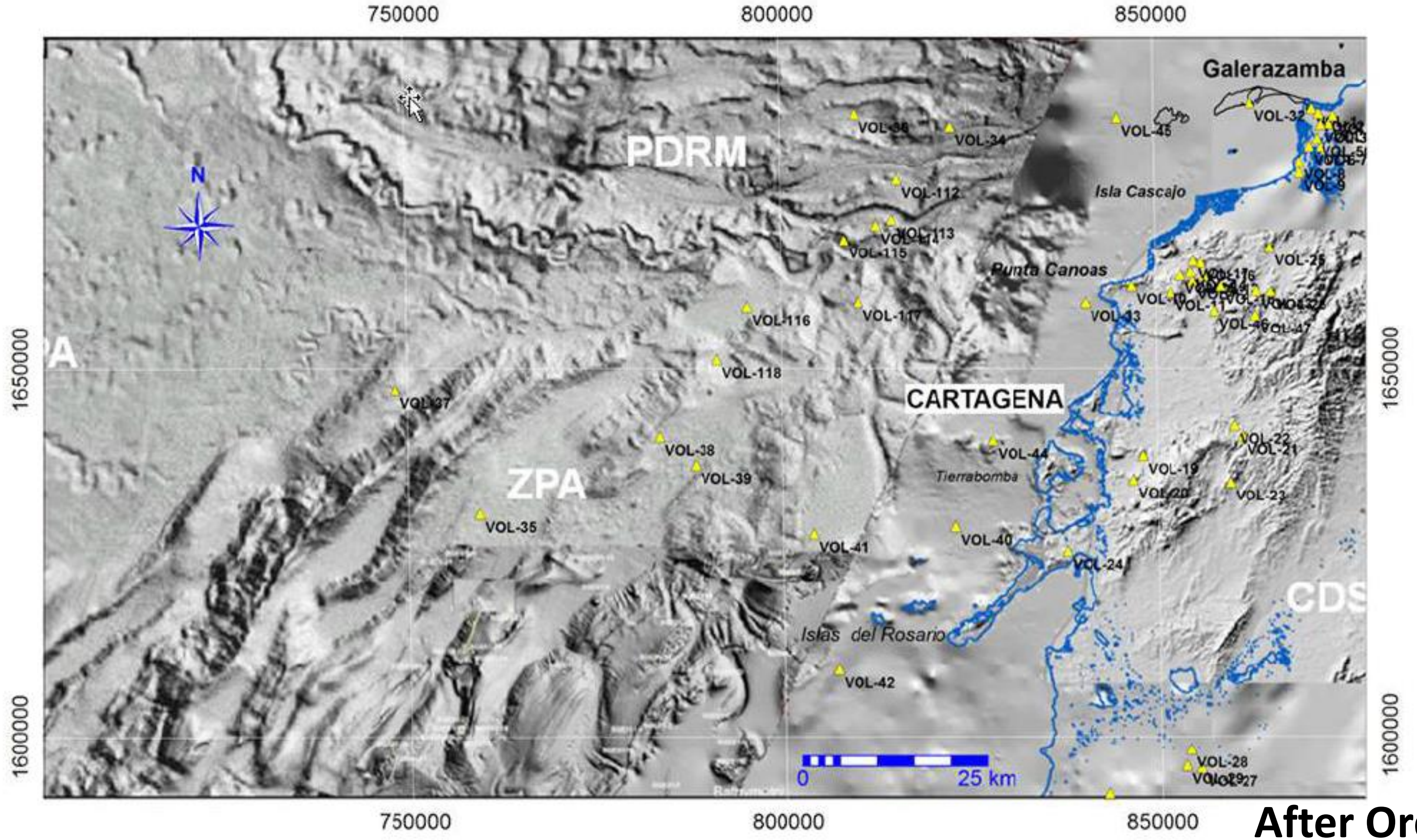

After Pindel and Barret, 2002




After Cediel et al., 2005 →

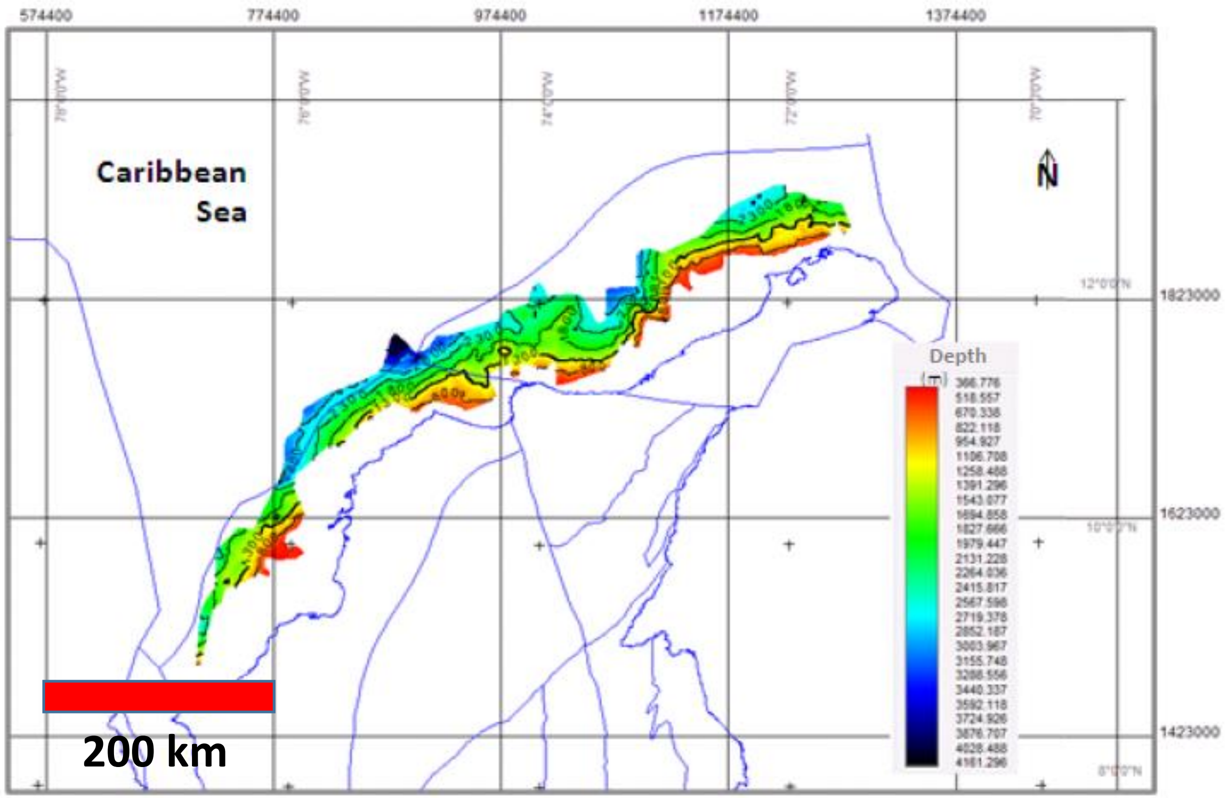
Cediel and Cáceres, 2000

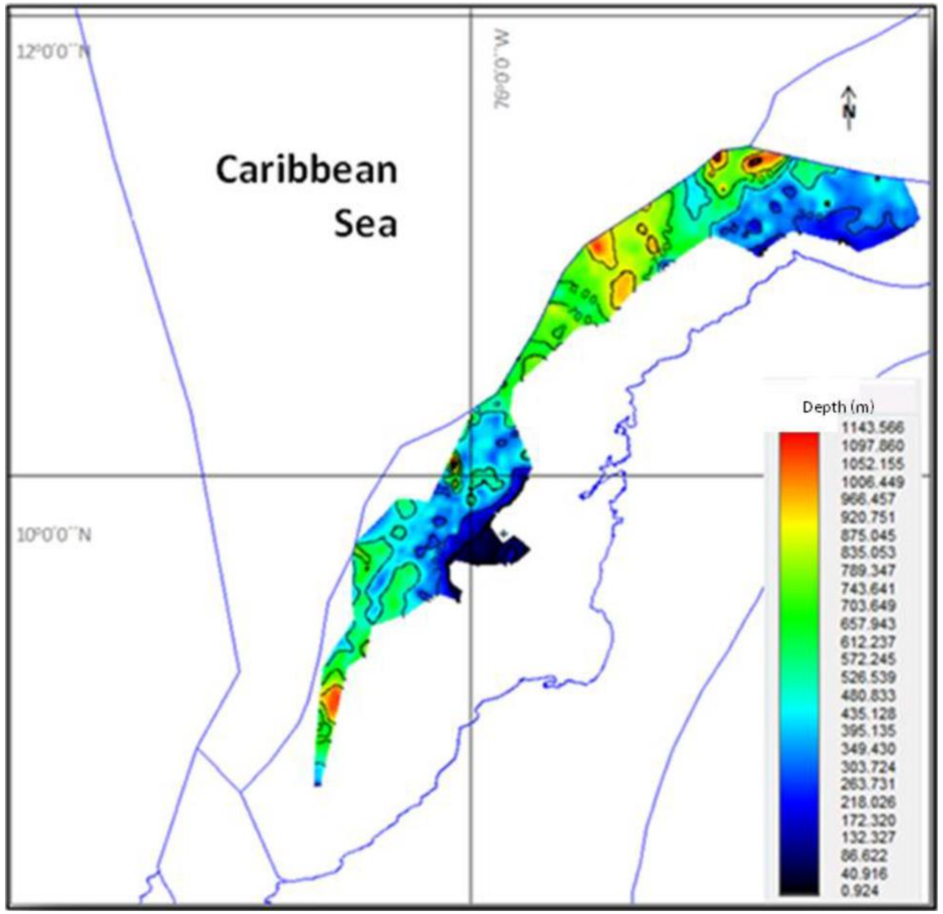
# Mud Volcanoes outcropping in the offshore shelf




**After Ordoñez, 2009**

# Gas Hydrates thickness in the Sinú offshore Belt



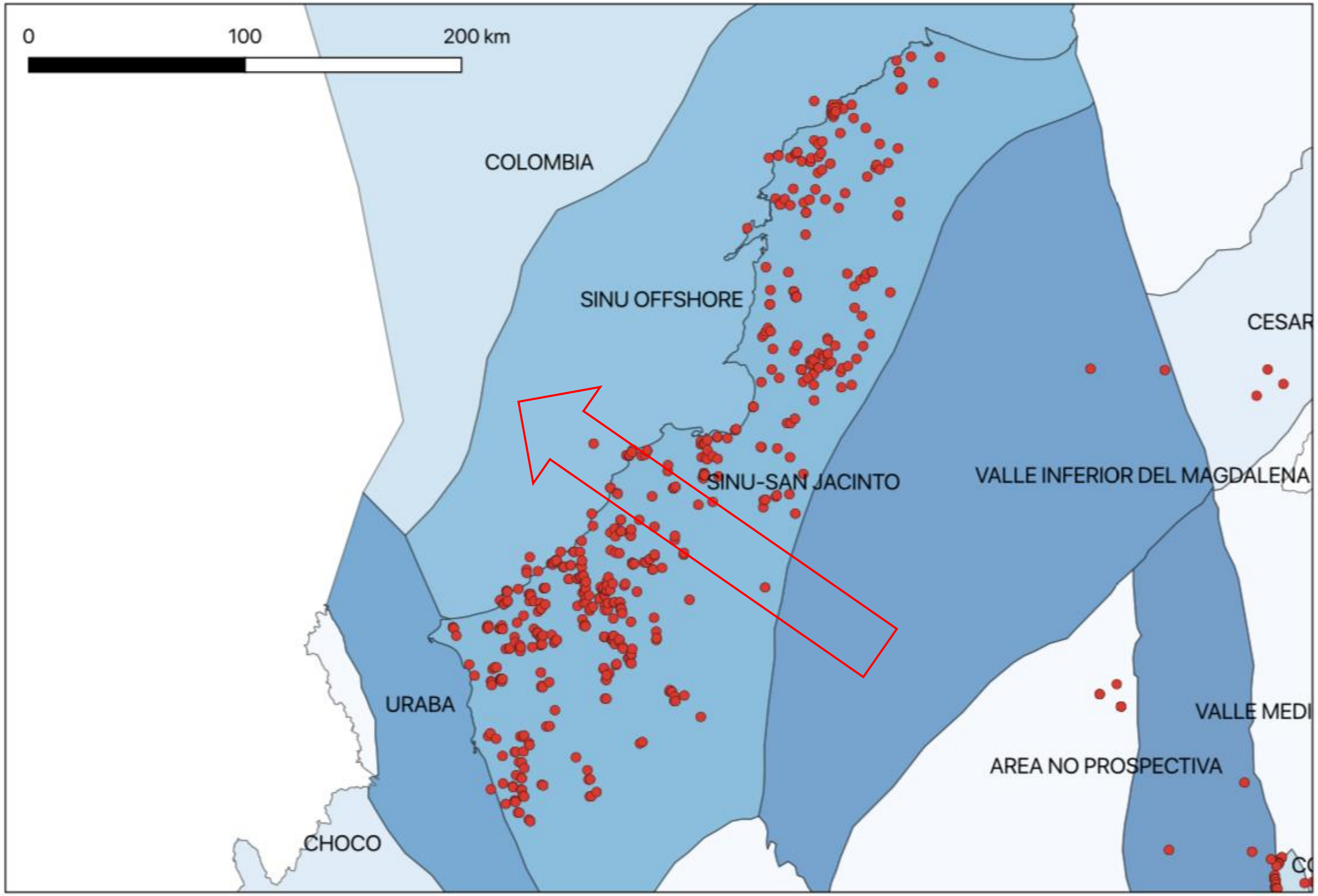




GHSZ depth varies from 300 m to 2500 m forming a strip
Parallel to the coastal line

GHSZ thickness from few meter to 1000 m
In the central area of the Sinu Fold belt

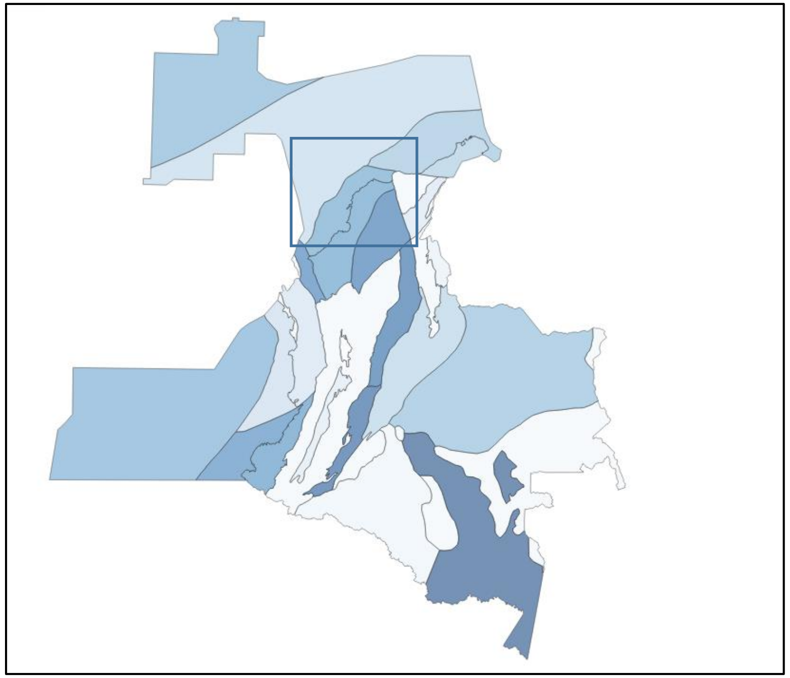
Modified after Lopez 2005, and ANH 2012

# Location of oil/gas seeps that coincides with mud volcanoes




Mud diapir migration

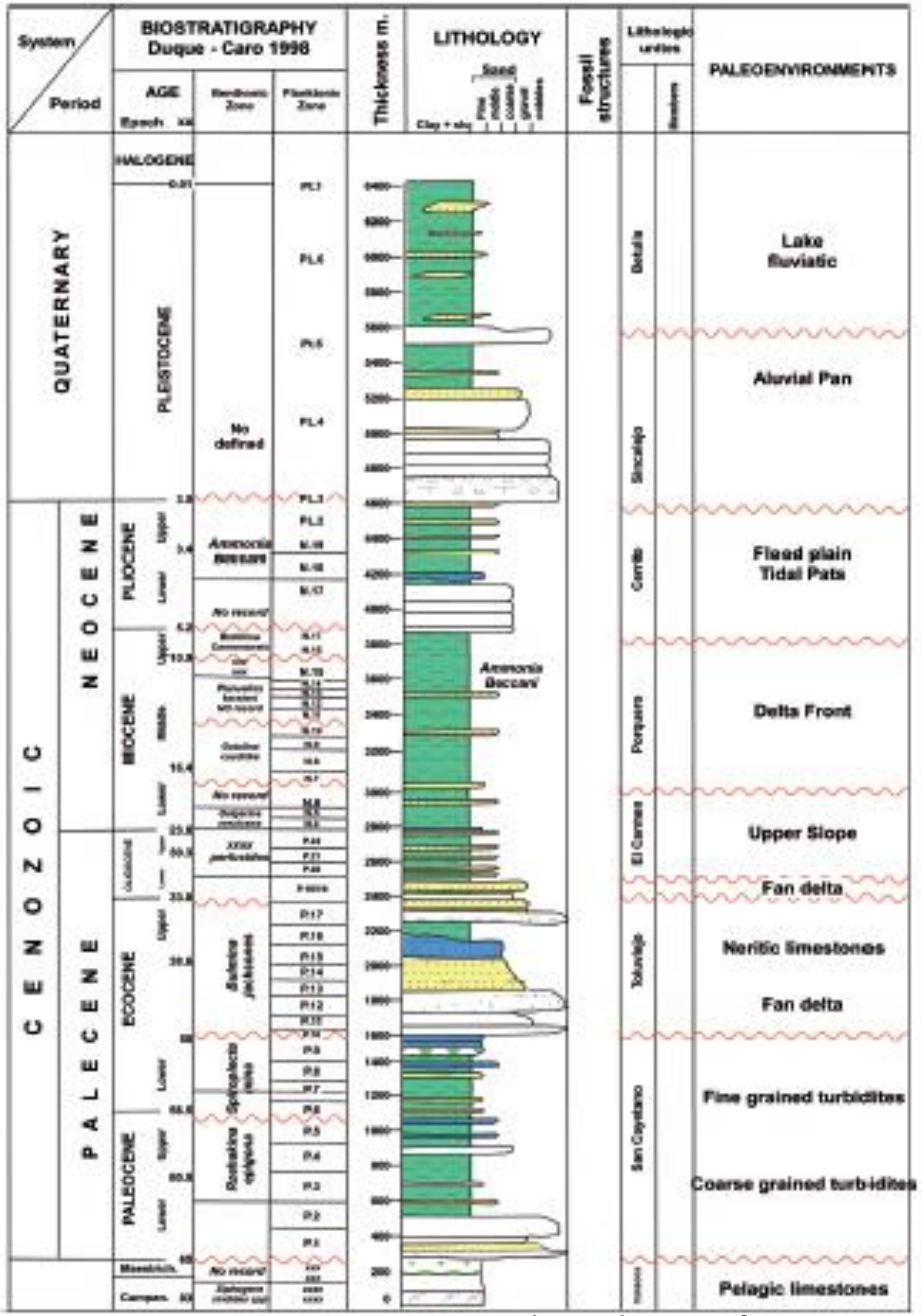
MAPA DE CUENCAS



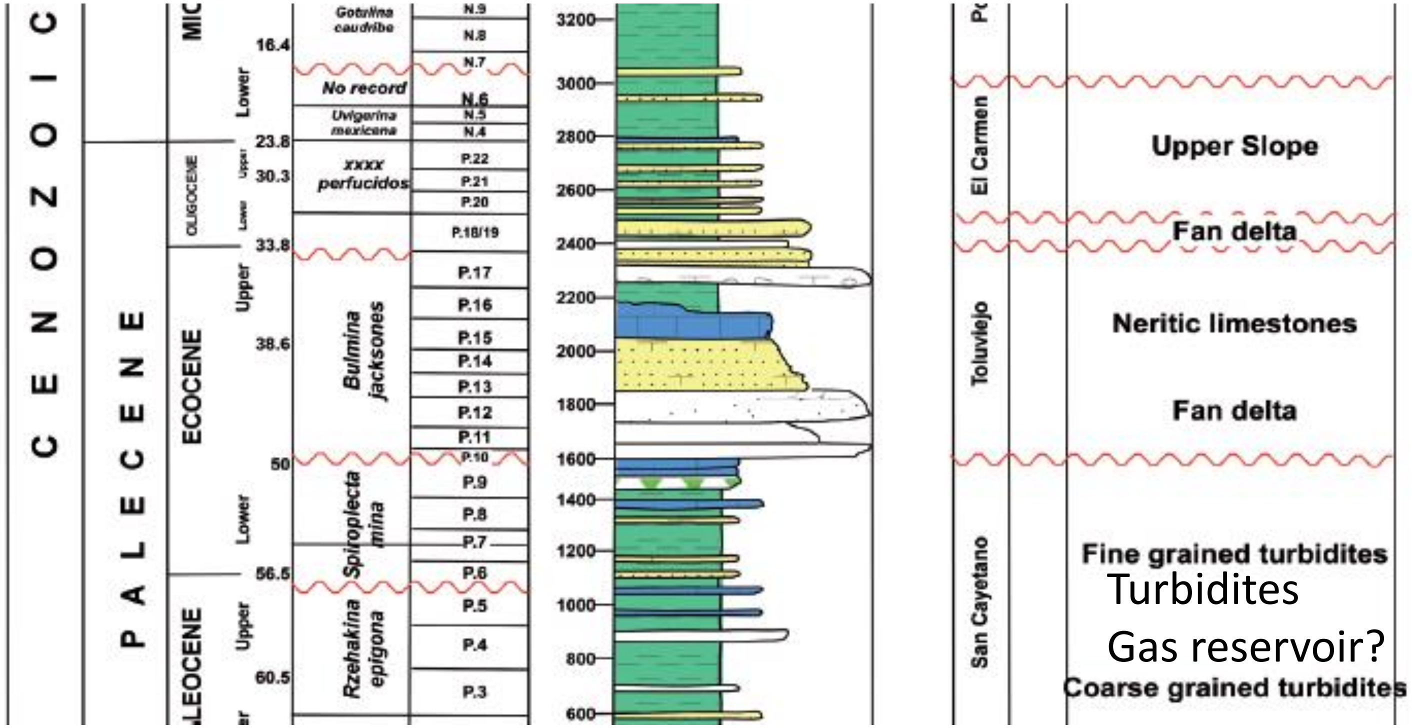
# Structure of Mud Volcanoes


Mud volcanoes in onshore and offshore areas are  present along faults, either thrust or strike slip faults. Forming strata-volcano by accumulation of mud flows during continuous or intermittent mud eruptions

# Stratigraphy of the Sinú fold belt



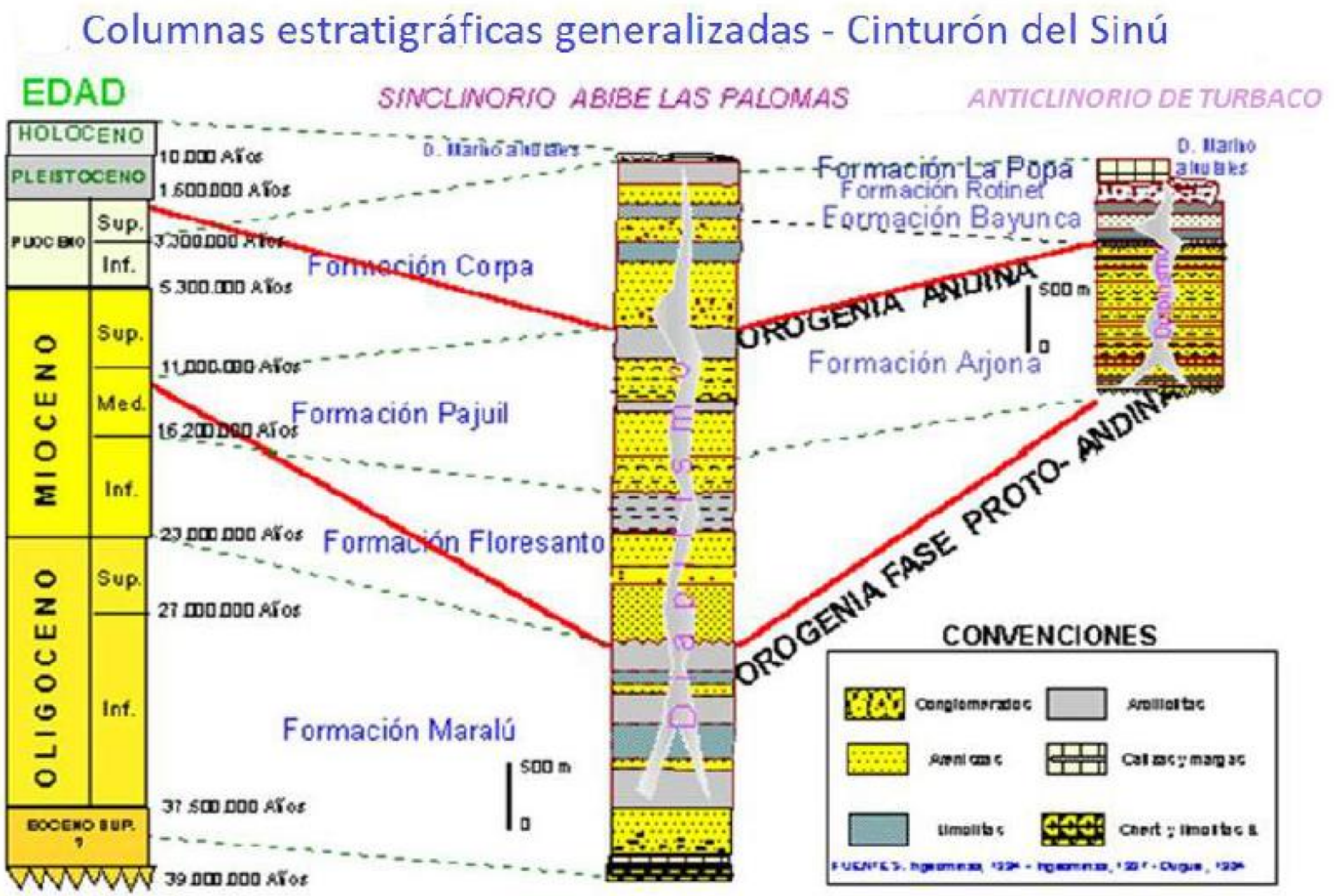

Stratigraphy chart of Guzman , 2004




The stratigraphic record starts in the Paleogene and continuous to the Neogene and Quaternary, numerous unconformities are identified and have been related to diapirism and thrusting by Duque–Caro, 1984.

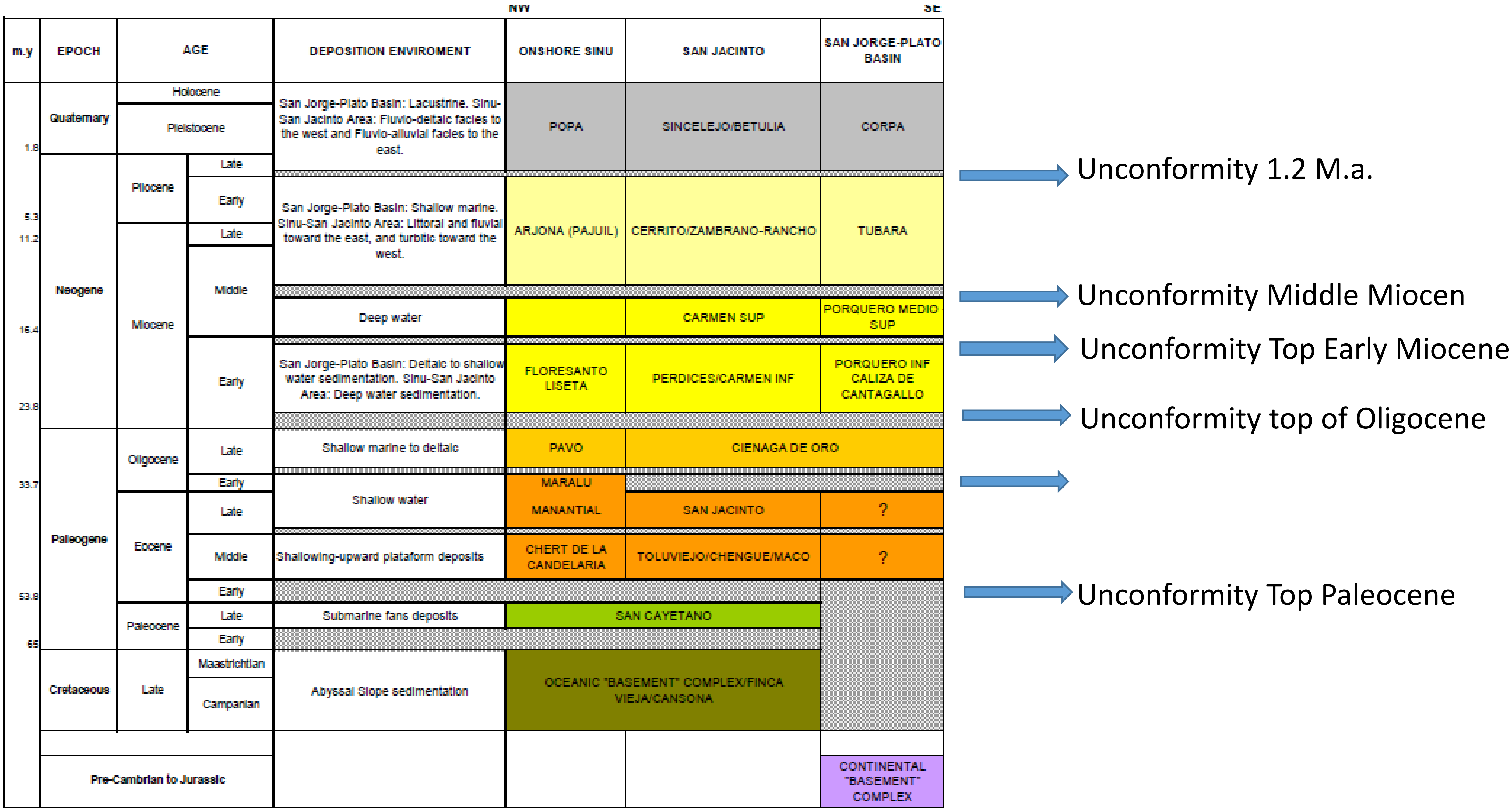
The main facies is mudstone (shale).The secondary facies are sandstone; and Neritic limestone identified as source rocks

# Stratigraphy of the Sinu Fold belt



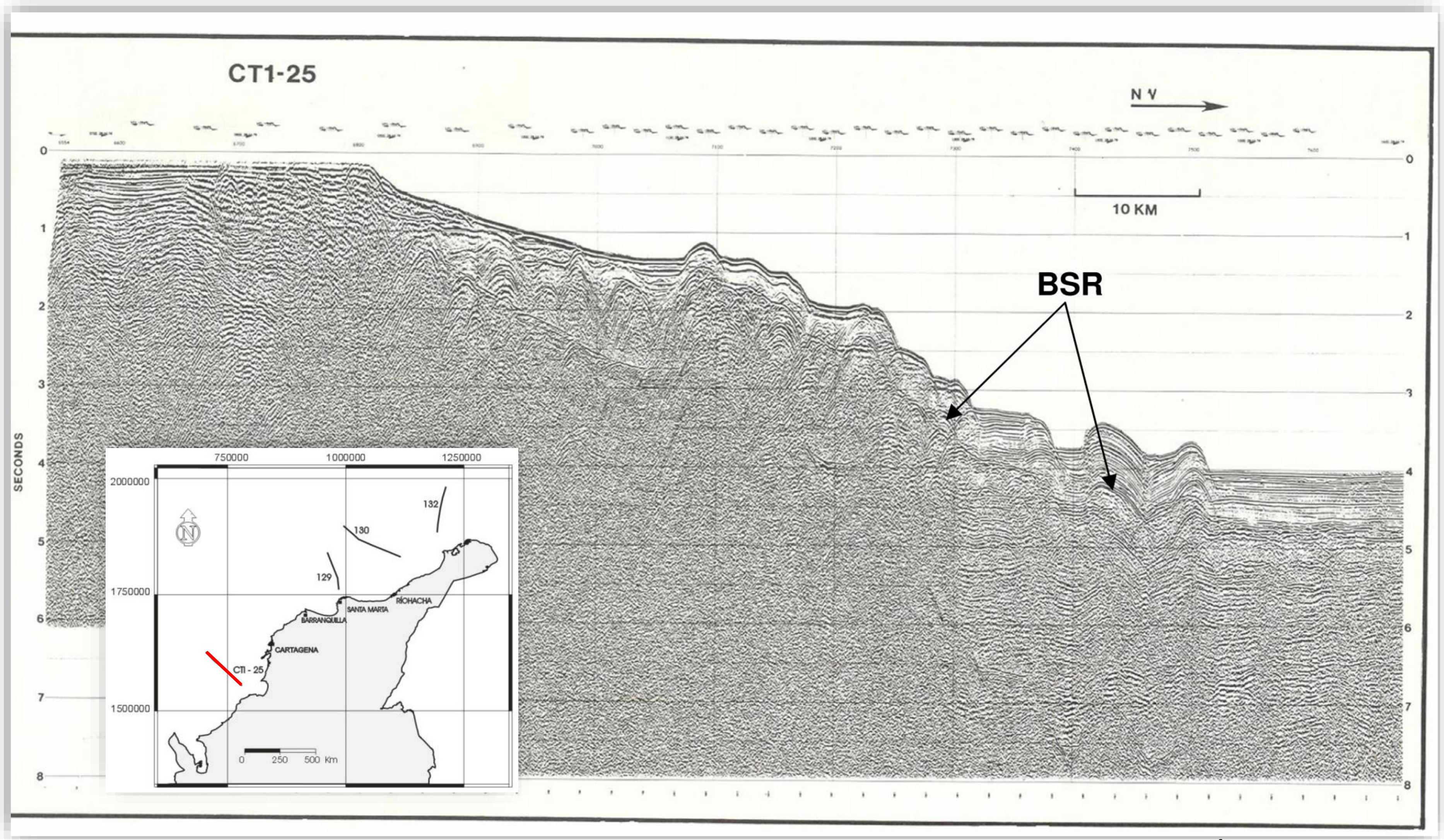

Duque-Caro, 1984 recognized that most of the Sinu Belt Unconformities are related to mud diapirism

After Carvajal 2017




After Mantilla 2007

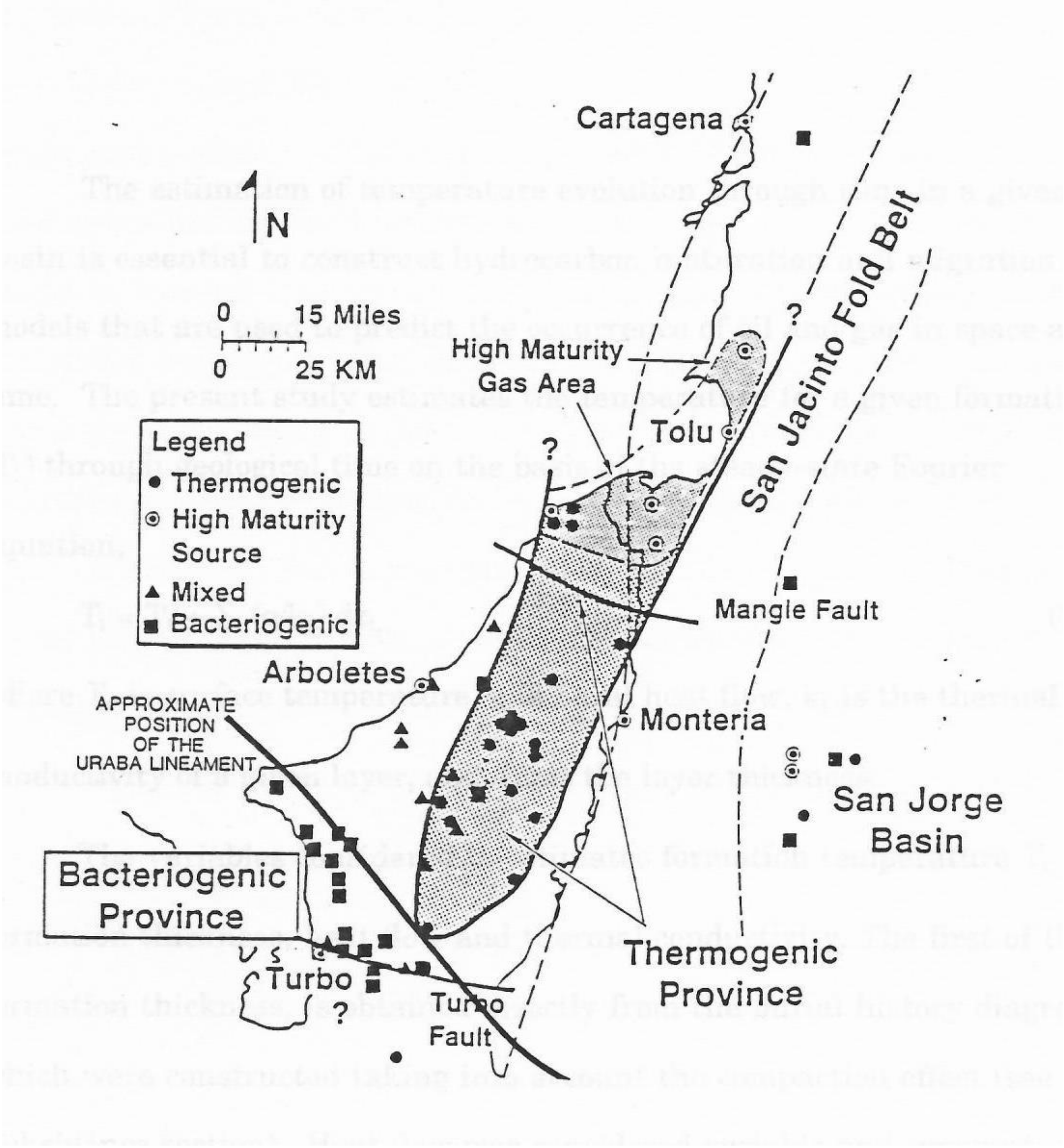
# Occurrences of Gas Hydrates in the Caribbean shelf of the Sinu Fold-belt, Colombia




López., 2005

BSR identification along with mud diapirs and Mud volcanoes structures indicate the presence of gas hydrates In the Sinu Fold belt , that extend from Colombia to Venezuela Forming the South Caribbean deformed belt

# Gas seeps composition and origin in the Sinu Fold Belt




Garcia-Gonzalez, 1991

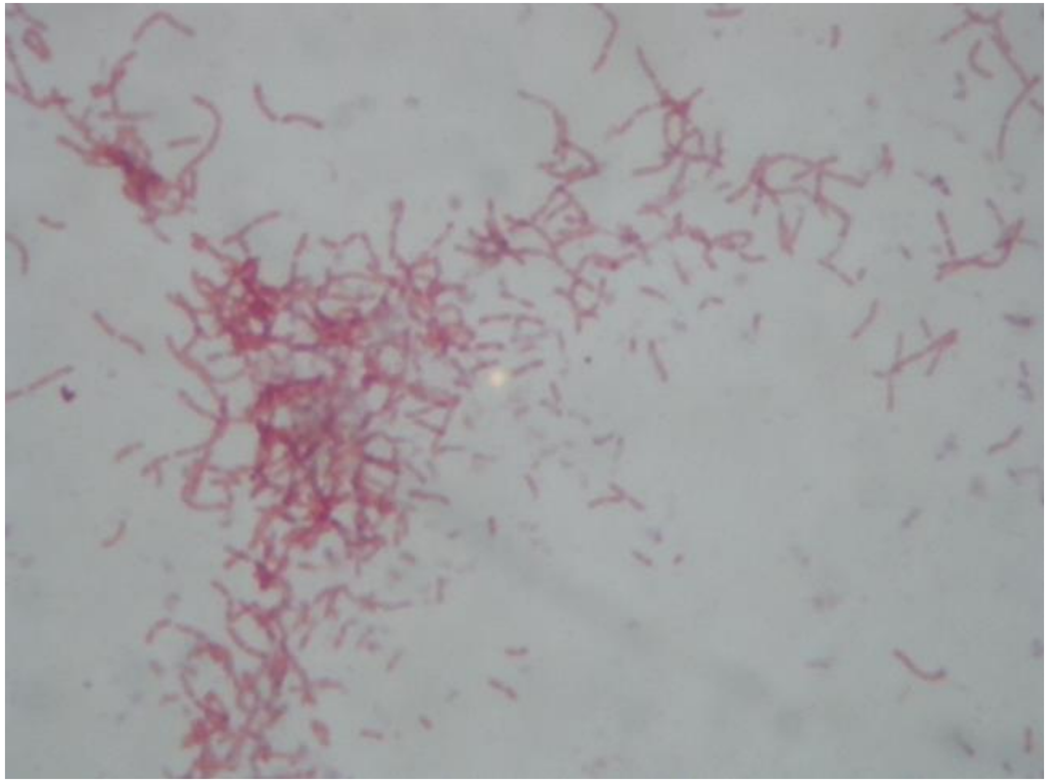
| HC | % vol |
|---|---|
| Metano | 91,640 |
| Etano | 2,350 |
| Propano | 1,544 |
| i-Butano | 0,515 |
| n-Butano | 0,432 |
| neo-Pentano | 0,005 |
| iso-pentano | 0,222 |
| n-pentano | 0,074 |
| n- Hexano | 0,009 |
| n-Heptano | 0,003 |
| CO2 | 1,843 |
| Nitrogeno | 1,350 |

Gas and condensate analysis from Arboletes mud volcano sample.

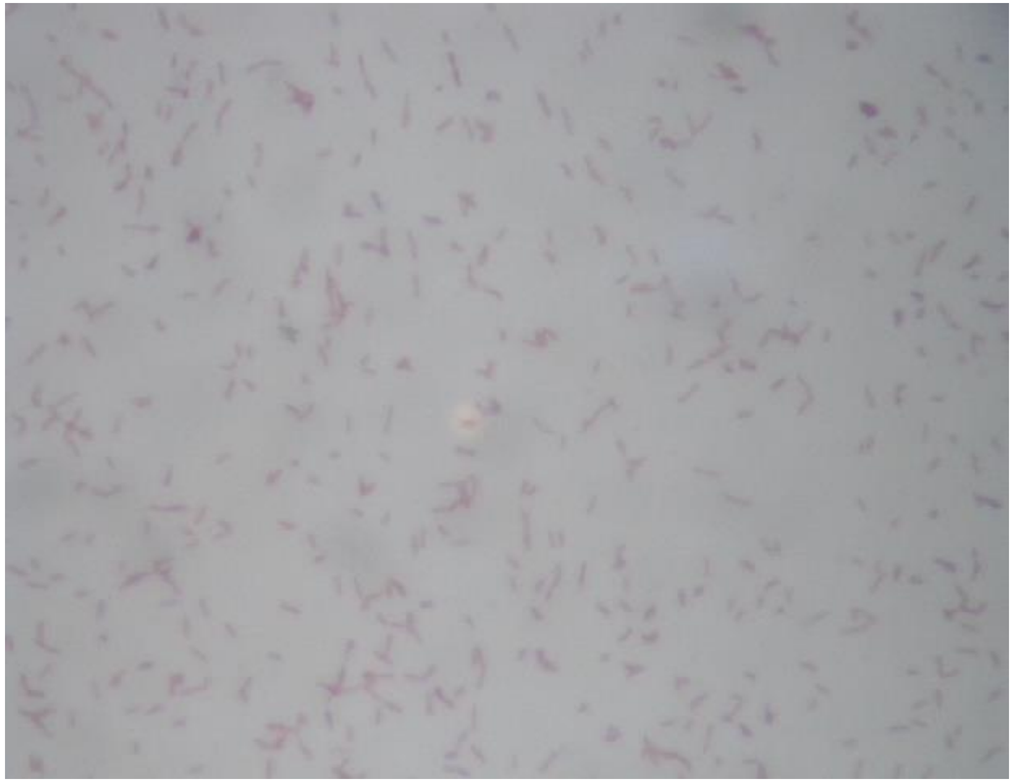
This composition and the bacteria found in the mud, indicates that biogenic gases are formed by biodegradation of oil

Regional distribution of Thermogenic, Biogenic,and mixed gases in the Sinu Fold belt. Gas samples obtained from Oil and gas seeps found along with mud volcanoes

Biogenic gases are associated to present Bacteria activity in mud volcanoes, Halomona and Marinobacter genus are associated to low temperature (> 4°C ) indicating its possible relation to gas hydrate

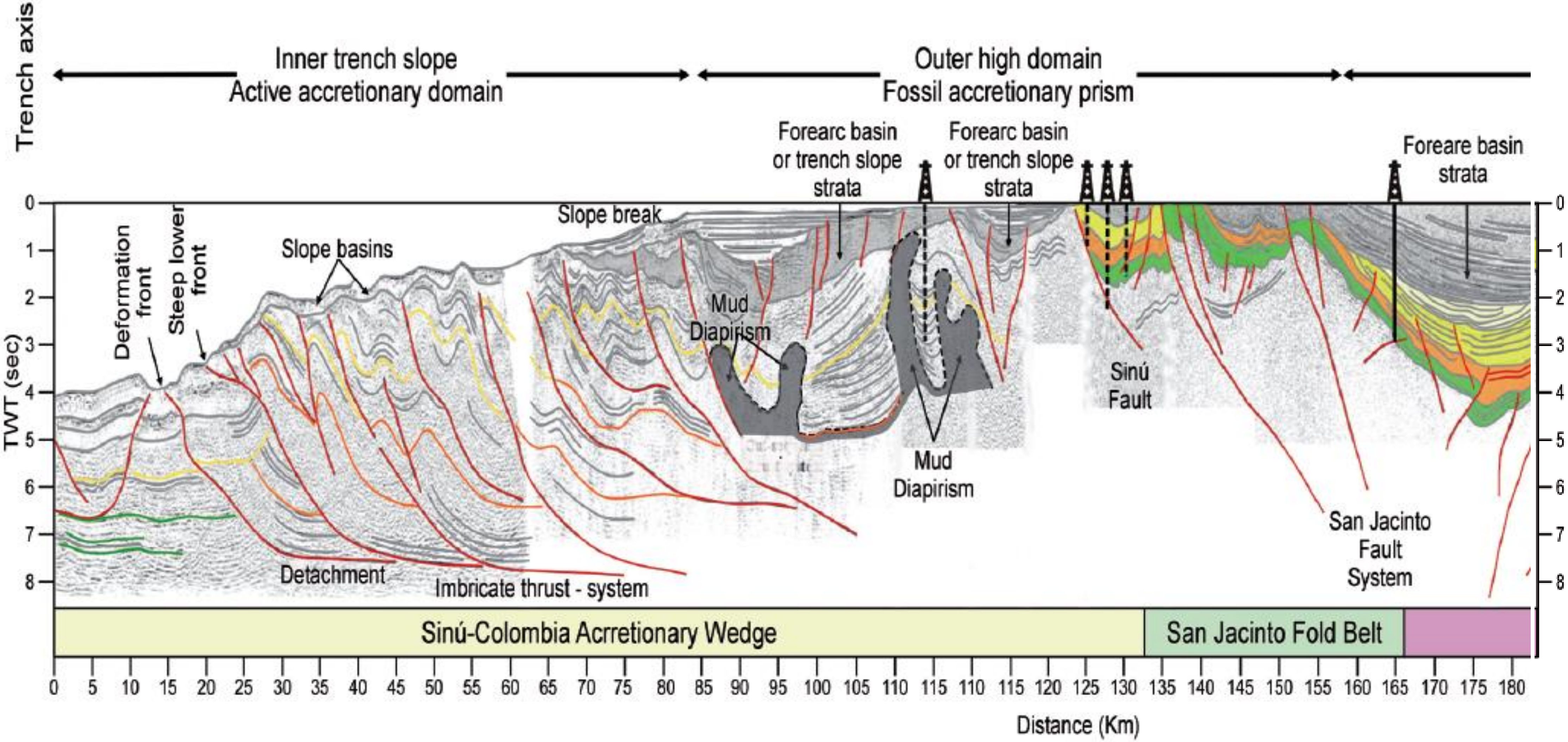


Halomona genus bacteria associated with high salinity environment



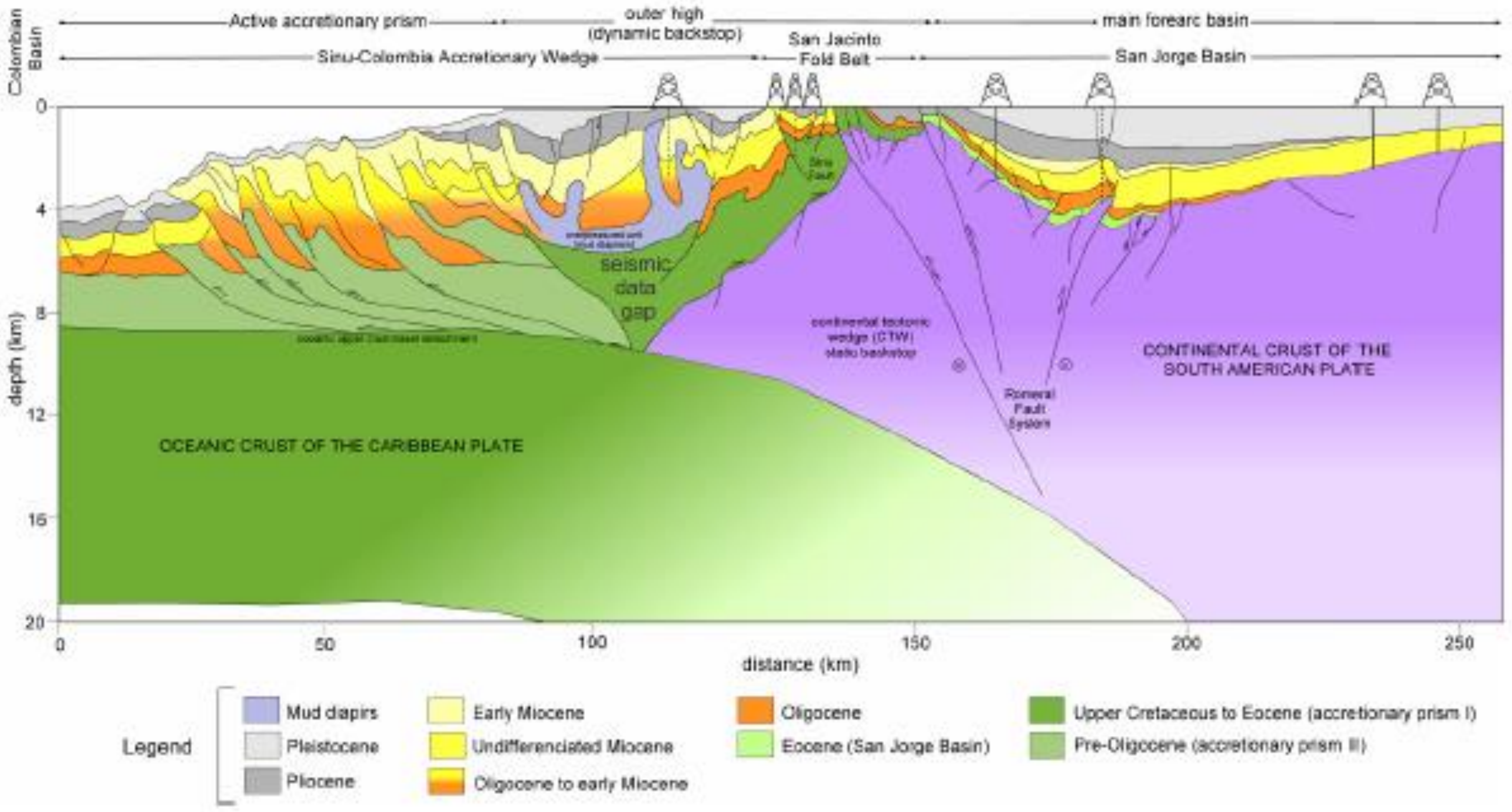
Marinobacter genus bacteria associated to Marine environment

# Cross section showing deep intrusive mud diapirs in the Sinú and San Jacinto Fold-belts of Colombia




Mantilla., 2007

# Are mud diapirs deep and young intrusive structures originated from pre-Oligocene Fm, that are intruding Pleistocene sediments?



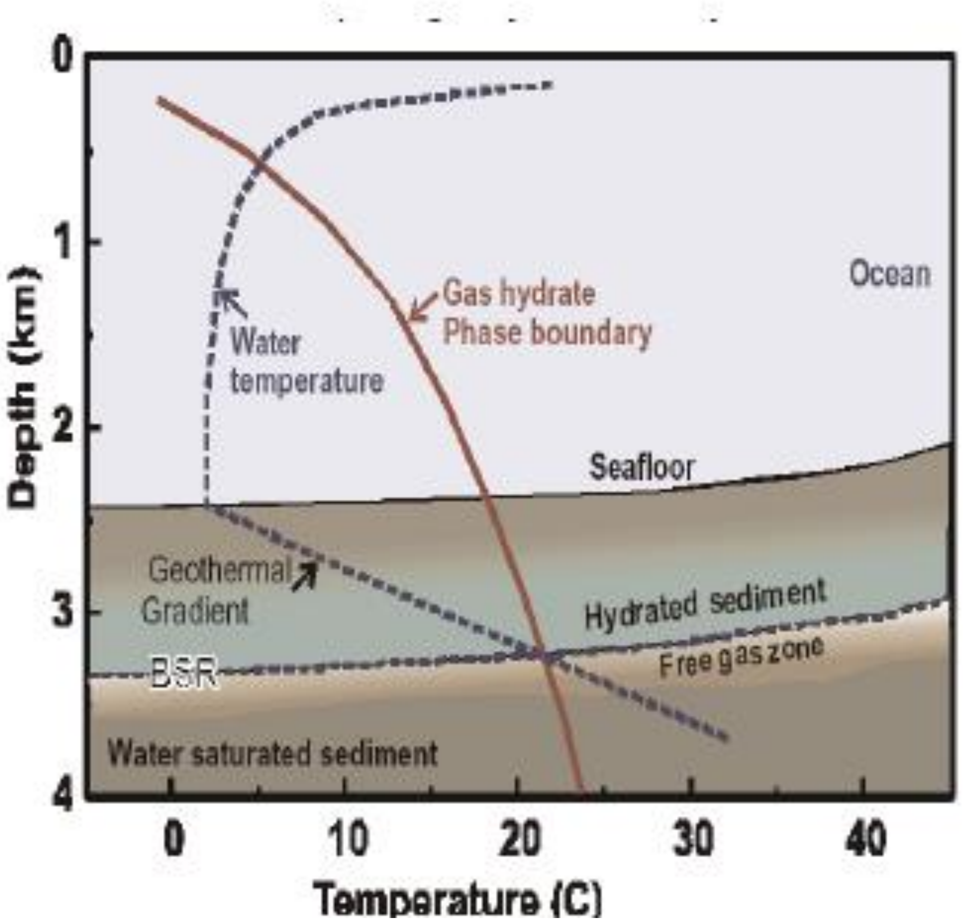

What is the timing of mud diapirs emplacement or intrusion?

Are mud diapirs source rocks oil and gas prone?

What is the temperature and maturation range?

What is the role of gas hydrate on this interpretation?

# Stability Field of hydrocarbon gas hydrates
# Explaining the existence of gas hydrates in the Caribbean




Stability zone for oceanic gas hydrates, after Hyndman and Dallimore, 2000

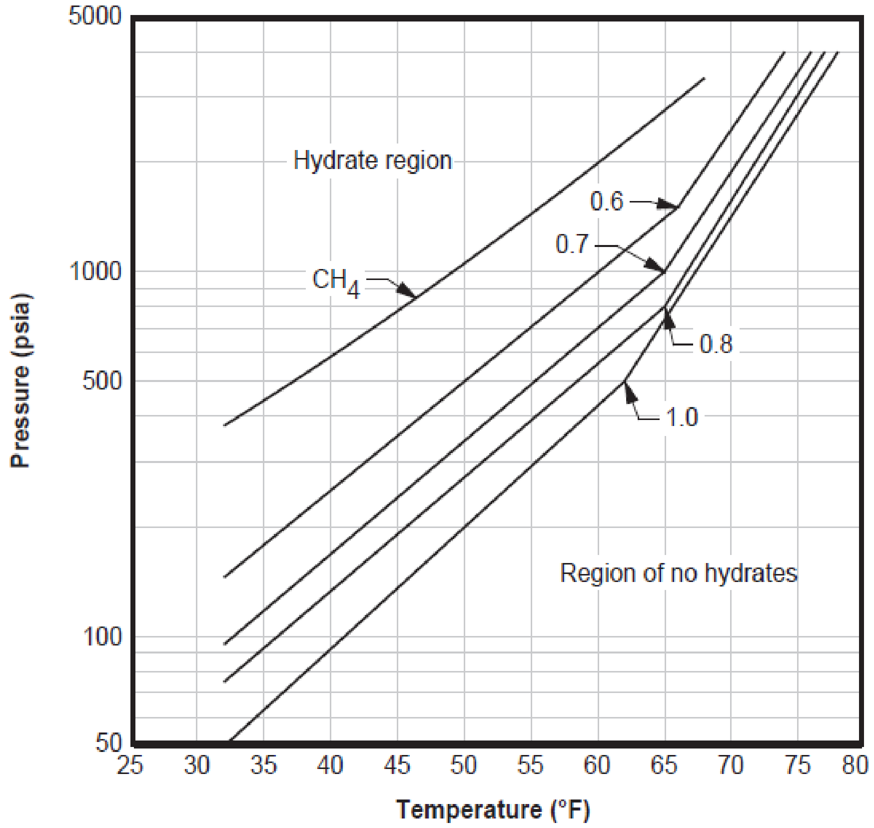
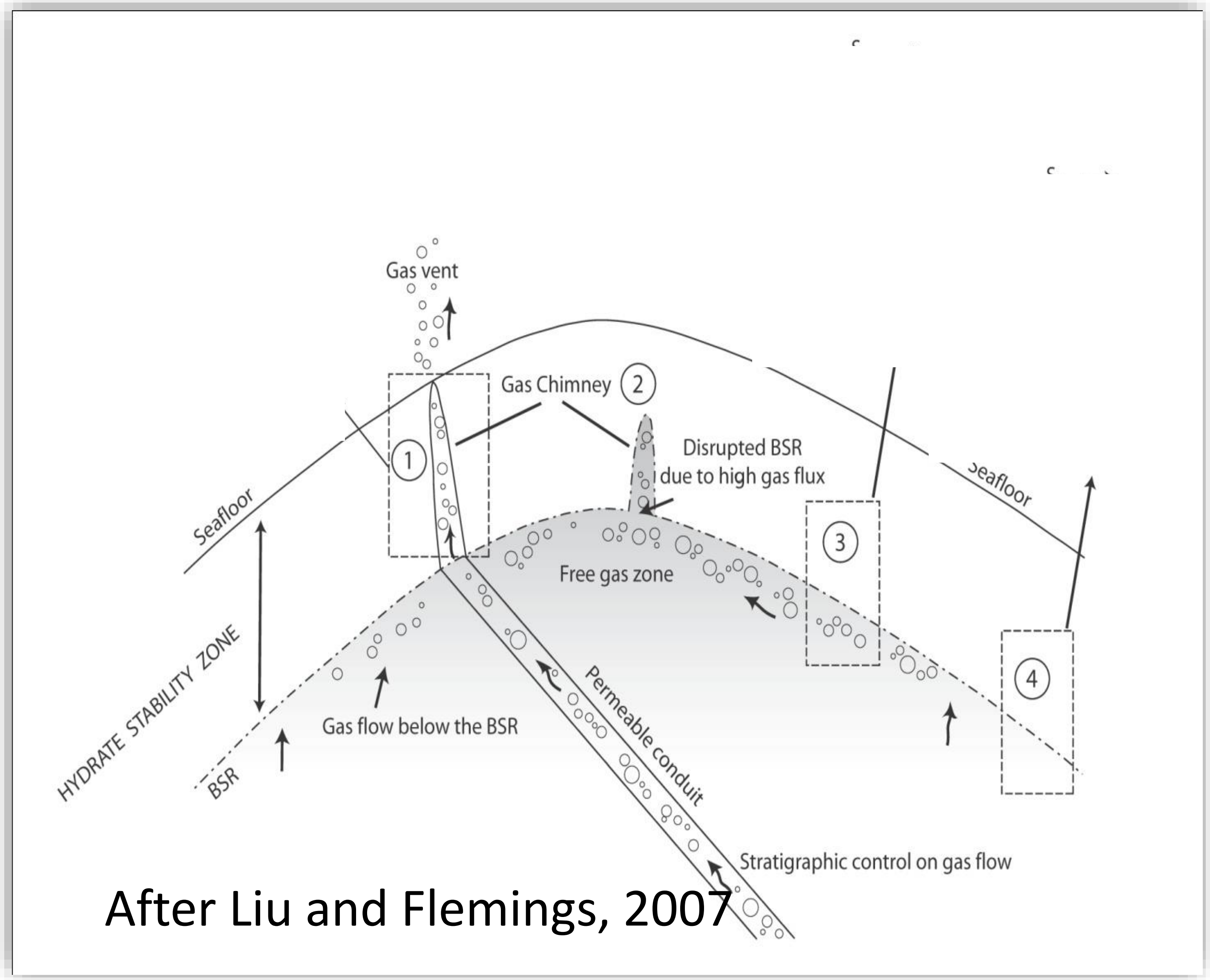



Figure 3.3 *Hydrate Locus for Sweet Natural Gas Using the Gas Gravity Method—American Engineering Units.*

Stability of methane and natural hydrocarbon gases including C1 to C7 in the Sinu fold belt

Tinivella and Giustiniani, 2013

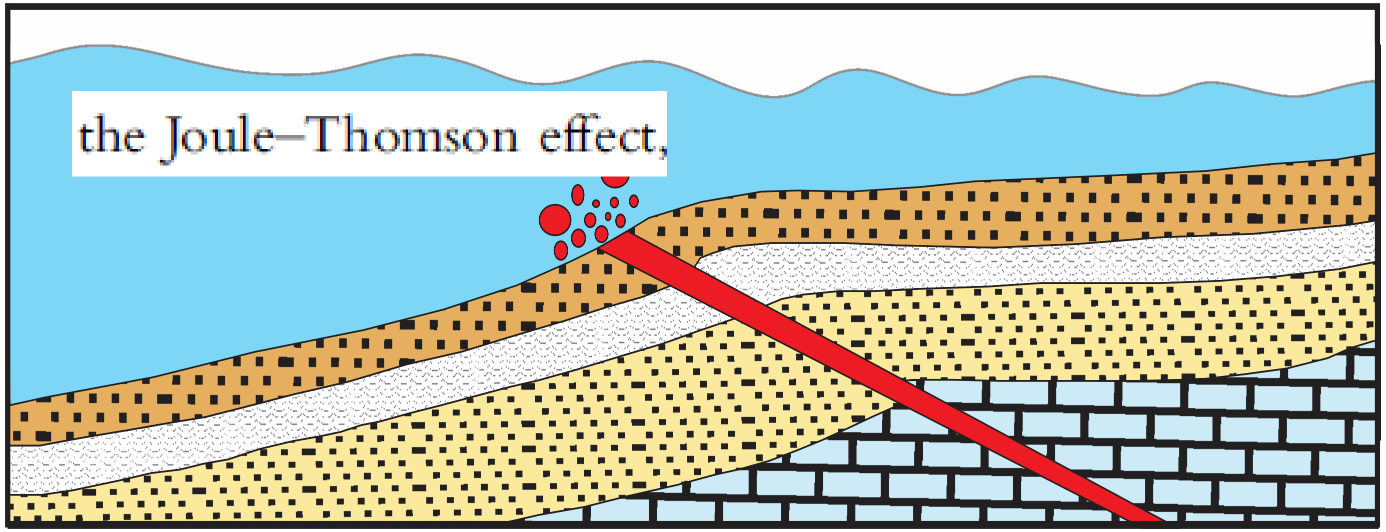
# Formation of Gas Hydrates and subsequent destabilization and formation of Mud diapirs and volcanoes

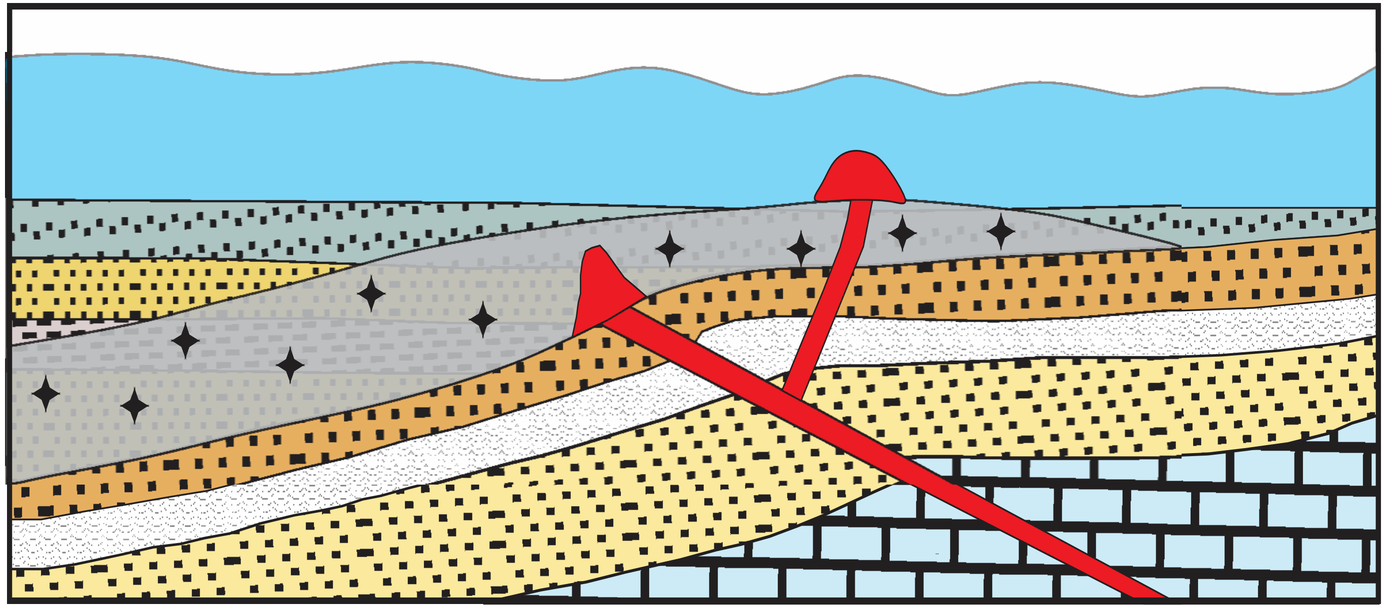



After Liu and Flemings, 2007

1) Venting of thermogenic gases on the sea floor, and subsequent formation of gas hydrates
2) Gas chimneys get reduced in size as the GHSZ increase its thickness.
3) Gas chimney eventually diminish as the GHSZ reaches its maximum thickness.
4) A change in sea temperature or change in geothermal gradient cause destabilization of the GHSZ, consequently large volumes of gas and condensates get liberated forming rising bubbles as gas chimney or diapirs.
5) After reaching the sea floor or the costal plane, large volume of gas-water-saturated-mud spill over the surface forming mud volcano, like strata-volcano structures

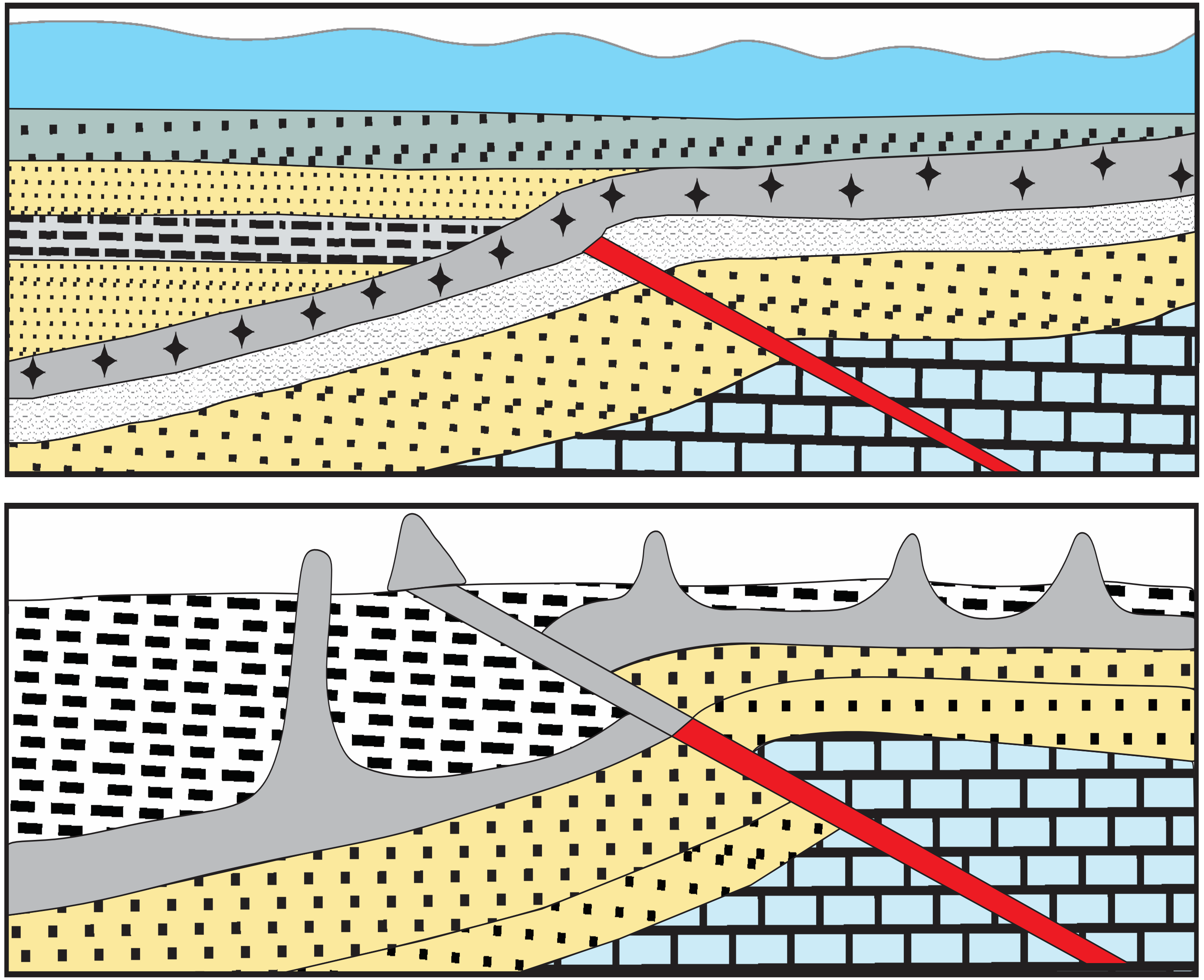
# Formation and evolution model of gas hydrates, mud diapirs and mud volcanoes in the Sinu fold belt



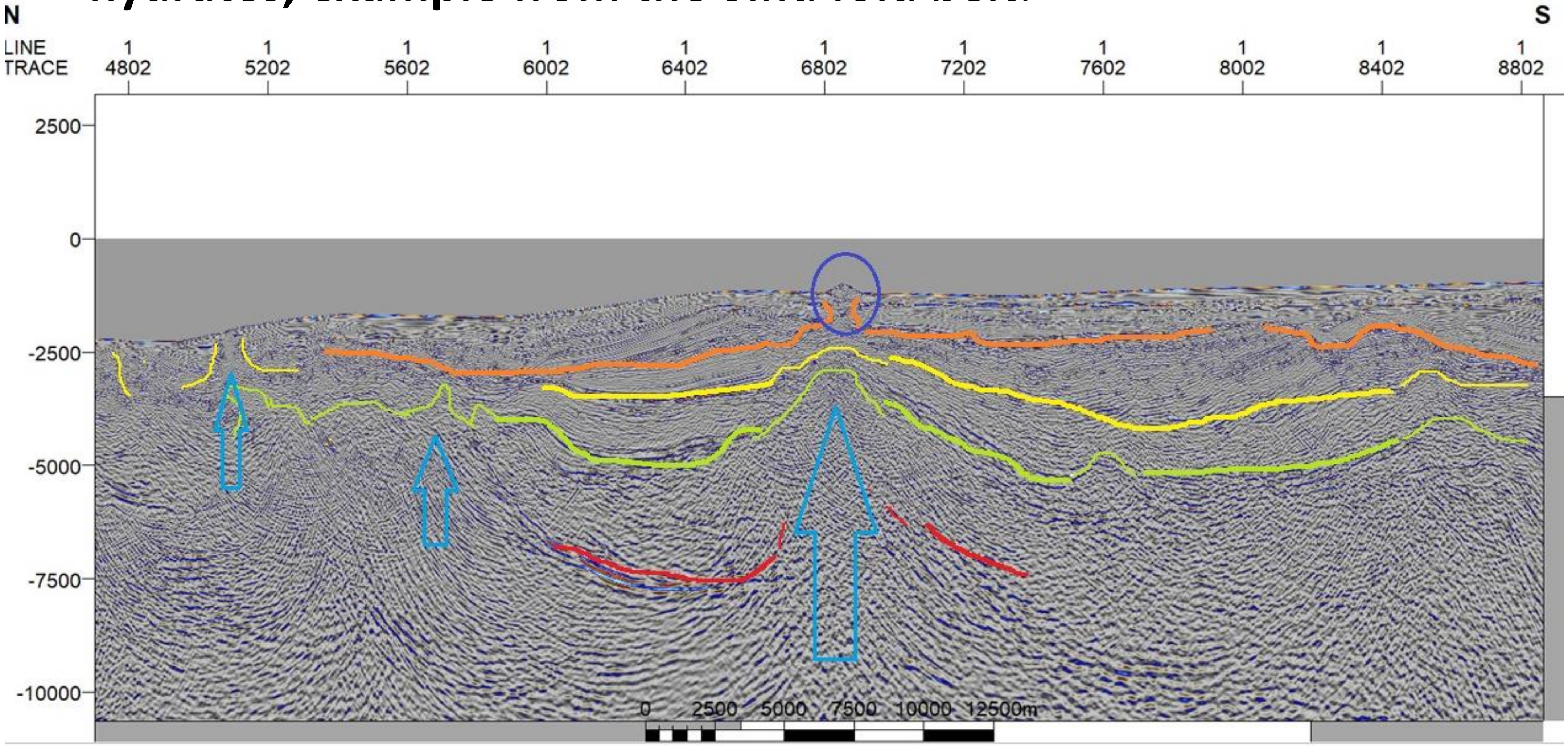
- ✓ Thermogenic gas venting on the sea floor, Gas migrates from Deep source rocks of Pre-Oligocene age
- ✓ Gas venting on sea floor promotes gas hydrates formation in the uppermost unconsolidated and water saturated sediments
- ✓ As gas hydrates increase their thickness and extension, a regional seal trap free gas beneath the BSR.
- ✓ The RGSZ get unstable and mud diapirs and volcanoes appear

# Formation and evolution model of gas hydrates, mud diapirs and mud volcanoes

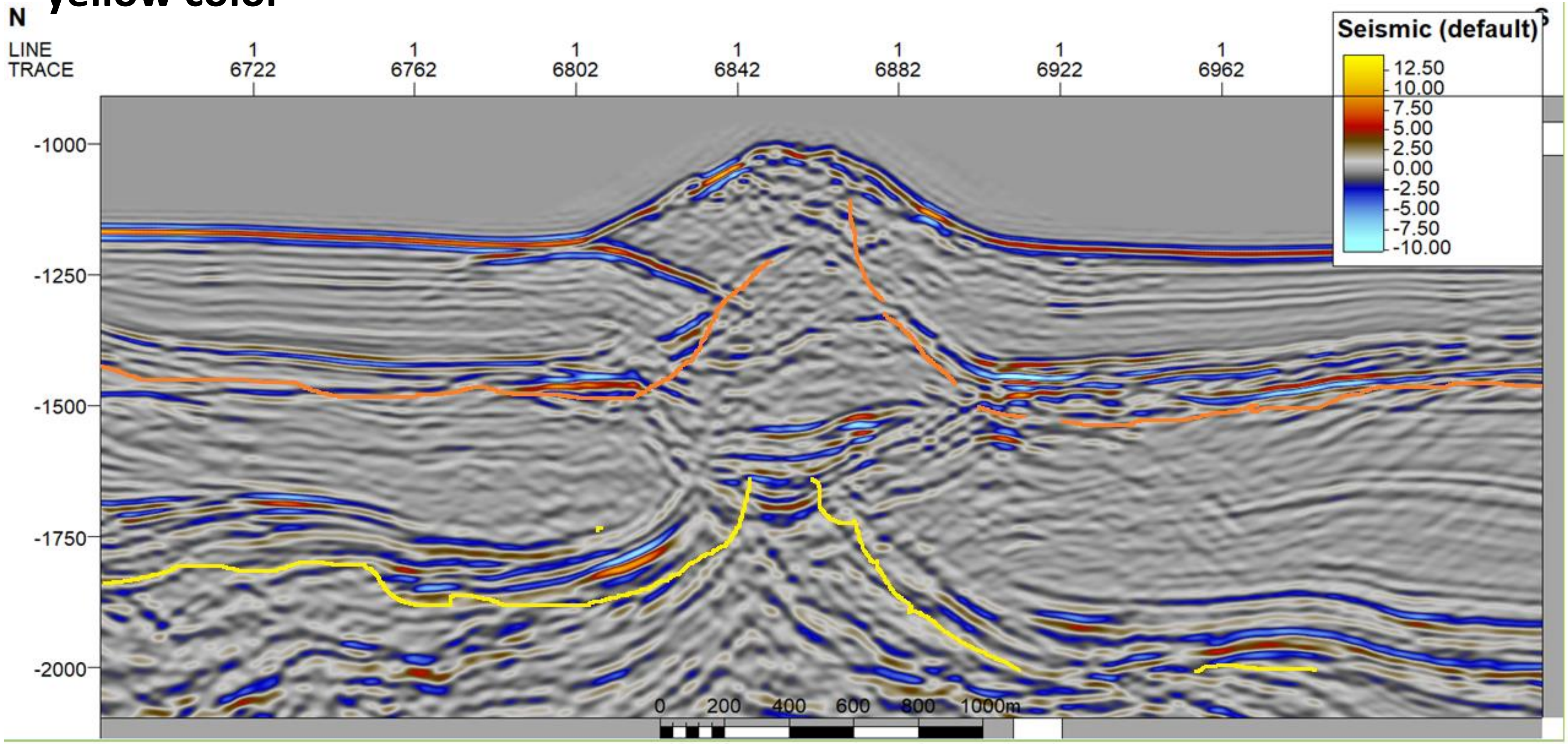


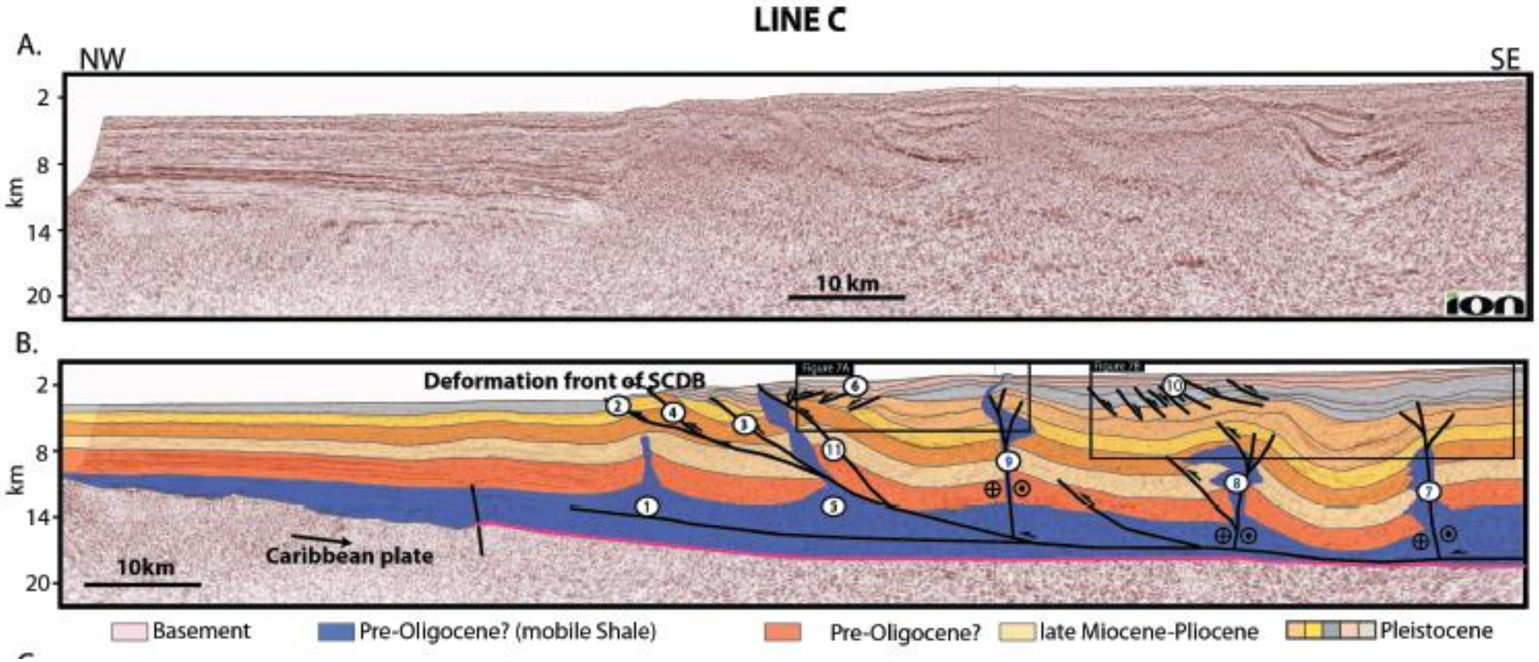
✓ During burial the bottom boundary (BSR) gets unstable due to temperature increase, following gas chimneys are formed reaching the sea floor surface forming mud diapirs and mud volcanoes structures. Thrust faulting also promote destabilization of the BSR . Mud diapirs and volcanoes belong to the seal rock in the gas hydrates petroleum

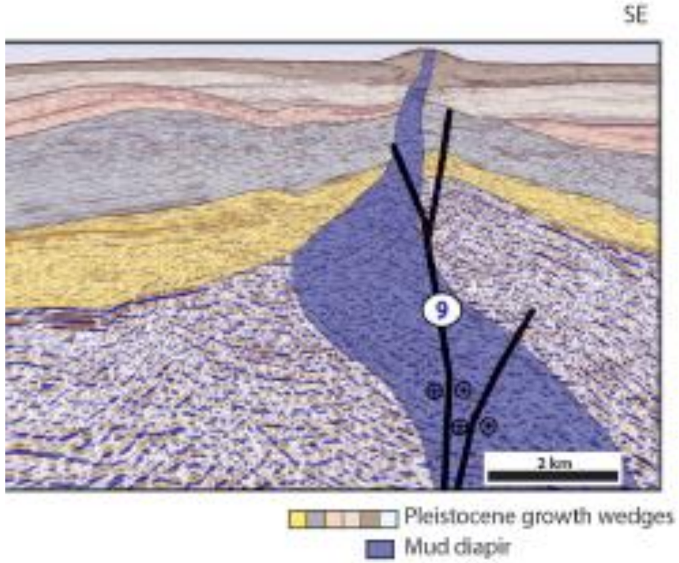
**Example of Gas conduit (gas chimney) through as thick sedimentary sequence, associated with a relics of BSR. This structure growth along with burial, sedimentation, formation and destruction of gas hydrates, example from the Sinu fold belt.**

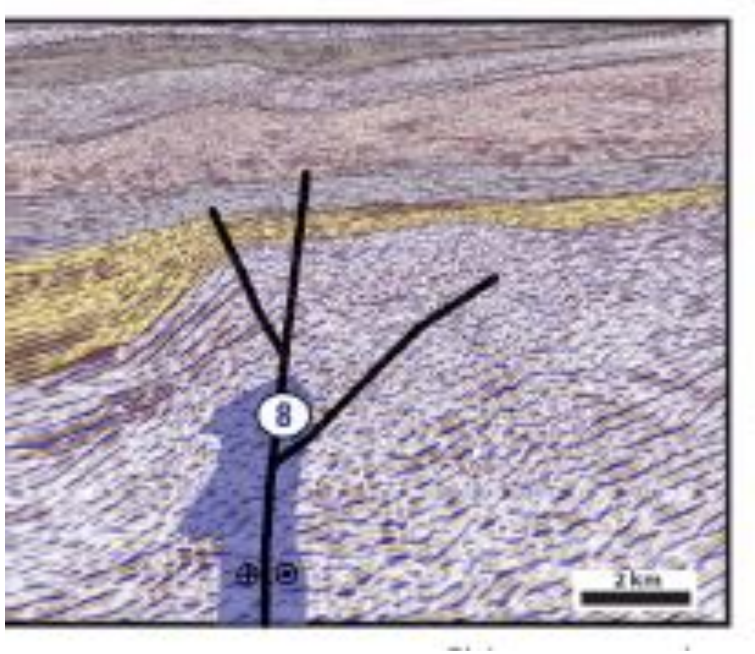


**Detail of mud diapirs reaching the sea floor and forming a mud volcano. This structure or phenomena prevail through geological time since the Miocene in the Sinu Fold Belt. Its origin is closely related to the formation and destruction of gas hydrates along faults. Notice the presence of a paleo BSR indicated in yellow color**






After Bernal et al., 2015

Mud diapirs structures are not formed by deep intrusive shales (> 8 km deep) as indicated by Bernal et al, 2015 ; Instead this structures are formed by shallow intrusions during the continuous formation and subsequent destruction of gas hydrate in a high subsidence and Sedimentation rates.

Mud volcanoes are present in the Sinu coastal plain along Fault and their origin is related to thick Gas Hydrates Stability Zones (GHSZ). These GHSZ became unstable releasing great volume of hydrocarbon gases and water that rise toward the sea floor.

# Conclusions

- In the Caribbean as in other areas, seismic lines clearly show the formation of shallow (< 1.2 km) intrusive like structures associated with destabilization of the Gas Hydrate Zone.
- These structures are also known as gas chimneys and growth along with sedimentation, forming large diapirs that after reaching the sea surface form mud volcanoes.
- The existence of thick Gas Hydrate Stability zone allows sedimentation on top of thick sediment sequences. This happen  when a low geothermal gradient is present that allow the formation and preservation of thick GHSZ.

# Conclusions

- In coastal plains mud diapirs continue their activity rising toward surface forming mud volcanoes due to the accumulation of thick sediment sequence on top of unconsolidated sediments that were previously gas hydrates,
- consequently mud volcanoes and diapirs will continue as long as large volumes of gas and oil rise toward surface.
- Over-pressured shale zones are required to be present for the formation of mud diapirs

# Conclusions

- Mud diapirs are the late expression of gas hydrates and cannot be considered as source rocks, instead mud diapirs are seal rocks in the petroleum system.
- Mud diapirs are growing structures that occur along fault planes. These structures growth along with burial and sedimentation.
- Gas reservoirs associated with Gas Hydrates zones and mud diapirs layers should be explored beneath mud diapir layers in the Paleocene to Miocene turbidites.
- Mud diapirs present different thermal properties to salts diapirs. Mud diapirs present low heat conductivity and salt diapirs present high heat conductivity. These different scenarios explain why no large gas and oil accumulations have been found in the Sinu fold belt.

# Conclusions

- In the Sinu fold belt thermogenic gases generated from Pre-Oligocene source rocks, spark the formation of gas hydrates gases.
- The presence of biogenic gases in mud volcanoes is explained by the bacteria activity that generates gases from biodegradation of oil generated in Pre-Oligocene rocks.

# Acknowledgements

- ✓ Authors thank the Universidad Industrial de Santander for funding of this research project