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3D GEOMETRY AND EVOLUTION OF SHALE DIAPIRS IN THE EASTERN VENEZUELAN BASIN

Leonardo Duerto & Ken McClay

Fault Dynamics Research Group

❐ ABSTRACT

The frontal fold of the Interior Range fold Belt of Eastern Venezuelan Basin (EVB) is characterized by a 150 Km long and 15 Km wide N20E oriented mud diapir belt. Four types of diapirism related folding have been identified based on morphology, growth strata geometries, and shortening. The mechanism of folding is a progressive rotation and limb length variation due to the rise of Lower Middle Miocene shale. Diapirs developed from west to east controlled mainly by the advancing underlying thrust sheets during the Caribbean Collision in the area. Shale shows strong lateral variations in composition, the most mobile shale is restricted to the basin foredeep. There are evidences of early diapiric intrusions and diapiric evolution from west to east. The initial age of shale movement is late Miocene and has a continuous movement record until end Pliocene-Early Pleistocene. Calderas and toe thrusts are potential exploration targets.

❐ INTRODUCTION

The EVB is located in the triple junction of the North American Plate, the Caribbean Plate and the South American Plate. The Eastern Venezuelan Basin (EVB, Fig.1-1) is the second most important basin in Venezuela for oil potential. It contributes with almost 40 % of the Present Day hydrocarbon production.

The basin, opened to the east, is overlain by a great amount of mud volcanoes as well as gas and oil seepages (Fig.1-7). Diapirs have always been seen as obstacles in the interpretation of the underlying oil-rich Cretaceous units. The increasing needof new discoveries has motivated a better understanding of shale diapirs as they have an important sedimentary control on the distribution of Neogene reservoir sands.

❐ TECTONO-STRATIGRAPHY

More than 25,000 feet of sediments from Cretaceous through present day have accumulated in the EVB (Fig.1-2). The history of sedimentation started in Cretaceous time with the development of a carbonate platform (Fig.1-3). These carbonates represented by the Guayuta Group were deformed in Oligocene - Early Miocene time due to the subduction of the Caribbean Plate and related imbrication and duplexing (Fig. 1-3). During Oligo-Miocene, deep water shales and turbidites were deposited in the foredeep. These shales and turbidites, which have an important HC potential, were remobilized into diapirs at the deformation front during the final stages of the basin evolution (Fig. 1-3). Prior to the deposition of near shore to continental facies of upper La Pica, Las Piedras and Mesa formations, listric faults were developed over Early-Middle Miocene shales. The Caribbean Plate displacement gave rise to an eastward migration of the depocenters (Di Croce et al., 2000, Fig. 1-4). Shales deposited in the foredeep (Fig. 1-5) are called Roblecito in the West, Carapita in the Maturin area, and La Pica in the east of the EVB (Fig.1-4).

❐ SEISMIC STRATIGRAPHY

The seismic data from the EVB is generally poor due to the occurrence of gas, shale and high bedding dips associated with the complex structure of the area (Fig. 1-6). The top of Cretaceous generally has a strong reflectivity associated with the limestone (M1). Overlying the Cretaceous is a small remnant of the Paleogene section, which was truncated prior the deposition of the deep-water shales in Early Miocene time. The main effect of the Gas-Shale diapirism on the seismic image is the reduction of the seismic velocities and the loss of seismic resolution (Collier, 1990).
With Upper Miocene M3 and M3a surfaces, angularities were developed, as shown in all the seismic data, within the depositional sequence until Pleistocene, when changes in sedimentation rate occurred.

❐ MUD VOLCANOES and SEEPAGES

The diapirs are surrounded by numerous oil fields (Fig. 1-7). The most important field related to the sedimentary wedge over the shales is Pedernales, which comprises production and reservoir zones of Miocene age. One of the main characteristic of the diapirs is the presence of mud volcanoes. From Maturin Town to the east, many mud volcanoes have been reported (Petito,1979). Although small, no more than 10 m. high (Fig. 1-8) they are frequently related to gas and oil seepages (Fig. 1-9).

Mud volcanoes are E-W aligned and continue through Trinidad and offshore Barbados Ridge Complex (Huyghe et al. 1999). Studies on the NE-SW-oriented mud volcanoes of the Columbus Basin (Zamora, 1999) indicate a strong sedimentary loading and the existence of counter regional listric faulting through which shale growths in the form of diapirs and mud volcanoes.

PLATE TECTONIC SETTING

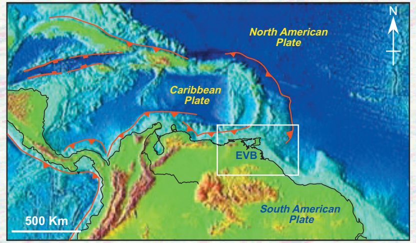

Figure 1-1. Location of the Eastern Venezuelan Basin in the context of the plate tectonic setting.

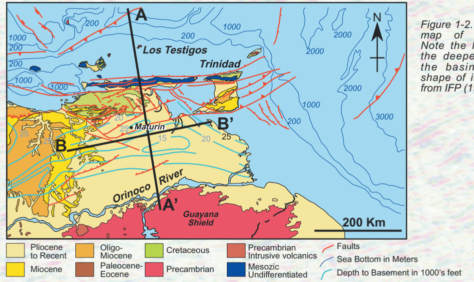

Figure 1-2. Geological map of the EVB. Note the location of the deepest part of the basin and the shape of it. Modified from IFP (1990)

NNW-SSE REGIONAL SECTION, EASTERN VENEZUELAN BASIN

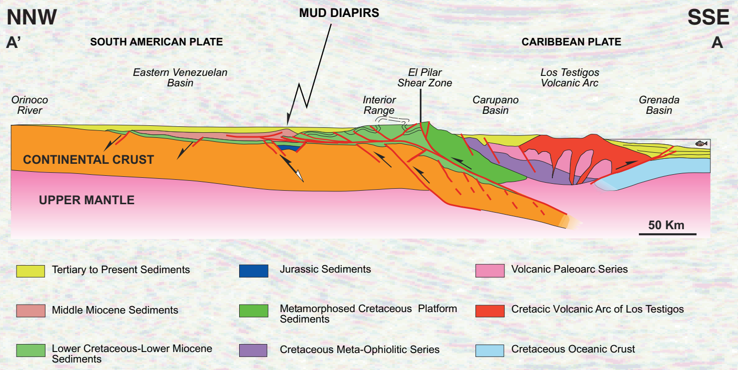

Figure 1-3. Regional NNW-SSE Cross-section. Note the location of the diapirs in the front of the deformation. (Modified from Chevalier, 1994).

LOCATION OF THE SHALE IN THE OIL CONTEXT

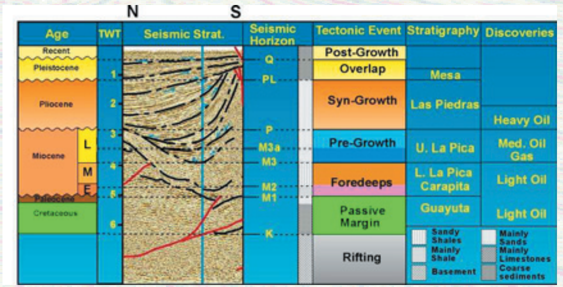

Figure 1-6. Seismic Stratigraphy. There are three growth sequences associated to the diapir evolution, the pre-growth unit with sediments controlled partially by the diapir, the syn-growth unit strongly affected by the diapir and the Overlap sequence.

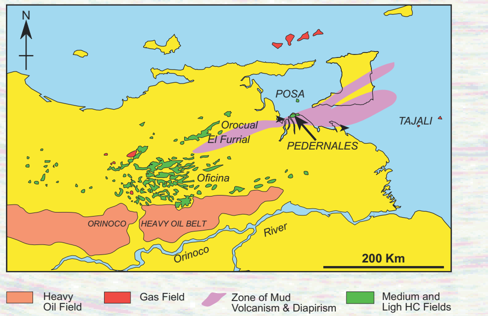

Figure 1-7. Location of the main gas and oil fields in the EVB. Note the location of the diapir strip in the basin and the main fields associated with Neogene reservoirs, i.e. Pedernales, Posa and Tajali.

W-E CHRONOSTRATIGRAPHY

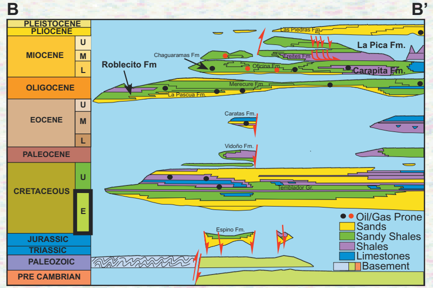

Figure 1-4. Simplified Chronostratigraphic chart of the EVB. Shales are shown in purple (modified from Di Croce et al. 2000). Since Oligocene there have been three depocenters with overpressured shales in the EVB-Roblecito, Carapita, and La Pica. Location is shown on Figure 2.

SEDIMENT SOURCES

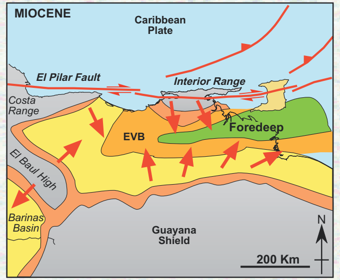

Figure 1-5. Sources of Sediments from the positive areas since Miocene into the EVB. Modified From Yoris and Ostos (1997)

MUD VOLCANOES EASTERN VENEZUELAN BASIN

Figure 1-8. Mud Volcanoes as this one from the Orinoco Delta are small but frequently associated with gas and petroleum.Photo from BEG-UTexas Site.

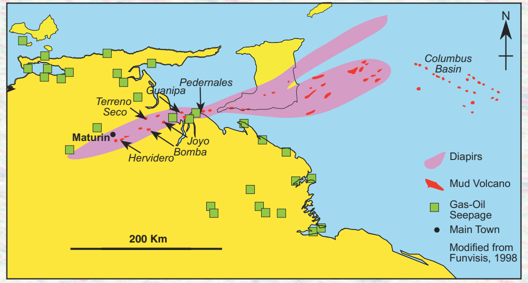

Figure 1-9. Location of mud volcanoes and gas seepages in the EVB. Note the convergence of mud volcanoes in the diapir area

Mud Volcanoes	N⁰	Gas	Oil
Hervidero	3	X	X
Terreno Seco	1	X	
Joyo	1	X	
Guanipa	3	X	
Pedernales	7	X	X

Table 1-1. Mud volcanoes and associated oil or gas shows. (Source Petito, 1979).

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❒ METHODOLOGY

This research involves interpretation of 219 2D seismic lines covering more than 10.000 Km, recorded from 1969 to 1994. The seismic data were combined with information from 23 selected wells. In addition to standard seismic interpretations detailed structural analyses consisted of shortening calculations (using bed lengths) above and below the ductile shales in the sections (Fig. 2-1). Shortening analyses together with the seismic interpretations enabled us to divide the subject area into four zones of diapirs. The change in reflection characteristics within individual seismic lines is related to the presence of gas and low velocity materials (i.e., shale and gas). Identification of these areas permitted delineation of shale calderas and diapir conduits (Fig. 2-2.). Figure 2-3 shows representative seismic lines across diapir structures in the study area.

❒ ZONE I

This zone is in the eastern part of the diapir belt and is dominated by smooth, north-vergent anticlines that are produced as major backthrusts with detachment zone in Miocene shales. The anticlines are developed over a south-vergent thrusts system that involves Cretaceous rocks (Fig. 2-4).

There are no active mud volcanoes in Zone I but there is evidence of shale diapiric activity. Line T4 shows a deformed chimney (Fig. 2-4). The chimney, onlapped by Pliocene sediments, is located over a compressional structure. The presence of this chimney indicates undercompacted sediments at the western margins of the foredeep basin. Diapirs chimneys are not present in the north and south of this zone because of the lack of overpressured shales there.

❒ ZONE II

In the northern part of this sector, the presence of normal faults above the Miocene shale section (Fig. 2-5), as well as the presence of collapsed diapirs (Fig. 2-9), is evidence of shale re-mobilization. The initial age for shale mobilisation is Middle Miocene (Fig. 2-9), but this is probably associated with listric normal fault movement. The rise of the shale could have being initially controlled by these faults but there is no conclusive evidence. The location of the main thrusts under the shale, the changes in reflector characteristics due to low velocity materials at 2 sec. TWT, together with the growth stratal architecture at 1 sec. (Fig. 2-9), show that this was a mud volcano that initially uplifted the beds during the Pliocene but collapsed in the Pleistocene the caldera is shown in line 8419 (Fig. 2-9). There is also evidence of mud intrusives using faults as main fluid channelways in the southern part of line T3, but these have not reached the surface. The anticline related to the diapir is southward vergent.

❒ ZONE III

The diapir in this zone is formed by Miocene shales that form a single rounded stock (Fig. 2-6). This zone contains the thickest shale unit in the region. The orientation of the diapir is coincides with the eastern border of the main thrust sheet in the Maturin area. Mud volcanoes occur at the crest of the diapir and are formed by upward flux of overpressured shales along normal faults above the buried stock.

There is no evidence of diapirism in the Upper Miocene but the growth sedimentation associated with the mobilised shale indicates that the diapir structure formed mainly in the Plio-Pleistocene.

❒ ZONE IV

These diapirs are sourced from the overpressured Miocene strata and have a double walled shape with E-W strike (Fig. 2-7). Many active mud volcanoes are present above these diapirs. The volcanoes display structures that indicate a reservoir volume together with chimneys that reach the surface along normal faults above the chamber (Fig. 2-8). Growth stratal onlaps indicate that initial diapir movement occurred in the Late Miocene.

The main phase of diapir growth occurred in the Plio-Pleistocene. The post-growth strata architecture shows only slight indications of diapir reactivation.

METHODOLOGY

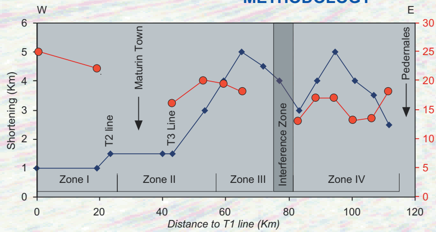


Figure 2-1. Plot of net shortening of the diapirs at base of Pliocene (black rhombus) and under the shale at Top of Cretaceous (red circles) measured in the plane of the profile. The diagram indicates different amounts of shortening for the Pliocene and Cretaceous units depending on the location of the line in the Basin . Note that shortening in Cretaceous units is larger in the West than in the East, and the shortening in the Pliocene Units is greater on the east.

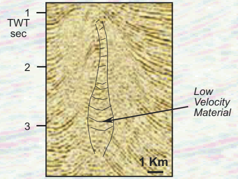


Figure 2-2. Illustration of the changes in reflection patterns due to diapir intrusion.

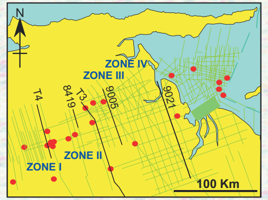
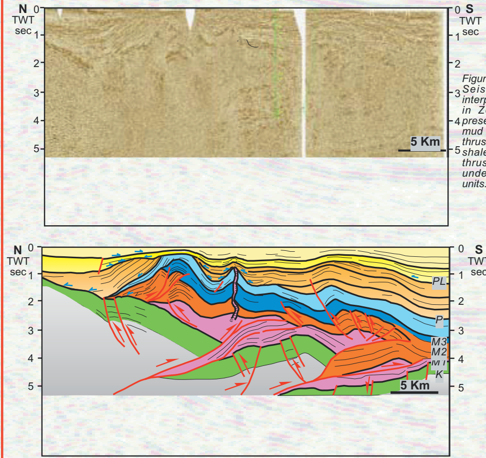


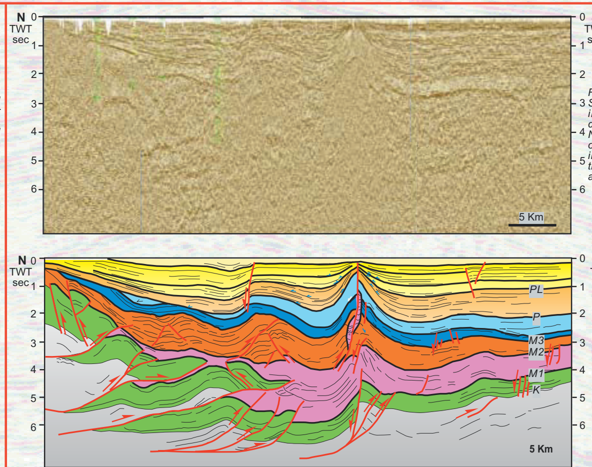
Figure 2-3. Location of seismic lines showed here and wells used in the interpretation.



ZONE I

LINE T4

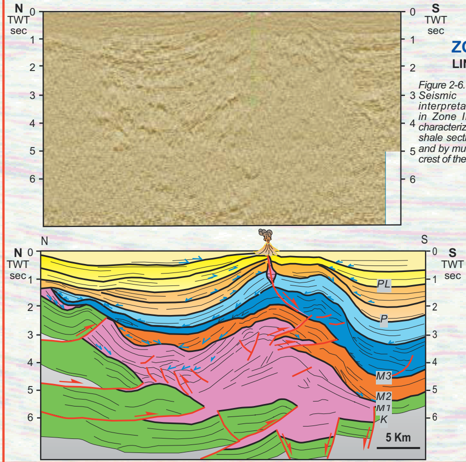
Figure 2-4. Seismic section and interpretation of a diapir in Zone I. Note the presence of a deformed mud chimney, and back-thrusting in the Miocene shales in response to thrusting in the underlying Cretaceous units.



ZONE II

LINE T3

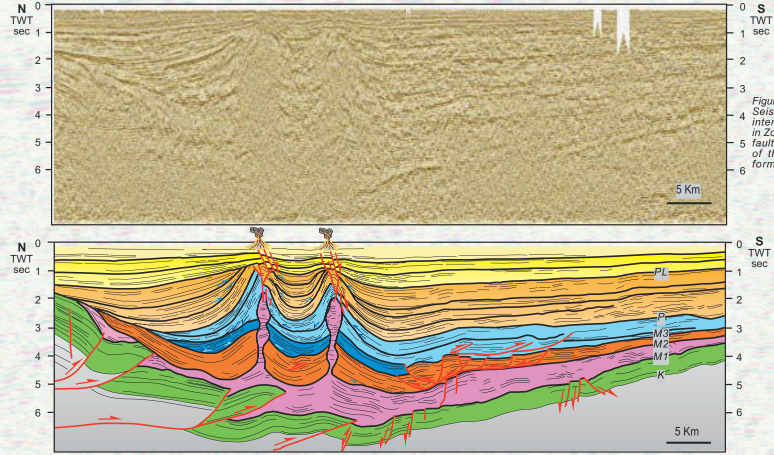
Figure 2-5. Seismic section and interpretation of a diapir in Zone II. Note the presence of major diapiric intrusion that used the extensional faults as fluid channelway.



ZONE III

LINE 9005

Figure 2-6. Seismic section and interpretation of a diapir in Zone III. This zone is characterized by the thickest shale section in the region and by mud volcanism in the crest of the structures.



ZONE IV

LINE 9021

Figure 2-7. Seismic section and interpretation of diapirs in Zone IV. Note the listric faulting at the bottom of the section and the formation of calderas.

MUD VOLCANOES

Detail LINE 9021

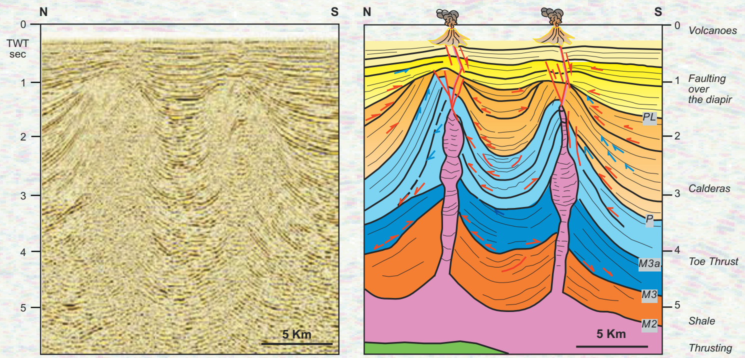


Figure 2-8. Detail of seismic section and interpretation of diapirism in Zone IV. Note mud vocanoes produced by chimneys that reach the surface along normal faults above the mud chamber.

DIAPIR COLLAPSE

Detail LINE 8419

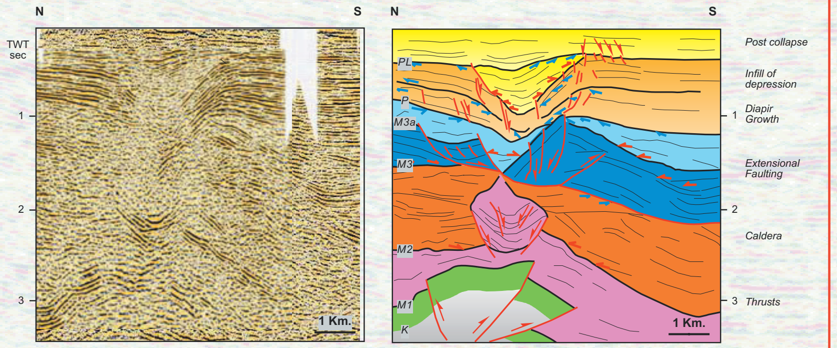


Figure 2-9. Detail of seismic section and interpretation of a collapse in the northern part of Zone II. Note the infill strata on top of the inclined reflectors and stratal truncations indicating progressive diapir growth.

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❐ COMPOSITE OVERVIEW OF THE DIAPIR ZONES

From the map in Figure 3-1 note that:

- ❐ Zones I, II and III are aligned with the WTS. Zones I and III accommodate the flanks of the thrust and Zone II the frontal part of it.
- ❐ Zone IV is aligned with the ETS.
- ❐ The thickest shale unit is located in the east of Zone III, and the maximum depth to basement is reached between Zone II and III.
- ❐ There is a variation in the size of diapirs from east to west. Where the shale thickness is thin evidences of diapirism are few (east). Where shale thickness is greater overpressuring conditions are reached and diapiric intrusions are more relevant (west).
- ❐ The boundaries of the foredeep movable shales mark the limit of the diapirs appearance. Diaprism is produced where overpressure shale exist, in other cases shale becomes detachment zones for thrusting.
- ❐ The collapse in the north of Zone II is aligned with the frontal part of WTS, and the San Juan graben with the lateral ramp of ETS.

❐ FAULT GEOMETRIES

Four main tectonic features in the diapirs have been identified:

- ❐ High angle planar normal faults developed over the anticlines parallel to the direction of the belt (E-W). These faults have been used by overpressured shales to reach surface and form mud volcanoes.
- ❐ Pre-growth-sequence thrusting with south vergence developed between mud walls in Zone IV.
- ❐ Listric faulting over shale beds; these faults are found in the south of the diapir belt and embedded in it.
- ❐ Normal faulting developed over collapsed diapir-anticlines in a circular or elongated pattern (north of Zone II and IV)

❐ MUD DIAPIR EVOLUTION

- ❐ Pre-Growth stage. Shale was deposited in an eastern open restricted foredeep in Early-Middle Miocene times.
- ❐ Initial Instability in the shale occurred during Late Miocene forming small anticlines that controlled the sedimentation around them (Fig 3-2B) at this stage the uplift rate was major than the sedimentation rate.
- ❐ Syn-Growth episode. Diapirs had its main evolution at Plio-Pleistocene. The high sedimentation rate and increment in the tectonic load enable the raising of overpressured conditions in the shale (Fig. 3-2C).
- ❐ Collapse and Migration of diapirism. Displacement to the east of the thrust system produced the migration in the same direction of the overpressuring conditions. Diapirs collapsed after the source depletion and new volcanoes were formed in the direction of the tectonic transport (Fig. 3-2D).

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MAP OF DIAPIRS AND ASSOCIATED STRUCTURES IN THE EVB

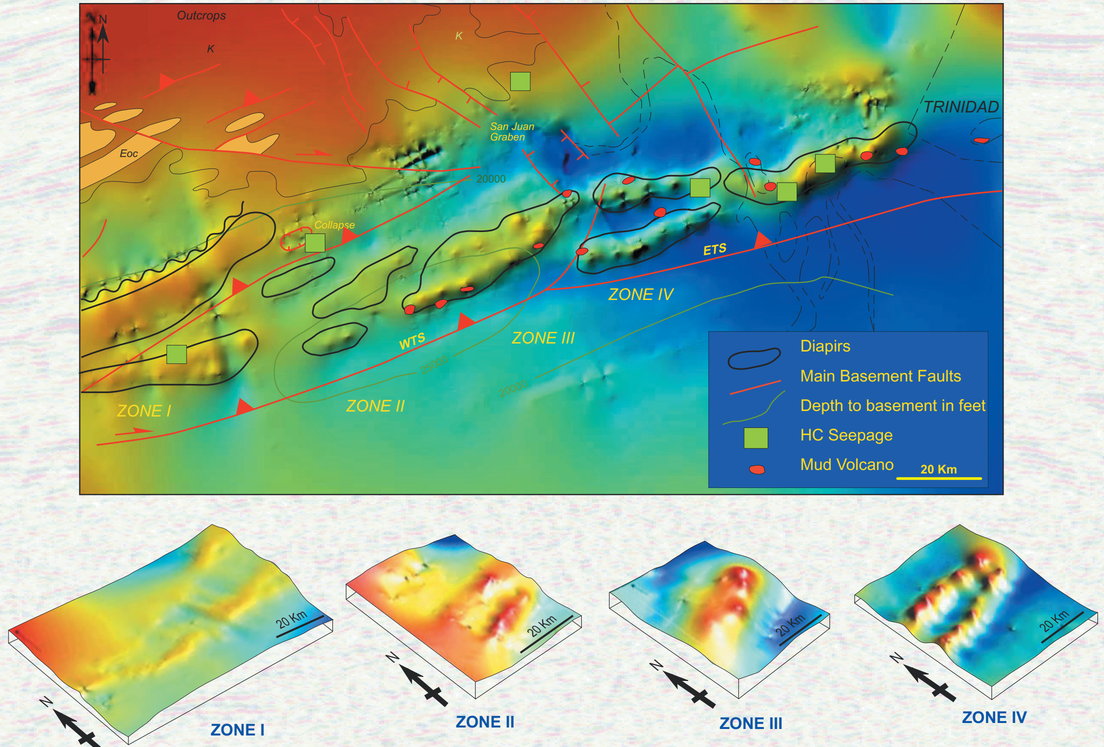

Figure 3-1. Composite map showing the seismic image extrapolated from 2D seismic data, surface geology and regional faults. The map was preapared using the base of Pliocene. Note the shape of diapirs in Zone I, slightly curved in the extreme west and the mirror image on Zone III slightly curved northeastward. The map shows the coincidence of thrusting and diapirism. Note also the appearance of normal faulting in the north of Zone II and IV.

MUD DIAPIR EVOLUTIONARY MODEL

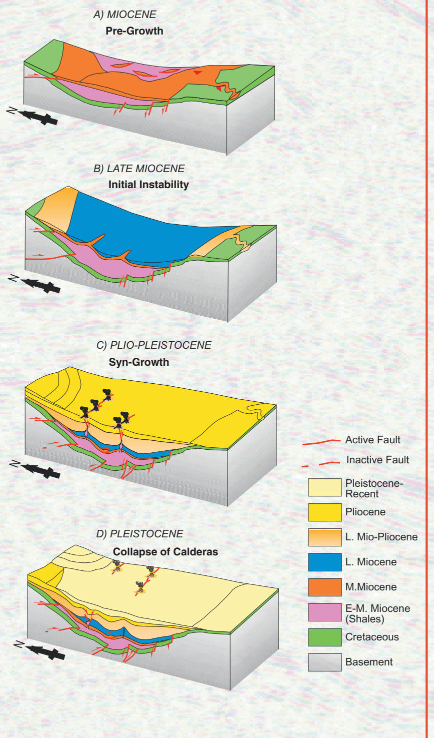

Figure 3-2. Four episodes of diapirism in EVB. A) Pre-Growth stage, normal faulting B) Initial instability with sedimentation controlled by diapirs rise, C) Syn-Growth with the formation of Mud volcanoes and calderas. D) Collapse of calderas, followed by the displacement of thrusting eastward.

DISCUSSION

❐ TRIGGERING OF DIAPIRISM

The four zones of diapirism identified are related to the main thrust sheets of the area. Overpressured shales and diapirs are produced in the tip of the thrust sheets where high pore fluids pressures are favored by the high horizontal compression. Diapirs are the shallow expression of underlying tectonic structures and can be used as an indicator of thrust sheets. The initial overpressured zone must have been localized in the northeast of the foredeep at the maximum depth to the basin. The effect of the thrust system was the southeastward displacement of the shale unit and the piling of the shale in the limit of Zone III.

❐ SHALE

The area has a strong lateral variation in shale composition. Diapir formation in the middle of the foredeep is a consequence of this. In the west were movable shale was scarce there are few evidences of real diapirism, and shale mobilization was as backthrusting in response of underlying thrusting. in the east where the movable shale is wider, the diapiric structure is double. Movable shale seem to have had more than one episode of mobility controlled by the progression of the deformation and thrusting eastward.

❐ GROWTH FOLDS

The model of folding that best suites the folds associated with diapirs in the EVB, based on the studies on growth folds published by Poblet et al. (1997), is a progressive rotation and limb length variation, due to the absence of growth triangles. These folding may be modeled using trishear with a nonrigid limb rotation.

❐ DIAPIR EVOLUTION

Diapirs have evolved from west to east. In Zone I and II there are evidences of early diapiric intrusions that were abandoned after the thrust system move eastward. Collapses in shale deposits and remobilization was mainly driven by the thrust system evolution. The initial age for the movement of shale in the area was Late Miocene, and had a continuous development until end Pliocene-Early Pleistocene were conditions in the sedimentation-uplift rate changed.

❐ HC POTENTIAL

Mud diapirs can be seals for HC. The formation of calderas can favor the formation of reservoirs in Early Miocene sands (Fig 3-3). The zone with more prospectivity for this kind of accumulation is Zone IV. Another possibility of structural reservoirs is the presence of Toe Thrusts in the pregrowth sequences. The impact of argillokinesis on HC migration path and Gas is a matter to be solved by future studies. The analysis of diapirs morphology adding more 3D seismic surveys can improve the understanding of diapirism and can help to identify new HC potentials.

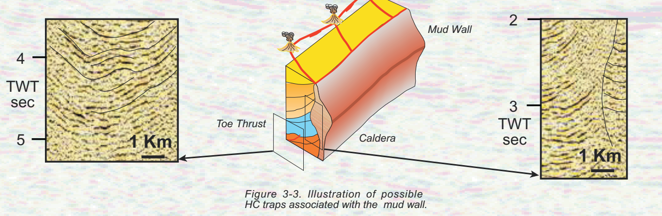

Figure 3-3. Illustration of possible HC traps associated with the mud wall.