# Trapping vs. Breaching Seals in Salt Basins: A Case History of Macaroni and Mt. Massive, Auger Basin, Gulf of Mexico

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## Abstract

**Prior to testing the Mt. Massive prospect at the Garden Banks block 600, the seismic anomalies and the structural positioning relative to Macaroni Field at Garden Banks block 602 all pointed to a low risk prospect. Testing results of well #1 Garden Banks 600 were disappointing as most of the targeted objectives were wet sands.**

**The geopressure profile and sealing capacity at site 602 show a different compartment setting than site 600. A ridge of salt below the Macaroni structural setting offers an explanation for the effective seals at the targeted strata and resulting entrapment of commercial hydrocarbons. However, the salt wall that bounds the southwestern flank of the Auger basin at the Mt. Massive prospect is responsible for breach of seals.**

**The complex interaction between salt and its' surrounding sediments makes risk assessment of a prospect or play concept a challenge. Geopressure compartmentalization in the Tertiary-Quaternary salt basins of the Gulf of Mexico is created mainly by the principal stresses resulting from interaction between the sediment's load and salt tectonics. Salt emplacement and displacement history, in relation to the surrounding sediments, sheds light on the possible sealing integrity.**

**Predicted pore pressure in the shale beds, relative to the measurable pressure in the reservoir type sand facies, is the back-bone of assessing entrapment and sealing capacity. Moreover, defining the fracture pressure envelope in relation to the effective stress window allows estimation of the column height of the hydrocarbon in the trap, i.e., retention capacity.**

## Concepts and Methods

Entrapment of hydrocarbon in the deep water salt mini basins of the Gulf of Mexico (GoM) is more complex in nature, compared to the conventional traps on the shelf. Commercial oil and gas reserves are usually found in a reservoir type facies (mainly sand). Seals are usually built up from very low permeable rocks such as shale and mud stones.

The predominance of salt in the deep water of the GoM leads to an elaborate interaction between salt and its surrounding sediments. Salt emplacement and displacement history impact lithology, structure setting, stress's orientation and consequently the subsurface geopressure compartmentalization (Shaker and Smith, 2002) in these mini-basins. Compartments are the main catalyst for setting up the trap capability of retaining hydrocarbons in the objective structural play concept.

The building blocks of subsurface geopressure compartmentalization are mainly: Lithology/ Stratigraphic, Structure Setting, and Stress Fields.

### Lithology and stratigraphy

The interbedding of highly permeable beds (sand, oolites, etc.) with low permeable ones (shale, mudstone, etc.) creates the foundation of the vertical subsurface partitions. The stratigraphy, paleoenvironments and depositional styles establish the lateral communication and the spatial distribution between these units. Since ductile salt (mostly Allochthonous) represents the bed rock of these young Plio-Pleistocene sediments, it shapes these mini-basins in a unique setting and interacts with the surrounding sediments.

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## Structural Setting

Salt bodies and the related structural features can be multiple and complex. They take the shape of diapirs, ridges, pierces, synclinal withdrawal basins, overhangs, canopies, sheets, salt weld etc. However, in this paper the following two simplified cases will be discussed:

- Salt ridges, where salt grows upward contemporaneous with sediments deposition on the ridge flanks. Pinch out and facies change takes place. Coarse high permeable sediments deposit on the down dip and trough positions and low permeable beds deposit near the salt-sediment interface.
- Salt pierces and truncations, where salt cuts through the overlying younger sediments (post deposition) creating a gouge zone at the salt-sediment interface (wall).

In addition to the main structural features, secondary structural elements, mainly faults, can have a direct impact on the geopressure compartmentalization.

## Stress Fields

Stress fields and orientation in a specific section in the subsurface determines the development and strength of the pressure and fracture profiles. There are three main stress fields: maximum, intermediate, and minimum. The maximum (principal) stress (PS) is responsible for the acceleration of the pore pressure (PP) gradient whereas, the minimum stress field represents the formation fracture limit (FP). The relationship between the maximum stress field and the pore pressure (PP) was established in 1943 by Terzagi: PP=PS- Effective Stress (ES). This equation generally applies in a tectonic relaxed basin where basin subsidence accommodates sediment influx. In this case, PS is vertical and usually measured as the weight of the sediment and water column, i.e., overburden (OB). The unique salt petrophysical properties, such as low density, impermeability and its ductile nature, create new parameters and dimensions to the principal stress (Fig. 1). The orientation of the stress value fields becomes more affected by the salt flow, emplacement, displacement, and detachment. Due to salt buoyancy (SB), the salt diapirs and ridges contribute to the increase of the PS and consequently accelerate the pressure gradient (PG) in the sediment above the salt. On the other hand, sub-salt sediments are subject to PS decrease and retardation in PP development. Salt withdrawal basins and pierces show relatively low PG.

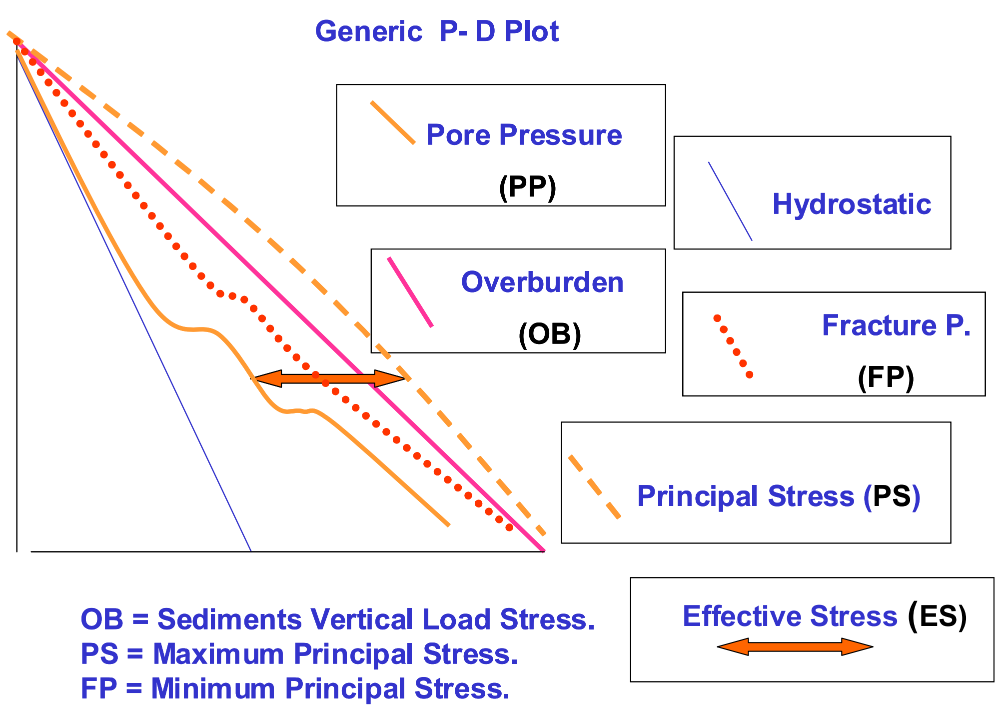


**Figure 1. Generic P-D (pressure-depth) plot.**

An increase of principal stress, with depth, due to sedimentation load accelerates geopressure. In a tectonically relaxed system, pressure progresses, with depth, in a cascade fashion. Seal failure and upward communication are the main cause of pressure regression. Sealing capacity is measured by the difference between the PP in successive compartments, whereas the difference between the PP and the FP is referred to as the retention capacity (Shaker, 2001).

The measured actual pressure data acquired by Repeat Formation Tester (RFT) and Modular Dynamics Tester (MDT) establishes the progress and regress in the pressure envelopes (Shaker, 2002a).

## Geopressure Analysis

At the early Pliocene the sea level dropped almost 300 feet sending an influx of sediments to the deep part of the GoM basin. This was followed by several intermittent and short term eustatic changes during the late Pliocene-Pleistocene which led to multiple episodes of fast fill, spill and meandering of sedimentation avenues. About one half of the drainage area of North America delivered sediments into the northern Gulf of Mexico during the Pliocene and Pleistocene. Sediments of up to 25,000 feet were deposited in the Green Canyon area during this period (Villamil et al., 1998). This high rate of sedimentation led to the vast withdrawal of the massive allochthonous salt. The ductile nature and low density of the salt created multiple mini-salt basins filled with younger sediments.

The sediment feeder system usually changes course and salt gives way to the new sediment load and leads to structural instability. Moreover, it activates the salt movement upward creating ridges, piercing features, rim faults, salt gauges, welds, etc. In the scope of this paper, two examples will be discussed to show the effect of salt emplacement timing, and the depositional axis position in relation to geopressure compartmentalization and hydrocarbon entrapment (Fig. 2).

Auger Basin is considered one of the highly prolific salt withdrawal mini-basins in the deep water of offshore Louisiana. Several play concepts were tested in this basin. Macaroni Field and Mountain Massive prospect, at the southern tier of the Auger basin, represent only two different geological setting case studies among several in this basin: the ridge and pierce cases respectively.

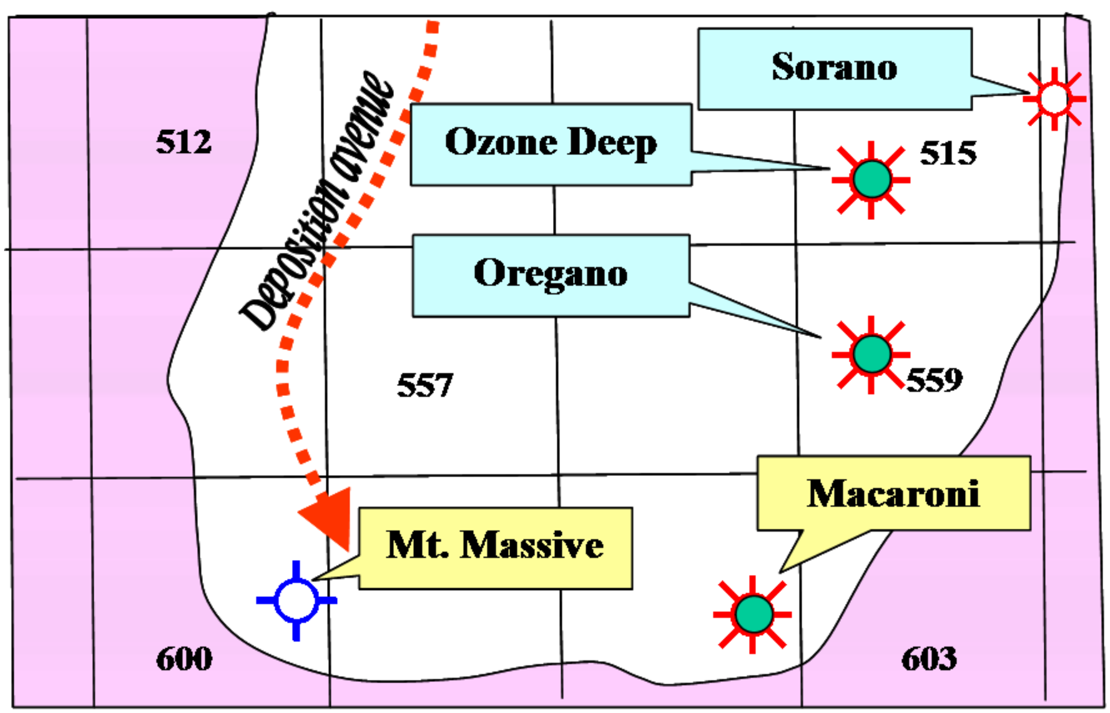


**Figure 2. A sketch map shows the salt boundary, depositional avenue, fields, and the location of Mt. Massive in relation to Macaroni Field.**

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## Macaroni Field (GB 602)

In this play concept, overlying sediments are deposited as the salt ridge grows upward. The targeted reservoir beds are usually thinning out on a ramp. Well #2 in GB 602 (Macaroni Field) was designed to penetrate successive amplitude anomalies on the western flank of a salt ridge between the Auger and Mason basins. This ridge bounds Auger Basin from the east side where most of the producing fields are located (Oregano, Sorano and Cardamon). Garden Banks 602 Field producing reservoirs are represented by a sequence of amalgamated sheet sands (HGS, 2003) that are set on a salt ramp and pinch out toward the salt sediment interface (Fig. 3).

### *Geopressure analysis of GB 602 #2*

Resistivity was used for transformation of effective stress to pore pressure (Eaton, 1975). Compartmentalization analysis shows the top of geopressure in this well is at 16,350 feet. The transition from the normal to the geopressure system was gradual. Mud weight was increased from 10.9 pounds per gallon (ppg) to 12.9 ppg to compensate for the increase of connection and background gases to 340 units. Three main compartments were noticed in this well (Fig. 4):

- The upper one (A) is between 18,000 feet and 19,600 feet. No hydrocarbon was found in the sandy section in spite of the fact that predicted pore pressure in the shale shows a transgression. This is due to the possible well trajectory that was structurally down-dip at this level.
- The middle (B) compartments between 20,100 feet and 20,800 feet show a breach seal with a pressure regression of about 1000 psi. This is possible due to the presence of a fault cut.
- The lower (C) one shows mild sealing capacity of an average of 750 psi. Multiple pays (not full to base) were found between 21,850 feet and 22,100 feet and also between 23,100 feet and the bottom of the hole (TVD). The retention capacity of the shale that seals this compartment is expected to be very high and can hold 2000 feet of hydrocarbon in un-faulted structural closure. But, the presence of minor faults dissecting the Macaroni structure (Fig. 3) leads to reduction in the retention capacity of the seal and the presence of wet sand at the base of pay zones. The in-place reserve estimate in this field is about 400 million barrels oil equivalent (MMBOE).

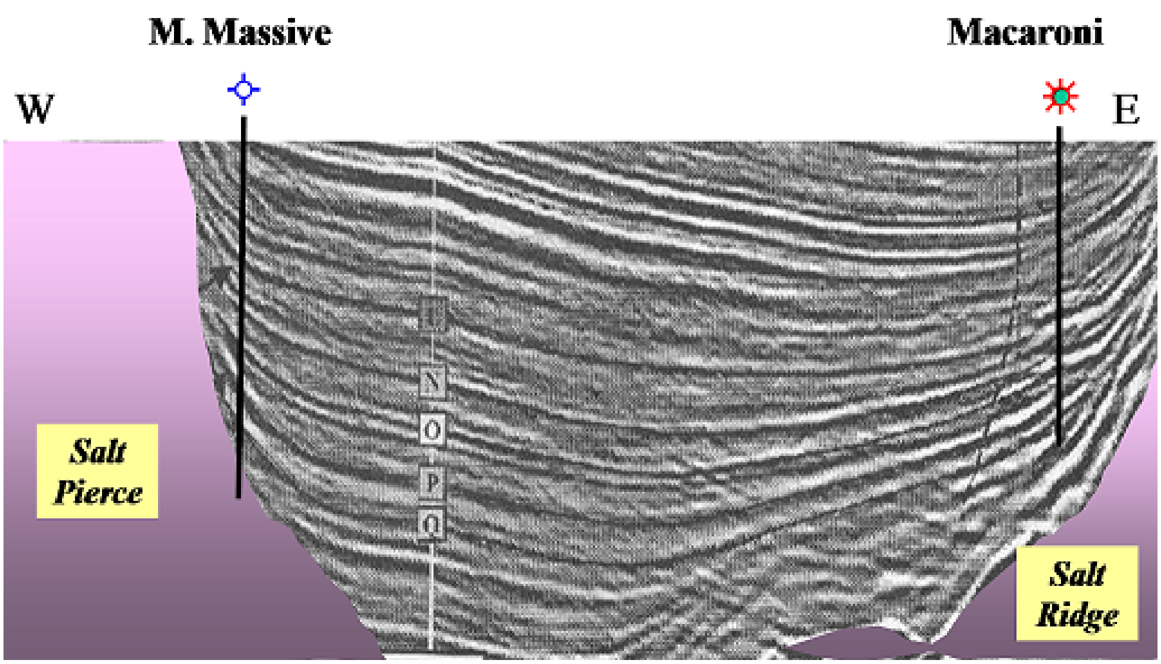


**Figure 3. An arbitrary seismic cross section shows the correlation between Macaroni Field (GB 602) and Mt. Massive prospect (GB 600). This figure has been modified after the Houston Geological Society Symposium # 2.**

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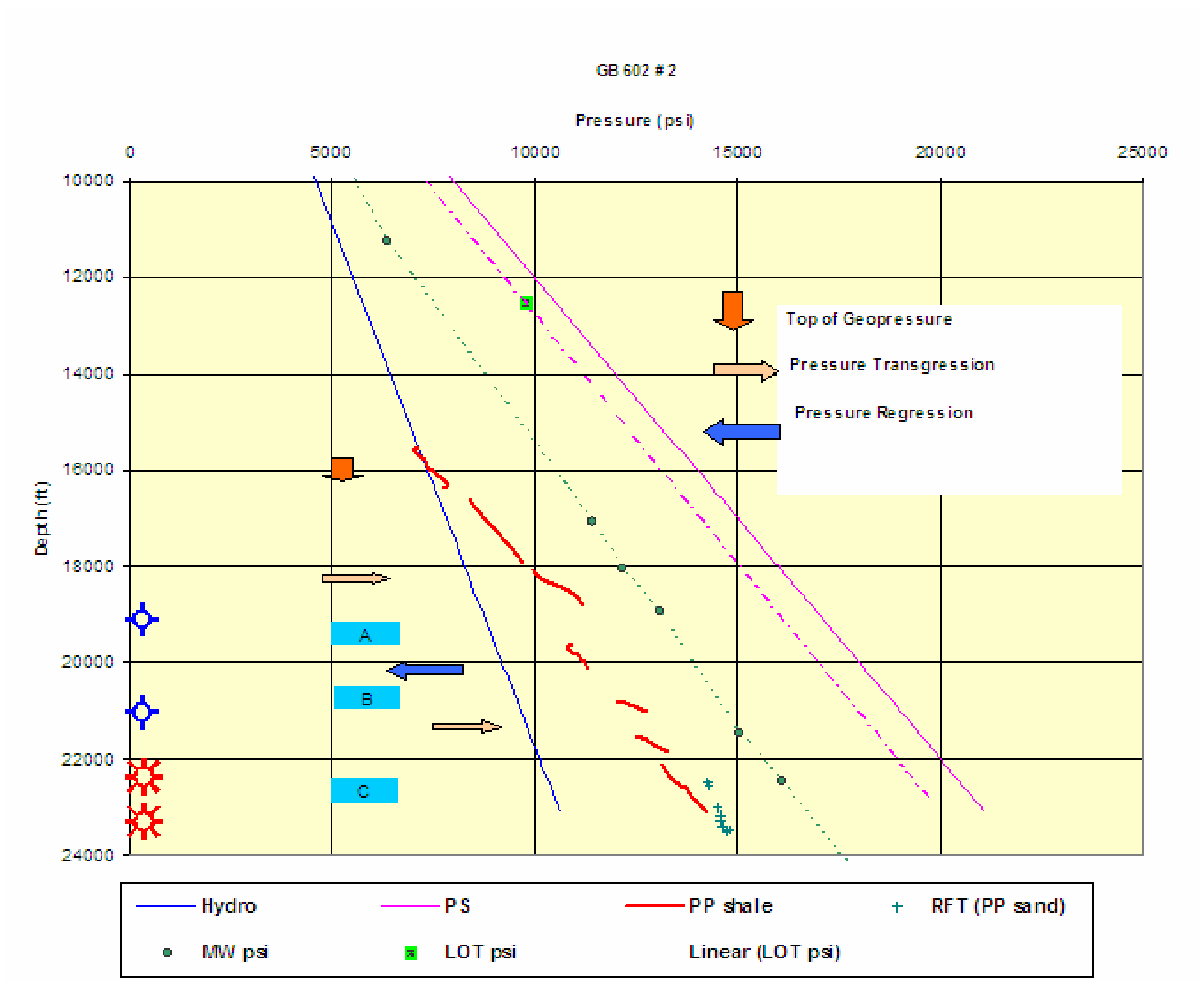


**Figure 4. Geopressure analysis and subsurface compartmentalization of GB 602 # 2. The gas symbol represents pay zones. The dry hole symbol represents the main wet reservoirs.**

## Mountain Massive (GB 600)

In this geological setting, the salt has penetrated the overlaying sediment post their deposition. Usually the salt sediments interface is characterized by sediment truncation against the salt wall. The presence of a gouged zone with a possible high permeable zone is due to the thrust of salt upward. This interface zone can act as a fluid conduit. This leads to bleed off the geopressured compartments (Fig. 5).

Mountain Massive prospect (GB 600) is located on the southwest side of Auger Basin. It is separated from the Macaroni field (GB 602) by a trough. Mt. Massive and Macaroni Fields share the same stratigraphic column, except the sediment shows thickness expansion in the west side (Fig. 3). The sediment feeder avenues were predicted to be in proximity to the western side of the basin prior to salt piercing. The tested sequence, which shows seismic amplitude anomaly, was proven to be thick wet sand. The well was plugged and abandoned.

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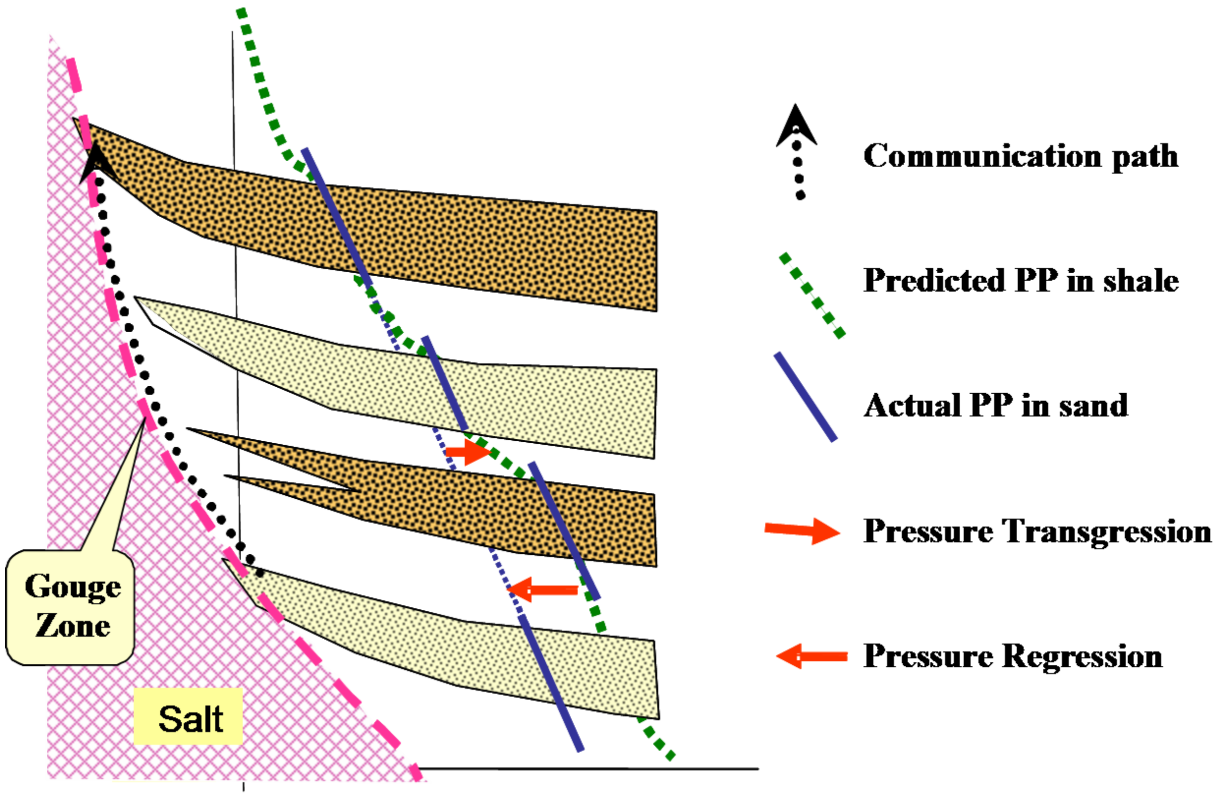


**Figure 5. A geopressure model shows PP transgression where reservoir type beds (sand) pinch out before they reach the salt gouge zone. On the other hand, regression (breach) takes place where salt pierces the reservoir section.**

*Geopressure analysis of GB 600 #1*

Resistivity was used for transformation of the effective stress to PP. The predicted PP and the indirect PP measurements from the drilling data show the following (Fig. 6):

- Possible weak top of geopressure at 15,100 feet. The mud weight was raised to 13.2 ppg due to an increase in the background gas.
- Gradual weak increase in the predicted pore pressure gradient in the shale.
- The geopressure profile does not show noticeable sealing capacities (<100 psi). Two thin non-commercial pay zones of 20 feet thick between depths of 19,800 feet to 19,900 feet were found in this well (not the main objectives).
- At the base of the well (just above the salt interface) a possible pressure transgression was observed. This could be due to the local sheared shale at the lower portion of the well where the bottom hole penetrated the salt bed rock. Noteworthy; an abundance of buckling shale was observed at the shale shaker drilling through the salt sediment interface zone.
- The sand pressure (reservoirs) in the geopressured section is predicted to be less than the calculated shale pressure. This was verified due to:

  The in-mud weight was equal to the out-mud weight.

  Absence of mud cuts.

  The background and connection gases were flat and minor.
- A discrepancy between the predicted shale PP and PP in the sand led to an overbalance drilling (mud weight exceeds requirement).

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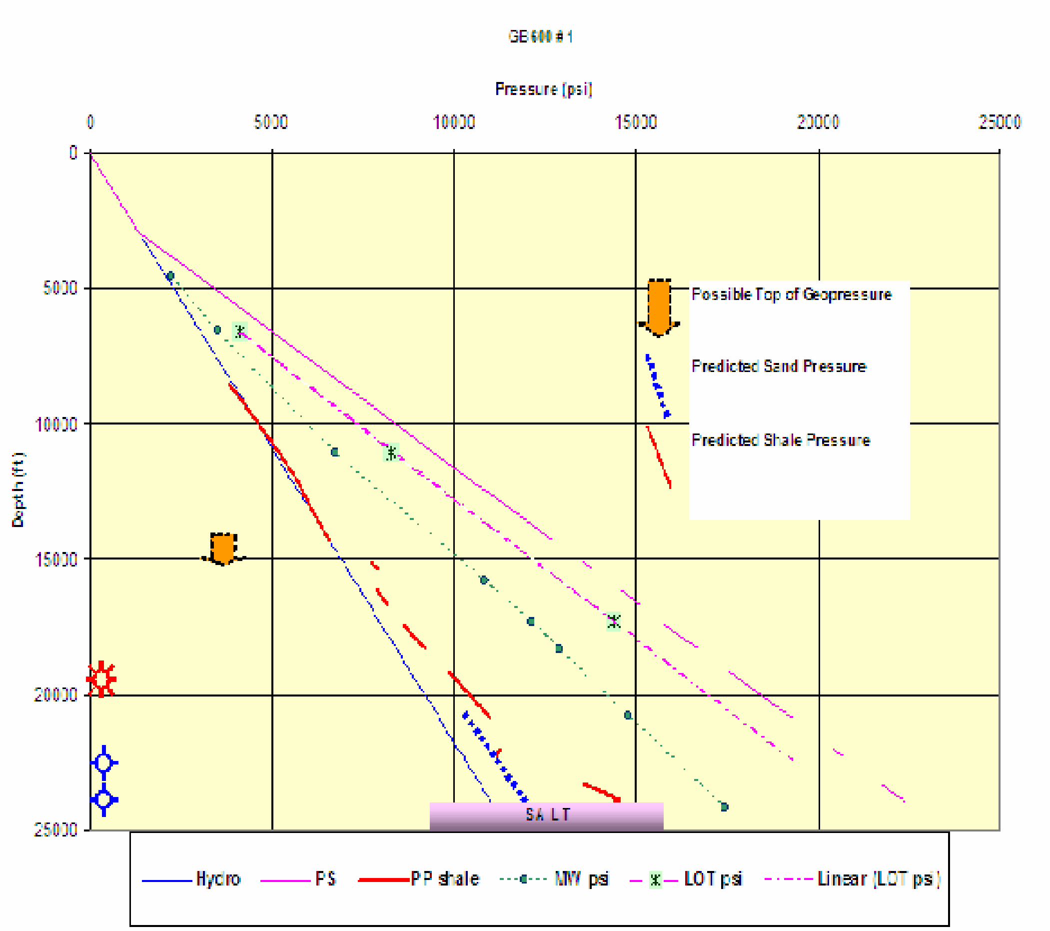


**Figure 6. A pressure–depth plot of GB 600 # 1 shows the lack of sealing capacity between the different compartments.**

Therefore, the lack of geopressure compartmentalization in this location was responsible for the absence of sealing capacities and, consequently, reservoirs breaching. The apparent higher pore pressure in the shale can be explained by the slow pressure decay process in the shale (seals) relative to the sand beds (reservoirs) through the interface zone (Shaker, 2002b).

## Summary

Good quality reservoirs and competent seals are the backbone of finding commercial hydrocarbon. In the GoM deep water, thick water column and the presence of complex structure associated with allochthonous salt bed rock makes this mission a challenge.

Pore pressure prediction as a result of integrating geological building blocks and petrophysical properties institute the foundation of the subsurface compartmentalization. The complex nature of the structural setting caused by the interaction between salt and sediments creates a variety of exploration plays. The two models studied in this paper represent a sample of these multiple concepts. The history of salt emplacement and displacement sheds light on the strength and orientation of the principle stress and fluid communication in the mini-basins.

The depositional history of the sediment in relation to the emplacement of salt ridges and pierces help in establishing fluid communication in the southern part of the Auger basin. Salt ridging contemporaneous to sediment's input creates a facies change and consequently an up dip sealed reservoir. Conversely, salt pierces post sedimentation can facilitate fluid communication and lack of sealing capacity.

Pressure transgression and regression can be established by studying the interrelationship between predicted shale PP and measured sand PP. Transgressive pressure profile deems to be more successful than the regressive ones. The justification of Macaroni success and Mt. Massive failure is based on study of the interaction between the salt and sediment input. Geopressure analysis sheds a great deal on the risk assessment of any play concept. Compartmentalization appraisal should go hand-in-hand with all other tools used to generate a prospect.

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