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Spatial variations in salinity and temperature around the Bay Marchand salt dome, offshore Louisiana

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SPATIAL VARIATIONS IN SALINITY AND TEMPERATURE AROUND THE BAY MARCHAND SALT DOME, OFFSHORE LOUISIANA

A Thesis

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Master of Science

in

The Department of Geology and Geophysics

by

Laurie Richards
B.S., The University of Tulsa, 2008
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ABSTRACT

The Bay Marchand field is located about 60 miles south of New Orleans, Louisiana on the continental shelf. The structurally complex field has produced over 960 MMBOE as of 2012 (http://www.eplweb.com), with many of these hydrocarbons being trapped against the massive salt dome and associated faulting present in the area. A study by Bruno and Hanor (2003) documented the presence of a high salinity plume off the southeast flank of the dome that had less saline and less dense pore water below it. The purpose of this study was to investigate the spatial variations in pore water salinity and temperature on the shallow flanks and crest of the dome that was proposed to be the potential source of the plume mapped in the adjacent Bruno and Hanor (2003) study area. SP and resistivity logs, as well as log header data for 19 boreholes drilled in Bay Marchand were used to calculate salinities, temperatures, and pressures across the area. Results indicate that salt dissolution has led to the presence of four high salinity plumes migrating down-dip away from the dome. Temperature and pressure data suggest the downward migration of seawater as the most likely source of the water supplying the plumes. The plumes appear to be bracketed by major faults in the area. Incorporation of 3D seismic data and fault mapping may be of interest in the future.
INTRODUCTION

The Bay Marchand salt dome is located on the continental shelf offshore of Lafourche Parish, Louisiana (Figure 1) and is thought to be the largest salt dome in the Louisiana Gulf Coast region (Frey and Grimes, 1970). The top of the dome is at a depth of approximately 2,000 feet (600 m) below sea level (Figure 2). The dome covers more than 140 mi$^2$ (360 km$^3$) at a depth of 20,000 feet (6100 m), and to that depth is estimated to contain approximately 200 mi$^3$ (520 km$^3$) of salt (Frey and Grimes, 1970). Such massive salt structures are known to play a significant role in the hydrogeologic and diagenetic evolution of sedimentary basins, though the numerous studies on this subject matter suggest that no two salt domes are exactly alike (Bennett and Hanor, 1987; Bray and Hanor, 1990; Lin and Nunn, 1997).

Bay Marchand is also one of the world’s giant oil fields. As of 2012, the greater Bay Marchand area had a cumulative production of 960 MMBOE (http://www.eplweb.com). The field is located on top of and adjacent to the Bay Marchand salt dome, which acts as a stratigraphic trap for much of the hydrocarbon reserves present (Ingram, 1990). Extensive drilling around the dome has led to a database of hundreds of well logs, providing an excellent source of public data for the hydrogeologic study of the area. Bruno and Hanor (2003) utilized spontaneous potential (SP) logs to estimate formation water salinities in an area covering the southeast flank of the dome (Figure 2). Their results showed the presence of a high salinity plume migrating from the dome, down-dip through a sand dominated section of Pliocene and upper Miocene sediments. Salinities in this plume are in excess of 100 g/L, approximately three times that of normal marine salinity (35 g/L). Bruno and Hanor (2003) concluded that the
spatial variations in salinity were consistent with dissolution of the dome as the likely source of the plume, though a point of origin was not located within their study area.

More recent investigations into this study have led Bruno and Hanor (personal
Figure 2. Top of salt structure map. Study area highlighted in black. Bruno and Hanor (2003) study location highlighted in red. Offshore blocks and their block numbers also listed. Concavity in salt structure circled in blue.
communication, 2009) to hypothesize that the high salinity plume on the southeast flank originates in the concavity near the top of the northeast quadrant of the dome (Figure 2). Volume balance constraints require that new water, possibly from the overlying seafloor, replaced water removed from the salt face by the plume.

The existence of three hydrogeologic regimes has been well documented around both onshore and offshore salt features in the Louisiana area of the Gulf of Mexico sedimentary basin (Hanor and Sassen, 1990; Bruno and Hanor, 2003; Steen et al. 2011). The shallowest regime consists of hydropressed fluids that have salinities ranging from fresh to normal marine (35 g/L). Flow of fresh waters in this regime is topographically driven around onshore salt features (Bruno and Hanor, 2003). A much deeper, overpressured regime also contains formation fluids with near marine salinities or less. Fluid flow within this regime occurs as episodic expulsion of fluids upward along fault planes and fractures (Hanor and Sassen, 1990; Lin and Nunn, 1997). The middle regime is hydropressed to moderately pressurized, and contains formation waters with salinities three to four times that of marine salinity, such as the high salinity plume mapped by Bruno and Hanor (2003) at Bay Marchand. Fluid flow in this third regime is controlled in part by spatial variations in fluid density resulting from variations in formation water salinity and temperature, and as a result, dense brines flow down-dip (Bruno and Hanor, 2003; Ranganathan and Hanor, 1988).

The purpose of the research described in this thesis was to investigate the hydrogeologic environment and fluid flow patterns over the crest and shallow flanks of the Bay Marchand salt dome immediately northwest of the Bruno and Hanor (2003) study area (Figure 2), focusing in particular on the possibility of locating zones of
preferential salt dissolution on the dome that could be the source of the Bruno and Hanor (2003) plume. Indications of fluid migration pathways from salinity data may also prove to be of economic importance, by helping to understand the migration/entrainment of hydrocarbons in the area as well.
GEOLOGIC SETTING

Introduction

The Bay Marchand field is located about 60 miles south of New Orleans, Louisiana covering parts of offshore Lafourche Parish and Federal waters immediately to the south (Figure 1). Often referred to colloquially as a salt dome, the Bay Marchand salt feature is really a bulbous allochthonous salt sheet (for the sake of brevity, this thesis will continue to refer to it as the Bay Marchand salt dome) (Pindell, 1985). Subsequent salt tectonics brought on by rapid sediment accumulation in the Tertiary led to the formation of the Bay Marchand-Timbalier Bay-Caillou Island salt complex that is present today (Figure 3) (Frey and Grimes, 1970). Gravity and seismic data have shown that these individual domes are connected as a continuous salt ridge that runs east-west parallel to the Louisiana coastline (Frey and Grimes, 1970). The Bay Marchand dome was first detected in 1927 by the Gulf Oil Corporation utilizing a refraction seismic survey. However, the first true discovery well was not drilled until 1949 by The California Company (now Chevron Oil Company) (Frey and Grimes, 1970). Production hit a high in the 1960s and 1970s with the help of 2D seismic data. A decline in production followed, and then with the acquisition of the first 3D seismic survey of the area in the 1980’s, production hit another peak (Abriel et al., 1991). With the help of seismic data, continued refinement of fault mapping in the area has established Bay Marchand as a very structurally complex dome in the offshore Louisiana area (Snavely and Sarwar, 1988).

Stratigraphy

The dominant sedimentation pattern along the Gulf Coast during the Tertiary was regressive, resulting in the outbuilding of a continental shelf and one of the world’s
Figure 3. Structure map of the top of the first Miocene sand around the Bay Marchand-Timbalier Bay-Caliou Island salt ridge. Modified from Frey and Grimes (1970).
thickest sections of terrigenous clastic sediments (Limes and Stipe, 1959; Galloway et al., 2000). Occasional transgressions interrupted the overall outbuilding trend, and are evidenced by the presence of marine shales containing deep-water fauna interbedded with nearshore sediments (Limes and Stipe, 1959; Galloway et al., 2000). Sediments of Miocene age and younger, were deposited by ancestral Mississippi and Tennessee river deltas (Galloway, 2005), and extend over a very large geographic area, thickening downdip before thinning somewhat slightly to the south (Frey and Grimes, 1970). Figure 4 shows a generalized north-south cross section across the Gulf Coast shelf that indicates the approximate location of facies shifts within each biostratigraphic unit, ranging from massive sandstones in near shore deposits to an intermediate zone of interbedded sandstone and marine shale to massive shales at the farthest distance from the shore (Frey and Grimes, 1970). Type logs and cores from the Bay Marchand area show that the Pleistocene and Pliocene sections contain mostly massive sandstones with some interbedded shales, whereas the Miocene section transitions from a thick accumulation of interbedded sandstone and marine shale to more massive shales in the deeper part of the section (Figure 5) (Frey and Grimes, 1970).

**Structural Setting**

In general beds dip radially around the salt dome, but because the area is so disrupted by faulting, local dips can vary quite significantly (Abriel et al., 1991; Frey and Grimes, 1970). Faults in the area include: several major normal faults, radial faulting patterns around the salt dome, growth faults with associated antithetic faults, and near the crest of the dome, many graben type fault features (Figure 6) (Frey and Grimes, 1970; Snavely and Sarwar, 1988).
Figure 4. Generalized north/south cross section along the Gulf of Mexico highlighting facies shifts within each biostratigraphic unit. Position of the coast line approximates the location of the Bay Marchand field. From Frey and Grimes (1970).

Figure 5. Partial well log of well # 13112-1. Log section on the left shows log curves from 3800' to 5900'. Section on the right shows log curves from 5900' to 7800'. Sands, as indicated by the SP curve, are colored in yellow. Notice the distinct shift from thick, blocky sands on the left to thin interbedded sands on the right. Pliocene/Miocene boundary is marked in red.
Figure 6. East-west cross section over the Bay Marchand salt dome, highlighting the complex faulting in the area. From Bruno and Hanor (2003), modified from Snavely and Sarwar (1988).
Study Area

This study focused on an area of approximately 20 mi$^2$ (52 km$^2$) over the crest of the Bay Marchand dome and the shallow flanks. It is northwest and adjacent to (partially overlapping) the Bruno and Hanor (2003) study area (Figure 2).
METHODS

Introduction

Wireline logs for 19 vertical wells across the study area were utilized for their header data and spontaneous potential (SP) and resistivity responses (Figure 7). Today, many, if not most offshore wells are drilled directionally from a platform that serves as a single structure to host multiple wells. For simplicity, this study preferentially used well logs from vertical wells, which often represents an older well. Information about the well logs used in this study, including the logging date and the source of the log, are listed in Appendix I.

Temperature and Temperature Gradients

Recorded bottom hole temperatures (BHTs) from the log header data were used to calculate an apparent temperature gradient for each well, using an assumed sea bottom temperature of 75 °F. Temperatures were corrected using the Kehle (1971) correction curve for the cooling effects of circulating fluid:

\[
T_{\text{corr}} = T_{\text{log}} - 8.819 \times 10^{-12} \times D^3 - 2.143 \times 10^{-8} D^2 + 4.375 \times 10^{-3} D - 1.018
\]

Where: 
- \(T_{\text{corr}}\) = corrected temperature in °F
- \(T_{\text{log}}\) = temperature reading from the log in °F
- \(D\) = subsea depth of temperature reading in ft

It is worth noting that 7 wells had multiple logging runs and therefore multiple temperature data points, making those temperature results more reliable than wells with only one data point. Apparent temperature gradients were calculated using the equation:

\[
T_{\text{grad,app}} = (BHT_{\text{corr}} - T_s) / (\text{SS depth}_{\text{BHT}})
\]

where: \(T_{\text{grad,app}}\) = apparent temperature gradient in °F/f
Figure 7. Map of study area showing the locations of wells and cross sections. Wells shown in green dots, labeled in black text. Cross sections labeled in red text. Bruno and Hanaor (2003) well locations and cross sections also shown with blue dots. Dashed line indicates a gap in the data where salinity and temperature were not interpolated.
BHT\textsubscript{corr} = corrected BHT in °F 
T\textsubscript{s} = surface temperature in °F 
SS depth\textsubscript{BHT} = subsea depth of the BHT reading in ft

In wells with more than one temperature recording, apparent temperature gradients for the intervals in between measurements were calculated as:

\[ T_{\text{grad,app}} = \frac{(\text{BHT}_{\text{corr,lower}} - \text{BHT}_{\text{corr,upper}})}{(\text{SS depth}_{\text{lower}} - \text{SS depth}_{\text{upper}})} \]

where: \( T_{\text{grad,app}} \) = apparent temperature gradient in °F/ft 
\( \text{BHT}_{\text{corr,lower}} \) = corrected BHT of the lower reading in °F 
\( \text{BHT}_{\text{corr,upper}} \) = corrected BHT of the upper reading in °F 
\( \text{SS depth}_{\text{lower}} \) = subsea depth of the lower BHT reading in ft 
\( \text{SS depth}_{\text{upper}} \) = subsea depth of the upper BHT reading in ft

The apparent temperature gradient in each well was used to interpolate between BHT recordings.

**Calculating Salinity from Spontaneous Potential**

The electrochemical component of the SP log is of primary importance in estimating the salinity of a formation fluid (Lin and Nunn, 1997). Electrochemical potential recorded by the SP log is an indication of the degree of disparity in ionic mobilities when two solutions having different ionic activities are in contact, such as mud filtrate and formation water (Lin and Nunn, 1997). Bateman (1985) developed a relationship to estimate formation water salinities using SP response, mud filtrate resistivity (Rmf), mud filtrate temperature (Tmf), and formation temperature (Tm). This study utilized an Excel spreadsheet developed by Hanor (personal communication, 2011) that employs the Bateman and Konen (1977) technique to perform salinity estimations.
SP values were recorded from logs as a mV deflection from the shale baseline. Measurements were taken only in wet sands (low resistivity responses) with thicknesses of 30 feet or greater. It is noted that thin sands give erroneously low salinity estimations (Doll, 1948). Other factors that may influence SP response and introduce error into the salinity estimation include, but are not limited to: thinly interbedded shales present within the sand, presence of hydrocarbons and damage to the formation, including mud filtrate invasion (Doll, 1948).

The majority of wells in this study were drilled and logged in the 1950s, and problems with the logging tool, lack of experience logging in an offshore environment, and possible inaccurate recordings by the loggers could all contribute to error as well. Many logs at this time did not record Rmf measurements. In wells that lacked recorded Rmf data, estimations of Rmf at 75 °F were made using a relation developed by Funayama (1990). Funayama (1990) used over 400 Rm/Rmf pairings from log headers across an area in central Louisiana to develop a statistical relationship between the two sets of data. Sensitivity of salinity values to changes in Rmf were also investigated, and he found that a 10 per cent difference in Rmf causes a 3 per cent change in the calculated salinity (Funayama, 1990).

**Spatial Variations in Temperature and Salinity**

A series of cross sections, A-A’, B-B’, C-C’, and D-D’ were contoured for both the temperature and salinity data. Cross sections A-A’, B-B’, and C-C’ run from northwest to southeast, while D-D’ runs somewhat normal to these, from northeast to southwest (Figure 7). The layout of the cross sections was selected with an emphasis placed on being able to tie the results into the cross sections created by Bruno and Hapor
(2003) that extend to the southeast of this study area. Horizontal slice maps of the salinity data were also created at depths intervals of 1000 ft (300 m) down to a depth of 6000 ft (1800 m).

**Pressure**

Although mud weights are not a direct measurement of formation pressure since it is assumed that they are always overbalanced, they can serve as a good general indicator of areas of pressure anomaly. Mud weight(s) from the log header data and their corresponding depths, were used to calculate geostatic ratios by converting them to a pounds per square inch (PSI) over feet ratio.
RESULTS

An abrupt change in log character, tied to a change in the dominant lithology is present across the study area, and approximates the Pliocene-Miocene boundary (Figure 5). Pliocene sediments in this study area are dominated by thick, blocky sands whereas Miocene sediments consist of thinner interbedded sands and shales. Although we know from other studies that the Bay Marchand field is complexly faulted (Snavely and Sarwar, 1988; Frey and Grimes, 1970), the well data available to this study cannot resolve most of the faults.

Salinity

Formation waters of the Pleistocene and upper most Pliocene sections have salinities near that of normal marine water (35 g/L). With few exceptions, there is an abrupt shift within the formation waters of the Pliocene section from normal marine salinities to hypersaline brines in excess of 150-200 g/L in some cases. Often salinities begin to decrease again near the Pliocene-Miocene boundary, but there are some cases in this study which show that the hypersaline brines continue into the upper Miocene.

Along cross section A-A’ (Figure 8) salinities near that of normal marine salinity (35 g/L) can be seen down to approximately 2000 ft (~600 m). Below this depth salinities increase fairly rapidly to 50 g/L. On either side of the top of salt as seen along this line there are areas of high salinity ( >100 g/L). The high salinity region to the southeast extends past the limits of this study, but when the results from Bruno and Hanor (2003) are included, it can be seen that this is the up-dip extension of the high salinity plume that they mapped. The high salinity region seen on the northwest end of this cross
Figure 8. Salinity cross section A-A’. Dashed contours indicate results are based on data from only one well. Yellow dots on well paths show depths at which salinity calculations were made. The two well paths shown side-tracking off of #F1 are #F3 and #F5 respectively, and are discussed in the appendix but not included in the contouring. Contoured by hand. Fault mapped by Bruno and Hager (2003).
section does not appear to extend beyond the cross section, instead extending away from
the dome taking the path of the maximum dip angle, which is oblique to the cross section.
However, it must be considered that well #70 does not extend down to the salt face.
Below the high salinity region on the southeast flank of the dome, there is a significant
reversal in salinity to near seawater values. This vertical salinity profile (Figure 9) is
repeated through much of the study area with the exception of an area near the crest of
salt along cross section A-A’. Here, centered around well #F1 and in between two high
salinity regions, salinities are between 30 g/L and 50 g/L down the entire section above
salt, which is at a depth of approximately 5750 ft (~1750 m) (Figure 9).

Two high salinity regions are also seen along cross section B-B’ (Figure 10). The
high salinity area mapped on the southeast side of the top of salt appears to be sitting
immediately on top of salt and centered around well #B1. The orientation of this may also
be oblique to the cross section as it does not extend along the line past well #B1. The
high salinity region to the northwest of the top of salt has salinities in excess of 200 g/L
and appears to extend past the limits of the study.

Cross section C-C’ (Figure 11) only covers an area on the northwest side of the
top of salt. A high salinity region extends across most of this section, with salinities in
excess of 150 g/L. D-D’(Figure 12) extends from southwest to northeast, and intersects
each of the other three cross sections. This cross section exhibits the same general pattern
seen in the other cross sections with two high salinity regions, one on each side of the
crest of salt. Salinities along this section range from normal marine (35 g/L) to about 150
g/L. It appears that the two high salinity regions seen along this cross section contact the
Figure 9. Vertical salinity profile of wells #70, #55 and #F1. The red line marks seawater salinity. The curve seen in the first two wells is similar to what is seen across most of the study area, where salinities increase through the Pliocene and top of the Miocene, and then, may decrease again. Well #F1 is an exception to this salinity pattern.
Figure 10. Salinity cross section B-B'. Dashed contours indicate results are based on data from only one well. Yellow dots on well paths show depths at which salinity calculations were made. Well #A1 is not shown as none of the data are used from this well. Contoured by hand.
Figure 11. Salinity cross section C-C'. Dashed contours indicate results are based on salinity data from only one well. Yellow dots on well paths show depths at which salinity calculations were made. Distance from well #M1 to the Bruno and Hanor (2003) data was too great to interpolate in between. In addition, none of the data on cross section C-C' is on the same flank of the salt dome as the Bruno and Hanor (2003) data. Contoured by hand.
Figure 12. Salinity cross section D-D’. Dashed contours indicate data from only one well. Yellow dots on well paths mark depths at which salinity calculations were made. Points where D-D’ intersects A-A’, B-B’, and C-C’ are marked along top of cross section. Contoured by hand.
salt near wells #I1 on the southwest side of the salt crest, and #55 on the northeast side of
the salt crest.

Salinity results from borehole #A1 which is seen in both B-B’ and D-D’, were left
out of salinity contouring due to concerns with data quality. SP values through the entire
section of well #A1 were unusually low while the resistivity curve did not indicate the
presence of fresh water, suggesting that there might have been a problem with the
logging tool. Additional information on the salinity data for this is included in the
Appendix. Concerns were also initially raised about the data quality of another well, #F1,
due to the low salinity anomaly it produced. Investigations into this matter led to research
into two subsequent sidetracked wells, #F3 and #F5. Though these wells are not straight
holes, survey data was used to plot their approximate position along cross section A –A’
(Figure 8). Results from salinity estimations on logs from these two sidetracked wells led
to confirmation that lower salinities do appear to exist in the formation waters throughout
the entire vertical section that #F1 cuts. Further information about these two wells can
also be found in the Appendix.

Salinity mapping at depth intervals of 1000’ (Figures 19-24) shows the horizontal
extent of the high salinity regions progressively with depth. In Figure 19, at a shallow
depth of only 1000’ subsea, there is little evidence of high salinity. However, there is a
region adjacent to the coastline with salinities less than that of seawater (< 20 g/L). By
2000’ (Figure 20) the low salinities are gone and in the northwest region of the study area
what appears to be the first sign of a high salinity region starts to develop. The high
salinity regions begin to show up on the east side of the crest of the dome by 3000’
(Figure 21), and by 4000’ (Figure 22) it appears that there are three separate high salinity
Figure 13. Salinity slice map at 1000'. Dash-dot line indicates the limit of the data. Tongue of less than 20 ppt water can be seen extending from the coastline.
Figure 14. Salinity slice map at 2000'. Dash-dot line indicates the limit of the data at this depth. A high salinity plume is beginning to develop at this depth in the northwest region of the study area.
Figure 15. Salinity slice map at 3000'. Dash-dot line indicates the limit of salinity data at this depth.
Figure 16. Salinity slice map at 4000'. Dash-dot line indicates the limit of salinity data at this depth.
Figure 17. Salinity depth section at 5000'. Dash-dot line indicates limit of salinity data at this depth.
Figure 18. Salinity depth section at 6000’. Dash-dot line indicates limit of salinity data at this depth.
regions. By 6000’ (Figure 24), the high salinity regions on the east side of the crest of the dome appear to have merged, and what seemed to have originated on the northwest flank of the dome appears to have split into two, with one side now extending in the southwest direction.

**Temperature**

Temperatures varied spatially in different ways across the study area. Isotherms in the northeast to central part of the study generally mimic the structure of the top of salt, with two major exceptions along cross section B-B’ (Figures 15 and 16). In this cross section, wells #B1 and #J1, each on either side of the crest of the dome, show a significant down dip in the isotherms. Both of these anomalies are outside of the typical range of error of BHTs (± 3-5 °C). Toward the southwest end of the study area, along cross section C-C’, isotherms are relatively flat-lying, with only a slight upwelling trend near salt (Figure 17). Running southwest to northeast and cross cutting the other three cross sections, isotherms all along D-D’ gently mimic the structure of the salt, rising up on either side to meet above the crest (Figure 18).

**Pressure**

Mud weights from the log headers in this study indicate that there are no significant areas of overpressure, although Bruno and Hanor (2003) showed that shale dominated sediments in the deeper section of the Miocene are overpressured.
Figure 19. Temperature cross section A-A’. Yellow X’s indicate depths at which BHTs were recorded. The Bruno and Hanor (2003) portion of the cross section was contoured using temperature-depth pairs provided by the authors (personal communication, 2012).
Figure 20. Temperature cross section B-B'. Yellow X's indicate depths at which BHTs were recorded. The Bruno and H ancor (2003) portion of the cross section was contoured using temperature-depth pairs provided by the authors (personal communication, 2012).
**Figure 21.** Temperature cross section C-C'. Yellow X's indicate depths at which BHTs were recorded. The Bruno and Hanor (2003) portion of the cross section was contoured using temperature-depth pairs provided by the authors (personal communication, 2012).
**Figure 22.** Temperature cross section D-D'. Yellow X's indicate depths at which BHTs were recorded. The Bruno and Hanor (2003) portion of the cross section was contoured using temperature-depth pairs provided by the authors (personal communication, 2012).
DISCUSSION AND CONCLUSIONS

The hydrogeology of the Bay Marchand field is complex. Here, the first regime is shallow and hydropressed with normal marine salinities or less (≤ 35g/L). One possible explanation for the presence of such low salinities is that fresh water flushed horizontally through exposed and shallow shelf sediments during the last ice age. Figure 19 shows a shallow tongue of low salinity (<20 g/L) pore water that extends from the coast. This could represent the mixing of such water with more saline seawater.

An overpressured regime with salinities ranging from normal marine to approximately 75 g/L, was seen in the deeper Miocene section studied by Bruno and Hanor (2003) to the southeast of this study area. However, geostatic ratio data indicates that there is no significant pressure anomaly in this study area. As shown in Figure 5, the Miocene section over this portion of the dome lacks much of the thick shale section described by Bruno and Hanor (2003), and instead has thinner interbedded shales and sands. Bruno and Hanor (2003) documented a strong correlation between the top of overpressure and the transition from blocky Pliocene sands to thick Miocene shales, the absence of which might explain the absence of geopressure in this study area.

The middle regime is a moderately pressurized regime with hypersaline brines, in excess of 150-200 g/L in some cases. Lithology appears to be [a] the major controlling factor on the vertical migration pathways of these brines, because the [stratigraphic position of the ] plumes correlate[s] well with the sand dominated section of the Pliocene and very upper Miocene (Figures 8, 10-12).

Numerous studies around salt features, both onshore and offshore, have demonstrated that isotherms above salt tend to mimic the structure of the salt (Steen et
al., 2011). This is an indication of the ability of salt to radiate heat up to the surface due to the much higher thermal conductivity of halite in comparison to typical sedimentary rocks (O’Brien and Lerche, 1988). Temperature mapping around the Bay Marchand dome showed a general trend of upwelling isotherms toward the crest of the dome. Two distinct anomalous temperature features were found along cross section B-B’ (Figure 16), breaking the upwelling trend of isotherms on either side of the crest of salt. This indicates that something is causing pockets of cooler temperatures in the vicinity of each of these wells, #B1 and #J1, and may be evidence of cooler waters migrating downward along faults and fracture patterns in these locations. Salinity contouring has shown well #B1 to be very near to the location of origin for the large salinity region mapped off of the east side of the dome, mapped in both this study and in Bruno and Hanor (2003). This supports the idea that water may be migrating downward at this location, creating a pocket of preferential salt dissolution, creating high salinity plumes that are moving away from the dome. Well #J1 has two BHT data points supporting the anomalous result, and is also very close to the origin of a different salt plume moving from the northwest side of the dome.

Mapping of the spatial extent several high salinity plumes found within this section are concurrent with the hypothesis that shallow dissolution of the salt dome is occurring in four distinct locations where the plumes are in direct contact with salt (Figures 19-24), though the sparse well data in this study only directly shows this occurring at one of these locations, well #B1 on cross section B-B’ (Figure 10). Faults were not mapped in this study, although when compared to Figure 3, the plumes seen in Figures 19-24 are clearly moving down-dip and appear to be confined (in the horizontal
sense) by some of the major first order faults in the area (Figure 23). These slice maps show at a single depth where the high salinity areas are, but understanding what is happening between these static glimpses requires interpretation. The complexity of the permeable pathways and the connectivity of these high salinity plumes can be seen when they appear to merge or split on a depth slice.

The cause of preferential dissolution in a few localities along the shallow portion of the salt dome is inferred to be due to a source of replacement water to those particular locations. The source of the water is not known, though there are several possibilities. Previous studies have found likely the expulsion of water from the deeper overpressured zone upward along faults and fractures (Lin and Nunn, 1987; Evans, et al., 1991). Though the exact locations of faults are unknown in this study, the Bay Marchand field is one of the most complexly faulted salt domes in the Gulf Coast region, with many potential pathways of upward fluid migration. Several studies have documented upward fluid migration adjacent to salt, including a study by Bennett and Hanor (1987) of the Welsh dome in southwest Louisiana (Figure 25). Bray and Hanor (1987) and Anderson (2012) documented upward expulsion of water at the St. Gabriel field. In these examples, salt dissolution occurs as water travels upward adjacent to the salt face, and thermohaline convection carries the high salinity plumes vertically above the dome until they become too dense and convective overturn begins to carry the plumes downward and away from the dome. Although pore water salinities greater than that of seawater (35 g/L) do extend over the crest of the dome in Bay Marchand, the lack of geopressure in the study area makes upward fluid expulsion an unlikely source of the water supplying the high salinity plumes.
Figure 23. Striking similarities exist between faults mapped by Frey and Grimes (1970), top image, and the high salinity plumes mapped in this study. Indicates that faults may be barriers, at least in the horizontal sense, to the flow of these plumes.
Figure 24. N-S cross section across the Welsh salt dome in Jefferson Davis parish, Louisiana showing variation in pore water salinity. Notice the high salinity plume extending above its point of contact near the crest of the dome. Modified from Bennett and Hanor (1987).

Figure 25. N-S cross section highlighting contrasts in pore water salinity across faults in the southern part of the Bruno and Hanor (2003) study area. From Bruno and Hanor (2003).
A study of fluid migration pathways in the Louisiana portion of the Gulf Coast (Hanor and Sassen, 1990) led to the discovery of biodegraded crude oils to a depth of about 5000 ft (~1500 m), which was interpreted as evidence for the downward migration of oxygenated meteoric waters. This is another possible source of water for salt dissolution, and salinity results from this study show an area around well #J1 where less saline (perhaps more oxygen rich?) waters are found to a depth of approximately 5000 ft (~1500 m) near the top of the salt dome. Temperature results are consistent with the downward migration of cooler waters around borehole #J1, and it is also near a location on the salt dome that appears to be an area of preferential dissolution as one of the high salinity plumes originates there. Although geochemical data of the crude oils in this area were unavailable for this study, such data would be of great interest for future studies.

The low salinity anomaly found at well #F1 does not have a corresponding temperature anomaly, and it is not in a location that places it near a point of origin for any of the high salinity plumes mapped. This indicates that this is not an area of downward fluid migration. There are many potential explanations for the dramatic difference in salinities between well #F1 and the wells to the north and south of well #F1. One possible explanation is that well #F1 passes through an area of low permeability that acts as a stratigraphic barrier to fluid migration. As mentioned previously, the Bay Marchand field is complexly faulted containing many growth faults, radial faults, and graben features (Frey and Grimes, 1970; Snively and Sarwar, 1988). Well #F1 may be located in a graben with sealing faults preventing the migration of saline rich waters through this area. As previously discussed, the low salinity pore waters found at #F1 may be remnant from fresh water flushing during the last ice age.
Salinity reversals beneath some of the plumes mapped appear to reflect the mixing of the high salinity waters in the plumes with the normal marine (35 g/L) salinity waters that are usually found in marine sediment. In some cases, below this mixing zone is a return to salinities near 35 g/L. This is different from the results of Bruno and Hanor (2003) that show a correlation between salinity reversal and the top of geopressure, and may indicate that the salinity reversals rely more on lithology than pressure regime.

Previous studies have found that depending on the ability of a fault to seal, abrupt changes in salinity across a fault are a possibility (Figure 26) (Bruno and Hanor, 2003). Though Figure 23 indicates that the plumes in this study are likely to be confined in the horizontal sense by first order faulting, many studies indicate that Bay Marchand is much more complexly faulted than this, implying that the plumes mapped in this study must extend across some amount of faulting. At this scope it is unclear whether or not the salinity contours would be offset by the faulting. Refinement of this study utilizing seismic data and fault mapping may provide insight into the effect of second order faulting and the complexity of fluid migration in this region.

Results of this study indicate that four high salinity plumes have migrated radially away from the Bay Marchand salt dome a result of halite dissolution near the crest of the salt dome. Lithology is a major controlling factor on the extent and pathways of the plumes, as the plumes migrate down dip along blocky sands. The lack of geopressure in this study area indicates that the upward expulsion of fluid as a source of water as seen near other salt features is not likely. Instead, downward migration paths, possibly along faults, are supported. The plumes migrating to the southeast and northeast are associated
with cooler temperature anomalies, further indicating the downward migration of cooler water near their respective points of origin on the salt dome.
REFERENCES


Ingram, R.J., 1991. Salt tectonics: Introduction to Central Gulf Coast Geology, p. 31-60.


**APPENDIX I: LIST OF WELLS USED IN THIS STUDY**

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APPENDIX II: A SAMPLE CALCULATION

The raster log from borehole #55 is shown below with sands highlighted in yellow and depths where SP measurements were taken marked with a red x. A millimeter deflection from the baseline (drawn in blue) was recorded, and a conversion of 2.375 millivolts/millimeter was calculated. Depth of measurement, depth of top and base of the logging run, mud weight, BHT, $R_m$, $T_m$, $R_{mf}$, and $T_{mf}$ were also recorded.

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APPENDIX III: A CLOSER LOOK AT WELL #A1

The salinity calculations made from the SP log of well #A1 were eliminated from the results of this study due to suspicion that there was an error with the logging tool. The resistivity log gave no indication that fresh water was present in the borehole which would have cause the SP log to record porous sandy intervals as a positive swing in SP when we are used to seeing them as a negative swing in SP when brackish water is present. The log from a nearby borehole, #30 (listed in Appendix 1), was examined to see if it might verify the results from #A1. Note that #A1 was drilled and logged in 1949, and #30 in 1984. The results from #A1 were not confirmed. Well #30 was not included in the cross sections either because it contained only 4 points of salinity measurement. The above reasons plus the age of the log in #A1 led to the decision that it should be left out of the results section.
APPENDIX IV: A CLOSER LOOK AT WELL #F1

Well #F1 gave salinity results that varied from the pattern of many of the other wells in the study enough to raise question about the validity of this log. Though the results from #F1 were included in the salinity contouring, it is important to show the variations that were produced by looking into salinity calculations from two side tracked wells, #F3 and #F5. Both of these sidetracks, including the original hole #F1, were drilled and logged in 1950, all using similar drilling mud compositions as indicated by the log headers. The cross sections below show all three well paths on each, but are separately contoured for #F3 and #F5, assuming that particular well has correct data, and disregarding the other two logs. Well #F1 can be seen in Figure 8. What we see is that though the results do vary and change the contours significantly around the three boreholes, there is little effect on the rest of the cross section. Regardless of which cross section one assumes to be “true”, there is a consistent and sharp downward inflection of the salinity contours around well #F1. For the scope of this study, this was determined to be sufficient evidence for the general pattern of salinities, though the exact values certainly have error.
Figure IV.1. Salinity cross section A-A' using the results from wells #F3 and #F5, respectively. Yellow dots indicate depths at which salinity calculations were made. Contoured by hand.
VITA

Laurie Beth Richards was born in 1985 in Tulsa, Oklahoma. She graduated from Booker T. Washington High School in Tulsa in May 2004 after completing her senior year at School Year Abroad in Beijing. After two years of studying Chinese at Trinity University in San Antonio, Texas, a chance job working for a small oil company led to a renewed interest in all things science, and in August 2006 she returned to Oklahoma to study geophysics at the University of Tulsa. After earning a Bachelor’s of Science in Geosciences in December 2008, Laurie took a short break from her academic career and moved to New Orleans, Louisiana. In January 2010, Laurie began her studies at Louisiana State University under Drs. Jeffrey Nunn and Jeffrey Hanor, and will graduate with a Master of Science in geology in May 2013.