Structural Overview of the Outer Shelf, Deepwater, and Ultra-deepwater Gulf of Mexico, Relationships between Salt Features and Minibasin Morphology

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Introduction

A Regional understanding of salt/sediment interaction is a key factor in evaluating exploration risk in the Gulf of Mexico. An important geologic phenomenon that results from this interaction is the minibasin. This study categorizes these minibasins into groups based on their morphology and their interaction with salt. To accomplish this the structural setting in which minibasins reside is described using a large, recently acquired, seismic dataset covering the outer shelf and slope. Salt emplacement models are outlined and these, for the most part, explain the observed characteristics and evolution of salt and associated minibasins.

Database

The seismic database covers 70,000 mi.^{2} and consists of two datasets. On the outer shelf a large 3D dataset of 30,000 line miles was used, extracted from 29 surveys and covering 10,000 mi^2. The extracted lines formed a 1/2 by 1/2 mile grid. In the deepwater region a 60,000 mi.^{2} seismic survey, consisting of a 2 by 2 mile grid of recently acquired and processed 2D data was used which totalled 60,000 line miles. The 3D seismic data is oriented N-S / E-W and the deepwater 2D data is oriented NW-SE / NE-SW. Figure 1 shows the area of seismic data coverage for this study.

Well data was tied to the seismic using check shot surveys. Logs were available from 77 wells that had tagged the top of salt. Paleo reports from 63 wells were also used along with 40 check shot surveys.

Five horizons were interpreted: seabed, top salt, base salt, Discoaster surculus (DS) Sequence Boundary (approx. 2.4 ma) and Miocene Discoaster B (MDB) Sequence Boundary (approx. 5.5 ma). In addition, a seabed to top salt isotime was constructed.

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Structural overview

The structural composition of the western Gulf of Mexico is outlined below with a description of two of the regional horizons, top salt and DS, shown in Figures 1 and 2, along with a seabed to top salt isotime, shown in Figure 5.

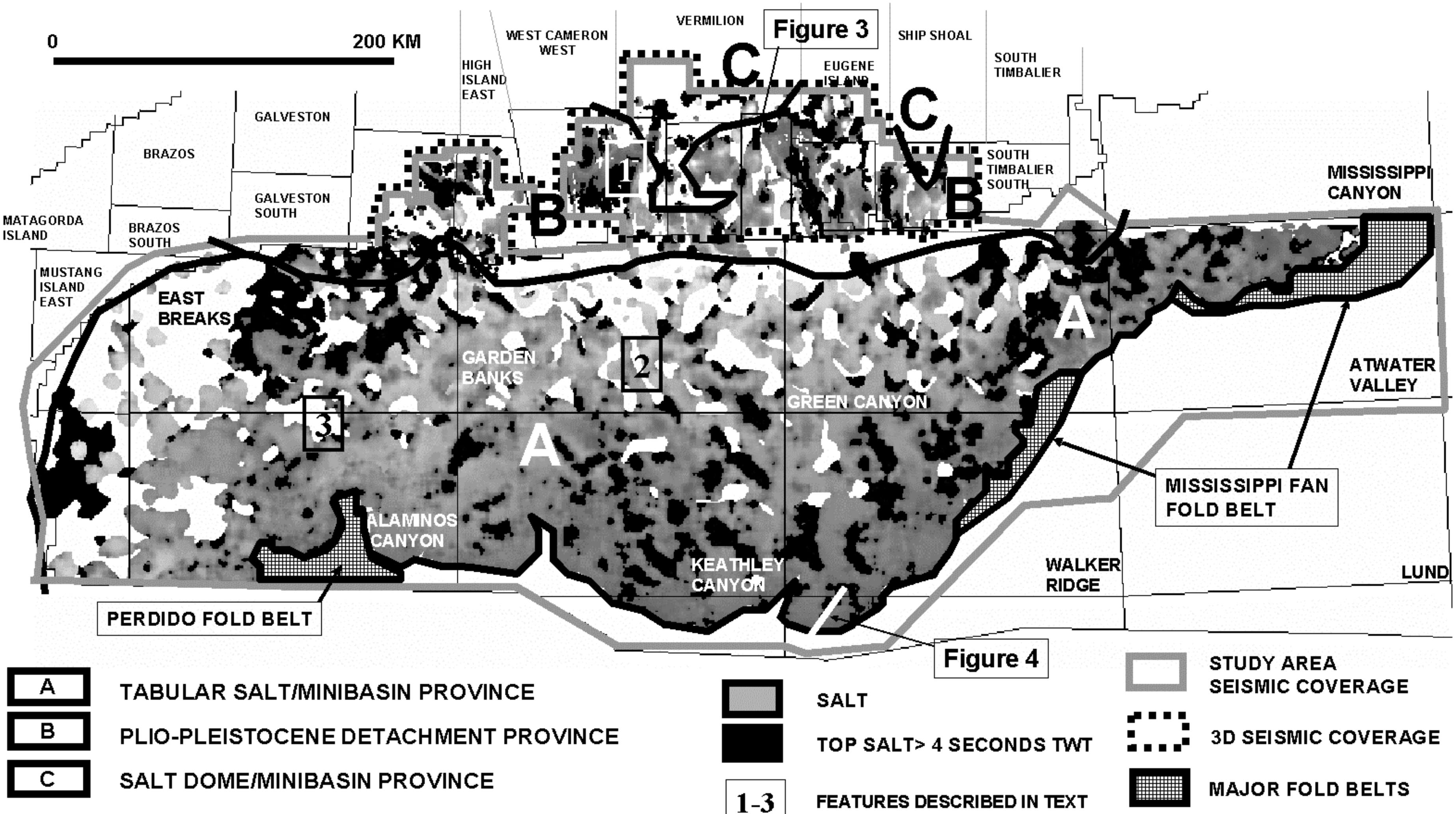
a) Top salt

Figure 1 shows the distribution of the top of salt across the study area. Areas of salt at greater than 4 seconds TWT are shown in black. The map shows the complex distribution of salt. In general, salt is occurring deeper basinward although this is largely a result of increasing water depth. The salt approaches the seabed towards the edge of the allochthonous salt province, causing an overall basinward decrease in the supra-salt sediment cover. However, on the outer shelf there are localized deeper salt regions, for example in West Cameron South (location 1 on Figure 1). These are related to collapsed salt canopies and sheets that are now largely evacuated of salt. These are examples of the Roho provinces described by Schuster (1995) and outlined below.

Other features can be observed on the map such as circular and NW-SE trending deeper salt regions, indicating overlying minibasins, which are common in Keathley Canyon and Walker Ridge. In these areas the salt is formed largely of sutured canopies which are locally depressed by minibasins. Some of these minibasins occur within ‘windows’ in the salt (i.e. a Primary minibasin, described below). Further north in northern Garden Banks, and to a lesser extent in East Breaks and Green Canyon, some large minibasins between salt sheets occur. These basins are very thick, and welded floors are not easily identified seismically. However, there are indications that welds link these salt sheets. In this study if there was doubt about the nature of the minibasin weld floor then they were left as blank areas on Figure 1. Linear depositional fairways between salt sheets and canopies can also be identified in Garden Banks, some with a NNW-SSE trend (location 2 on Figure 1). Large basinal regions are found further west, an example of which is located astride the East Breaks/Alaminos Canyon border in which the Diana and Hoover discoveries are located (location 3 on Figure 1). The western edge of the study area is a region largely evacuated of salt with only isolated diapirs remaining.

b) DS (2.4 Ma Sequence Boundary)

The structurally high regions of the DS Sequence Boundary are shown in light gray on Figure 2 and structurally low areas shown in black. White areas inside the study region represent either salt, where overlying sediments are interpreted to be younger than 2.4 Ma, or areas where a DS reflector cannot be seismically identified. No DS interpretation was available from the 3D seismic dataset on the outer shelf.



After Diegel, 1995

Figure 1 Major Structural Provinces, Top Salt Distribution and Seismic Database Coverage

In the west (Corpus Christi, Port Isabel and western East Breaks Protraction Areas) the horizon is at its structural shallowest (< 500 ms TWT in places) and is also highly faulted. The rest of the map can be subdivided into two provinces: a structurally quiescent region outboard (basinward) of the Sigsbee Escarpment and the complex allochthonous salt province. The DS horizon in the allochthonous salt canopy province occurs as both perched supra-salt minibasins or in more linear fairways between canopies and sheets. These fairways sometimes terminate in basins surrounded by salt, which presumably formed a barrier against which sediments were trapped. In central Garden Banks one such linear primary basin trends NNW-SSE for some 40 miles, terminating in northern Keathley Canyon (A on Figure 2). Another example occurs in central Green Canyon, trending almost N-S for over 50 miles into central northern Walker Ridge (B on Figure 2). As mentioned, the DS horizon has also been interpreted in supra-salt canopy minibasins. These are best displayed on the supra-salt isotime map of Figure 5 as circular or elliptical thicks. Generally, there is progressively less supra-salt cover moving towards the edge of the allochthonous salt province and there are large regions where DS has not been interpreted, particularly in western Keathley Canyon. It is also scarce in Walker Ridge. In central and eastern Keathley Canyon more DS has been interpreted in the minibasins, which, in this region, have thicker fill.

c) Seabed to top salt isotime

Figure 5 shows the variation in sediment thickness above the salt. Thinnest supra-salt cover lies in western Walker Ridge and parts of southern Green Canyon, with salt occurring at the sea floor in places. The dark gray/black areas of the map indicate many of the supra-salt minibasin locations. These often display circular/sub-circular or elongate geometry, but can also be more irregularly shaped. A number of elongate minibasins occur in Keathley Canyon, exhibiting a predominant NW-SE trend. The sedimentary fill can also show asymmetric reflector patterns across the minibasins, indicating basin rotation with associated sediment thickening.

By contrast, on the outer shelf the supra-salt cover is significantly thicker than in the slope region. A significant part of this thick supra-salt shelf trend is related to regions of highly evacuated salt. Also on the outer shelf are large salt massifs and large inter-salt minibasins and sediment fairways, as well as minibasins in hangingwalls of counter-regional faults.

Salt Geometry

The study area lies predominantly in three salt provinces, as described by Diegel et al. (1995). The largest in area is the tabular salt/minibasin region (A on Figure 1), roughly located from the shelf edge out to the allochthonous salt edge, represented, in part, by the Sigsbee Escarpment. The second (B on Figure 1) is a Plio-Pleistocene detachment province located on the outer shelf. The third is a dome/minibasin province in the northern edge of the study area (C on Figure 1). In these areas we can observe different styles of salt geometry, described below.

a) Diapirs

In the study area diapirs are predominantly features that are part of larger salt structures such as sheets and canopies, described in more detail below, with isolated diapirs relatively rare. Diapirs can be of three types, as described by Vendeville and Jackson (1992a): reactive, where extension creates room for diapir to grow; active, where the diapir creates room by upward movement; and passive, where the diapir is in equilibrium with the surrounding sediments. Diapirs can change from one type to the other during the evolution of a salt mass as the structural environment around it changes through time.

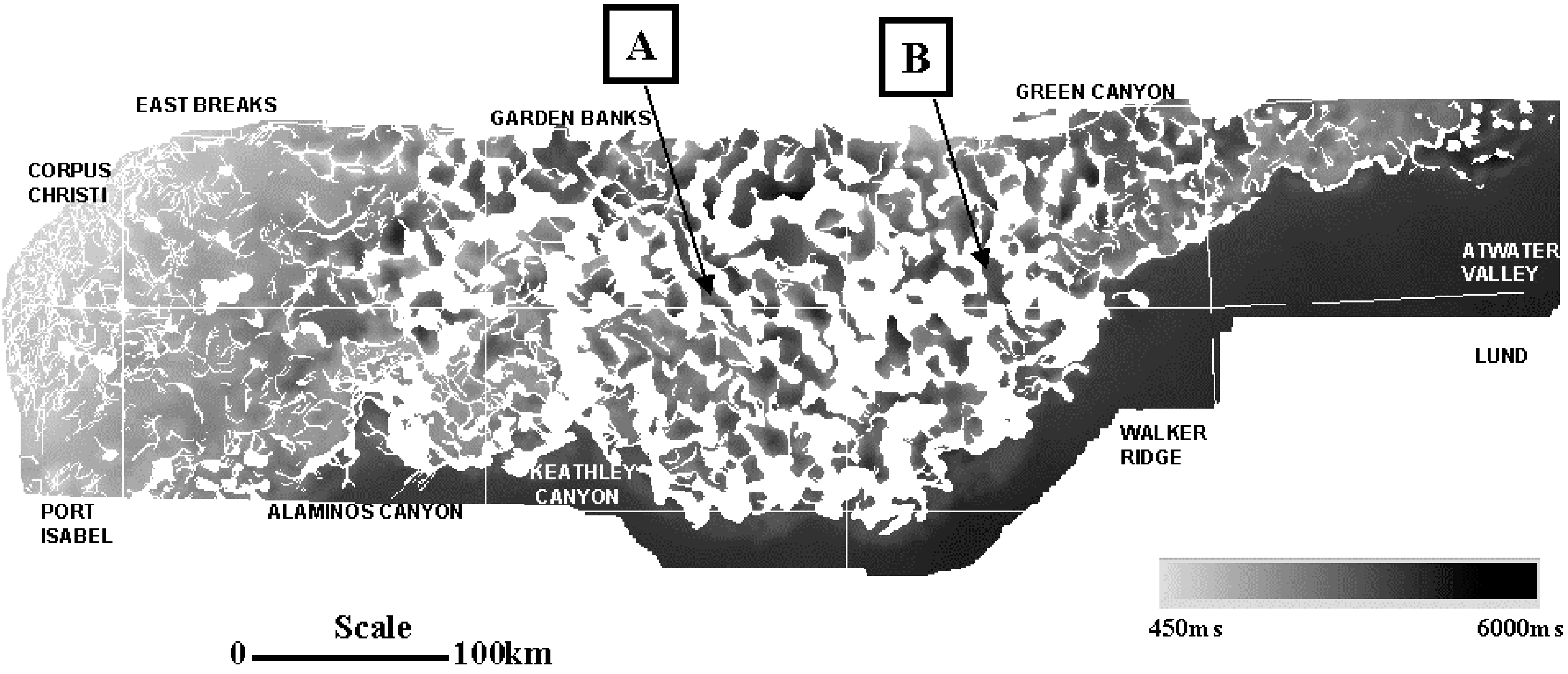


Figure 2 Distribution of DS 2.4 Ma Sequence Boundary

Reactive diapirs are often associated with localized extension above salt sheets. These are not common in the study area but are found most on the outer shelf (B on Figure 1). Active diapirs are relatively rare, according to Rowan (1995), and, where identified, are characterized by the uplifting of one flank of a salt body rather than by piercement. These types tend to be scattered around the northern part of the study area (B and C on Figure 1). Passive diapirs are a common occurrence in the study area. This is primarily because much of this allochthonous salt, which dominates region A of Figure 1, is emplaced very close to the seabed. With such a thin veneer of sediment the salt doesn't have to move aside significant overburden as it deforms.

b) Extensional or "Roho" Systems

These are large areas of gravity-driven extension characterized by large down-to-basin listric faults that often sole out onto salt-weld glide planes or decollement surfaces. Salt has been evacuated away predominantly basinward but has also moved to the periphery of these systems. Toe thrusts can also be found at the leading edge of these systems. This creates numerous supra-weld rotated fault blocks, sometimes producing huge dip differences across the weld surface. The similarity of the term to 'Moho' is not coincidental as seismically both these events are seen as major discontinuities. The discontinuity of the Roho system is the weld unconformity with the highly tilted supra-weld fault blocks overlying sub-weld strata of generally low dip. These are common features of region B on Figure 1. A smaller scale example of one of these systems is shown on the southern part of Figure 3.

c) Lateral sheets

These are large salt masses that originally formed from vertical or slightly tilted salt walls. They are often associated with counter-regional faults or fault welds. These sheets tend to flow laterally during times of low sedimentation rates.

They also often flow close to the paleo-seabed in a 'glacier flow' manner. Extensional systems, as described above, can occur above individual sheets consisting of three main components: reactive diapirs at the proximal location of the sheet, i.e. nearest the counter-regional fault feeders; a thinned region of salt with rotated fault blocks resulting from extension; and thrusting at the distal edge of the sheet. Wrench faulting may also occur along the sides of these sheets.

The geometry of the base salt can give us clues to the evolution of the sheet. Generally, the base of these sheets is fairly smooth with little structural relief, except for major dip changes in the vicinity of a counter-regional fault (see Figure 3). However, smaller-scale base salt features also occur involving relatively steeply-dipping regions, described as "ramps" by McGuinness and Hossack (1993) and linked by intervening "flats". These features are the result of relative changes between the salt and sedimentation rates during sheet evolution. Ramps represent periods when the rate of salt emplacement slows relative to the sedimentation rate. Flats represent periods of rapid lateral salt emplacement relative to the sedimentation rate.

d) Canopies

These are generally large salt bodies that have amalgamated to form continuous salt masses. They can be in various stages of evolution from individual sub-circular to circular salt bodies that are still strongly effecting bathymetric relief to highly welded regions, above which are circular to sub-circular minibasins. It is possible that the current highly coalesced nature of the present day salt distribution is composed of clusters or families of canopies that formed megacanopies that in turn amalgamated. A seismic example is shown in Figure 4. Base salt geometry can help us identify the locations of feeders where they lie below thick salt. Which can spread out considerable distances from its original feeder. A common base salt feature is the salt "keel". These can range in shape from cones to linear wedges. These locate the canopy's feeder, which originally formed as individual diapirs or salt walls.

e) Welds

Welds are regions where salt has been evacuated, often leaving a high amplitude seismic event sometimes located at a major unconformity. They occur throughout the study area but are less common in the tabular salt province (A on Figure 1), where massive salt canopies and sheets predominate. Four weld types are described below: Primary, Vertical, Fault and Horizontal: The Primary weld marks the location of the autochthonous salt layer. Salt from this level has largely been evacuated in the study area with only remnants trapped behind deep counter-regional faults or in the cores of deep anticlines related to the fold provinces seen at the edge of the allochthonous salt, namely, the Perdido and Mississippi Fan Fold Belts (Figure 1). It is extremely hard to see this weld in the study area, due to the allochthonous salt, except through "windows" that occur between salt massifs. Vertical welds indicate the former position of salt, locating the initial stages of salt canopy formation, described above. They can also display linear trends, indicating the former presence of salt walls. Fault welds include the counter-regional faults that are described in more detail in the next section. Vertical and fault welds can be termed secondary welds. Horizontal, or tertiary, welds are of two types with different origins. The "Roho" Systems described above consist of horizontal welds that tend to parallel or sub-parallel the subsalt reflectors and show relatively few truncations against the weld, as shown in Figure 3. Another type is pseudo-horizontal, predominantly circular to sub-circular in plan view, and is part of a collapsed salt canopy system. The subsalt reflectors show evidence of high angle cutoffs against the weld that can indicate the position of the former salt canopy.

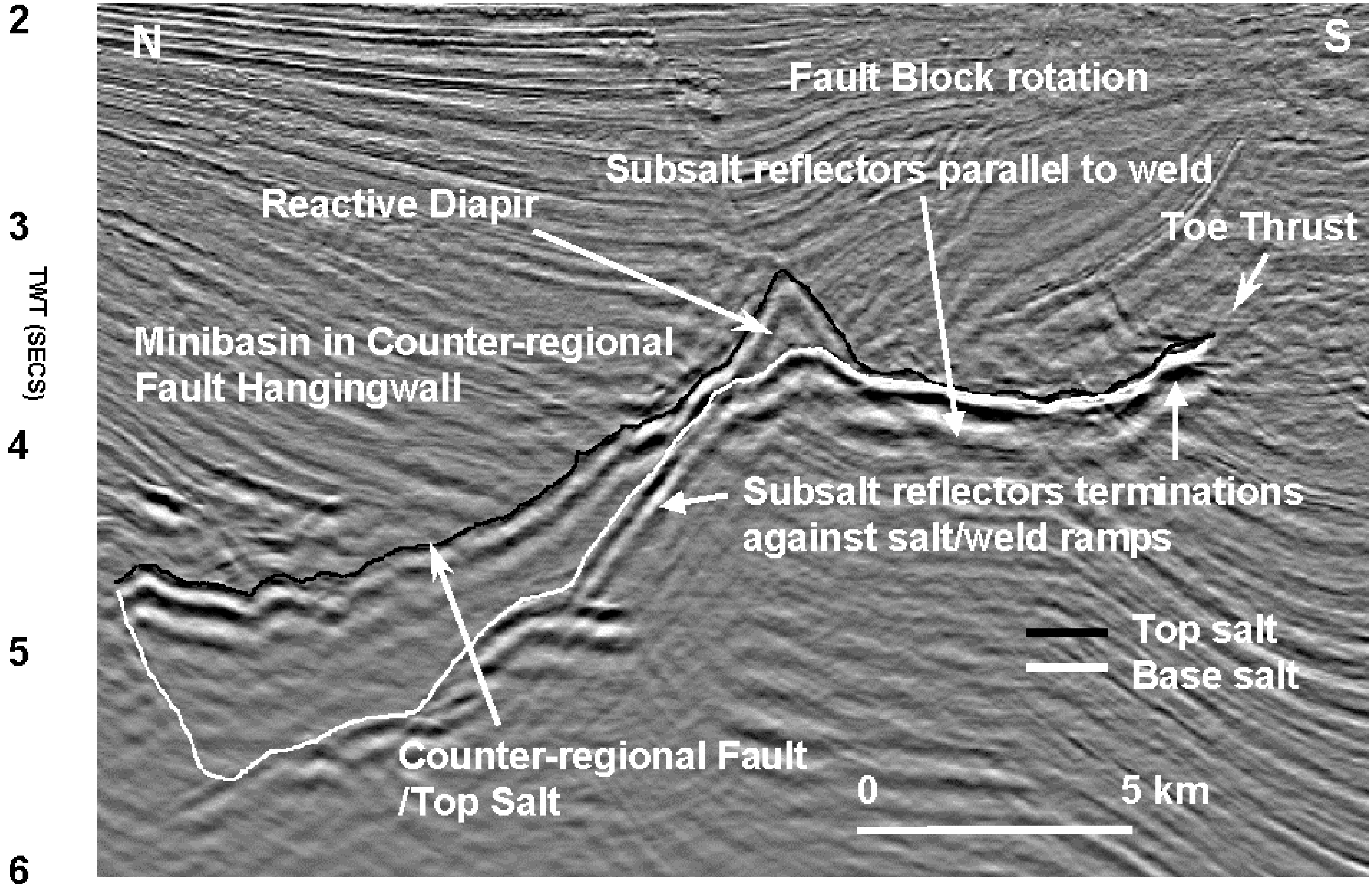


Figure 3 Salt Body Showing Complex Evolution from Initial Vertical to Subsequent Lateral Emplacement. Data Courtesy of Schlumberger Geco-Prakla

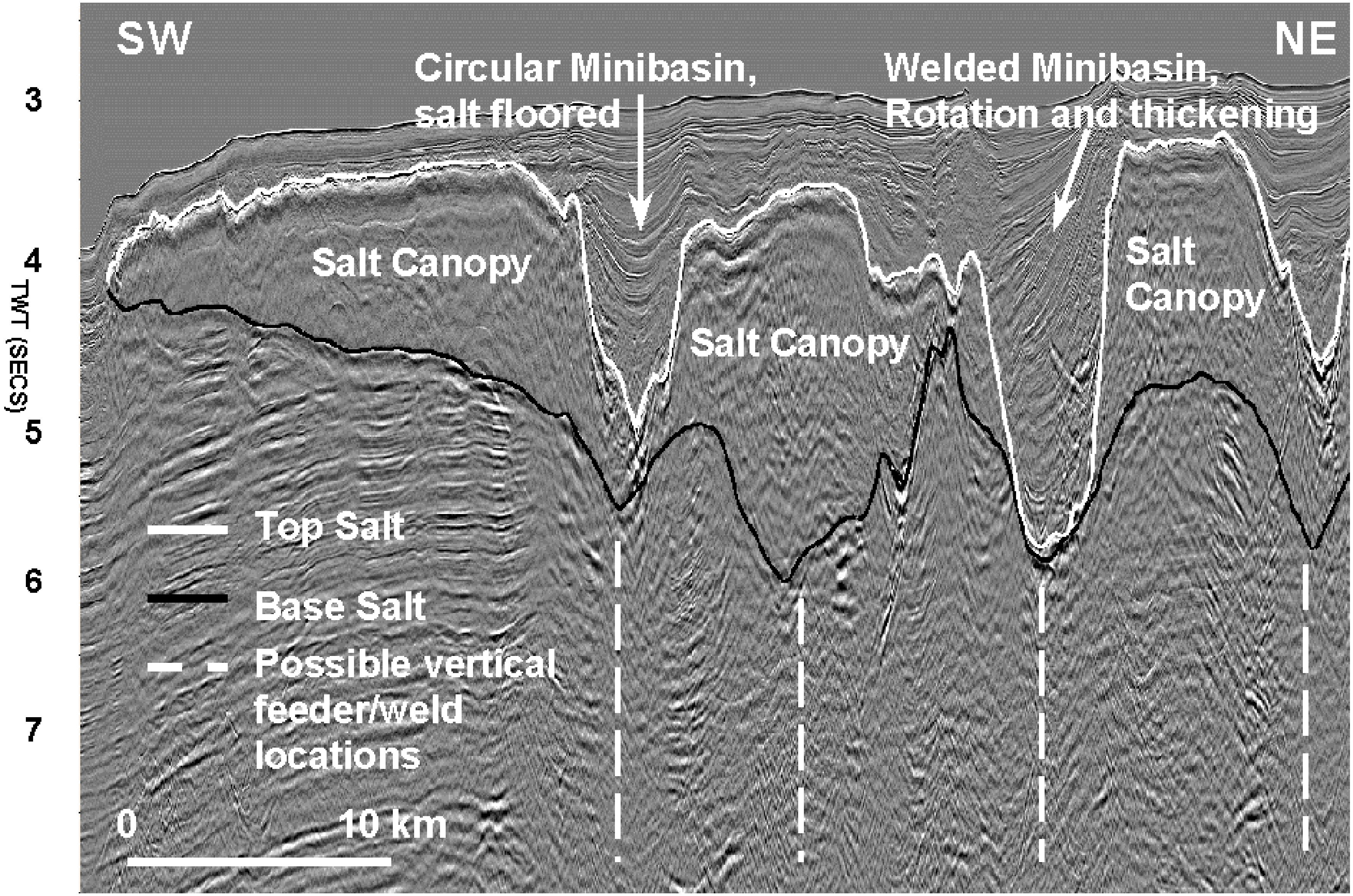


Figure 4 Large Salt Canopy Systems at the Edge of the Allochthonous Salt Province.
Data courtesy of TGS-Nopec and Schlumberger Geco-Prakla

Salt Emplacement Models

The understanding of salt/sediment interaction in the Gulf of Mexico is dependent on the ability to explain and relate the salt features described above in terms of a dynamic evolving system. There are two elegant models that provide us with much of this understanding. One is the Counter-regional model described by Schuster (1993, 1995) and Rowan (1995), the other is the Salt Stock Canopy model described by Rowan (1995), and summarized by Fox (1998). These models are outlined briefly below. An important part of the salt emplacement process involves the effect of salt on bathymetry. In both these models salt spreads laterally close to the paleo-seabed. One can get an idea of the complexity of this effect by looking at a present day bathymetry map that shows the current influence of salt near the seabed. The salt often creates extremely tortuous routes that sediment is forced to follow. The effect of the salt on bathymetric relief, both today and in the past, thus has important implications as far as sand distribution is concerned, as these inflated regions will cause the sediment to bypass preferentially into adjacent lows and will also produce condensed sections above the salt.

a) Counter-regional Fault

In the outer shelf of offshore Louisiana there are numerous counter-regional faults (Diegel et al., 1995), often associated with large salt sheets located in their footwalls. Initial salt walls may gradually move basinward forming a tilted linear salt structure. By forming a barrier, sediments pond landward of the salt wall and thicken into it, eventually moving more salt upward. At this stage, salt movement and sedimentation rates are similar but at some point a lateral salt emplacement phase occurs and a salt sheet forms with sheet emplacement occurring close to the paleo-seabed. The movement of large volumes of salt eventually depletes the salt supply from below and a fault weld forms as part of the counter-regional fault. Further changes in the sedimentation and salt movement rates can set up a second period of vertical salt movement followed in turn by a second period of lateral salt spreading. This forms a stepped counter-regional fault system with the majority of the salt pushed out to the leading edge of the sheet, with the counter-regional fault weld trailing behind. If extension is significant then Roho Systems can form as a later phase of development.

b) Salt Stock Canopy

This is a common salt emplacement mechanism in the study area. Canopies generally develop from a point feeder source. It begins to spread laterally forming a mushroom-type geometry. As long as the growing diapir still has salt supplied from the 'mother' salt below then this salt feature will often significantly effect bathymetric relief. Eventually, though, the supply of salt from below is curtailed as the upper salt mass pinches off. Sediment begins to pile on top of the salt and the canopy begins to collapse with salt being

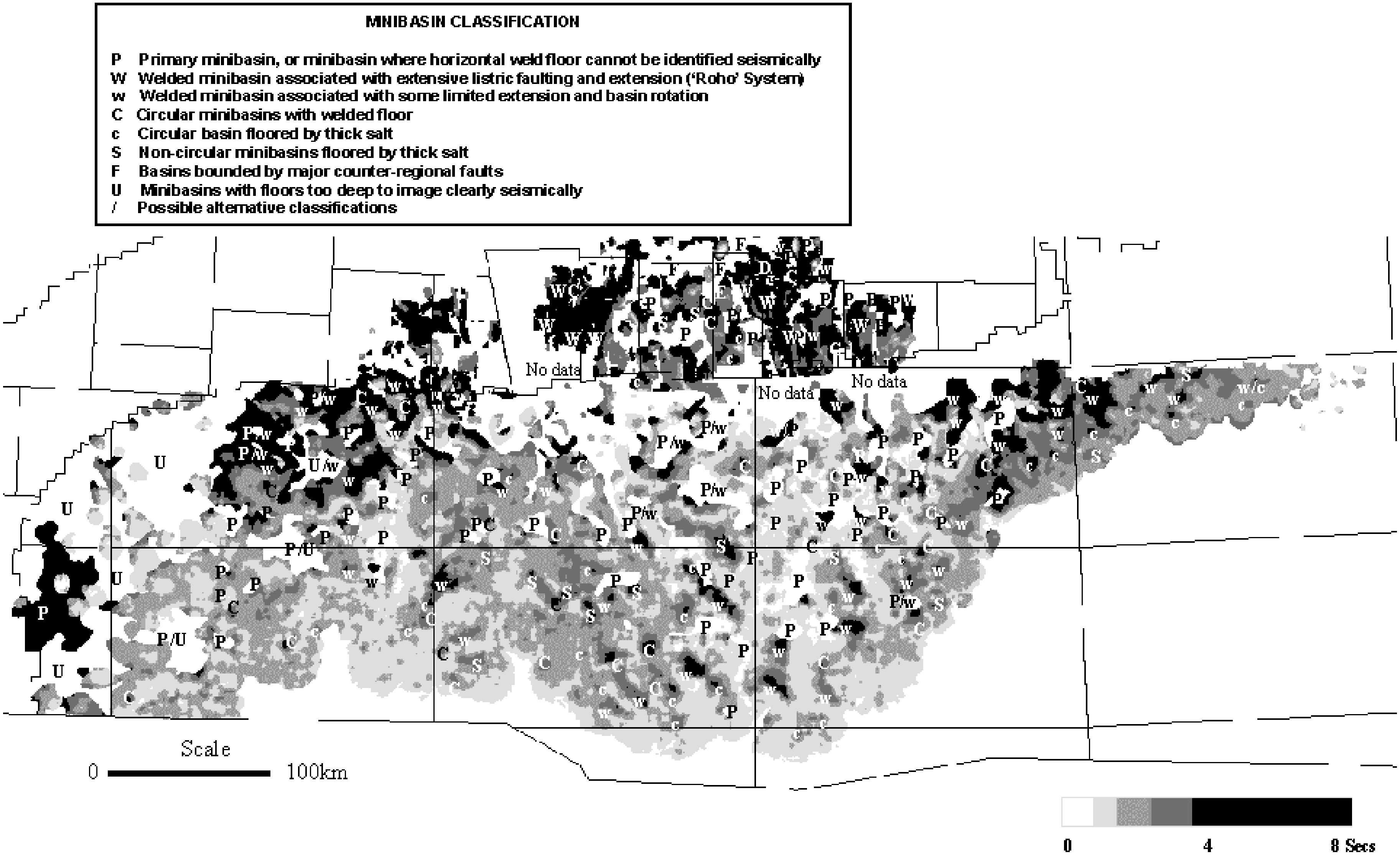


Figure 5 Supra-salt Isotime Map with Minibasin Classification

squeezed to its periphery. Ultimately, salt welds form in the central portions of the canopy which progress outward until thick salt occurs only around the rim of the canopy. Minibasins thus form above the collapsing canopy with a characteristic circular geometry. Good examples of the mature stages of this evolutionary process occur on the outer shelf. Here, canopies initially formed and coalesced together. Eventually, they collapsed to form large salt weld provinces. These canopies are less deformed in the deeper water regions, such that minibasins will tend to be younger and smaller than on the outer shelf, often still floored by thick salt. Many will still be connected to the salt supply below, evidenced by the bathymetry relief effects.

Minibasin Classification

This structural study has identified a variety of minibasin types, some with characteristic geometry. Minibasins have been produced by different types of salt/sediment interaction, described above. These are now categorized below and located in Figure 5.

Primary Minibasins (P on Figure 5)

These minibasins are generally very thick and have not been influenced by salt throughout its history. They are floored by autochthonous salt, or its welded equivalent, the primary weld. The true geometry of these basins is often obscured by salt, with only parts of the basin being visible through salt 'windows'. There are two general window shapes, irregular and linear which occur throughout the study area. An example of a Primary minibasins, seen through one of these linear, windows is shown at location 'A' in Figure 2. Some of these may mimic, to some extent, the geometry of the complete basin which extends under salt. This could be a result of a long established sediment fairway which, if high enough sedimentation rates were maintained, could prevent salt encroachment. Primary basins can be misclassified if seismic resolution is not good down to the primary weld. What is interpreted as a primary weld may, in fact, be an earlier laterally emplaced and evacuated salt system. Salt sheets may also be linked by a weld below a very thick minibasin. These minibasins would be incorrectly identified if the weld has been misinterpreted.

b) Welded Minibasins (W and w on Figure 5)

These have been sub-divided into two types, both associated with extension. Large salt decollement regions occur primarily on the outer shelf and represent a salt evacuation province of amalgamated collapsed salt canopies and lateral sheets. These are characterized by listric faulting, significant supra-salt extension and fault block rotation of the 'Roho' Systems described above (W on Figure 5). More localized examples can occur associated with individual sheets (see Figure 3). The other type of welded mini exhibits more limited extension, is often more irregularly shaped, and occurs throughout the study area (w on Figure 5). Many of these types are associated with basin rotation and sediment thickening.

c) Circular Minibasins (C and c on Figure 5)

Circular minibasins that are related to salt stock canopy collapse, described above, occur throughout the study area (C on Figure 5), with the original salt stock feeder often located below the minibasin depocenter. The welds that result from canopy collapse are different to those of the Roho systems. Subsalt reflectors in Roho systems generally subparallel the weld. Welds associated with collapsed salt stock canopies can show distinct high angle subsalt reflector terminations. In the deeper water regions many of these basins are still underlain by salt, often thinned but with no welding (c on Figure 5). If these minibasins are forming over collapsing canopies then the basin depocenters would mark the locations of canopy feeders.

Non-circular Minibasins floored by thick salt (S on Figure 5)

These minibasins are often associated with basin rotation and sediment thickening described in section b) above but differ in that these basins are floored by thick salt.

e) Minibasins bounded by major counter-regional fault welds (F on Figure 5)

These minibasins are associated with large counter-regional faults and form in their hangingwall and predominate on the outer shelf. These basins form by ponding of sediments landward of initial salt walls. This sediment loading also tends to move the salt walls basinward such that over time the wall has a tilted appearance and also moves the minibasin depocenter basinward (i.e. to the south in Figure 3). Salt subsequently evacuates from the feeder and emplaces laterally. Sediments will eventually override the salt sheet.

There are two other minibasin phenomena that don't belong to a particular category but need to be mentioned for completeness.

f) Subsalt minibasins

The minibasin types described above can occur under salt sheets, associated with earlier salt emplacement phases. Minibasins perched above welded salt from an early salt emplacement phase can now lie below a sheet from a later phase. An example of this occurs in the Enchilada subsalt Field region (Robison et al., 1997). As mentioned above, Primary minibasins can also extend under salt sheets and canopies and can be bounded and confined by salt feeders.

g) Colliding minibasins

Salt walls between adjacent basins can deflate over time causing basins to juxtapose. Sometimes this can produce some spectacular structuring as one basin overrides the other, sometimes forming large overthrusts. These occur both on the outer shelf and slope regions.

Summary

A regional understanding of the evolution of the Gulf of Mexico is critical in order to most effectively reduce exploration risk in the search for hydrocarbons. The way salt evolves and interacts with the sediment being supplied into the Gulf determines where and when reservoirs form. One product of salt and sediment interaction is the minibasin which is an important geologic phenomena in terms of reservoir accumulation. This study has outlined how they form and why they differ and shows how they fit into current models of salt evolution. This is achieved by incorporating a large regional interpretation using modern seismic datasets.

Acknowledgements

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