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Chapter 8

The Characteristics of Geopressure Profiles in the Gulf of Mexico Basin

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ABSTRACT

This paper is a summary of our work on the relationship between undercompacted shale and abnormal pressure in the Tertiary portion of the Gulf of Mexico Basin. A major objective of this study is to map the depth to the top of the undercompacted shale, as located using shale density (cuttings samples), conductivity, sonic, plus bulk density logs relative to the depth to the top of abnormal pore pressure as determined using bottom-hole pressure (BHP) and repeat formation tester (RFT) data. Geopressure profiles (formation pressure versus depth curves) were most useful for such mapping because the geopressure profiles showed linear segments in which pressure gradients were constant. Although the top of abnormal pressure and the top of undercompaction sometimes occur at the same depth in a given field area, often these boundaries are separated by hundreds of feet (tens of meters) and in some cases by vertical distances of over 2000 ft (600 m). Two types of field areas in the Tertiary portion of the Gulf of Mexico are distinguished based on whether or not the top of undercompaction and the top of abnormal pressure correspond. Tertiary fields have geopressure profiles characterized by pressure gradients showing either three (the Alazan-type field) or four (the Ann Mag-type field) linear segments. One consequence of our work is that electropressure methods which assume that the top of abnormal pressure is always coincident with the top of the zone of undercompaction are unreliable when used for a quantitative estimate of geopressure.

INTRODUCTION

Upon the discovery that shale properties correlate, at least indirectly, with formation pressures, researchers proposed techniques for estimating virgin reservoir pressure in sandstone beds by the analysis of electric logs of adjacent shale beds (Wallace, 1964; Hottman and Johnson, 1965; MacGregor, 1965; Foster and Whalen, 1966; Ham, 1966; Mathews and Kelley, 1967; Fertl, 1976). Electric logs detect changes in shale properties (i.e., conductivity and sonic velocity) that vary as a function of shale porosity. In general, porosity of a shale decreases with depth as water is displaced by cementation of pores and squeezed out by mechanical compaction in response to overburden weight (Bradley, 1986). If water is unable to escape, further compaction is impeded, and with addition of overburden, the shale is said to become undercompacted. The zone of low-density shale is known as the zone of undercompaction and consists of shales having anomalously high porosity and concomitant low density associated with a high water content. The word *undercompaction* is used because shale density in the undercompacted zone is lower than it would be for normal compaction at the depth in question. The basis for estimating formation pressure using logs, electropressure techniques, is that shale compacted under hydrostatic conditions exhibits a characteristic density, acoustic travel time, or conductivity which changes as a function of depth of burial, depending on the age of the shale. A common expectation in the literature is that a divergence from those electric log signals expected for normally compacted shale indicates undercompaction and presumably marks a concomitant buildup of abnormal fluid pressure (Hottman and Johnson, 1965).

The thesis of this paper is that undercompaction as detected by electric logs does not necessarily signal the top of abnormal formation pressure. To show this we map the relationship between depth to the top boundary of abnormal pressure and depth to the shale density reversal as signaled by electric logs. At the same time we examine the characteristics of formation pressure as a function of depth in the Tertiary portion of the Gulf of Mexico.

THE GEOLOGY OF THE NORTHERN GULF OF MEXICO

Our study in the northern Gulf of Mexico Basin focuses on 20 oil and gas fields divided into two groups: onshore South Texas fields and offshore Texas and Louisiana fields (Figure 1). Fifteen of the 20 fields are located in the Tertiary oil- and gas-producing trends of South Texas, geologically a part of the Rio Grande Embayment. Onshore South Texas is characterized by rapid Eocene and Oligocene deltaic sedimentation and a complex system of coastward-dipping syndepositional growth faults that become progressively younger to the east and toward the Gulf. The thickest regressive sequences of the Eocene–Oligocene deltaic sedimentation are thick progradational wedges of sand deposited during the late Paleocene–early Eocene (Wilcox) and the mid- to late Oligocene (Frio–Vicksburg). During Frio–Vicksburg time, the Rio Grande Embayment was filled by the Norias delta system that deposited thick sections of sand throughout the area.

The second group of Gulf Coast fields is situated in the heart of the Plio-Pleistocene producing trend (offshore Texas and Louisiana). Fields in this area are generally larger and situated on salt domes or involved tectonically with salt. Some of these fields are located close to the axis of the Mississippi River delta and thus are in areas of rapid and thick late Tertiary sedimentation. Rapid deltaic sedimentation, growth faults, and salt domes characterize the depositional and structural style of the offshore Texas and Louisiana area. Fields in the Plio-Pleistocene trend allow analysis of abnormal pressure and compaction in areas of extremely high recent sedimentation rates with active salt tectonism.

METHOD OF DATA COLLECTION

Compaction and formation pressure data were collected from 20 oil and gas fields to determine the depths to the top boundaries of the undercompacted shale zone and the abnormal pressure. The data are then compiled in the form of pressure-depth profiles for further analysis.

Determination of Top of Undercompaction

The depth to the top boundary of the undercompacted zone was identified using a combination of conductivity, sonic, and density logs. The top boundary is defined as an abrupt increase in electrical conductivity, an increase in sonic travel time, and a drop in density, all of which are associated with a retention of pore water in the undercompacted shales (Fertl, 1976; Magara, 1978; Leftwich, 1993).

An initial electric-log database of compaction plots consisting of 471 conductivity plots, 232 sonic log plots, 119 shale density plots, and 46 density log plots was provided by various oil companies. Additional plots were prepared from logs purchased from Petroleum Information Service (PI). A mean depth to the top of undercompaction was determined for each field by using the compaction plots on several wells in each field area. A well-by-well compilation is given in Leftwich (1993).

Determination of Depth to Top of Abnormal Pressure

Geopressure profiles (pressure-depth curves) were constructed largely from original shut-in bottom-hole pressure (BHP) measurements recorded in numerous wells within each field. Such data were recorded by the various operators during the completion and production phases of each well and are available through a Houston-based company, Petroleum Information Service (PI). In some cases repeat formation tester (RFT) and other wireline (WLT) pressure data supplemented the BHP data.

Geopressure profiles for many fields show several segments having linear trends. As a consequence, we computed a best fit or we hand-fitted a line to linear segments of the pressure-depth profiles. A pressure gradient for each segment was then calculated and recorded on each plot. The depth of the top of abnormal pressure, a break in slope of the geopressure profiles, was determined for each field by visual inspection to ±100 ft (±30.48 m).

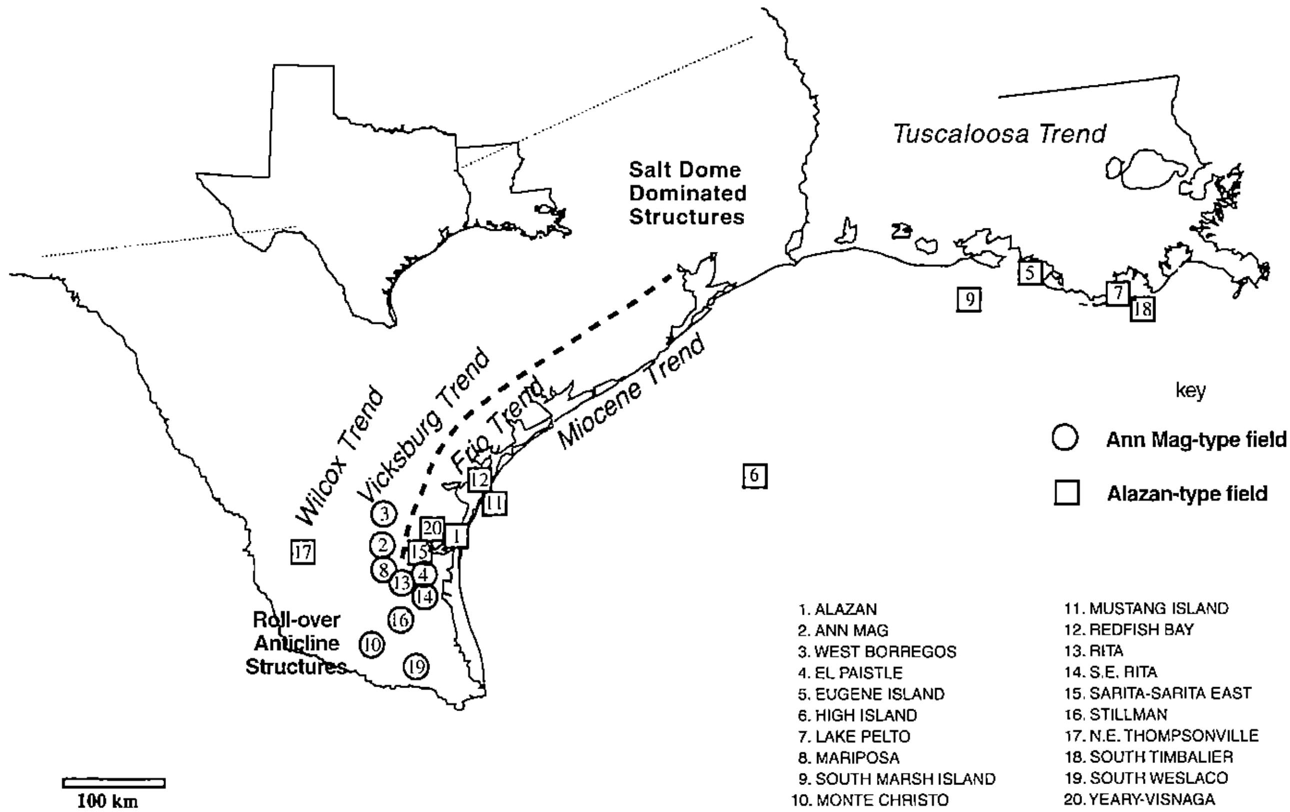

Figure 1. Map of Gulf Coast oil and gas fields for which geopressure profiles have been compiled in this paper. Ann Mag-type and Alazan-type fields are distinguished on this map.

OBSERVATIONS

A Case Study: The Ann Mag Field

The Ann Mag field is operated by Maguire Oil Company of Dallas, Texas, and is located in Brooks County, Texas. Geologically, the field is situated in the Frio–Vicksburg trend of the South Texas Rio Grande Embayment (Figure 1). This field exhibits a typical example of the structure, stratigraphy, and geopressure development observed in many onshore fields of the northwestern Gulf of Mexico Basin. In addition, the Ann Mag field is fairly well developed and contains many abnormally pressured wells in which the operator has made numerous wireline (WLT) and bottom-hole pressure (BHP) measurements. Furthermore, Maguire Oil Company graciously granted complete access to all available logs, detailed well files, cuttings samples, and cores on all wells in the field.

Top of Undercompaction

The top of undercompaction was identified in Ann Mag field wells from electric log conductivity plots (Leftwich, 1993). Using these tops of undercompaction the mean top of the zone of undercompaction in the Ann Mag field was established at 8980 ft (2737 m). The conductivity anomalies (tops of undercompaction) identified on plots of Ann Mag field wells illustrate that there is a relationship between the sand-shale stratigraphy and the top of undercompaction in the Ann Mag field. These logs show that the top of the undercompacted zone starts at depths where sands become less abundant above long shale sections (Leftwich, 1993).

Top of Abnormal Pressure

A geopressure profile constructed for the Ann Mag field allows us to identify the top of abnormal pressure at a depth of approximately 7500 ft (2286 m). The most striking feature of the Ann Mag pressure-depth profile is that it is divided into four linear segments with characteristic pressure gradients (Figure 2). The top segment is the normal pressure gradient of 0.445 psi/ft (10.1 MPa/km). Immediately below the top of abnormal pressure is a normally compacted section with a pressure gradient of 1.094 psi/ft (24.7 MPa/km). Below the top of undercompaction is a section with a high gradient of 2.391 psi/ft (54.1 Mpa/km) down to a depth of approximately 10,500 ft (3200 m). The deepest section has a pressure gradient of about 0.84 psi/ft (18.9 MPa/km) that is poorly constrained because of the small number of data points. When encountering these linear pressure-depth segments in other fields, they are labeled as segments ONE through FOUR

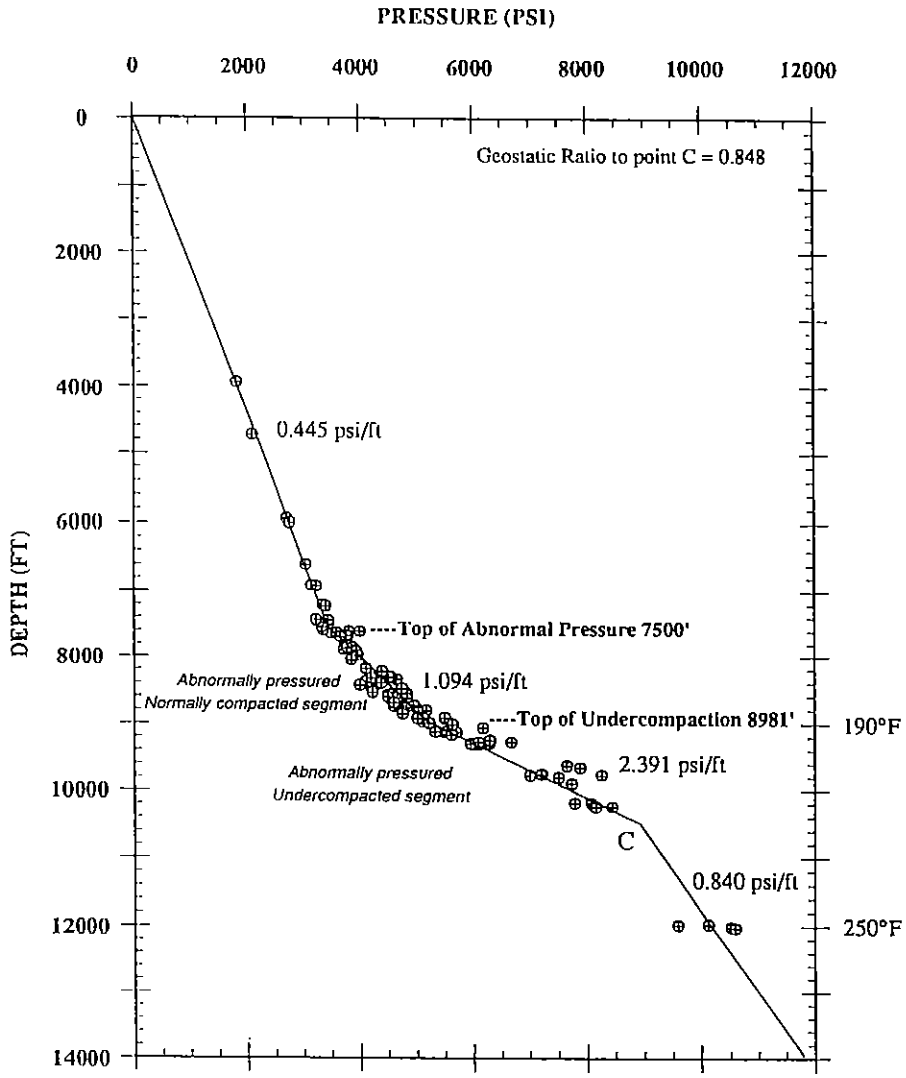

Figure 2. The geopressure profile for the Ann Mag field, Brooks County, Texas. Database includes BHP and RFT tests (5 data points excluded).

moving downward in a field. Segment FOUR is better defined in other fields where more data exist. Note that the mean top of the zone of undercompaction in the Ann Mag field at a depth of 8980 ft (2737 m) is 1480 ft (451 m) below the mean top of abnormal pressure in this field.

The skeptic will undoubtedly argue that the raw data in Figure 2 follow a curve more like the "lazy S" of Chapman (1980). However, Figure 2 is the compilation over an entire field. Pressure data from single wells serve as the best evidence for linear segments in pressure-depth profiles. Pressure segment TWO for the Rupp 1 well is particularly well defined (Figure 3). A computer-calculated curve fit to the data points comprising this segment indicates a linear curve fit with a regression coefficient of 0.993. An abrupt change in pressure gradient that occurs in going from the normally pressured section to the abnormally pressured section is also consistent with linear pressure-depth segments. Furthermore, the change from normal compaction to undercompaction occurs abruptly, rather than gradually. This abrupt change is also accompanied by an abrupt change in pressure gradient in going from pressure segment TWO to pressure segment THREE in the Ann Mag field.

Geopressure profiles were constructed from a number of wells at various locations on the structure that define the field. Because the depth to sandstone beds within each field is controlled by structure, the local structure must affect the geopressure profiles as is seen in two wells from the Ann Mag field, the Rancho Neal Rupp 1 and the Maguire Oil Sullivan 9 (these wells are 2200 ft apart) (Figure 4). The two wells are structurally the same down to approximately 8200 ft with their pressure versus depth curves essentially coincident (point A, at a depth of 8225 ft). Below point A, the Sullivan 9 well gradually gains structure relative to the Rupp 1 well, and a log correlation of the two wells at a mean depth of 8565 ft reveals that the Rupp 1 is 50 ft high to the Sullivan 9 well. At a depth of 8565 ft the geopressure profile for the Sullivan 9 well is offset approximately 90 ft high relative to the Rupp 1 geopressure profile. The difference in structure between the two wells accounts for the offset in the pressure curves. As the depth increases, the structural difference between the two wells

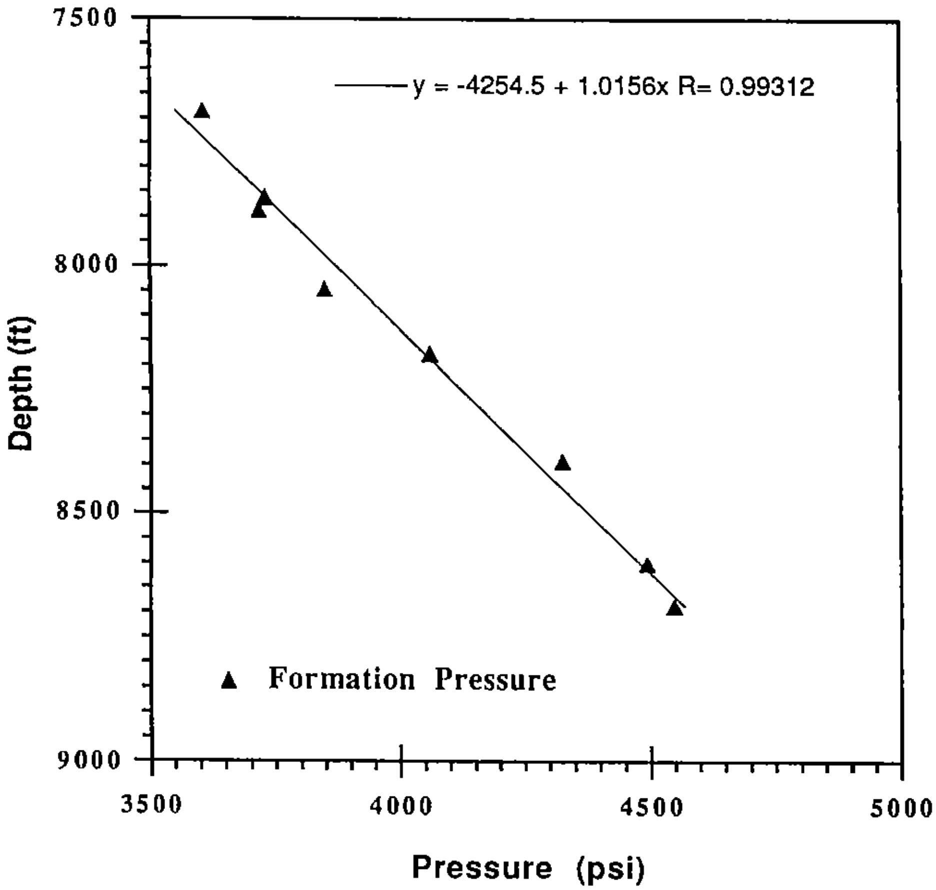

Figure 3. Geopressure profile segment TWO for the Rancho Neal Rupp 1 well in the Ann Mag field, Brooks County, Texas. Database includes RFT tests.

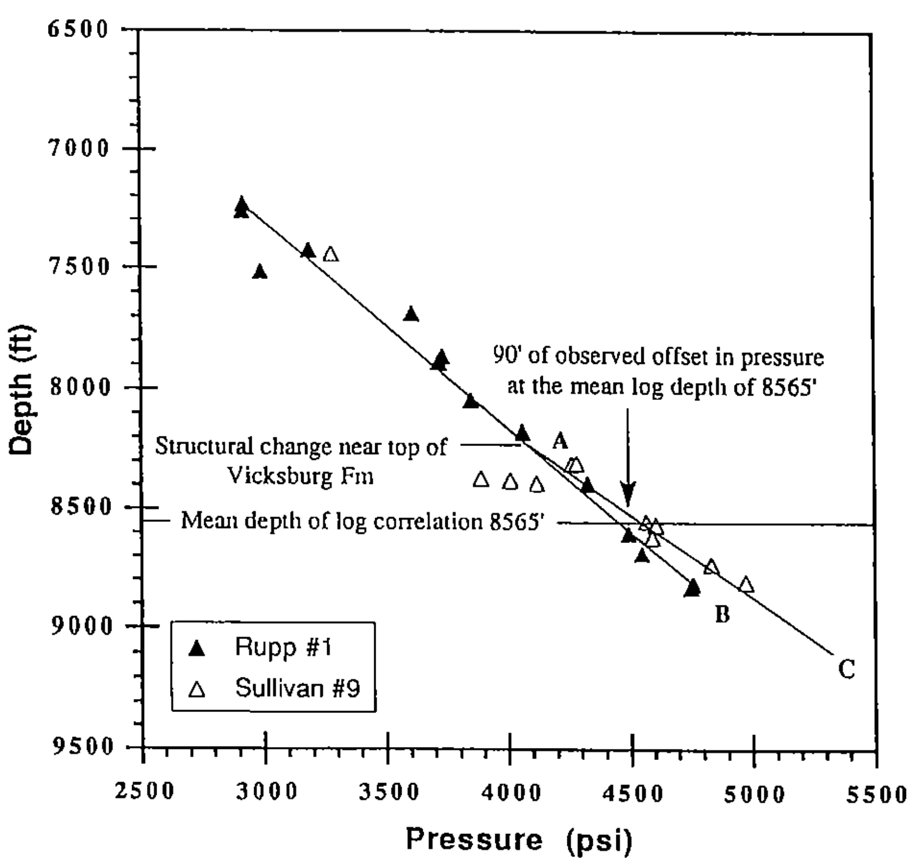

Figure 4. Geopressure profiles for the Rancho Neal Rupp 1 and the Maguire Oil Sullivan 9 wells in the Ann Mag field, Brooks County, Texas. This plot demonstrates the effects of structure on geopressure profiles.

increases and the separation between the pressure profiles increases. The structural relief in the 20 field areas of this study was on the order of a few hundred feet and this added an apparent scatter to the pressure data in a given geopressure profile.

In summary, the Ann Mag field shows four linear pressure segments with the top of undercompaction defining the boundary between segments THREE and FOUR. Although the fourth segment is poorly constrained in the Ann Mag field due to lack of data, a linear trend is well constrained in other Tertiary fields.

Undercompaction in the Gulf of Mexico Basin

Log Correlations

Various logs from the same well may indicate slightly different depths to top of the zone of undercompaction. Hence, it is important to establish that the depth to undercompaction obtained by any one of the four logs (i.e., conductivity, shale density [from cuttings], sonic, and bulk density) is, within a given tolerance, the same as that obtained from the other logs. To establish the reliability of individual logs as a measure of the top of undercompaction, a large industry database was searched and evaluated. The study confirms that the depths to the top of undercompaction as indicated by the different logs are consistent within the same wellbore to ±500 ft (Leftwich, 1993).

Correlation of undercompaction across a field is another problem. The top of undercompaction does not correlate with any particular time-stratigraphic boundary across a field, but rather correlates very well to the top boundary of certain thick marine shale lithostratigraphic units. Variations in the depth to the top of undercompaction in a given field are largely associated with variations in structure through the field. One reason for this is that the growth faults and their associated folds in a given field cause offsets and variations in the depth to the controlling lithostratigraphic unit, which in turn causes variations in the depth to the top of undercompaction. These differences in elevation of the top boundary of undercompaction in a given field lead to correlations across fields of no better than 500 ft (154 m).

A Data Compilation

We compiled data on undercompaction and formation pressure from 20 fields in the Gulf of Mexico Basin (Leftwich, 1993). In some fields (e.g., El Paistle and Alazan) the top of undercompaction varies as much as 2000 ft (610 m) from well to well, whereas in other fields (e.g., Ann Mag) the well-to-well variation is less than 500 ft (154 m). In a large number of cases the top of abnormal pressure and the top of the zone of undercompaction do not occur at the same depth in a given well or field. The top of abnormal pressure may occur above the top of undercompaction, may be coincident with the top of undercompaction, or may be below the top of undercompaction. The next question concerns the nature of the geopressure profile associated with these three cases.

Geopressure Profiles in the Gulf of Mexico Basin

Ann Mag-Type Fields

The quantity and depth distribution of pressure data vary from field to field. However, enough data are available to show that the Ann Mag field geopressure profile is typical of fields in which the top of undercompaction is below the top of abnormal pressure. Another example of a field with the top boundary of abnormal pressure above the top boundary of undercompaction is the South Weslaco field in Hidalgo County, Texas (Figure 5). A pressure-versus-depth plot for this field was constructed using RFT and bottom-hole pressure (BHP) data. The field is normally pressured (0.458 psi/ft. or 10.4 kPa/m gradient) down to a depth of approximately 7500 ft (2300 m). The top of the undercompacted zone was established using electrical conductivity methods and was found to occur in the main portion of the field at a depth of 9000 ft (2770 m). Again a separation is observed between the top of abnormal pressure and the top of undercompaction, which in this case is approximately 1500 ft (462 m). A straight line fit to the abnormally pressured data shows a gradient of 1.512 psi/ft (34.2 kPa/m). In the Weslaco field the available pressure data define two linear segments (i.e., segments ONE and TWO). Only two of the four linear segments appear because there are no pressure data below the top of undercompaction.

The West Borregos field (Figure 6) reveals another example suggesting that pore pressure increases in linear segments with depth. The stratigraphic section containing hydrostatic pore pressures has a pressure gradient of 0.450 psi/ft (10.2 kPa/m) down to 6050 ft (1844 m). From 6050 ft (1844 m) down to 7900 ft (2408 m), the uppermost abnormally pressured segment consists of normally compacted sediments but has a pore pressure gradient of 0.944 psi/ft (21.4 kPa/m). Below 7900 ft (2408 m) in the abnormally pressured and undercompacted section of the West Borregos field, the pore-pressure gradient is much higher, 3.650 psi/ft (82.6 kPa/m). At the West Borregos field three linear segments are defined (i.e., segments ONE, TWO, and THREE). The fourth linear segment may exist at depth but wells in the field are not deep enough to measure it.

In Monte Christo (Figure 7), where a large number of pressure measurements exist, four pressure-depth segments (segments ONE, TWO, THREE, and FOUR, respectively) are defined. Pressure segment FOUR (0.706 psi/ft) is better constrained than in the Ann Mag field. In the three fields mentioned above—South Weslaco, West Borregos, and Monte Christo—the gradient of pressure segment TWO is 1.512, 0.994, and 1.231 psi/ft, respectively. These gradients, which fall between the top of abnormal pressure and the top of undercompaction, are lower than the gradients of pressure segment THREE of the Ann Mag and Monte Christo fields. Four-part segmentation is apparent where enough pressure data exist to delineate the pressure-depth profiles and where the top of abnor-

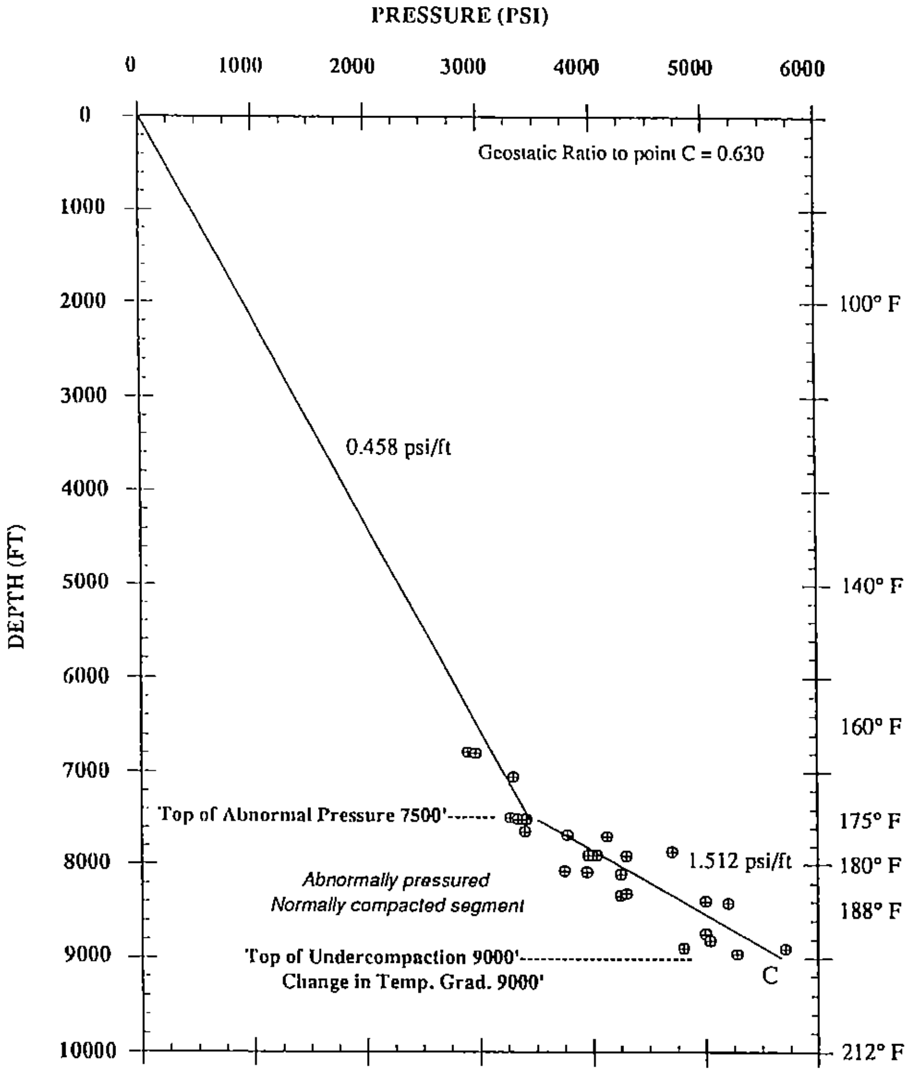

Figure 5. Geopressure profile for the South Weslaco field, Hidalgo County, Texas.

mal pressure occurs above the top of undercompaction. We have labeled these segments as ONE, TWO, THREE, and FOUR from top to bottom. Gulf Coast fields having a pressure segment TWO are classified as Ann Mag-type fields.

Alazan-Type Fields

In the Alazan field (Figure 8) the top of undercompaction occurs at essentially the same depth as the top of abnormal pressure. Three segments exist with the middle segment having a pressure gradient as high as that of segment THREE in the Ann Mag and Monte Christo fields. Segments in the Alazan field are equivalent to segments ONE, THREE, and FOUR in the Ann Mag and Monte Christo fields. Segment TWO is missing because the top of abnormal pressure and the top of undercompaction are coincident. Fields with segment TWO missing are classified as Alazan-type fields.

The distribution of Ann Mag-type and Alazan-type fields is shown in Figure 1. The preliminary results from the South Texas region suggest that Ann Mag-type fields (generally Vicksburg sandstones, i.e., older) are indeed found further west and down section from Alazan-type fields (generally Frio sandstones, i.e., younger). The dashed line in Figure 1 divides the Frio and Vicksburg trends. While this line divides Ann Mag-type and Alazan-type fields in South Texas, such a division to the northeast is yet to be tested.

DISCUSSION

Electropressure techniques to quantify subsurface pressures led to the common notion that the top of abnormal pressure and the top of the undercompacted zone occur at the same depth. Such a notion was reinforced by the assumption that all of the sediments on the normal compaction trend were always normally or hydrostatically pressured. We have now shown using wireline-test pressure data that this assumption is incorrect. In some fields the top of abnormal pressure

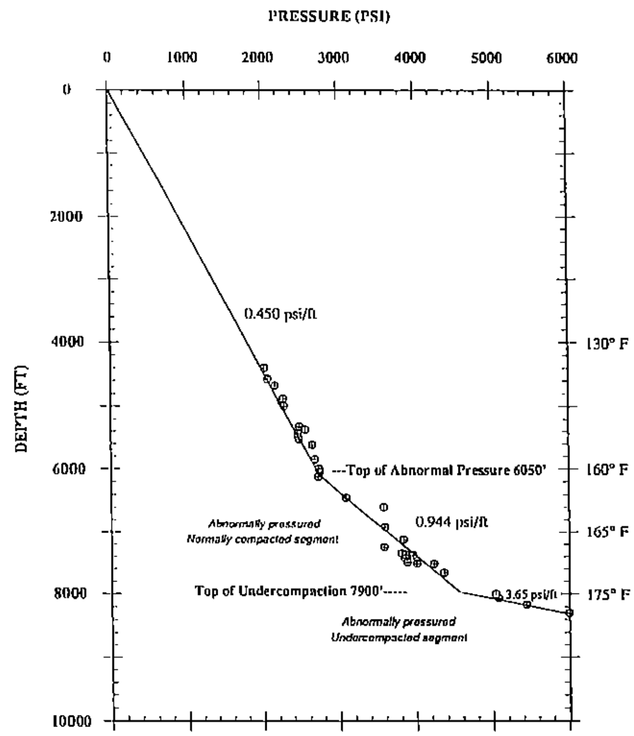

Figure 6. Geopressure profile for the West Borregos field, Kleberg County, Texas.

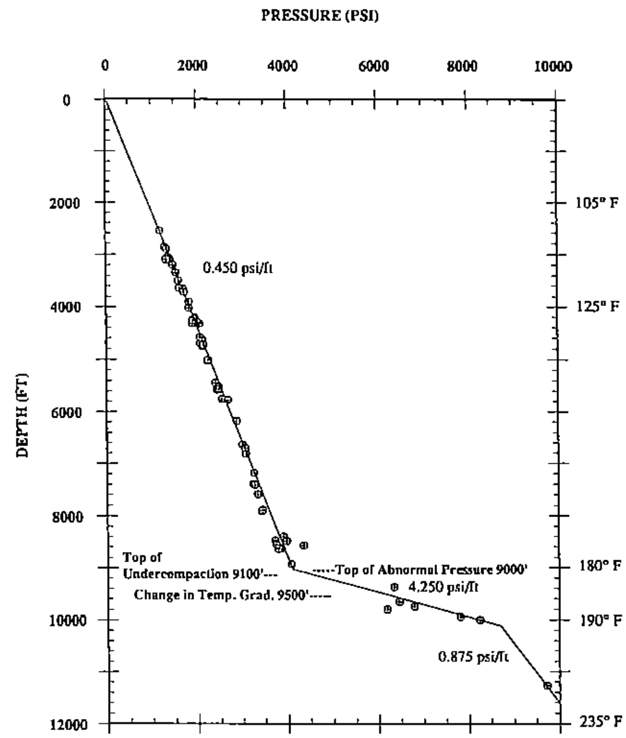

Figure 8. Geopressure profile for the Alazan field, Kleberg County, Texas.

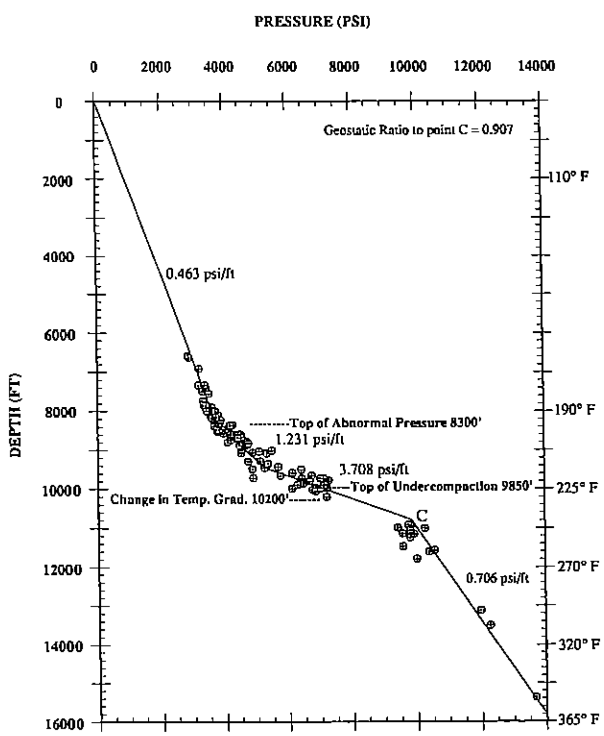

Figure 7. Geopressure profile for the Monte Christo field, Hidalgo County, Texas. (100 BHP measurements from 87 wells with 11 data points excluded.)

and the top of undercompaction occur at the same depth; in most cases they are separated. The separation varies from field to field and usually averages about 1000 ft (308 m), but separations as great as 2500 ft (770 m) are observed.

Pore-Pressure Gradients

Calculated pressure gradients were determined for the top three pressure segments of 13 of the 20 field areas studied (Leftwich, 1993). Based on the pressure gradients, four pressure-compaction states can be identified: normally pressured, normally compacted; abnormally pressured, normally compacted; abnormally pressured, undercompacted; and normally pressured, undercompacted sediments. The gradients for pressure segments TWO and/or THREE of each field are plotted against the separation between the top of abnormal pressure and depth to the top of undercompaction for each area (Figure 9). Abnormally pressured, undercompacted sections invariably contain pressure gradients (segment THREE) that are higher than pressure gradients found in normally compacted but abnormally pressured sections (segment TWO) (>2 psi/ft [45.3 kP/m] versus ≈ 1 psi/ft [22.6 kPa/m]). In fields where undercompaction and the top of abnormal pressure are nearly coincident, pressure segment TWO is missing and the pressure gradient jumps immediately to values in excess of 2.0 psi/ft (45.3 kP/m) (i.e., Alazan and Yeary fields).

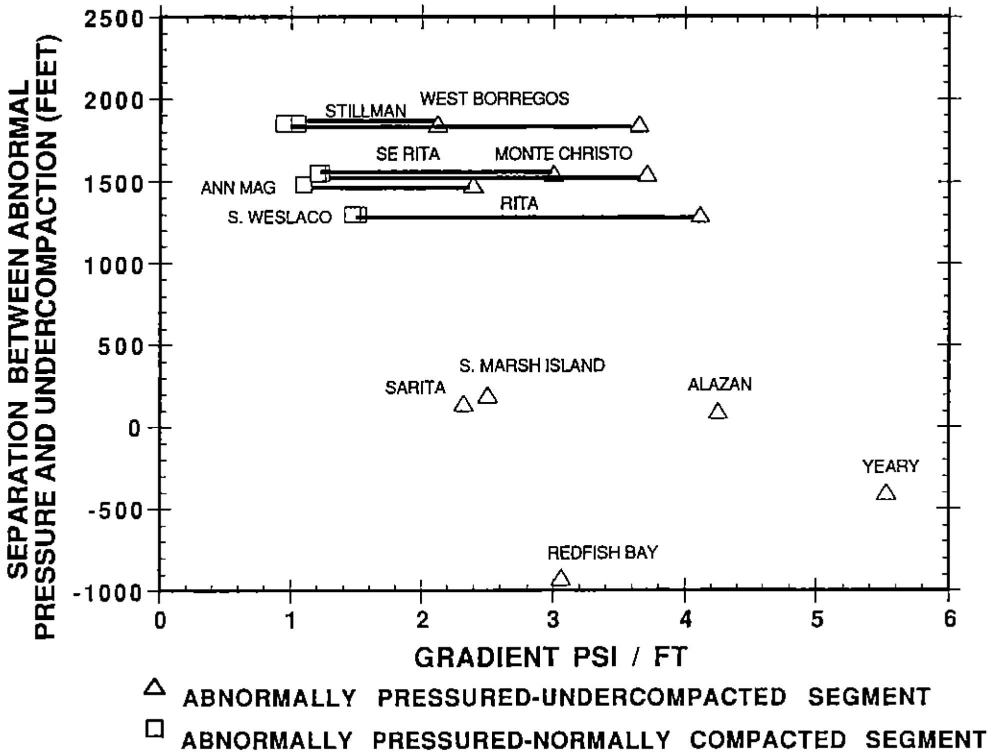

Figure 9. Gradients of segments versus the separation between the top of abnormal pressure and the top of undercompaction. The square symbols on the plot represent the gradients of the abnormally pressured, normally compacted sections plotted as a function of the corresponding separations between the top of abnormal pressure and undercompaction. The triangular symbols represent the gradients of the abnormally pressured, undercompacted sediments plotted as a function of the corresponding separations. Fields showing both an abnormally pressured, normally compacted section and the abnormally pressured, undercompacted section are plotted with both gradient symbols connected by a line. Other fields plotted with only one symbol are areas where there are data from either the abnormally pressured, normally compacted segment or the abnormally pressured, undercompacted section but not both.

The incremental increases in pressure gradients that were observed in the Gulf of Mexico can be modeled using layers of different hydraulic conductivity. Variations in hydraulic conductivity in the overburden section are in turn principally a function of the sand-shale ratio and the distribution of sand and shale in the overburden section (Leftwich, 1993). Generally, the more sands in the section the higher the hydraulic conductivity. The hydraulic conductivity of the normally pressured, normally compacted section is higher than that of the abnormally pressured, normally compacted section. Further, the hydraulic conductivity of the abnormally pressured, normally compacted section is higher than that of abnormally pressured, undercompacted section. The three different pressure-compaction regimes indicated on the Ann Mag-type curve shown in Figure 10 might be thought of as layered with respect to hydraulic conductivity, where $K_1 > K_2 > K_3$. This three-layer model is similar to that presented by Wallace et al. (1979) for the correlation between gross lithology and fluid pressure.

The hydraulic conductivity of the undercompacted zone (K_3) has the lowest value, and this fits well with observation because undercompaction usually occurs in a geologic sequence where rocks of lowest permeability predominate, i.e., marine shale sections. In the West Borregos field the top of the Jackson marine shale occurs at approximately 7900 ft (2408 m), which is the same depth as the occurrence of the top of undercompaction (Leftwich, 1993). Likewise, in the Ann Mag field (Figure 2) the top of undercompaction that occurs in this area at 8980 ft (2737 m) is coincident with the top of a thick marine shale section which occurs in the field at that depth.

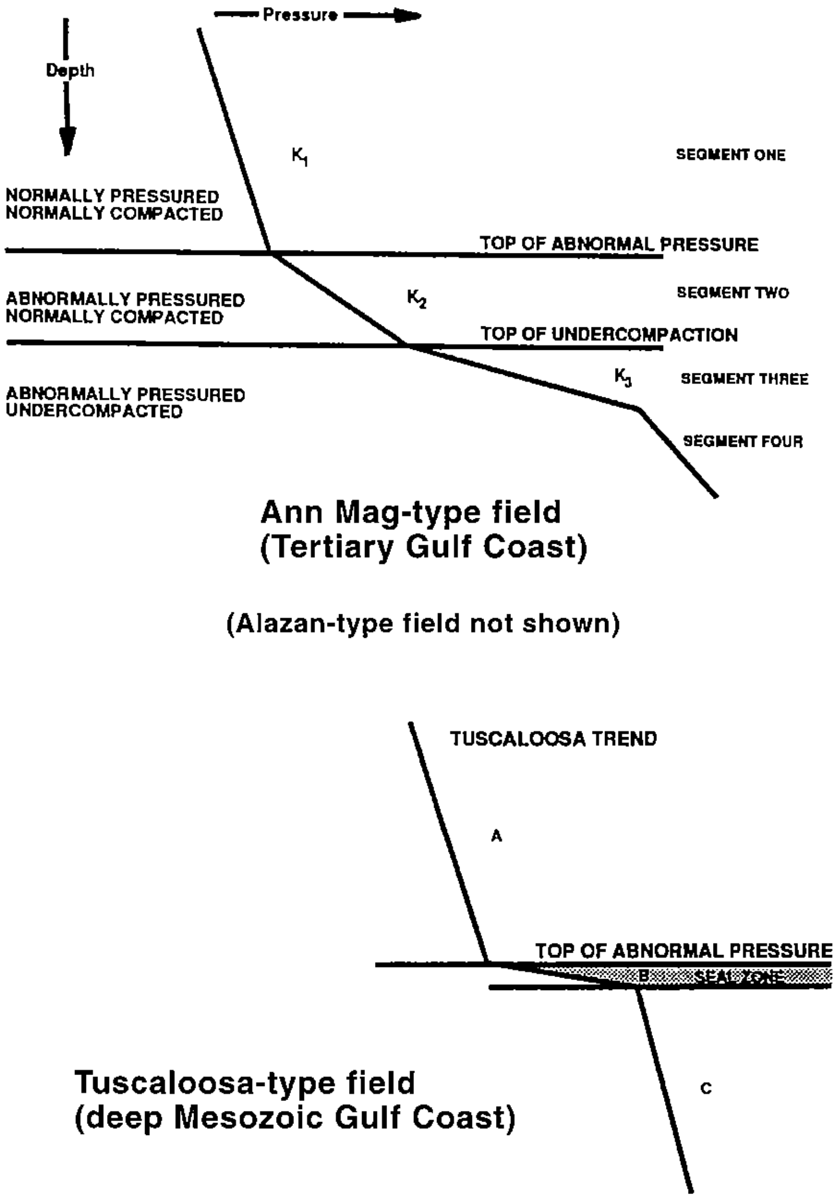

Figure 10. Ann Mag-type (Gulf Coast Tertiary) and Tuscaloosa-type (Louisiana Cretaceous) (Weedman et al., 1992) geopressure profiles. Also shown are three possible pressure-compaction states and hydraulic conductivities where $K_1 > K_2 > K_3$.

Gulf Coast Tertiary Versus Cretaceous Tuscaloosa Geopressure Profiles

Both types of Tertiary geopressure profiles are distinct from those encountered in older rocks of the Gulf of Mexico where a pressure seal cuts through thick Cretaceous sand bodies within the deep lower Tuscaloosa trend of Louisiana (Weedman et al., 1992a, b). The distinction in geopressure profiles is attributed to differences in lithology, stratigraphy, and seals. Geopressure profiles in the deep Tuscaloosa sandstones are characterized by a much thinner pressure transition (≈ 60 ft) (i.e., a pressure seal à la Powley, 1990) where the local pressure gradient is as much as 19 psi/ft (0.43 MPa/m) (pressure segment B of Figure 10). We know less about the shallower Tertiary geopressure profile above the Tuscaloosa trend, but we know that it is overpressured at depths of ~14,000 ft, with a regression to normal pressure at the top of the lower Tuscaloosa Formation. Tuscaloosa-type geopressure profiles are characteristic of pressure compartments (Hunt, 1990) with pressure segments A and C having a gradient of about 0.45 psi/ft, which is characteristic of freely communicating pore fluid in relatively permeable rocks. Above pressure segment A of the Tuscaloosa-type geopressure zone, there is a shallower abnormal pressure zone that could be characterized by either an Ann Mag or Alazan geopressure profile. The present data are too sparse to distinguish between the two.

In comparing Tuscaloosa-type and the two Tertiary geopressure profiles, pressure segments A and ONE are the same. While pressure segment C has a hydrostatic gradient, it is distinguished from pressure segment A by abnormal fluid pressures and it does not have the same pressure gradient as pressure segment FOUR. Likewise, pressure segments B, TWO, and THREE are all distinct from each other (Figure 10).

Table 8-1. Ranges for pressure gradients for each pressure segment.

Segment:	ONE & A	TWO	THREE	FOUR	B	C
Gradient :	0.46–0.48	0.9–1.5	2.0–4.5	0.85–0.90	20.00 +	0.46–0.48

Thus, we have recognized that geopressures within the Gulf of Mexico are characterized by at least six different pressure segments. Table 8-1 gives ranges for pressure gradients for each of the six pressure segments in terms of psi/ft.

CONCLUSIONS

The top of abnormal pressure and the top of the zone undercompaction as indicated by shale density, sonic, and conductivity logs usually do not occur at the same depth at a given location. Rather, these tops in most wells are separated by hundreds of feet (tens of meters) and in some wells by vertical distances of over 2000 ft (600 m). Furthermore, the top of abnormal pressure is usually above or coincident with the zone of undercompaction, and therefore the zone of undercompaction in many cases is abnormally pressured. Since the top of abnormal pressure and the top of the zone of undercompaction are usually not coincident, the use of electropressure methods to determine geopressures quantitatively yields results that are in many cases inaccurate and unreliable. The Tertiary section of the Gulf of Mexico Basin is characterized by two geopressure profiles consisting of three or four linear segments. These are the Ann Mag-type profile with four segments and Alazan-type with three segments.

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